Featured Articles

Endoscopic and Nonendoscopic Approaches to Single-Level Lumbar Spine Decompression: Propensity Score Matched Comparative Analysis and Frailty Driven Predictive Model

Clinical Characteristics and Treatment Outcomes of Long-Level Intramedullary Spinal Cord Tumors: A Consecutive Series of 43 Cases
Dongao Zhang, Tao Fan, Wayne Fan, Xingang Zhao, Cong Liang, Yinqian Wang, Kun Wu

Technique of Distraction, Compression, Extension, Reduction to Reduce and Realign Old Displaced Odontoid Fracture From Posterior Approach: A Novel Technique
P. Sarat Chandra, Raghu Samala, Ramesh Doddamani, Satish Verma, Pankaj Singh, Mahendra Singh Chauhan

The Role and Future of Endoscopic Spine Surgery: A Narrative Review
Hyungjoo Kwon, Jeong-Yoon Park

Concepts and Techniques to Prevent Cervical Spine Deformity After Spine Surgery: A Narrative Review
Robert K. Merrill, John C. Clohisy, Todd J. Albert, Sheeraz A. Qureshi
Aims and Scope

Neurospine provides spine clinicians and researchers with peer-reviewed articles on basic and clinical investigation of spine and spinal cord to enhance patient management, education, clinical or experimental research, and professionalism. The journal will consider submissions in areas on craniocervical to lumbosacral spine including the followings: neuroscience and pain research, bone and mineral research, disc and joint research, bio and industrial technology, pathophysiology, risk factors, symptomatology, imaging, treatment, rehabilitation of spine, spinal cord and peripheral nerve diseases. Specifically, basic and technology researches include the most influential research papers from all fields of science and technology, revolutionizing what physicians and researchers practicing the art of spinal neurosurgery worldwide know. Thus, we welcome valuable basic and translational technology research articles to introduce cutting-edge research of fundamental sciences and technology in clinical spinal neurosurgery. Clinical or basic research articles, review articles, case reports, technical notes, and letters to the editor written in English will be accepted.

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From the Editor-in-Chief: Featured Articles in the March 2023 Issue

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In the March issue of Neurospine, we feature the articles listed below:

Technique of Distraction, Compression, Extension, Reduction to Reduce and Realign Old Displaced Odontoid Fracture From Posterior Approach: A Novel Technique
Chandra and colleagues investigated a new method of reducing the fractured displaced dens using a posterior only approach only in 14 patients with a displaced and irreducible old fracture dens causing cord compression (type I fracture, n = 11; type II fracture, n = 13). In the new method, the C1 arch was drilled and removed first, then the C1 lateral masses on both sides were completely drilled and a spacer was placed between the occiput and C2 facet. Intraoperative reduction was then performed, utilizing the spacer as a fulcrum, and achieving complete reduction.

Concepts and Techniques to Prevent Cervical Spine Deformity After Spine Surgery: A Narrative Review
Merrill and colleagues described current concepts and techniques for preventing postoperative cervical spine deformities. The most common cause of cervical spine deformity is iatrogenic. Therefore, this review emphasizes the importance of proper positioning, facet joint resection less than 50%, and preservation of C2 muscular attachments, reciprocal and compensatory cervical spine response to adult thoracolumbar and lumbar deformity correction.

Clinical Characteristics and Treatment Outcomes of Long-Level Intramedullary Spinal Cord Tumors: A Consecutive Series of 43 Cases
Zhang and colleagues analyzed a total of 43 consecutive patients with long-level intramedullary spinal cord tumors. Their long-level intramedullary spinal cord tumors were glioma (53.5%; ependymal tumors, 25.6%; low-grade astrocytic tumors, 20.9%; high-grade astrocytic tumors). In patients with ependymal tumors and low-grade astrocytic tumors, aggressive tumor resection did not increase the risk of long-term functional deterioration and allowed long-term survival, but in patients with high-grade astrocytic tumors, patients were at higher risk of neurologic deterioration and difficult recovery.

Endoscopic and Nonendoscopic Approaches to Single-Level Lumbar Spine Decompression: Propensity Score-Matched Comparative Analysis and Frailty-Driven Predictive Model
Kassicieh and colleagues compare endoscopic spine surgery (ESS) and non-ESS ap-
proaches for single-level lumbar decompression and proposes a frailty-driven predictive model for non-home discharge disposition. ESS for single-level lumbar decompression contribute to reduced operative time, hospital length of stay, and non-home discharge disposition.

The Role and Future of Endoscopic Spine Surgery: A Narrative Review

Kwon and Park describe that ESS will become more important for minimally invasive spine surgery in the future as the number of elderly and highly complex patients continues to increase and efforts to improve ESS techniques and apply new technologies will make ESS one of the best options for entire spine diseases by overcoming current ESS limitations.

- **Conflict of Interest:** The author has nothing to disclose.

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Strategies for Globalizing Endoscopic Spine Surgery

Ram K. Alluri, Jeffrey C. Wang
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The development of arthroscopic, endoscopic, robotic, and laparoscopic techniques has revolutionized the delivery of surgical care throughout the world. Particularly, arthroscopic techniques in musculoskeletal care now allow for patients to achieve similar outcomes with significantly less postoperative pain, faster recovery, and shorter hospitalization, compared to traditional open procedures. For a period of time, spine surgery has lagged behind other surgical specialties in the development of minimally invasive techniques that can achieve similar clinical outcomes as traditional open approaches. However, patient demand, market pressures, trends towards performing spine surgery in ambulatory surgery centers, and technological advances have increased the widespread adoption of minimally invasive spine surgery, particularly over the last decade.

Endoscopic spine surgery (ESS) is one of the least invasive spine surgery techniques currently available, allowing for decompressions and fusions through single or multiple sub-centimeter percutaneous incisions. The first generation of ESS was described in the late 1980s when Kambin incorporated endoscopic visualization with percutaneous procedures. Improved optics, larger working channels, enhanced instrumentation and continuous irrigation significantly advanced ESS to what it is today. Currently, there are several endoscopic platforms, constantly evolving techniques, and a growing body of scientific literature demonstrating the safety and efficacy of ESS to treat a multitude of cervical, thoracic, and lumbar spine pathology.

ESS procedures have significantly increased in recent years, with the highest utilization currently in Asian markets. Recent studies demonstrate that approximately 70% of Asian spine surgeons perform ESS, compared to significantly less in the United States and Europe. The reason for the relative lag in the adaptation of ESS across the United States is multifactorial, but in part due to capital cost required to start an ESS program, limited billing codes for ESS, a steep learning curve, and lack of formal training. Currently there are only a handful of spine fellowships throughout the United States that offer a robust training experience in ESS. Most United States spine surgeons learn endoscopy through weekend courses or via domestic and international travelling fellowships. National spine societies such as the North American Spine Society (NASS) are trying to combat this void by offering formalized training sessions, such as at the NASS International Meeting in Bangkok July 2023, cochaired by the senior author of this editorial. As the popularity of ESS continues to increase in the United States, it is likely that a growing number of fellowship programs will invest in acquiring ESS technology and training currently faculty such that they can train the next generation of spine surgeons.
The drive to transition more spine surgeries to the ambulatory surgery center, patient demand for faster recovery and less postoperative pain, and surgeon interest in learning minimally invasive spine surgery has led to an all-time high interest in ESS globally. In order for the field to continue to grow, it is paramount to continue to demonstrate the safety, efficacy, and possible superiority of ESS to treat spine pathology. Special issues such as the current issue in Neurospine are paramount to evolving the field. There continues to be a need for unbiased peer-reviewed literature assessing outcomes, complications, and cost-efficacy compared to more traditional procedures to treat similar pathology. More surgeons need to publish their outcomes, as the majority of the scientific literature is published by providers and centers with significant ESS experience, thereby the translation of their results to other spine surgeons remains questioned.

Such as arthroscopy revolutionized the care of many musculoskeletal disorders and is now a mainstay of treatment, the authors of this article are confident ESS is entering a golden age in the realm of spine surgery and its adoption will continue to rise globally.

- **Conflict of Interest:** The authors have nothing to disclose.

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Paradigm Shift in Spinal Surgery

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Advancement in medical treatment leads to increase life expectancy and population ageing. The corresponding increase in the incidence of degenerative spinal conditions are top 10 causes of disabilities worldwide.¹ As science advances with new procedures, there is a demand for more advanced technology and surgical techniques in spinal surgery to minimise collateral soft tissue damages to provide improved clinical outcomes with less perioperative morbidities for our patients. This demand gives rise to the evolution of endoscopic spine surgery.² Despite the many benefits of spinal endoscopy, there is a steep learning curve in spinal endoscopy.³ Surgeons who are practising the art of spinal endoscopy should be familiar with open surgical techniques and spinal anatomy. As endoscopic spine surgery is a fast evolving field, it is important for practicing endoscopic surgeon to keep current with the latest literature and updates. Since the previous special edition of Endoscopic Spine Surgery in Neurospine in 2020, there is continual development of technology in spinal endoscope in terms of lens clarity, variety of angulation, light transmission, radiofrequency energy systems, spinal endoscopic instruments, and further refinement of surgical techniques by worldwide endoscopic surgeons. This leads to an expansion of clinical indications for endoscopic spine surgery.⁴⁻⁶ In this special edition, we have articles from uniportal full-endoscopic and unilateral biportal endoscopy addressing various conditions in spine with advanced endoscopic techniques involving cervical and thoracic decompression as well as endoscopic spinal fusion techniques.

We are confident this current special issue of Endoscopic Spine Surgery in Neurospine will become a core forum for spine scholars who are interested in endoscopic spine surgery. We wish you success in your academic, clinical and endoscopic spine surgical career.

• Conflict of Interest: The authors have nothing to disclose.

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INTRODUCTION

Various spinal diseases and related pain is a very common phenomenon, and it is reported that more than two-thirds of the population experience these spine related symptoms during their lifetime. These diseases already have become a great socioeconomic burden, and as we are living in an aging society, it is obvious that we will encounter more of these patients in our daily practice and will inevitably have to manage more spinal disease cases in the near future.

It is very well accepted that nonsurgical treatment should be the first line therapy for most pain related spinal disorders. Nonetheless, surgical decompression with or without fusion procedures continue to be the treatment of choice for those who fail to improve from nonsurgical therapy. The primary goals of spinal surgery are relieving symptoms, enhancing quality of life while preserving the function of the spine. To reach this goal and optimize the outcome of spinal surgery with respect to clinical, functional, patient self-reported, and cost-effectiveness, development and advancement of new surgical techniques are critical.

Just like the introduction of laparoscopes or robot surgeries was an evolution for abdominal general surgery, utilization of endoscopic spine surgery (ESS) has revolutionized the surgical treatment of spinal diseases. This cutting-edge technique is now gaining great popularity recently with significant evidence. Despite the relatively steep learning curve for the acquisition of its techniques, ESS has carved an important niche in the armamentarium of the spinal surgeon. This is owed to the proven safety and efficacy of endoscopy in surgery of the degenerative spine as compared to open surgery or other conventional minimally invasive techniques.

The Neurospine organized a North American Spine Society (NASS)/Neurospine ESS special issue subtitled; The road to expansion and standardization of ESS, and we believe it will be a great opportunity to share our thoughts on ESS with a brief overview on the existing evidence in this short essay.

DEVELOPMENT AND UTILIZATION OF ESS

ESS was first introduced and developed by several pioneers who had great enthusiasm for minimally invasive spine surgery (MISS) techniques. Drs. Kambin and Sampson presented a successful percutaneous removal of disc material via the famous “Kambin’s triangle” in the 1980s, and Dr. Yeung reported his great early results of disc removal under visualization using the novel ESS device of his own in the late 1990s. Although the relatively
steep learning curve and technical barriers behaved as barriers for the rapid adoption of ESS in the early days, steady groundwork for more than 20 years supported the development of ESS and finally it emerged as a novel cutting-edge major MISS technique.

Transforaminal approach to the lumbar spine pathologies allowed spinal surgeons to reach the whole nerve root route starting from the extraforaminal – foraminal to the intra canal space without necessity of excessive bone/joint or ligament sacrifice. Interlaminar approach mirrors the traditional microscopic techniques as they resemble the very same approach that most spinal surgeons are familiar with. While this approach has advantage in terms of familiarity, it also has greater benefit with improved visualization and more tailored targeting owing to the greater maneuverability and availability of greater range of visualization with angled cameras. Utilization of biportal ESS systems has also brought diversity to the field of ESS and offers greater degree of surgical variety by persistently widening the range of diseases that can be treated by ESS.

Nowadays, the benefit zone of ESS is getting wider starting from relatively low complexity procedures such as simple lumbar microdiscectomies, laminotomies or lateral recess decompressions, up to more complex procedures such as cervical or thoracic decompressions or even spinal fusion procedures.

GAINING EVIDENCE AND POPULARITY

Following the wide acceptance of ESS throughout the globe, the surgical technique as well as technical development have been extensively researched and the number of research related to ESS have also greatly increased. While the annual number of publication related to ESS were sparse in the early 2000s, the number surged up starting from the mid 2010s and recently more than 200 publications are being reported annually. China, South Korea, USA, and Germany are noted as top countries contributing to publication in the field of ESS, representing the worldwide popularity and interest from various regions and continents. Various globally recognized scientific peer-review journals are presenting large number of articles related to ESS, reflecting the significant impact of ESS in the field of spinal surgery. These journals include but are not limited to orthopedic journals, neurosurgical journals, pain journals, and general medical journals.

The utilization of ESS has gained great interest worldwide and has now become an increasingly popular procedure, and global effort unifying the nomenclature has also been made as it is critical to delineate a united nomenclature among ESS surgeons. There are many places in the globe where ESS has already become an major surgical option like the aforementioned countries, and at the same time there are many other parts of the globe that are at the beginning of adopting the new technology. It is obvious that ESS is a widely accepted and scientifically proven technique for various spinal pathologies, and with advancement of the technique itself and related technology, the use will be more adopted in the near future.

UTILIZING MODIFIED TECHNIQUES AND FUTURE APPLICATIONS

The development and universalization of ESS naturally leads to modification of the techniques in order to optimize the procedures for each different clinical situation. Contralateral interlaminar approach can be utilized to reach and decompress the contralateral lateral recess and the foramen without being blocked by the facet joint. The lower lumbar extraforaminal stenoses including the caudal most lumbosacral spine, Bertolotti’s syndromes can be successfully decompressed by modified interlaminar approaches. By modifying the interlaminar endoscopic unilateral laminotomy for bilateral decompression, bilateral lateral recesses can be decompressed via single approach and even sparing the midline ligamentum flavum for selective cases.

Several complex clinical scenarios such as pseudoarthrosis, revisional surgery, calcified thoracic discs, or fusion techniques were once considered as relative contraindications for ESS. However, experienced ESS surgeons have presented good surgical, clinical outcome for these cases utilizing full-endoscopic techniques, proving that modification of techniques can be applied for more complex cases. Most notably, the use of ESS in fusion surgery is becoming popular. Both full-endoscopic ESS and biportal ESS are showing very good clinical and radiologic results for lumbar fusion surgeries. Recent reports are even presenting favorable outcomes for spinal infectious diseases or oncologic problems, suggesting the possibility of even wider range of ESS application.

CLOSING – WHY ENDOSCOPIIC SPINE SURGERY?

As previously described, since the introduction of ESS, it has consistently developed to this day built on the endless endeavor of the pioneers. It provides a minimally invasive approach to...
various spinal pathologies with greater benefit to patients with similar or even better outcomes compared to conventional techniques. Scientific evidence of its efficacy, safety and cost-effectiveness is accumulating and subsequently its utilization is becoming popular worldwide. Modification of the techniques and utilization of them are amplifying the range of diseases that can be treated by ESS, and ceaseless effort of applying new technology will further enhance the ability of ESS surgeons. There is no doubt ESS will be an essential part in the field of spinal surgery. Here’s our answer to “why endoscopic surgery?”

- **Conflict of Interest:** The authors have nothing to disclose.

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Anterior Endoscopic Cervical Discectomy: Surgical Technique and Literature Review

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The conventional surgical technique for radiculopathy with cervical disc herniation (CDH) is anterior cervical discectomy and fusion, with a good clinical outcome and fusion rate. However, significant perioperative morbidity related to extensive surgical exposure has been reported. Therefore, anterior endoscopic cervical discectomy (AECD) using a working-channel endoscope has been developed to reduce surgical complications and tissue damage. The objective of this study was to describe a cutting-edge technique for AECD of soft CDH. The primary indication is cervical radiculopathy with or without axial neck pain due to soft CDH. The surgical procedure consists of 2 parts: (1) a safe anterior percutaneous approach under fluoroscopic control and (2) selective endoscopic discectomy and foraminal decompression using specialized mechanical tools under endoscopic visualization. The clinical outcomes are comparable to those of conventional surgery and show the benefits of minimally invasive spine procedure. Perioperative data revealed typical minimalism, including reduced muscle damage, blood loss, operative time, and recovery time. With technical advancements in surgical instruments and optics, AECD will become more practical and safer. AECD is effective in selected CDH cases with cervical radiculopathy. However, high-quality clinical studies are needed to verify the effectiveness of this endoscopic cervical spinal procedure.

Keywords: Cervical, Discectomy, Endoscopy, Foraminotomy, Intervertebral disc herniation, Percutaneous discectomy

INTRODUCTION

The standard surgical technique for cervical radiculopathy with cervical disc herniation (CDH) is anterior cervical discectomy and fusion (ACDF), which is a reliable surgical option with an acceptable fusion rate.1-6 However, there are considerable surgical morbidities that may interfere with patients’ recovery to their normal lives: (1) approach-related problems such as difficulty in swallowing, hematoma, hoarseness, and esophageal injury;7,8 (2) fusion-related events such as motion limitation, non-union, and hardware failure;9,10 and (3) adjacent segment disorders.12,13

Since Hijikata14 and Kambin and Sampson15 first introduced percutaneous lumbar discectomy, various endoscopic spine surgery techniques have been developed. With regards to the cervical spine, some pioneers have evolved minimally invasive surgical techniques via a percutaneous anterior cervical approach. A percutaneous approach using a small working channel endoscope instead of an open anterior approach may reduce approach-related adverse events and extensive tissue trauma. Currently, anterior endoscopic cervical discectomy (AECD) and modified procedures have been reported to be effective in appropriately selected CDH cases.16-25 However, technical modifications of this procedure are variable and need to be integrated and standardized.

This article describes the basic technique of AECD, and discusses its clinical outcomes and technical modifications, including the scientific evidence.
INDICATIONS

The clinical indications for AEDC are: (1) severe cervical radiculopathy with or without neck pain, (2) discogenic cervical headache, (3) cervical myelopathy with a high risk of requiring extensive open surgery under general anesthesia, and (4) persistent or progressive symptoms despite at least 3 months of nonsurgical therapy. The radiological indications are: (1) soft CDH compressing the spinal cord or exiting nerve root demonstrated on computed tomography (CT) and magnetic resonance imaging (MRI) and (2) preserved intervertebral disc space. The procedure can be performed when the situation meets the radiological and clinical criteria simultaneously.¹²

The contraindications are: (1) calcified or hard CDH; (2) advanced spondylosis with collapsed disc space; (3) cervical myelopathy with cervical stenosis, ossification of the posterior longitudinal ligament, or ossification of the ligamentum flavum; (4) segmental spinal instability or kyphotic deformity; (5) other neurological or vascular diseases mimicking degenerative disc pathologies; and (6) a history of anterior neck surgery at the index level.

SURGICAL PROCEDURES

The step-by-step surgical procedure of AEDC for cervical radiculopathy with soft CDH consists of (1) an anterior percutaneous approach under fluoroscopic control and (2) selective discectomy and foraminal decompression through endoscopic visualization.²²

1. Patient Position, Anesthesia, and Skin Marking

The procedure can be performed under either general or local anesthesia according to the patient’s condition and the surgeon’s preference. In the case of local anesthesia, the basic premedication comprises midazolam (0.05 mg/kg, intramuscularly) and fentanyl (0.8 μg/kg, intravenously) administration on call. The local anesthetics can be added as required during the procedure. The patient is placed in a supine position with their neck extended on a radiolucent spine table. After adequate anesthesia and positioning, essential anatomical structures are marked under fluoroscopic guidance, including the index level, carotid pulse, and medial margin of the sternocleidomastoid muscles.

2. Fluoroscopic-Guided Percutaneous Anterior Cervical Approach

The basic concept of the surgical approach is a percutaneous anterior approach through the safe working zone between the carotid artery and the trachea into the cervical disc. The deep fascia separates the vascular compartment (including the carotid artery and vein) and visceral compartment (including the trachea and esophagus). Therefore, a simple finger pressure between the vascular and visceral parts can easily create a safe working zone.

Contralateral access is recommended because it provides a better visual field for the lateral and foraminal zones of the disc. After confirming the operative disc level using anteroposterior (AP) and lateral fluoroscopic views, the surgeon palpates the carotid pulse and keeps it lateral from the surgical field. The surgeon then presses the space between the carotid vessels and trachea with their fingers, pushing the trachea to the contralateral side. When the surgeon feels the anterior surface of the disc with their fingertips, an 18-gaunged approach needle is inserted into the disc space directly from the midzone of the anterior disc surface to the lateral target disc point (Fig. 1A). After confirming adequate needle trajectory and landing point on the AP and lateral fluoroscopic views, intraoperative discography is performed to stain the herniated disc fragment and identify the leakage status with a mixture of indigo carmine and contrast media. Next, a guidewire is introduced through the needle sheath into the disc, and a stab skin incision, less than 5 mm, is made horizontally at the index cervical disc level. After sequential dilation using dilators of different sizes, a round or rectangular working sheath is placed to ensure the surgical field of the herniated disc (Fig. 1B). A trephine can be inserted through the working sheath and cut into the annulus to reduce the intradiscal pressure and resistance.

3. Endoscopic-Guided Selective Discectomy and Foraminotomy

The main procedure in this step is the selective removal of herniated fragments under endoscopic visualization while preserving the central nucleus of the maternal disc. An ellipsoid working channel endoscope is introduced through the working sheath, and the posterior disc space is identified through endoscopic visualization. The surgical disc space is continuously irrigated with antibiotic-containing saline at a rate of 30–40 mL/min. Disc decompression is first performed in the posterior sub-annular area to reduce intradiscal pressure and create adequate working space. This initial decompression and release process should be performed using endoscopic forceps, a semiflexible radiofrequency tip, or a side-firing laser, until the annular fissure and herniated disc fragment are identified. Then, the an-
nular anchorage is released using an endoscopic cutter or other devices until fibrotic adhesion and the herniated disc fragment are separated. The herniated element can then be selectively removed piece by piece using fine endoscopic forceps. During selective decompression, thecal sac pulsation can be gradually detected through the torn annular fissure. Decompression can proceed to the foraminal zone. After selective discectomy and foraminotomy, the epidural space and decompressed exiting nerve root can be seen through the opened annular fissure (Fig. 1C).

4. Final Checking Point
The final point of the procedure can be determined by the solid pulsation of the thecal sac and free mobilization of the exiting nerve root (Fig. 1D). Surgeons should examine whether there is any dural membrane breach in the surgical field. They should also check for any epidural or bone bleeding to prevent postoperative hematoma. After surgery, the endoscope is withdrawn, and the wound is closed with a one-point subcutaneous suture and skin tape. Postoperative MRI or CT scans may be checked for precise decompression of the primary pathology as required (Fig. 2). If there are no significant adverse events, the patient can be discharged within 24 hours postoperatively (Fig. 3).

RESULTS
According to our comparative cohort study between the AECD group (51 patients) and ACDF group (64 patients), the 5-year clinical outcomes were identical between the groups. The mean
Fig. 2. A 48-year-old female patient underwent anterior endoscopic cervical discectomy at the C4–5 level. (A, B) An approach needle is introduced between the carotid artery and the tracheoesophagus. Note the endotracheal tube or tracheal air shadow is pushed contralaterally using the fingertips, ensuring the safety working space in the fluoroscopic view. (C, D) After placing the working sheath intradiscally, a selective discectomy is conducted under endoscopic visualization.

Fig. 3. Postoperative status of a 48-year-old female patient with soft cervical disc herniation at the C4–5 level. (A) Preoperative axial and sagittal magnetic resonance (MR) images demonstrate an extruded disc compressing the spinal cord and exiting nerve root. (B) Postoperative axial and sagittal MR images show a well-decompressed status immediately after the procedure. Note the selective removal of the herniated disc while preserving the central nucleus. (C) The patient’s symptoms improved immediately without any adverse events. She could return to ordinary work within 1 month postoperatively with minimal surgical scar.

Visual analogue scale scores for radicular pain improved from 4.58 ± 1.95 to 1.35 ± 1.34 in the AECD group and from 3.91 ± 1.78 to 1.14 ± 0.85 in the ACDF group. The neck disability index improved from 51.87 ± 21.47 to 7.82 ± 13.41 in the AECD group and from 58.27 ± 17.73 to 6.59 ± 10.14 in the ACDF group. According to the global results based on the modified MacNab criteria, the success rates were 88.24% and 90.63% in the AECD and ACDF groups, respectively.
We found that the endoscopic procedure showed the typical characteristics of minimally invasive surgery: shorter operative time, shorter hospital stay, and earlier return to work. The mean operative time was 55.20 ± 18.03 minutes in the AECED group versus 124.53 ± 35.68 minutes in the ACDF group (p < 0.001). The mean postoperative hospital stay was 2.18 ± 1.16 days versus 5.23 ± 2.39 days, respectively (p < 0.001). The time to return to work was 3.14 ± 1.08 weeks vs. 10.84 ± 3.12 weeks, respectively (p < 0.001).

Complications were similar between the groups. The most common complication was transient swallowing difficulty (1.96% vs. 4.69%, respectively), which improved within 4 weeks postoperatively. Two patients in the AECED group (3.92%) underwent subsequent ACDF because of recurrent disc herniation in 2 months. One patient in the ACDF group (1.56%) underwent subsequent posterior cervical foraminotomy and fusion because of postoperative foraminal stenosis and instability 12 months later. There was no statistical difference in the revision rate (p = 0.58).

DISCUSSION

1. Journal Review

The AECED technique has several benefits in minimally invasive surgery.26 First, the anterior percutaneous approach with a thin working channel endoscope (3–4 mm in diameter) can preserve anterior cervical musculoskeletal structures. Therefore, postoperative scarring or surgical complications can be minimized. Overall, the recovery and rehabilitation times can be shortened compared with open surgery. Second, selective and delicate removal of herniated disc fragments can preserve the maternal nucleus. Moreover, unnecessary fusion or instrumentation can be avoided while maintaining segmental stability. Third, considering the surgical approach, herniated discs at any zone, from the central to the foraminal, and any degree of herniation, from an annular tear to extrusion, can be effectively removed under sophisticated endoscopic control. Finally, AECED may be performed under either general or local anesthesia according to the patient’s condition and request. Therefore, this technique can be applied to patients at risk for general anesthesia. Biomechanical or finite element studies revealed that anterior endoscopic cervical procedures showed a shorter surgical path, smaller surgical diameter, and less biomechanical influence on the cervical spine.27

By contrast, AECED has inevitable shortcomings related to technical limitations. Spine surgeons are unfamiliar with cervical endoscopic procedures, which require a steep and long learning curve. Training courses and extensive clinical experience are mandatory for aspiring endoscopic surgeons to obtain good outcomes. In addition, surgical indications and clinical applications are limited to soft disc herniation. A collapsed disc, posterior stenosis, calcified pathologies, and severe myelopathy may be contraindicated in actual cases.

Various cases of CDH have been reported in different anatomical situations. Many technical reports and case series of AECED have been published, and the reported success rates have varied from 51% to 95%.20,25,28 Most authors have concluded that endoscopic anterior cervical procedures are efficient for selected CHD, with the benefits of minimal invasiveness. However, scientific evidence of its clinical effectiveness is yet to be sufficiently elucidated. Some authors have published comparative cohort studies demonstrating the clinical efficiency of AECED with minimal invasiveness.22,29 However, few randomized controlled trials (RCTs) have been conducted to verify the effectiveness of this procedure. Ruetten et al.30 compared the clinical and radiological outcomes between full-endoscopic anterior cervical discectomy (54 cases) and ACDF (49 cases) over a 2-year follow-up period. They concluded that the endoscopic cervical procedure was a sufficient and safe alternative to ACDF in selected cases. There is also a lack of reliable meta-analyses or systematic reviews on AECED, but only technical or narrative reviews so far.26,28,31 High-quality RCTs and systematic reviews are needed to verify the relevance and effectiveness of AECED compared with standard ACDF.

2. Technical Point

Critical technical points should be emphasized to achieve relevant and reliable results using this minimally invasive technique. The point-oriented percutaneous anterior approach is key to clinical success. The approach needle should be inserted from the contralateral side through the safe working zone, which is the interfascial space between the carotid sheath (vascular axis) and tracheoesophageal compartment (visceral axis). The surgeon’s fingertips can create a safe working zone under fluoroscopic guidance. Endotracheal tube shape or tracheal air shadow may be helpful indicators of the visceral axis. The access trajectory should be directed toward the annular fissure and herniated disc fragments. The second key to success is appropriate release of the annular anchorage before removal of the herniated disc fragments. Generally, there is a solid and tenacious adhesion between the annular fissure and offending pieces. A premature attempt to remove the elements without an adequate re-
lease process cannot result in sufficient decompression because the endoscopic devices are relatively delicate and small. The exact closing point of the AECD technique may be the last but most crucial key to success. To declare the endpoint of the surgery, the surgeon should confirm that the affected neural tissues “breathe” without any remaining tethering. The minimal condition for the definitive endpoint is solid pulsation and free mobilization of the thecal sac and nerve root, regardless of surgical exposure of the neural tissues in the endoscopic surgical field.

3. Technical Modification

With the development of endoscopic technologies, technical modifications have emerged with unique advantages. First, AECD via a transcorporeal approach was designed with the benefit of selective discectomy while preserving the maternal disc space.32-37 Second, AECD with the interbody fusion technique combines endoscopic discectomy and immediate instrumented fusion.38-40

4. Anterior Versus Posterior

The percutaneous endoscopic cervical procedure may be performed through the anterior or posterior approach. Both approaches might be practical if the surgeon applied the process for adequate indications.26,28 In general, the direction of the approach may be determined according to the zone of neural compression. If the primary pathology is located at the lateral border of the myelon, the posterior approach may be useful because the posterior endoscopic approach is simple and more accessible than the anterior approach. In contrast, the anterior approach may be more effective for the case of central or paracentral pathologies since the cervical spinal cord must not be retracted into the medial direction during the procedure. Therefore, the surgeon should choose the path according to the patient’s pathology.

CONCLUSION

AECD and other modified techniques may be effective in treating cervical radiculopathy with CDH. Precise percutaneous anterior cervical localization and selective decompression of the critical point are key to success. It can result in relevant clinical outcomes with minimal invasiveness in terms of skin incision, operative time, blood loss, hospital stay, anesthesia, and recovery time. However, more high-quality clinical studies are needed to verify the effectiveness of this endoscopic cervical spinal procedure.

NOTES

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Uniportal, Transforaminal Endoscopic Thoracic Discectomy: Review and Technical Note

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Symptomatic thoracic disc herniations are a rare entity and their operative treatment is challenging. Open approaches, despite providing excellent access, are associated with significant access morbidity from thoracotomy, and this has led to an increased interest in minimally invasive techniques such as mini-open approach, thoracoscopic approach and the endoscopic approach. In this article, we describe the technical points for performing a transforaminal endoscopic thoracic discectomy and summarize its literature outcomes in the context of other minimally invasive approaches.

**Keywords:** Transforaminal endoscopic thoracic discectomy, Decompression, Minimally invasive spine surgery, Thoracoscopic approach, Mini-open approach

**INTRODUCTION**

Symptomatic thoracic disc herniations are a relatively rare entity in that they represent less than 1% of all disc herniations, however, literature from autopsy and magnetic resonance imaging (MRI) studies has reported an incidence of up to 15.2% of thoracic disc herniations in the general population.1,7 Although many may be asymptomatic, clinical presentation of thoracic disc herniations can be quite significant and include myelopathy, thoracic radiculopathy, axial back pain, gait instability and bowel and/or bladder dysfunction.7

The operative treatment of thoracic disc herniations is challenging due to the presence of ribs, narrow spinal canal dimensions and vascular anatomy of the spinal cord. Initial approaches utilizing a central decompressive laminectomy were fraught with iatrogenic complications due to the manipulation of the spinal cord, which paved the way for other approaches including transpedicular and costotransversectomy.2,8 However, the limited working window of the aforementioned approaches led to the widespread adoption of the anterior transthoracic approach which utilizes a thoracotomy to perform the discectomy, followed by potential fusion based on the amount of bony resection.2,8

Despite providing excellent access, the associated morbidity of a thoracotomy including postthoracotomy pain led to an increased interest in minimally invasive techniques for approaching thoracic disc herniations such as mini-open approach, thoracoscopic approach and the transforaminal endoscopic approach.7,9 The transforaminal approach was first reported by Kambin who described the safe transforaminal triangle for a percutaneous discectomy in 1973.10 After instrumentation and technique improvements and popularization of its use in the lumbar spine, the past decade witnessed an increased use of the transforaminal endoscopic approach in the thoracic spine.11,12

We herein describe the technical points of performing a transforaminal endoscopic thoracic discectomy (TETD) and summarize the outcomes in the literature.

**SURGICAL TECHNIQUES**

1. **Indications**

Any thoracic disc herniations at any level, except T1/2 could
be a candidate of TETD. T1/2 foraminal or paracentral disc herniations can be accessed with a posterior interlaminar approach like a posterior cervical endoscopic foraminotomy and discectomy, given the risk of functioning T1 nerve root damage and narrow intercostal space.

Paracentral soft disc herniation with myelopathy with/without thoracic radiculopathy will be the ideal indication of TETD (Fig. 1). Since not a small number of thoracic disc herniations show calcification, partially calcified thoracic disc herniations would also be an indication of TETD, unless it is an extensive ossification of the posterior longitudinal ligament. If the calcified disc herniation has a dural adhesion, a ‘floating’ technique; involving the removal of the disc and leaving the calcific shell if the calcified disc is all detached from the disc and the posterior longitudinal ligament, may provide significant improvement (Fig. 2). Combined ossification of the yellow ligament (ossification of ligamentum flavum) may not be effective with TETD, but cases combined with central/paracentral disc herniation could have favorable outcomes as enucleation through TETD can provide some central decompression after shrinkage of the disc material.

Central disc herniations can be more difficult to access than paracentral disc herniations. The central disc fragment can be removed successfully with TETD approach if it is a loose soft nucleus fragment, through a more shallow access angle after the transforaminal approach. But effective central decompression may not be easy when the central disc is calcified or has a thickened annulus component. In those cases, central enucleation could cause shrinkage of the central fragment with the healing process, but this is not always possible.

2. Positioning and Operating Room Set-up

The patient is positioned prone over a radiolucent operative table. Intraoperative neuromonitoring including somatosensory evoked potential and motor evoked potential are optional if the procedure is under general anesthesia. The authors recommend neuro-monitoring when spinal cord compression is severe or
when the patient has underlying significant neurological deficits. At the authors’ institution, neuromonitoring is routinely performed for surgery involving any spinal cord level because of possible medicolegal issues if it is not contraindicated.

The arms are positioned on side arm boards and the leg position can be in mild flexion of hip and knee joints without any pressure points. The thoracic spine area is prepped and draped in a sterile fashion and a C-arm is positioned so that true anteroposterior (AP), lateral and oblique views are available. Irrigation pump pressure is set at 35 mmHg with room temperature saline.

3. Portal and Access Angle

The portal for TETD would be variable depending on the pathology; paracentral versus central disc herniation. A central disc herniation may need a portal with more lateral location. Also, the soft tissue thickness of the patient at the level of access is another factor to consider. The distance from the midline varies from 5 cm to 9 cm. The easiest way for localization is drawing a line from the target point to the skin and measuring the distance between the midline and the skin entry on a computed tomography or MRI gantry axial image (Fig. 3).

Generally, the access trajectory targets the lateral aspect of the facet for additional lateral facetectomy and foraminal expansion (foraminoplasty). Usually, the access angle is steeper (smaller angle from the midline) than conventional lumbar transforaminal discectomy, around 45°, because of the convexity of the rib cage and pleural cavity. But an operator may lower their hand to increase the approach angle (increase the angle from midline) with the same portal after decompression of the para-central area, to gain better access to the central spinal canal.

Under fluoroscopic guidance, an 8-inch discography needle is placed targeting the posterolateral corner of the disc. The end of needle should be located at the center to the lateral half of the lower pedicle on an AP view and posterior aspect of the disc on a lateral view for a good starting point (Fig. 4).

![Fig. 3. Axial magnetic resonance image demonstrates the location of portal (the entry of a discography needle) and access angle. The entry is located at around 5–8 cm from the midline, and the access angle is around 45° because of the rib cage.](image)

![Fig. 4. The initial discography needle and guide wire should touch the posterolateral corner of the intervertebral disc (A, B) on fluoroscopic images. (C, D) The obturator and working cannula is touching lateral aspect of the facet joint.](image)
can be advanced toward the center of the disc to inject diluted methylene blue to stain the disc material as needed. Sequential soft tissue dilators and obturator are inserted before the placement of the working sleeve (Fig. 4).

4. Exposure, Lateral Facetectomy, Foraminotomy

Intervertebral foramen of the upper to mid thoracic spine, from T2 to T10, have different anatomical characteristics compared to the lower thoracic spine from T10–12.

The intervertebral foramina have smaller dimensions, the disc spaces are partially covered by the corresponding rib head at T9/10 and above. Lateral facetectomy and rib head resection are required to access the epidural space at the upper and mid thoracic spine. Transforaminal approach to T10/11, T11/12 and T12/L1 disc space will be similar to the upper lumbar spine, because their intervertebral foramina are wider, and the disc spaces are not covered by the rib heads (Fig. 5).

Another unique point of the transforaminal approach is that the pedicles of thoracic spine are caudally angled compared to the disc space, as such the superior aspect of the lower pedicle is partially blocking the access of the disc space plane (Fig. 5).

After placement of the working sleeve, the soft tissue consisting of muscles and ligaments should be cleaned using a flexible radiofrequency tip to expose the lateral aspect of the facet and rib head. Using an endoscopic drill (usually 3.5-mm diameter diamond burr), the lateral aspect of the facet joint is burred to

Fig. 5. Computed tomography (CT) images demonstrate anatomical characteristics of the thoracic spine. (A) T10/11, T11/12 disc space is not covered by the corresponding rib heads (red arrows), but at the levels above T10, the disc space is partially covered by the rib heads (arrow head), drilling of the superior aspect of the rib head maybe needed to access the disc space, especially toward the central located disc fragment. Since pedicles of thoracic spine have a caudal angle, the upper part of the pedicle usually blocks access to the disc space (the dotted lines). Drilling of the upper pedicle-superior end plate junction provides easier access to the disc space. (B) Oblique view of a 3-dimensional CT images of the foramen. To expose the intervertebral foramen of thoracic spine, lateral facetectomy will be necessary, drilling of up to 50% of the joint surface, superior pediculectomy to the superior end plate, and superior aspect of the rib head as needed (red area). (C) An axial CT images shows lateral facetectomy and the superior end plate resection with an endoscopic burr (the red circle).

Fig. 6. Intraoperative pictures of sequential steps showing exposure of a right side T9/10 intervertebral foramen and intervertebral disc space. (A) After soft tissue removal, lateral aspect of the inferior articular process (IAP) of the cranial vertebra was drilled. (B) After the IAP resection, the superior articular process (SAP) of the inferior vertebra was drilled to open the foramen. (C) Superior aspect of the lower pedicle was drilled to expose the disc space. (D) After lateral facetectomy and drilling of the superior pedicle, the upper (arrow heads) and lower end plate (arrows), the disc space was exposed.
access the disc space (up to 50 % of the joint) (Fig. 6). The superomedial aspect of the rib head may require resection as needed to expose the disc space or advance the working cannula towards the midline. The rib head can be resected using an endoscopic burr. Superior pediculectomy is required if adequate visualization of the disc is not enough with lateral facetectomy alone (Fig. 6). Once the foramen has been enlarged with lateral facetectomy and the rib head resection, the next steps are similar to the endoscopic lumbar discectomy.

5. Discectomy

After docking the beveled end of working cannula on the posterolateral corner of the disc, endoscopic scalpel, cutting punches or variable sized endoscopic pituitary rongeurs can be utilized for the annulotomy and disc fragment removal (Fig. 7). Injecting 2–3 mL of diluted methylene blue in the disc space with an 8-inch discography needle will be helpful to locate the ruptured disc fragments.

Thoracic intervertebral disc spaces are usually not high enough to advance a 7-mm diameter working cannula. To access the more central side, both upper and lower end plates can be partially removed using a small diameter (2.5 or 3.5 mm) endoscopic drill. Calcified annulus can be drilled also (Fig. 7). When the ventral epidural space with epidural fat and pulsating dural sac are visible under endoscopic vision, the decompression would be sufficient (Fig. 7).

6. Wound Closure and Postoperative Care

The authors prefer placing an 1/8 inch diameter silicon drain through the portal to avoid possible epidural hematoma. Application of skin glue or steri-strips over 1 or 2 subcutaneous sutures will be sufficient for wound closure.

DISCUSSION

Traditionally, thoracic disc herniations are accessed through open approaches such as transpedicular, costotransversectomy or anterior transthoracic. More recently, less invasive options including mini-open, thoracoscopic and endoscopic approaches have become popular.

There have been a few case series in the literature describing TETD and its outcomes (Table 1). In 2010, Choi et al. initially reported on 14 patients who underwent TETD for soft thoracic disc herniations under local anesthesia with sedation and showed improvements in patient visual analogue scale (VAS) for back and leg pain and Oswestry-Disability Index (ODI) scores. Their mean operative time was 61 minutes and there were no surgical related complications reported.

Bae et al. reported their case series of 92 consecutive patients with symptomatic thoracic soft disc herniations who underwent TETD under local anesthesia with sedation. At a mean follow-up time of 38.4 months there was significant improvement in both VAS pain and ODI scores. Their complications included one patient with transient motor weakness, 3 patients with lower extremity parasthesias, and 2 patients with symptomatic recurrent herniation with 1 requiring reoperation and the other improving nonoperatively.

For patients with lower thoracic spinal stenosis, Guo et al. reported on 6 consecutive patients who underwent transforaminal endoscopic thoracic decompression and discectomy and demonstrated significant improvement in the Japanese Orthopaedic Association scale from a mean of 4.4 preoperatively to 6.6 at 1-year follow-up, and improvement in Frankel grade of all patients from incomplete motor loss (grade D) to normal (grade E) by the 3-month follow-up mark with no reported thoracic, vascular, infectious or permanent neurologic complications.

As reported by Uribe et al., open approaches for thoracic disc

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Fig. 7. Intraoperative pictures of the decompression. (A) After posterolateral discectomy, the lateral border of dura was exposed. (B) A radiofrequency probe or a dissector can be placed between the ventral dura and posterior annulus to confirm the plane and check for any adhesion. (C, D) After central discectomy, the pulsating ventral dura and epidural fat are visible without any compression.
herniations involve a mean blood loss of 562 mL and a mean hospital length of stay (LOS) of 8.6 days. An endoscopic approach minimizes the invasiveness and provides access to the spinal cord generally without the need for a facetectomy or pedicle removal, which in some cases can prevent the need for fusion as well. Moreover, apart from the improved cosmesis, reduced risk of infection, and lower blood loss, patients who undergo endoscopic technique do not need a chest tube and can be done under local anesthesia, resulting in a quicker recovery with a shorter hospital LOS compared with open approaches.6,7

While mini-open approaches are also becoming more popular due to their decreased invasiveness, the approach generally remains similar to the open approach in addition to the required bony work that still carries the risk of destabilizing facet bone.8 Uribe reported a series of 60 patients undergoing mini-open lateral approach for thoracic disc herniations, of which 55% were calcified. Seventy-five percent underwent a transpleural approach while 25% underwent a retropleural approach. They reported a median operative time of 182 minutes, median LOS of 5 days, and median blood loss was 290 mL. Most patients showed improvements in myelopathy, radiculopathy and pain, although 10% underwent posterior supplemental fixation for instability, and 78% required a chest tube. Complications included a durotomy in 7 cases (11.7%), one each of pneumonia, extrapleural free air, new lower extremity weakness, wound infection in posterior instrumentation, and mild intercostal neuralgia. There were 3 cases (5%) requiring reoperation for re-exploration, wound infection, and residual disc removal.2

Bae et al.7 compared 38 patients who underwent a microscopic posterior/posterolateral approach utilizing hemilaminectomy, medial facetectomy and in some cases partial pediculotomy for thoracic disc herniations, with 39 patients who underwent a TETD for the same indication at a single institution. They demonstrated shorter operative time (70.6 minutes vs. 175.7 minutes), lower blood loss (3.8 mL vs. 357.4 mL), shorter hospital LOS (7 days vs. 13 days), and greater patient satisfaction based

Table 1. Summary of transforaminal endoscopic thoracic discectomy clinical series reviewed

<table>
<thead>
<tr>
<th>Study</th>
<th>Indication</th>
<th>No. of patients</th>
<th>Clinical outcomes*</th>
<th>Complications (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choi et al.,4 2010</td>
<td>Soft thoracic disc herniation</td>
<td>14</td>
<td>VAS back 6.5 to 3  VAS leg 5.8 to 2.5 ODI 58.1 to 24.5 Follow-up 60.2 months</td>
<td>Not reported</td>
</tr>
<tr>
<td>Bae et al.,5 2020</td>
<td>Soft thoracic disc herniation</td>
<td>92</td>
<td>VAS 7.6 to 1.6 ODI 68.2 to 13.2 MacNab excellent/good outcomes 90.2% Follow-up time 38.4 months</td>
<td>Transient motor weakness (1), parasthesias (3), symptomatic recurrent herniations (2), reoperation (1)</td>
</tr>
<tr>
<td>Guo et al.,14 2019</td>
<td>Lower thoracic stenosis</td>
<td>6</td>
<td>JOA score 4.4 to 6.6 at 1 year VAS back 7.8 yo 1.9 VAS leg 8.7 to 0.3 Follow-up time 12.6 months</td>
<td>Not reported</td>
</tr>
<tr>
<td>Bae et al.,7 2022</td>
<td>Thoracic disc herniation</td>
<td>39</td>
<td>VAS 7.5 to 2.5 ODI 47.6 to 13.7 MacNab excellent/good outcomes 89.7% Follow-up time 11.2 months</td>
<td>Incomplete decompression requiring revision (1)</td>
</tr>
<tr>
<td>Bae et al.,16 2019</td>
<td>Upper thoracic disc herniation (T2–6)</td>
<td>14</td>
<td>VAS 7.3 to 2.3 ODI 53.5 to 16.9 MacNab excellent/good outcomes (86%) Follow-up 43.4 months</td>
<td>Not reported</td>
</tr>
<tr>
<td>Houra et al.,18 2020</td>
<td>Thoracic disc herniations (including 10 calcified)</td>
<td>16</td>
<td>VAS 8 to 1 ODI 59 to 13 Follow-up 5 years</td>
<td>Not reported</td>
</tr>
<tr>
<td>Gao et al.,6 2021</td>
<td>Thoracic disc herniations (including 9 calcified)</td>
<td>11</td>
<td>JOA from 7.4 to 10.2 VAS leg/thoracic 3 to 0.5 Follow-up time 15 months</td>
<td>Not reported</td>
</tr>
</tbody>
</table>

VAS, visual analogue scale; ODI, Oswestry-Disability Index; JOA, Japanese Orthopaedic Association score.

*Values are presented as means for VAS, ODI, JOA score and follow-up time, and percentage (%) for MacNab criteria outcomes. VAS, JOA, and ODI values are presented as mean preoperative to mean postoperative.
on MacNab criteria (89.7% vs. 73%) between the TETD and microscopic approaches, respectively. However, patients who underwent the microscopic approach had a greater proportion of concomitant ossification of ligamentum flavum than the TETD group (34.2% vs. 2.6%).

Thoracoscopic and transforaminal techniques are similar in that they are both needle-based and require the use of specialized endoscopes. Thoracoscopic however often requires a thoracic access surgeon given the lack of familiarity of working through the thoracic cavity with an endoscope, compared to the more posterior/posterolateral based transforaminal approach. In addition, TETD can be performed with local anesthesia and sedation which has increased in popularity lately in select patients to facilitate early recovery pathways. Thoracoscopy on the other hand requires the use of general anesthesia and single-lung ventilation. However, general anesthesia has benefits for neuromonitoring and is more comfortable for both patients and surgeons, although the ability to check a patient’s response under local anesthesia may obviate the need for neuromonitoring. Quint et al. reported their prospective cohort of 167 patients who underwent single level thoracoscopic discectomy and demonstrated improvements in VAS pain scores and the American Spinal Injury Association motor score at 2-year follow-up. Their reported complications included transient intercostal neuralgia (5.4%), dural tears (1.2%), respiratory complications (3.6% - including pleuritis, pneumothorax and pleural effusions), symptomatic postoperative instability (1.8%), incomplete decompression (1.8%), and motor deficit (1.2%).

Despite its overall advantages, TETD comes with its own limitations. Similarly, to the thoracoscopic approach, the cost of instrumentation, the 2-dimensional visualization of a 3-dimensional (3D) pathology, steep learning curve and difficulty in managing intraoperative complications are real concerns. In addition, TETD is more difficult in the upper thoracic spine due to the rib heads limiting foraminal access and the presence of the scapula. Bae et al. however demonstrated its feasibility in a series of 14 consecutive patients with soft disc herniations who underwent transforaminal endoscopic discectomy between T2 and T6 without any reported neurologic or vascular complications. Traditionally, relative contraindications for a transforaminal approach are calcified or sequestered discs due to the limited working window as a result of the constraints on the position of the endoscope. However, there have been reports of successful treatment of calcific thoracic discs performed endoscopically. Houra et al. reported their series of 16 patients treated with TETD for thoracic disc herniations, with 10 having partially or fully calcified discs, and demonstrating significant VAS and ODI improvements at 5-year follow-up and without reported surgical complications. The same author also showed that good outcomes are obtained without complications in 2 patients with large 2-level calcified disc herniations in the midlower thoracic spine using the endoscopic transforaminal approach. Moreover, Gao et al. reported their series of 11 patients with thoracic disc herniations, 9 of which were calcified, who TETD, without postoperative nerve injury, infection or hematoma formation.

Complications of TETD have been variably reported in the literature. Ruetten et al. reported a 20% (5 of 25) rate of complications including 1 dural tear during the resection of a calcific disc herniation (was covered with a synthetic dural substitute and a fat flap), 1 epidural hematoma, 2 transient intercostal neuralgias, and 1 deterioration of myelopathy from a giant disc herniation. No infections, pulmonary complications, or instability were reported up to 18 months of follow-up. Other complications such as vascular injuries and incomplete decompression are also possible especially in cases of inexperience/unfamiliarity with the anatomy or instrumentation. Pulmonary complications including pneumothorax due to targeting needle puncturing the pleura have also been reported, with some authors modifying the technique to using dilators without a targeting needle. Although there has not been a study specifically addressing the learning curve of TETD, a systematic review of complications associated with the learning curve of minimally invasive spine surgery in general demonstrated that operative time and complications are usually overcome in 20–30 consecutive cases for most minimally invasive techniques, and for full endoscopic lumbar discectomy, learning curves of 22–33 cases are reported in the literature.

A unilateral endoscopic interlaminar approach has also been described in the thoracic spine. Ruetten et al. reported on full endoscopic decompression of the thoracic spine including 20 cases using the interlaminar approach and 26 cases using the transforaminal approach with favorable outcomes. They reported 1 case of epidural hematoma and 1 case of transient arm dysesthesia as the complications of interlaminar approach. Given the minimal resectability of the thoracic dura and spinal cord, the interlaminar approach will be limited for most para-central disc herniations. However, the interlaminar approach would be useful in the selected cases of a disc herniation that is extruded past the lateral border of the dura or a dorsally migrated disc herniation.
CONCLUSION

TETD is a feasible option for patients with symptomatic herniated thoracic discs and compares favorably with open and other minimally invasive techniques in select patients.

NOTES

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REFERENCES

Perioperative Management for Full-Endoscopic Lumbar Discectomy: Consideration From the Perspective of Preventing Complication

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In recent years, full-endoscopic discectomy (FED) has expanded its range of indications with the development of devices and various techniques. The advantage of FED over conventional surgery is that it is a minimally invasive procedure. However, intraoperative and postoperative precautions must be taken to prevent complications. It is necessary to avoid complications that could compromise the outcome of the procedure. Effective perioperative management is necessary to avoid complications; however, there is no set view for perioperative management in FED. In this study, we perform a literature review to examine the effectiveness of perioperative management methods for FED. The key to ensuring the efficacy and minimal invasiveness of FED is prevention of complications. Based on the result and literature review, we believe that the most manageable postoperative management after FED is prevention of recurrent disc herniation and hematoma formation. A drain should be placed to prevent postoperative hematoma formation. It is advisable to evaluate the patient’s symptoms and monitor C-reactive protein and erythrocyte sedimentation rate levels during the first week after surgery. Postoperative antibiotics were administered for 1 day.

Keywords: Full-endoscopic lumbar discectomy Recurrent disc herniation, Perioperative management, Hematoma

INTRODUCTION

In recent years, full-endoscopic discectomy (FED) has expanded its range of indications with the development of devices and various techniques. The advantage of FED over conventional surgery is that it is a minimally invasive procedure. However, intraoperative and postoperative precautions must be taken to prevent complications. The minimally invasiveness of FED is one of its advantages; therefore, it is necessary to avoid complications that could compromise the outcome of the procedure. Effective perioperative management is necessary to avoid complications; however, there is no set view for perioperative management in FED, which is left to the discretion of each institution and surgeon.

In this study, we perform a literature review to examine the effectiveness of perioperative management methods for FED.

COMPLICATION OF FED

The key to ensuring the efficacy and minimal invasiveness of FED is prevention of complications. Perioperative management and special care should be taken during surgery to prevent complications. There is a paucity of literature describing the perioperative management of FED in detail.

The major complications of FED are (1) postoperative hematoma, (2) dural tear, (3) infection, (4) nerve root injury, (5) recurrent disc herniation, and (6) intracranial hypertension.

1. Postoperative Hematoma

FED is characterized by a limited surgical field because it does
The causes of hematoma formation include bleeding from soft tissues and removed bone, antiplatelet and anticoagulation medications, and segmental artery injury due to puncture manipulation. Intraoperative meticulous hemostasis is important to prevent its occurrence. The use of a gelatin-thrombin matrix sealant (Floseal, Baxter, Deerfield, IL, USA) may also prevent the occurrence of postoperative epidural hematomas. There is no consensus on whether or not a drainage tube should be placed after FED. Patients considered at high risk for hematoma formation, such as those with underlying medical problems or previous operative scarring, should have a drainage tube placed postoperatively. When drain was placed postoperatively, drainage was performed for 1–2 days. Even a small amount of hematoma formation could easily become symptomatic; therefore, continued drainage requires indwelling.

There are 2 types of postoperative hematoma: epidural hematoma and retroperitoneal hematoma. Ahn et al. reported that retroperitoneal hematoma occurred in 4 of 412 patients who underwent FED. Retroperitoneal hematoma is thought to be caused by puncture beyond the posterior vertebral line during the approach and damage to the terminal branch of the segmental artery. Coagulopathy and abnormal vascular motion have also been reported to be involved in the occurrence of this disease.

Great care should be exercised to avoid hemorrhagic complications in patients with medical problems, and an adequate technique for the transfornaminal approach should be used.

2. Dural Tear

Intraoperative dural tears have been reported to occur at a frequency of 0.6%–6.9%. This can be caused by intraoperative drilling, epidual fat removal at the pituitary forceps, or inadvertent manipulation during the use of the Kerrison punch.

If a dural injury can be recognized intraoperatively, it can be repaired on the spot; however, it may not be recognized intraoperatively and may be recognized several days after surgery as intractable radicular pain.

This may be due to the fact that a minor intraoperative dural tear may expand over time, causing root herniation and delayed appearance of symptoms. If symptoms improve immediately after surgery but worsen a few days later and magnetic resonance imaging (MRI) shows no evidence of recurrent disc herniation, a dural tear should be considered. Therefore, changes in symptoms should be monitored several days after surgery.

The gold standard method for repairing a dural tear is to perform open conversion followed by direct repair. If a dural tear occurs on the ventral side of the dura mater, repair by a transdural approach may be necessary. However, the change from endoscopic surgery under local anesthesia to open surgery to general anesthesia is disconcerting. Therefore, several endoscopic repair methods have been reported. Shin et al. described a method of performing a primary suture repair during endoscopic lumbar spinal surgery. A double-arm needle was used to thread through the dura. After a single knotting of the suture thread outside the endoscope, an endoscopic curette was used to push the knotted thread in and close the dura.

Park et al. described a dural tear management algorithm for biportal endoscopic spinal surgery. Dural tears smaller than 4 mm were followed up with bed rest for 24 hours. A hard sealant was applied to the dural tears between 4 mm and 12 mm, and the patient was kept in the hospital for 24 hours for observation. For dural tears > 12 mm, the algorithm depends on the location of the dural tear. If the dural tear is located in the dural sac (zone 2) or in the descending root (zone 3) with a regular margin, repair is performed using a nonpenetrating clip, the patient is hospitalized for 48 hours of observation, and external lumbar drainage is considered. If the lesion is in the emerging root armpit (zone 1) or in zones 2 or 3 with an irregular margin, it is converted to open surgery and primary repair is performed.

When neurological deficits due to dural tears occur, they may be permanent if not treated at the appropriate time. If neurological deficit develops after surgery, it should be evaluated and managed appropriately.

3. Infection

In FED, the skin incision is small, a sterile environment is easily maintained, and potential sources of infection are eliminated, thus reducing the possibility of infection. Postoperative infection is rare.

Ahn and Lee reported that postoperative spondylodiscitis occurred in 12 of 9,821 patients (0.12%) who underwent FED with a transfornaminal approach. Laboratory markers, such as erythrocyte sedimentation rate (ESR) and C-reactive protein (CRP) levels, were found to be elevated in postoperative spondylodiscitis cases. But early-stage MRI, which was performed before the 5th postoperative day, did not show definite evidence of spondylodiscitis. The causes of spondylodiscitis include inappropriate intraoperative techniques (repeated needling, nee-
dle insertion at a steep angle, and frequent in-and-out movements of the endoscope instruments with a long operation). From the viewpoint of early response to complications, we believe that evaluation of postoperative symptoms is important, and if infection is suspected, measurement of CRP and ESR would allow for early recognition.

4. Nerve Root Injury

The frequency of worsening neurological symptoms (motor deficit, dysesthesia, and paresthesia) after FED has been reported to be 0.7%–3.1%.²⁻¹⁴ It occurs mainly during FED via a transforaminal approach. Neuropathy after FED is distinguished as nerve root injury or irritation² and is caused by improper manipulation of the sheath during surgery in the transforaminal approach. Intraoperative sheath manipulation causes pressure on the exiting nerve root, resulting in injury. In the transforaminal approach, if the surgical field is narrow, that is, if Kambin’s triangle is small, the sheath may cause nerve sheath injury. Therefore, it is necessary to prevent the sheath from being subjected to nerve compression. Therefore, it is effective to perform surgery with a wider surgical field by partially drilling the facet to prevent complications.²⁻¹⁵

Choi et al.¹⁶ measured the shortest distance between the root and facet surface at the lower disc margin level on a preoperative MRI and compared the results between groups in which extending nerve root injury occurred (the shortest distance between the root and facet surface at the lower disc margin level was 4.4 ± 0.8 mm for group A and 6.4 ± 1.5 mm for group B, with a significant difference between groups A and B). The authors recommend preoperative measurement of the exiting nerve root and facet surface at the lower disc margin level, and if they are short, switching to other surgical methods should be performed instead of FED. Ju¹⁵ also mentioned the need to change the approach angle and skin incision site depending on disc morphology. Thus, a detailed evaluation of preoperative images can help prevent complications.

If the exiting nerve root is close to the superior articular process, consider adding a foraminaloplasty to prevent exiting nerve root injury due to sheath manipulation. Similarly, in the interlamina approach, it is necessary to consider methods to prevent root injury when the width of the interlamina is narrow.

If the herniated disc is located further away from the interlamina window, the cranial laminotomy for a shoulder type and upward migration or caudal laminotomy for downward migration. By performing bone removal until the lateral aspect of the traversing nerve can be seen, pressure on the root can be minimized. Recently, a newly designed endoscope for lumbar spinal stenosis has been reported, which has a 5.7-mm working channel and is effective for bone removal, especially when the interlamina space is less than 8 mm.¹⁷⁻¹⁸

Xie et al.¹³ reported that 15 of 479 patients who underwent full-endoscopic interlaminar lumbar discectomy and experienced postoperative paresthesia were treated with pregabalin, which significantly improved their symptoms at 8 weeks postoperatively. This led to the conclusion that postoperative paresthesia is a neuropathic pain, and it is reasonable to treat any occurrence of nerve root irritation as neuropathic pain.

5. Recurrent Disc Herniation

The frequency of disc herniation recurrence after FED has been reported to be approximately 3.6%¹⁹ and care to prevent postoperative disc herniation recurrence is important to improve the postoperative outcomes.

Unlike microdiscectomy, FED does not require laminectomy. Therefore, the posterior elements were retained postoperatively. This is believed to prevent postoperative pressure buffering of the disc.²⁰

Risk factors for postoperative disc herniation recurrence in FED include old age (>50 years), obesity (body mass index >25 kg/m²), upper disc (L1/2, L2/3, and L3/4),¹⁰ male sex, heavy work, facet joint degeneration, and early ambulation.²¹⁻²² Qin et al.²² reported a significantly higher recurrence rate in early ambulation patients who were ambulated within 24 hours after FED, and the importance of time to first ambulation as a factor in postoperative recurrence.

Hao et al.²³ reported that patients with preoperative MRI showing moderate changes between the affected vertebrae had a higher frequency of recurrent disc herniation after FED surgery due to endplate degeneration, which causes the cartilaginous endplate to detach and protrude from the hernia.

Miller et al.²⁴ reported that in lumbar disectomy cases, recurrence of symptoms and reoperation are more common when the annular defect is 6 mm or larger.

Based on the association between annular defect size and symptom recurrence, Chen et al.¹⁷ proposed that if the annular defect is less than 6 mm, sequestrectomy with fragmentectomy is suitable without increasing the risk of recurrent disc herniation.

The annular sealing method is used to prevent recurrence by coagulating and shrinking the area around annular fissure with a bipolar coagulator and sealing the annular defect.¹⁷⁻²⁵

Wang et al.²¹ found that the average time to ambulation was significantly shorter in recurrent cases (17 days in the recurrent
group vs. 24 days in the normal group) and emphasized the importance of limiting postoperative upright activity. It is believed that external stress on the lumbar region and incorrect postoperative rehabilitation may influence recurrence, and weight control, avoidance of heavy work, and strengthening rehabilitation are recommended.

Patients with a risk factor for recurrent disc herniation or those who have undergone a Modic change require careful postoperative management.

**CONCLUSION**

Based on the above, we believe that the most manageable postoperative management after FED is prevention of recurrent disc herniation and hematoma formation. A drain should be placed to prevent postoperative hematoma formation. It is advisable to evaluate the patient’s symptoms and monitor CRP and ESR levels during the first week after surgery. Postoperative antibiotics were administered for 1 day. Postoperative FED patients are allowed bed rest for 24 hours after surgery and then allowed to leave the bed with a lumbar brace. The lumbar brace was kept in place for 1 month after surgery (Table 1).

**NOTES**

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**Author Contribution:** Writing - original draft: TH; Writing - review & editing: TH, YO.

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Current Indications for Spinal Endoscopic Surgery and Potential for Future Expansion

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Endoscopic spine surgery (ESS) has evolved as a safe, effective, and efficient alternative for minimally invasive spine surgery (MISS). The innovation of full-endoscopic systems makes definitive decompression surgery through different approaches feasible. The approach can be determined according to the location of the target lesion or the surgeon’s preference. During the past 2 decades, ESS has expanded its indications from lumbar to cervical spines. Except for decompression, endoscopy-assisted fusion surgery is also developing. However, ESS is still evolving and has a steep learning curve. The revolution of technologies and ESS techniques will enable surgeons to treat various spinal diseases more practically. In recent years, the application of the computer-assisted navigation system and augmented reality have reformed imaging quality and interpretation. The endoscopic rhizotomy techniques have opened a new way for MISS of chronic low back pain. This review introduces the current indications of ESS and its potential future expansion.

Keywords: Endoscopic, Spine, Indications, Minimally invasive, Rhizotomy

INTRODUCTION

Nowadays, minimally invasive spine surgeries (MISS) have been a trend in modern spine surgeries. The common goal of spinal surgeries is to improve the quality of life by relieving pain and restoring functional disability. Furthermore, MISS is devoted to the issue of enhanced recovery after surgery. As for MISS, endoscopic spine surgery (ESS) has developed as an emerging alternative in the recent 2 decades. The ESS is superior to conventional surgery in less soft tissue damage, reduced blood loss, lower complication rates, decreased damage to the epidural blood supply and consequent epidural fibrosis, shorter hospital stays, and shorter time to return to work.¹⁹ In the 1990s, Kam-bin⁷ reported a posterolateral approach for percutaneous lumbar discectomy with the assistance of the arthroscope. As technology has advanced, the endoscope with a working channel has evolved with different systems designed for various approaches.¹⁰ The evolution of endoscopic equipment and techniques has expanded the indications of ESS.¹⁰ Therefore, evidence of ESS has multiplied to catch more attention from spine surgeons worldwide.

The initial stage of ESS was to treat herniated intervertebral disc (HIVD) at the lumbar spine through the natural orifices, such as the intervertebral foramen or interlaminar window. Transforaminal and interlaminar approaches are the basis of the endoscopic techniques to remove HIVDs through the above 2 anatomical structures. However, at the initial stage, a full-endoscopic discectomy was mainly for nonmigrated or low-grade migrated disc herniation due to the limitation of the bony structures. Thus, the advent of the endoscopic burr and bone reamer was the game changer. Pioneers of ESS applied the endoscopic burr to conduct foraminoplasty or laminotomy to increase the
space for entering the spinal canal.\textsuperscript{11} The foraminoplasty can expand the working space of the transforaminal trajectory by widening the intervertebral foramen. Likewise, the interlaminar window can be enlarged by laminotomy to reach the target lesion. Following these modified full-endoscopic techniques, indications of ESS have expanded to all kinds of decompressive surgeries from lumbar to thoracic and cervical spines.

For the past 30 years, various endoscopic spinal procedures have been developed to solve the degenerative disease of the spine. Some case reports also demonstrated the effectiveness and safety of endoscopic procedures for infection or neoplasm of the spine. In 2020, the AOSpine MISS task force published a consensus regarding the nomenclature of endoscopic spinal procedures.\textsuperscript{12} The consensus nomenclature summarized the current endoscopic procedures and classification based on the regions and techniques. In recent years, full-endoscopic techniques have been applied to treat various spinal diseases. The authors will give an overview of the current application and upcoming expansion of ESS in the article.

**CURRENT INDICATIONS FOR ENDOSCOPIC SPINAL SURGERY**

The location and level of the target lesion are essential factors in deciding the surgical approaches. The surgical anatomies at different spinal levels determine the ideal trajectory during the endoscopic approach. The cervical foramen is too narrow to allow the endoscope to pass through. Besides, critical arteries are located in the posterior aspect of the cervical intervertebral foramen and may be vulnerable to injury during the transforaminal approach. Therefore, the ESS is a mainly posterior or anterior approach at the cervical spine. At the thoracic spine level, the scapula may block the transforaminal route to the upper thoracic spine (T2 to T7 or T9).\textsuperscript{13} The thoracic cage and scapula will limit the posterolateral inclination of the endoscope during the transforaminal approach. Moreover, the imbricated thoracic lamina and a lack of a proper interlaminar window make the thoracic interlaminar endoscopic approach challenging. Therefore, modified techniques of ESS are necessary for the different target spinal levels.

The essential goal of the ESS is the decompression of neural structures that results from different pathologies. The evolution of ESS has expanded the indications to cervical and thoracic spine surgeries. Hence, the indication of ESS may be limited by the etiologies of spinal disease, and degenerative spinal diseases remain the most common indications for ESS. The decompression of neural structures by ESS can remove the pathologies, including HIVD, hypertrophic ligamentum flavum, facet joint cyst, overgrown facet joint, and osteophyte from subaxial cervical to the lumbar spine. The ESS can preserve collateral soft tissues and structures and avoid iatrogenic instability after an operation.

Another ideal indication for ESS is an infectious spinal disease, such as discitis with or without an epidural abscess. Patients who sustain infectious spondylodiscitis might have moderate to severe comorbidities or a high risk of surgeries, such as advanced age, immunocompromised, or unstable hemodynamics. Therefore, ESS has been applied to treat infectious spondylodiscitis with full-endoscopic discectomy, debridement, and drainage for infection control and restore neurological function. The endoscopic approach is beneficial to minimize surgical and anesthetic risks when it obtains causative organisms and directly decompresses the nerves by debridement and drainage of epidural abscess. The copious saline irrigation also decreases bacterial burden simultaneously.

The application of ESS in a spinal tumor is limited and challenging, especially in extensive, highly vascularized, or intradural tumors. Sharp and bimanual dissection of the tissue plane between the tumor and normal tissue is essential during microsurgery. The dissecting technique requires 2-hand cooperation. However, endoscopic surgery, either uniportal or biportal, is challenging in tumor dissection. Besides, hemostasis under endoscopic visualization can be difficult in highly vascularized tumors. Therefore, tumor biopsy for pathologic diagnosis or epidural tumor removal may be feasible by endoscopic approach in selected patients.

**1. Indications of ESS for Lumbar Spine**

Lumbar spinal diseases are usually suitable for ESS with different approaches. Endoscopic lumbar discectomy has been a standard MISS for all herniation types (Table 1). The transforaminal approach could be the first choice from L1 to L5, regardless of the disc location. At the L5-S1 level, the transforaminal approach can be restrictive by the high-iliac crest and narrowed foraminal area that results from a large L5 transverse process or hypertrophic facet joint.\textsuperscript{14,15} Foraminoplasty might be necessary for the situation or a highly migrated disc at other levels.\textsuperscript{16} Recently, Chen et al.\textsuperscript{17} proposed a suprapediculare retrocorporeal technique to solve the highly downward migrated disc. The interlaminar window is wider at the caudal level of the lumbar spine. Therefore, the interlaminar endoscopic approach is also an alternative at the L5-S1 level or for the highly
Table 1. Indications for lumbar full-endoscopic spinal surgery

<table>
<thead>
<tr>
<th>Herniated intervertebral disc</th>
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<tbody>
<tr>
<td>Central</td>
</tr>
<tr>
<td>Paramedian</td>
</tr>
<tr>
<td>Foraminal</td>
</tr>
<tr>
<td>Extraforaminal</td>
</tr>
<tr>
<td>Migrated disc</td>
</tr>
<tr>
<td>Lumbar spinal stenosis</td>
</tr>
<tr>
<td>Lateral recess stenosis</td>
</tr>
<tr>
<td>Central canal stenosis</td>
</tr>
<tr>
<td>Ossification of ligamentum flavum</td>
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<tr>
<td>Foraminal stenosis</td>
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<td>Infective spondylodiscitis</td>
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<tr>
<td>Pyogenic discitis</td>
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<td>Epidural abscess</td>
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<td>Revision surgery</td>
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<td>Recurrent disc herniation</td>
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</tr>
<tr>
<td>Bone cement leakage into canal or foramen</td>
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<td>Spondylolisthesis (≤ grade 2)</td>
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Down-migrated or axillary-type lumbar disc at the rostral level.\textsuperscript{18} Endoscopic lumbar discectomy can be feasible in recurrent cases by experienced surgeons. The previous study demonstrated comparable clinical outcomes compared with microdiscectomy.\textsuperscript{19} The endoscopic burr and bone reamer have brought ESS to a new era for treating lumbar spinal stenosis. For central canal or lateral recess stenosis, endoscopic surgeons can unilaterally decompress the thecal sac and traversing roots through an interlaminar approach. Complex pathologies, such as combined HIVD and spinal stenosis, can be also treated by full-endoscopic surgery.\textsuperscript{20} The bilateral decompression of central and lateral recess stenosis is feasible by the “over-the-top” technique.\textsuperscript{21} Recent studies showed comparable outcomes but fewer complications and shorter hospital stay after endoscopic surgeries.\textsuperscript{1,2,23} One study reported that full-endoscopic decompression was effective for lumbar spinal stenosis with low-grade fixed spondylolisthesis (≥ 3 mm without motion translation on the dynamic radiography) or mild-to-moderate scoliosis (≥ 10° coronal Cobb angle).\textsuperscript{24} The functional outcome was better in the endoscopic group without a higher risk of revision for fusion in the early postoperative period. However, further studies for long-term outcomes are necessary.

Foraminal stenosis is a common pathology at the advanced stage of lumbar degeneration. Traditionally, decompression of intervertebral foramen has a risk of iatrogenic instability due to injury to the facet joint. Therefore, fusion surgery is usually indicated in the scenario. With the advent of ESS, transforaminal endoscopic lumbar foraminotomy has been studied. The preliminary studies showed favorable outcomes at 1-year follow-up.\textsuperscript{25,26} For experienced surgeon, the technique can be useful for some iatrogenic problems. The previous studies have reported successful treatment of lumbar interbody cage migration after fusion surgery and intraspinal cement leakage after vertebroplasty by full-endoscopic decompression.\textsuperscript{27,28} The minimally invasive revision can decompress the nerves without reopen in selected patients.

Full-endoscopic debridement and drainage are an alternative for infectious spondylitis, especially in pyogenic discitis or epidural abscess. Patients with pyogenic spondylitis usually have comorbidities causing poor constitutional factors or compromised immune, which preclude them from being candidates for surgical debridement.\textsuperscript{29} Therefore, there are several benefits of full-endoscopic procedures for these patients. First, endoscopic debridement under local anesthesia can treat patients with high anesthetic risks. Second, the small incision and target-oriented approach avoid the physiological burden and iatrogenic injury to spinal structures during the operation. Third, continuous saline irrigation can significantly decrease the bacterial load of surgical sites. Effective spinal epidural abscess treatment is composed of identifying definite pathogens and adequate abscess evacuation. A previous study also reported that positive rates of bacterial culture were higher with percutaneous endoscopy than with computed tomography (CT)-guided biopsy (90% vs. 47%).\textsuperscript{30} Therefore, endoscopic debridement and drainage are beneficial for local control by drainage abscess and systemic control by identifying sensitive antibiotics for specific pathogens.

The endoscopy-assisted lumbar fusion surgery has been developing in recent years. Some pilot studies showed favorable outcomes in endoscopy-assisted transforaminal or posterior lumbar interbody fusion. For complex operations, prognostic factors are multiple, and there are diverse endoscopic and implant systems protocols. Many confounders, such as cage design (static or expandable), cage material, bone graft substitute, use of bone morphogenic protein, biomechanical profile, or endplate status, can affect the outcomes. The endoscopy-assisted lumbar interbody fusion techniques can minimize injuries to collateral soft tissue and endplate of vertebrae, which enhances postoperative recovery and shortens the hospital stay.\textsuperscript{31,33} Most importantly, awake surgery can be feasible with full-en-
Current Indications and Potential Expansion for ESS

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Fig. 1. The application of intraoperative navigation in full-endoscopic thoracic spine surgery. (A) Intraoperative computed tomography scan for localization and intraoperative neuronavigation. (B) The surgeon can localize the target and confirm real-time orientation during the operation.

Table 2. Common indications for thoracic full-endoscopic spinal surgery

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<th>Herniated intervertebral disc: soft disc</th>
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<td>Migrated disc</td>
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<th>Thoracic spinal stenosis</th>
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<td>Central canal stenosis</td>
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<td>Pyogenic discitis</td>
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<td>Epidural abscess</td>
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Endoscopic lumbar interbody fusion technique.\(^{34}\) However, endoscopic fusion surgeries are developing, and the ideal or newly designed instrument systems are on the way. The pilot studies mainly enrolled short segments of disease with low-grade spondylolisthesis. New technologies and further high-quality researches are necessary for the emerging application.

2. Indications of ESS for Thoracic Spine

Thoracic spine surgeries comprise less than 10% of spine surgeries.\(^{35}\) Thoracic HIVD and spinal stenosis are possible etiologies for ESS. The epidemiologic study of thoracic spinal stenosis showed that ossification of ligamentum flavum (OLF) was the most common etiology and accounted for 41.5% of the cases, while 32.4% and 18.7% were diagnosed with thoracic HIVD and ossification of the posterior longitudinal ligament (OPLL), respectively.\(^{36}\) Although the incidence of thoracic HIVD ranges from 7% to 37%, less than 1% of all TDH are symptomatic.\(^{37,38}\)

The indication of ESS for thoracic HIVD is the soft disc causing radiculopathy or myelopathy (Table 2). The paramedian or foraminial type of thoracic HIVD can be reached by interlaminar or translaminar approach. If the disc herniation is located at the central portion, a transforaminal approach with foraminoplasty or a transthoracic retropelvic approach can be an alternative to remove the lesion.\(^{39,40}\) However, the transthoracic retropelvic approach is limited above the T5 level due to scapula or risks of injury to major vessels, such as the azygos vein or aorta, according to a cadaveric study.\(^{41}\) Fortunately, thoracic HIVD is more common in the middle and lower levels of the thoracic spine. Besides, the transforaminal approach with foraminoplasty remains feasible at the upper thoracic HIVD in experienced hand.\(^{40}\) The calcified or hard disc and OPLL are relative contraindications to the endoscopic approach, and the thoracoscopic approach may be an alternative. Thoracic spinal stenosis due to OLF can cause myelopathy and is indicated to be endoscopic decompression. The technique of unilateral laminotomy for bilateral decompression (ULBD) helps decompress the thoracic cord safely.\(^{42,43}\)

Intraoperative localization is a critical issue while conducting thoracic spine surgeries. C-arm fluoroscopy is the most common modality to localize the index level during operation. However, the thoracic cage and scapula might affect the visualization and confuse the interpretation of the intraoperative fluoroscopy. Recently, the integration of an intraoperative navigation system with endoscopic surgeries has been reported. The intraoperative scan of CT can quickly identify the index level (Fig. 1).
Besides, computer-assisted navigation can guide the instruments in real-time during the operation without interruption for repeated scans. The evolution of imaging modality can help surgeons overcome the learning curve of thoracic ESS easily and safely.

### 3. Indications of ESS for Cervical Spine

Cervical HIVD, foraminal stenosis, and central canal stenosis are common indications for ESS (Table 3). The endoscopic approaches at the cervical spine are the anterior or posterior approach. As for cervical HIVD, conventional anterior cervical disectomy through the areolar plane between the esophagus and carotid artery results in minimal muscle trauma, and the risk of injuries to vessels and esophagus is low. Besides, there has been robust evidence of cervical arthroplasty showing favorable outcomes with artificial disc replacement. Therefore, anterior endoscopic cervical disectomy (AECDF) is usually considered when patients with a high risk of general anesthesia have cervical myelopathy or radiculopathy caused by soft disc herniation. The preliminary series showed comparable outcomes comparing the conventional anterior cervical disectomy with fusion. The operative time, hospital stay, and time to return to work were shorter in the AECDF group in a prospective cohort. Patients having a calcified or hard disc, severe spondylosis with decreased intervertebral space (< 5 mm), OPLL, or spondylolisthesis with instability were not ideal candidates for AECDF. Besides, When the disc herniation is in the paramedian or foraminal region, posterior endoscopic cervical disectomy or posterior endoscopic cervical foraminotomy (PECF) is a better solution to avoid fusion surgery and worsen disc degeneration. The endoscopic approach for the migrated disc in the cervical spine might be challenging because it is risky to retract the dural sac to reach the sequestrated fragment. Some recent reports proposed an anterior transcorporeal technique or posterior retrocorporeal technique to reach migrated fragments safely. However, the modified techniques are difficult for inexperienced surgeons. Further studies enrolling more cases with long-term results are necessary to evaluate the effectiveness and safety of these advanced techniques.

Foraminal stenosis with radiculopathy due to facet joint hypertrophy or osteophytes is an indication of PECF. PECF can decompress the existing root at the index level and preserve stability. Meanwhile, the herniated disc in the lateral canal or foraminal region can be removed. When patients present neck pain or myelopathy with OPLL or OLF causing central canal stenosis, PECF is not an ideal solution in such circumstances. Besides, patients with preoperative cervical kyphosis are not suitable for PECF.

Cervical spinal stenosis can result from hyperlordosis, shingling, and arthrosis with hypertrophic ligamentum flavum. Myelopathy due to dural sac compression is usually the introductory presentation. The pathologies may include the combination of structures surrounding the spinal canal. The cervical spinal stenosis with myelopathy due to infolding of ligamentum flavum is an excellent indication for cervical endoscopic ULBD. For cervical OPLL with less than 50% canal occupancy and without significant kyphosis, posterior endoscopic decompression can be an alternative. A single incision can be used up to 3-level decompression. However, the cervical spinal cord is more vulnerable to water pressure and excessive manipulation. Besides, multilevel decompression for the endoscopic approach is time-consuming and physically challenging for beginners. The evidence of cervical endoscopic ULBD for treating cervical spinal stenosis with myelopathy is insufficient. The decision-making depends on the patient's factor and the surgeon's experience. Further studies on the learning curve are necessary.

Full-endoscopic anterior cervical disectomy and fusion (ACDF) is an alternative for conventional ACDF. The outcomes are comparable according to small case series. However, the full-endoscopic approach can only achieve stand-alone cage fusion, and there is a lack of a locking plate system for endoscopic surgery. Therefore, the full-endoscopic ACDF may be feasible in single- or 2-level disease without subluxation. Though ACDF has been the gold standard for cervical HIVD, arthroplasty with artificial disc replacement has rapidly risen in the recent decade. The evidence supporting cervical arthroplasty has accumulated

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**Table 3. Indications for cervical full-endoscopic spinal surgery**

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<td>Paramedian</td>
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<td>Migrated disc</td>
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<tr>
<td>Stand-alone cage fusion (single or 2 levels)</td>
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<td>Cervical spinal stenosis</td>
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<td>Foraminal stenosis with radiculopathy</td>
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https://doi.org/10.14245/ns.2346190.095
to change the trend of treatment for cervical HIVD. The full-endoscopic ACDF is still developing and lacks evidence. Newly designed implants suitable for endoscopic approaches are necessary to accentuate the advantages of full-endoscopic ACDF.

**POTENTIAL FOR FUTURE EXPANSION**

In recent years, endoscopic lumbar interbody fusion has been developed and studied. The conventional design of the static cage for lumbar interbody fusion is not suitable for passing through the endoscope’s working channel. Therefore, modification of the implant designs or endoscopic instruments is mandatory to overcome the limit. The customized expandable interbody device has been available for endoscopic fusion systems currently. Wang et al.\(^50\) reported the technique of full-endoscopic transforaminal lumbar interbody fusion in awake patients. The preliminary outcomes of 100 patients with a minimum 1-year follow-up were favorable without nonunion. Endoscopic fusion enhances recovery in the ambulatory surgery setting, and this innovation enables lumbar fusion surgeries for those unable to undergo general anesthesia.

Endoscopic rhizotomy (ER) for different chronic low back pain (CLBP) has been an emerging alternative in recent years. The facet joint is innervated by the medial branch of the dorsal ramus, and facet arthropathy is a usual pain generator for CLBP. Percutaneous radiofrequency ablation is a routine intervention to manage the facet-oriented CLBP refractory to medical treatment.\(^51\) The percutaneous lesioning intervention effectively reduces pain by more than 50% in most patients. However, the duration of pain relief is 7.3–9.0 months on average after a single intervention.\(^52\) The intervention is based on fluoroscopic guidance and the patient’s report to localize the lesioning targets. Nerve regrowth can cause pain relapse, and repeated procedures may be necessary. On the contrary, ER of the nerve branches can ensure the rhizotomy under endoscopic visualization. The outcomes of the ER for facet joint syndrome were also superior to conventional radiofrequency lesioning regarding durability in previous studies.\(^53,54\) For failed back surgery syndrome responding to the facet joint block treatment, ER can provide long-term relief of CLBP after previous spinal instrumentation.\(^55\)

The ER is also effective in treating sacroiliac joint pain\(^56\) or occipital neuralgia.\(^57\) The preliminary study of endoscopic radiofrequency ablation of the sacroiliac joint complex revealed a favorable outcome with an 88.6% satisfaction rate in 17 patients during the 6-month follow-up.\(^58\) Chen et al.\(^56\) proposed a “cut-and-ablate” concept for the full-ER to ensure durable pain relief after the operation (Fig. 2). The preliminary study of the authors showed less relapsing pain during the 1-year follow-up in their technique compared to the cooled radiofrequency ablation treatment. However, the long-term outcomes remain further studies to prove which technique is better. Recently, the author also expands the indication of full-ER for coccydynia and
the preliminary results were favorable (Fig. 3).

Endoscopic surgery is seldom applied in treating neoplastic disease. The working space was narrowed, and it was challenging to manage brisk bleeding from the hypervascular tumor. Besides, bimanual dissection is not feasible with a full-endoscopic approach. Dural suture repair is technically demanding through the working channel of the uniportal endoscope. Therefore, it may be feasible for the full-endoscopic approach to remove the extradural lesions, which are usually spinal metastasis with epidural invasion. Decompression of the neural structure by a full-endoscopic approach under local anesthesia has been reported in patients with radicular pain due to sacral metastasis. For hypervascular tumors, transarterial embolization may help to control intraoperative bleeding. The metastatic spinal tumors are usually extensive and unresectable. The goal of the surgery is to restore neurological function by separation of the tumor and dural sac for decompression.

As for intradural lesion, case report revealed that full-endoscopic approach may be a potential alternative for the resection of intradural extramedullary tumor or the ligation of spinal dural arteriovenous fistula. However, indications are limited to small size tumors without significant nerve roots or spinal cord compression. It is challenging to debulk and detach the large-size tumor with full-endoscopic technique under limited visualization. Hybrid operation such as microscope-assisted endoscopic approach may be an alternative. Innovative tools or techniques are necessary to overcome the imperfection of full-endoscopic techniques in tumor dissection and dural repair.

CONCLUSION

Full-ESS is a diverse procedure with the evolution of instruments and the innovation of endoscopic techniques. Currently, ESS is suitable for the whole spine level. The indications of ESS have been expanded from discectomies to endoscopic fusion for lumbar degenerative disease. Full-ER for the denervation of branches of spinal nerves has been an emerging solution to treat CLBP or sacroiliac joint pain. The development of endoscopic tumor surgeries remains deficient due to its inherent limitation in instruments and dissection techniques. However, that does not influence the role of the ESS in the contemporary MISS. With innovative technologies and techniques, we look forward to breakthroughs in applying full-endoscopic spine systems for all kinds of spinal surgeries.

NOTES

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Jin-Sung Kim: 0000-0001-5086-0875
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23. McGrath LB, White-Dzuro GA, Hofstetter CP. Comparison


The Role and Future of Endoscopic Spine Surgery: A Narrative Review

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Many types of surgeries are changing from conventional to minimally invasive techniques. Techniques in spine surgery have also changed, with endoscopic spine surgery (ESS) becoming a major surgical technique. Although ESS has advantages such as less soft tissue dissection and normal structure damage, reduced blood loss, less epidural scarring, reduced hospital stay, and earlier functional recovery, it is not possible to replace all spine surgery techniques with ESS. ESS was first used for discectomy in the lumbar spine, but the range of ESS has expanded to cover the entire spine, including the cervical and thoracic spine. With improvements in ESS instruments (optics, endoscope, endoscopic drill and shaver, irrigation pump, and multiportal endoscope), limitations of ESS have gradually decreased, and it is possible to apply ESS to more spine pathologies. ESS currently incorporates new technologies, such as navigation, augmented and virtual reality, robotics, and 3-dimensional and ultraresolution visualization, to innovate and improve outcomes. In this article, we review the history and current status of ESS, and discuss future goals and possibilities for ESS through comparisons with conventional surgical techniques.

Keywords: Endoscopic spine surgery, Minimal invasive surgery, Navigation, Augmented reality, Robot-assisted surgery

INTRODUCTION

As life expectancy increases, spinal diseases are also becoming more frequent¹ and the demand for minimally invasive spine surgery (MISS) and endoscopic spine surgery (ESS) for surgical treatment of spine diseases has increased. Concomitantly, ESS has been recognized as an important technique for spine surgery.² Elderly patients with spinal diseases typically have many comorbidities and medical problems, and therefore the surgeon's burden increases. Improvements in ESS instrumentation (optics, endoscopes, endoscopic drills and shavers, irrigation pumps, and multiportal endoscopes) have addressed previous limitations of ESS, making it possible to apply ESS to a wider range of spine pathologies.³ ESS is now used to treat many degenerative spine diseases, including massive herniated discs and spinal stenosis.⁴

ESS is quickly replacing conventional lumbar spine surgery. Originally used primarily for discectomy, ESS is now used for interbody fusion with additional percutaneous screw fixation.³,⁵ Many studies have demonstrated that ESS can be safely applied in cervical and thoracic spine surgery.⁶,⁷ With improvements of the equipment, ESS is overcoming its limitations and becoming applicable not only in degenerative spine disease treatment but also to other pathologies such as tumors, trauma, and deformities.⁸,⁹ The purpose of this article is to review the history of ESS development, verify the current utility of ESS, and suggest directions of future development. In addition, we discuss the future goals and possibilities of ESS through comparisons with conventional surgical techniques.

HISTORY OF ESS

Krause and Oppenheim described the first lumbar discectomy in 1908, but the earliest surgical techniques were accompanied by serious complications such as cerebrospinal fluid leakage and segmental instability, which could lead to postoperative...
back pain. Therefore, many surgeons sought less tissue-damaging approaches. Yasargil and Casper separately introduced microsurgical approaches in lumbar disc surgery in 1977, and this technique has become the gold standard for spine surgery worldwide.

Early attempts to reach the disc space percutaneously started in the 1970s. Kambin and Sampson (1973) and Hijikata (1975) introduced a posterolateral approach for fluoroscopic-guided percutaneous discectomy through a cannula. Kambin and Sampson conducted numerous cadaveric studies and additionally described the safe triangular zone for docking and working on the transformaminal region, allowing a variety of surgical techniques to approach through the safe triangular zone. The first application of a modified arthroscope was announced by Forst and Hausman in 1983. Kambin et al. reported direct visualization using endoscopes in 1988. Schreiber et al. adapted arthroscopic instruments for removal of the nucleus pulposus under direct view in 1989, reporting an overall success rate of 72.5% for sciatica. Ten years later, a prospective randomized study by Hermantin compared video-assisted arthroscopic microdiscectomy to traditional open microdiscectomy and found that patients who underwent endoscopic surgery had higher satisfaction, shorter length of hospital stay, and less narcotic usage postoperatively than those who did not. Classical ESS using a single incision is now classified as “full endoscopic spine surgery” and comprises most ESS.

In the late 1990s, Yeung developed the first fully functional endoscopic system. Using a multichannel endoscope with continuous fluid irrigation, Yeung and colleagues described successful surgical outcomes in cases of disc herniation. Around the same time, Foley developed a tubular retractor and initiated microendoscopic discectomy, which became an important surgical technique in minimally invasive discectomy and fusion (Fig. 1).

However, tubular retractors require a microscope, and full ESS causes rapid surgeon fatigue, resulting in dangerous situations due to the narrow field limitation. Full ESS is performed through a single portal through which passes the light source, irrigation visualization, and the surgical instruments. Unilateral biportal endoscopic (UBE) spine surgery has been introduced and become widely accepted due to the familiar surgical view and allowing the surgeon free dexterity. In 1996, De Antoni et al. published the first technical note in which endoscopes and instruments were inserted independently through 2 portals. Two years later, they described the use of standard artthroscopic instruments for magnification, illumination, and irrigation and reported good clinical results. Soliman published surgical results for lumbar disc herniation and spinal stenosis in 2013 and 2015, using UBE techniques with independent portals, which is very similar to current methods (Fig. 2). UBE surgery offers low blood loss, early discharge, familiar working space, and a wide view.

CURRENT ROLE OF ESS

1. Lumbar Spine

1) Transformaminal approach

Transformaminal approach is the most traditional method used in ESS for discectomy. The endoscope is inserted towards Kambin’s triangle. The most important parts of the approach are safe docking and placing the spine endoscope under fluoroscopic guidance. The surgeon must have excellent understanding of radiologic imaging and of the patient’s anatomic restrictions, such as the iliac crest at the level of L5/S1. With improvements...
in ESS equipment, many studies demonstrated that complex cases of migrated discs also could be treated with partial resection of the pedicle and foramen.\textsuperscript{31,32} Osman reported in a cadaveric study that the transforaminal technique resulted in more expansion of foraminal space and less instability.\textsuperscript{33} In foraminal stenosis patients, the transforaminal approach is successful and has good long-term outcomes.\textsuperscript{34} A recent cadaveric study demonstrated that extensive foraminotomy in lateral recess with removal of the ligamentum flavum and superior articular facet is feasible.\textsuperscript{35,36}

Transforaminal endoscopic surgery could be an option for revision surgery, and transforaminal decompression of foraminal or lateral recess stenosis in patients with previous spinal surgery resulted in excellent or good outcomes after 2-year follow-up.\textsuperscript{37} Yagi et al.\textsuperscript{38} evaluated 48 consecutive patients who underwent previous spine surgery and performed revision surgery with the transforaminal endoscopic approach under local anesthesia, reporting successful outcomes. Several recent studies have reported that there were no significant differences in reoperation and complication rates between transforaminal endoscopic surgery and open microscopic surgery, but the endoscopic group showed less back pain postoperatively and shorter length of hospital stay.\textsuperscript{3} Because of the shorter operation time, the transforaminal approach can be performed as awake surgery. Telfeian et al.\textsuperscript{39} reported successful clinical outcomes after awake transforaminal endoscopic lumbar surgery in 52 consecutive patients over the age of 80.

2) Interlaminar approach

Transforaminal approaches can yield successful decompression in cases of posterolateral disc herniation and foraminal stenosis, but have limitations for the treatment of central stenosis. This limitation inspired the use of endoscopes for interlaminar approaches.\textsuperscript{40,41} Interlaminar techniques provides surgeons with more familiar visualization similar to conventional open surgery. Previously, transforaminal ESS was mainly performed for discectomy. With the development of the interlaminar approach, ESS has been applied to the surgical treatment of various stenoses, including central stenosis. In interlaminar approaches, using endoscopes helps preserve the bony anatomy and bilateral facet joints better than conventional open surgery.

Because of the high resolution due to zoom-in effects, ESS showed similar or superior results compared to tubular retractor and conventional discectomy and decompression (Fig. 3).\textsuperscript{4} A prior study analyzed 95 consecutive patients who underwent either tubular surgery or endoscopic decompression. The endoscopic group had better clinical outcomes and shorter length of hospital stay, fewer complications, and fewer revisions.\textsuperscript{42} Ruetten et al.\textsuperscript{43} performed a randomized controlled trial of 161 patients who underwent either endoscopic or conventional microscopic interlaminar decompression for lateral recess stenosis and found similar symptomatic recovery but lower rates of revisions and complications in endoscopic surgery patients. Lee et al.\textsuperscript{44} published a meta-analysis of 5 retrospective cohort studies involving 156 patients with neurogenic claudication due to central stenosis. Their results demonstrated significant improvements in Oswestry Disability Index (ODI) and visual analogue scale (VAS) scores.

Some prior studies compared full endoscopic and UBE surgeries. Hua et al.\textsuperscript{45} compared clinical outcomes of 2 endoscopic surgeries, and reported that the safety and efficacy of both procedures were similar, but operation time was shorter and central canal decompression was better in UBE surgery. Heo et al.\textsuperscript{46} compared 3 different types of minimally invasive decompressive surgery for central stenosis, and found that patients treated with full ESS complained less of postoperative pain while those treated with UBE showed less violation of the facet joints. There remains much room for improvement, but endoscopic techniques have proven their potential and role in spine surgery.

3) Lumbar interbody fusion

Minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF) with tubular retractor procedures have become more popular due to minimal disruption and faster recovery.\textsuperscript{21} For the same reasons, endoscopic lumbar interbody fusion is gaining attention, especially in elderly and highly morbid patients. In patients with unilateral foraminal stenosis and mild to moderate central stenosis, endoscopic fusion could be an attractive option; however, patients with bilateral foraminal ste-
nosis, severe central stenosis, or high-grade spondylolisthesis still have limitations for endoscopic lumbar interbody fusion.\textsuperscript{5,47}

The endoscopic transforaminal lumbar interbody fusion (TLIF) approach is almost the same as the MIS-TLIF technique. In addition, both full ESS and biportal endoscopic techniques could be applied in lumbar interbody fusion surgery. After docking instruments, laminotomy with central decompression is performed.\textsuperscript{48} Unlike simple decompression or discectomy under endoscope, an ipsilateral facet should be totally removed to create working space for endplate preparation and cage insertion (Fig. 4).\textsuperscript{3,49}

Many clinical studies have shown successful outcomes of endoscopic interbody fusion. Recent studies found that biportal endoscopic TLIF and MIS-TLIF showed no significant differences in clinical outcomes.\textsuperscript{50-52} Patients who undergo uniportal endoscopic fusion have better recovery, less demand for opioids, early mobilization, and shorter length of hospital stay.\textsuperscript{47} There are no significant differences in early and midterm postoperative outcomes and fusion rates between biportal and full endoscopic fusion groups.\textsuperscript{53} However, no prior research has reported long-term fusion rates over 2 years.\textsuperscript{48} Long-term outcomes and randomized controlled trials still remain to be performed.

2. Cervical Spine

Recently, application of endoscopic techniques in cervical degenerative spine disease has increased. Endoscopic surgery is now used for both anterior and posterior approaches. Posterior full endoscopic cervical foraminotomy and additional disectomy showed similar clinical outcomes to conventional anterior cervical discectomy and fusion.\textsuperscript{54} Guo et al.\textsuperscript{55} published a meta-analysis of 24 studies that supported the efficacy and safety of posterior endoscopic keyhole surgery compared to conventional anterior cervical discectomy and fusion. Cervical motion was preserved better in posterior full endoscopic cervical foraminotomy and disectomy, but the surgical indication is narrower.\textsuperscript{56} Patients who underwent endoscopic surgery had less blood loss, shorter operation times, and shorter hospital stays than those treated with conventional open foraminotomy.\textsuperscript{57} Cervical myelopathy was thought to be a contraindication of endoscopic cervical spine surgery, but recently, with the development of large-size full endoscopes and UBE, endoscopic laminectomy has also become possible.\textsuperscript{58,59}

Anterior cervical discectomy and fusion (ACDF) has been the gold standard of surgical technique in cervical disc herniation. Several recent studies showed good clinical outcomes of

![Fig. 4. Biportal endoscopic transforaminal lumbar interbody fusion (TLIF). (A) Preoperative magnetic resonance images showed degenerative spondylolisthesis L4 on L5 with right foraminal stenosis (arrow). The patient underwent biportal endoscopic TLIF. (B) Preoperative and postoperative lateral x-rays showed spondylolisthesis was reduced well with interbody cage and percutaneous pedicle screw fixation. (C) Endoscopic images show complete discectomy and endplate preparation and inserted titanium cage (arrow).](image-url)
anterior full endoscopic cervical discectomy in patients with soft disc herniation, unilateral radiculopathy, and central or paracentral disc herniation. Ahn et al. reported 5-year follow-up outcomes of anterior full endoscopic discectomy for soft disc herniation and showed comparable results with conventional ACDF. Zhang et al. performed a meta-analysis and demonstrated successful clinical outcomes and shorter operation time and hospital stay than conventional ACDF. Recently, full endoscopic ACDF was attempted, but no relevant research has been reported yet, and few studies are being attempted (Fig. 5).

Recently, studies have described endoscopic surgery with screw fixation. Zhu et al. attempted the posterior UBE approach for cervical stenosis and performed decompressive laminectomy and unilateral lateral mass screw fixation, and reported that open-door laminoplasty also was possible with UBE. Lvov et al. reported endoscope-assisted posterior transarticular standalone screw fixation of C1–2 in traumatic injury patients, and found better pain scale recovery after surgery, less blood loss, and shorter operation time. Kotheeranurak et al. announced a novel technique of full endoscopic anterior odontoid screw fixation, and reported successful outcomes in 4 traumatic injury cases.

3. Thoracic Spine

Because of the lower incidence of thoracic degenerative spine conditions, there is little relevant research. Many conventional thoracic spine approaches exist, but the majority require extensive resection of ribs and soft tissues, and are accompanied by various complications including intensive care unit stays and pulmonary dysfunction. To overcome complications of the conventional thoracic approach, Choi et al. studied transforaminal full endoscopic thoracic discectomy in 14 patients with thoracic soft disc herniation and 5-year follow-up. They reported significant improvements in VAS and ODI scores. Ruetten et al. studied 55 patients with thoracic disc herniation treated using a full-endoscope technique via interlaminar, extraforaminal, or transthoracic retropleural approaches, and found that sufficient decompression was achieved and no serious complications in their patients.

Although ESS is still a challenging surgery for thoracic myelopathy, Cheng and Chen reported 12 consecutive cases of full endoscopic thoracic decompression for thoracic spinal stenosis. They used both transforaminal and interlaminar approaches and reported successful clinical outcomes. Shen et al. also studied 360° full endoscopic decompression for thoracic spinal stenosis with myelopathy, with simultaneous transfo-

Fig. 5. A cervical ossification of the posterior longitudinal ligament patient underwent full endoscopic cervical discectomy and fusion. Preoperative (A) and postoperative magnetic resonance images (B). C-arm lateral image (C) during foraminotomy and operative view after cage insertion (D). (E) Final wound was about 2 cm. All images were provided by Dr. Kangtaek Lim.
raminal and interlaminar full endoscopic decompression, and reported favorable results.

Although some studies reveal good outcomes of endoscopic approaches in the thoracic spine, endoscopic techniques for thoracic spine surgery are limited and remain challenging because of the complexity of thoracic spine anatomy, including ribs, lung, pleura and great vessels, and risk of catastrophic injury, such as paraplegia. However, with the development of UBE techniques, ESS is a potential treatment for thoracic myelopathy accomplished by ossification of the ligamentum flavum, and fusion surgery for the thoracic spine is also being attempted (Fig. 6).

ADVANCED TECHNIQUES AND FUTURE DIRECTIONS FOR ESS

1. Navigation

Endoscopic surgery has a steep learning curve and involves difficulty in anatomy visualization. Recently, many attempts have been made to introduce navigation systems into ESS. Navigation provides highly accurate real-time anatomical information and guidance for instrument placement, for which 2-dimensional (2D) fluoroscopy is insufficient. Intraoperative computed tomography scans and guidance are safe and effective alternatives to fluoroscopy. Navigation with an intraoperative O-arm in conventional spine surgery allows high accuracy of pedicle screw placement and reduces complications and revisions. In ESS, this navigation system could help operators calculate an optimal trajectory and find ideal incision points in the early stages of surgery, and help confirm the exact locations of surgical instruments during UBE and full ESS (Figs. 7, 8). Quillo-Olvera et al. reported the possibility of increasing safety and accuracy by using navigation for pedicle screw fixation as well as accurate positioning of endoscopic instruments by using navigation for TLIF with biportal endoscope.

Standard navigation techniques require optic tracers, which takes up space during ESS (Fig. 7). To overcome this weakness, electromagnetic navigation (EMN) systems may be applied to full ESS, and a randomized controlled trial with EMN demonstrated similar clinical improvement and lower radiation exposure levels for both options. Another retrospective study found that the use of the EMN system significantly reduced operation time and radiation exposure. Navigation systems could provide greater safety and accuracy, and help overcome the steep learning curve of ESS.

Fig. 6. Thoracic disc herniation with myelopathy in T10-11 underwent thoracic discectomy and postero-lateral fusion by unilateral biportal endoscopic surgery. Preoperative (A) and postoperative magnetic resonance images (B). Postoperative x-ray (C) showed screw fixation. All images were provided by Dr. Mankyu Park.
Fig. 7. Biportal endoscopic surgery with navigation. The use of fluoroscope during endoscopic spine surgery could be replaced by navigation-assisted endoscopic surgery. An O-arm (A) is needed to apply navigation-assisted endoscopic surgery. Operation field with optical tracer (B), navigation and endoscope monitor (C).

Fig. 8. Real-time tracking of surgical instruments during navigation-assisted biportal endoscopic spine surgery. Navigation image (A) and endoscopic image (B). Instrument tip is located inside the disc.

2. Augmented Reality and Virtual Reality

Augmented reality (AR) is an interactive experience that combines the real world and computer-generated content. This novel technology is infiltrating healthcare and spine surgery. AR systems mainly serve as navigation tools in operating rooms. Standard navigation systems have limitations in simultaneous visualization, while head-mounted displays allow visualization of the surgical field and navigation data at the same time. AR helps reduce radiation exposure and operation time, and also provides safety and precision to beginners during pedicle screw fixation. Molina et al. studied the application of AR in pedicle screw fixation in a cadaveric model, and demonstrated that AR-assisted procedure is superior to free-hand techniques. AR assistants could be utilized not only for pedicle screw fixation, but also for finding the ideal trajectory and entry points like standard navigation systems in ESS.

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Virtual reality (VR) is a highly advanced technology that allows surgeons to experience surgery in a virtual world created by a computer. VR stimulators are gaining attention in education and preoperative planning. Zheng et al. reported that a VR preoperative planning system for full ESS could significantly improve accuracy and reduce operation times. Since ESS is performed with a monitor, it is an ideal surgery for VR education, which could help overcome the steep learning curve.

3. Robot-Assisted Surgery

Robot-assisted surgery is expanding in many surgical fields. Robot-assisted spine surgery is usually performed for pedicle screw fixation, and recent studies suggested that robot-assisted screw fixation has higher accuracy, shorter hospital stay, and lower radiation exposure than surgeries without robots. Gao et al. found that robot-assisted percutaneous pedicle screw fixation could be performed under regional anesthesia effectively and safely. Robots can place pedicle screws in precise positions, and robot-assisted spine surgery shares overlapping features with navigation systems. However, robots provide exact physical guidance to conduct preoperatively customized surgical plans. Therefore, the ESS also could apply robot-assisted for to accurate positioning of endoscopes at ideal locations. Wang et al. applied robot assistance in full endoscopic lumbar discectomy and validated its safety and effectiveness as an alternative to conventional fluoroscopic ESS. Robot-assisted ESS is also expected to help overcome steep learning curves by helping to put the endoscope in the correct position.

4. Ultraresolution (4K) and 3-Dimensional and Ultraresolution Endoscope Applications

Current 2D ESS has disadvantages due to lack of stereoscopic vision. Lack of depth perception causes unfamiliarity with surgical anatomy and influences the perioperative complications. Three-dimensional (3D) endoscopic equipment provides clear views of surgical anatomy, such as exposure of dura and nerve roots. Three-dimensional images can make surgeons feel dizzy, but have advantages for reducing learning periods and distinguishing lesions from normal neural structures. The adoption of ultraresolution and 3D images for ESS could enable surgeons to identify surgical anatomy more precisely, reducing unintended damage to vulnerable structures. Using a 4K ultraresolution endoscope, structures such as foraminal ligaments, which are difficult to observe with conventional microscopes, can be easily identified (Fig. 9). Furthermore, accurate perception of the degree of stenosis and disc protrusion using 3D visualization could reduce surgical uncertainty, followed by better decompression of neural structures and better surgical outcomes.

CONCLUSION

ESS has rapidly grown over the last 30 years. Although it was first introduced in the lumbar spine, ESS is now being applied to whole spine surgery, including the cervical and thoracic spine.
ESS has mainly been applied to disc herniation, but has been extended to other pathologies such as spinal stenosis and myelopathy. It was chiefly used for simple nerve decompression, but with the recent development of percutaneous screw fixation systems, almost all kinds of fusion surgery including cervical, thoracic, and lumbar spine fusion have become possible with ESS. The removal of extradural tumors has also been achieved with biportal ESS. However, the application of ESS to major areas of spine surgery other than degenerative diseases, including deformities and intra-dural tumors, is still limited (Table 1).

ESS is cutting edge spine surgery that can take advantage of various technologies, with the latest technologies including navigation, AR, VR, robots, and 3D image already having been adopted.

As the number of elderly and highly complicated patients continues to increase, ESS will become more important for MISS in the future. Further efforts to improve ESS techniques and apply new technologies will place ESS among the best options for surgical treatment of entire spine diseases by overcoming current limitations.

Table 1. Possible surgeries according to endoscopic spine surgery technique

<table>
<thead>
<tr>
<th>Location and type of surgery</th>
<th>Full endoscopy</th>
<th>Biportal endoscopy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cervical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior approach</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACDF with stand-alone cage</td>
<td>O</td>
<td>X</td>
</tr>
<tr>
<td>Discectomy and foraminotomy</td>
<td>O</td>
<td>X</td>
</tr>
<tr>
<td>Odontoid screw fixation</td>
<td>O</td>
<td>X</td>
</tr>
<tr>
<td>Posterior approach</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foraminotomy and discectomy</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Central decompressive laminectomy</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Lateral mass screw fixation</td>
<td>X</td>
<td>O</td>
</tr>
<tr>
<td>Laminoplasty</td>
<td>X</td>
<td>O</td>
</tr>
<tr>
<td>Thoracolumbar</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Posterior approach</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central decompressive laminectomy</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>OLF removal</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Foraminal decompression</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Discectomy</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Interbody fusion</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Tumor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extradural tumor</td>
<td>X</td>
<td>O</td>
</tr>
<tr>
<td>Intradural tumor</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

NOTES

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Complications and Management of Endoscopic Spinal Surgery

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In the past, the use of endoscopic spine surgery was limited to intervertebral discectomy; however, it has recently become possible to treat various spinal degenerative diseases, such as spinal stenosis and foraminal stenosis, and the treatment range has also expanded from the lumbar spine to the cervical and thoracic regions. However, as endoscopic spine surgery develops and its indications widen, more diverse and advanced surgical techniques are being introduced, and the complications of endoscopic spine surgery are also increasing accordingly. We searched the PubMed/MEDLINE databases to identify articles on endoscopic spinal surgery, and key words were set as “endoscopic spinal surgery,” “endoscopic cervical foraminoectomy,” “PECD,” “percutaneous transforaminal discectomy,” “percutaneous endoscopic interlaminar discectomy,” “PELD,” “PETD,” “PEID,” “YESS” and “TESSYS.” We analyzed the evidence level and classified the prescribed complications according to the literature. Endoscopic lumbar surgery was divided into full endoscopic interlaminar and transforaminal approaches and a unilateral biportal approach. We performed a comprehensive review of available literature on complications of endoscopic spinal surgery. This study particularly focused on the prevention of complications. Regardless of the surgical methods, the most common complications related to endoscopic spinal surgery include dural tears and perioperative hematoma, transient dysesthesia, nerve root injury and recurrence. However, endoscopic spinal surgery, including full endoscopic transforaminal and interlaminar and unilateral biportal approaches, is a safe and effective treatment for lumbar as well as cervical and thoracic spinal diseases such as disc herniation, lumbar spinal stenosis, foraminal stenosis and recurrent disc herniation.

Keywords: Endoscopic spinal surgery, Full endoscopic approach, Unilateral biportal approach, Complication

INTRODUCTION

As life expectancy increases, the number of patients with degenerative spinal diseases is increasing worldwide. As patients age increased, surgeons have to manage patients with increased medical comorbidities such as liver, lung, heart and kidney dysfunction, along with the increased risk of general anesthesia. Accordingly, recently, many elderly patients have preferred minimally invasive spinal surgery over conventional surgical methods, and endoscopy-based spinal surgery is being performed. Endoscopic surgery is also a subset of minimally invasive spinal surgery, which is rapidly and continuously evolving to help manage older patients at high risk for general anesthesia. Endoscopic surgery has advantages such as less muscle and bone damage, less pain, early rehabilitation, shorter hospitalization and an early return to work.

In the past, the use of endoscopic spine surgery was limited to intervertebral discectomy; however, it has recently become possible to treat various lumbar degenerative diseases such as lumbar spinal stenosis and foraminal stenosis, and the treatment range has expanded from the lumbar spine to the cervical and thoracic regions. However, as endoscopic spine surgery develops and its indications widen, more diverse and advanced surgical techniques are being introduced, and the complications of endoscopic spine surgery are also increasing accordingly.

Still now, literatures on the complications of endoscopic spinal surgery are very rare. Therefore, this study aimed to conduct a literature review of the complications of endoscopic spinal sur-
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gery and to predict the prognosis for the incidence of complications, and solutions to complications related to endoscopic spinal surgery.

MATERIALS AND METHODS

The PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analysis) guidelines were used as templates for this systematic review. These guidelines are an evidence-based minimum set of items aimed at helping authors improve the reporting of systematic reviews and meta-analyses. The review process started with a search of the PubMed and Cochrane databases to identify articles on spinal stenosis and endoscopic decompression protocol. A reviewer assessed all articles and references and agreed on which articles should be included. To prevent selection bias during the review, abstracts from the search were numbered and pasted onto a document after deleting the publication journal, author, and institution. The initial search included the keywords "endoscopic spinal surgery," "endoscopic cervical discectomy," "endoscopic cervical foraminotomy," "endoscopic lumbar discectomy," and "endoscopic lumbar decompression," which yielded 494 results. After duplicates were identified and removed, 421 articles were obtained.

The search also included the exact surgical technique term "endoscopic spinal surgery" and returned 188 articles published between 1980 and 2021. The exclusion criteria included no reported complication results (57 articles), microendoscopic surgery (23 articles), metastasis (7 articles), and studies not in English (7 articles). A total of 94 articles that met our inclusion criteria were identified through the search process and analyzed (Fig. 1). Additionally, we included 9 case studies and technical notes dealing with the complications of endoscopic spinal surgery. After excluding articles that met the inclusion criteria, 103 articles were included.

To date, randomized controlled trials (RCTs) on full endoscopic surgery have been scarce. There were only 3 RCTs for 2 full endoscopic interlaminar lumbar decompressions and full endoscopic cervical approaches. No RCT has compared full endoscopic transfenalar and interlaminar approaches and unilateral biportal approaches with complications. Therefore, direct meta-analysis was not possible for either method, and only a narrative analysis was performed.

RESULTS

A total of 103 articles related to complications of endoscopic spinal surgery were reviewed and analyzed.

Complications of full endoscopic surgery were reported in 38 articles in cervical spinal disease, 4 on complications of full endoscopic cervical surgery (Table 1), and 11 on full endoscopic...

Fig. 1. Flow diagram (PRISMA format) of the screening and selection process of full endoscopic spinal surgery.

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Twelve articles on complications of endoscopic thoracic spinal surgery were reported, 2 on review articles of full endoscopic thoracic surgery (Table 5), 7 on full endoscopic transforaminal thoracic approach (Table 6), and 3 on full endoscopic interlaminar thoracic approach (Table 7) including complications. However, there is no articles on biportal endoscopic thoracic surgery including complications.

Complications of lumbar endoscopic surgery were reported in 53 articles on full endoscopic lumbar decompression. Regardless of the transforaminal or interlaminar approach method, complications of full endoscopic lumbar decompression were reported in a total of 5 studies (Table 8).

A total of 24 studies reported complications for full endoscopic transforaminal lumbar decompression (Table 9) and total 24 articles describing interlaminar approach contained complications (Table 10).

The overall incidence of clinically symptomatic complications is below 10%. Most complications were minor, and life-threatening complications, such as thromboembolism, sepsis, severe bleeding, or pulmonary complications are less frequent than open surgery. The complications of endoscopic cervical surgery

<p>| Table 1. Complications of full endoscopic cervical surgery of reviewed study |</p>
<table>
<thead>
<tr>
<th>Study</th>
<th>Year</th>
<th>Design</th>
<th>Country</th>
<th>Approach</th>
<th>Complications (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guo et al.</td>
<td>2022</td>
<td>Systematic review meta-analysis</td>
<td>China</td>
<td>Full endoscopic</td>
<td>Total complication rate (4.7%), reoperation rate (1.1%)</td>
</tr>
<tr>
<td>Choi et al.</td>
<td>2017</td>
<td>Systematic review</td>
<td>Korea</td>
<td>Full endoscopic</td>
<td>Neurological injury, vascular injury, visceral injury</td>
</tr>
<tr>
<td>Quillo-Olvera et al.</td>
<td>2018</td>
<td>Technical review</td>
<td>Korea</td>
<td>Full endoscopic</td>
<td>Anterior PECD: vascular injury, hematoma, swallowing dysfunction, esophageal injury, nerve(spinal cord, dura) injury, infection Posterior PECD: neck pain, nerve(spinal cord, dura) injury, bleeding, high pressure irrigation, hematoma, instability</td>
</tr>
<tr>
<td>Bucknell and Gibson.</td>
<td>2018</td>
<td>Systematic review</td>
<td>UK</td>
<td>Full endoscopic</td>
<td>Anterior PECD: numbness (8), recurrent laryngeal nerve injury (2), discitis (1), vascular injury (3), persistent pain (3), neck pain (14), hematoma (2), headache (2), swallowing dysfunction (2), etc. Posterior PECD: transient dysesthesia (5), neck pain (2), nerve (spinal cord, dura) injury (8), infection (2)</td>
</tr>
</tbody>
</table>

PECD, percutaneous endoscopic cervical discectomy.

<p>| Table 2. Complications of full endoscopic anterior cervical surgery of reviewed study |</p>
<table>
<thead>
<tr>
<th>Study</th>
<th>Year</th>
<th>Design</th>
<th>Country</th>
<th>Approach</th>
<th>Complications (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ahn et al.</td>
<td>2005</td>
<td>Retrospective study</td>
<td>Italy</td>
<td>Full endoscopic</td>
<td>Swallowing difficulty (2)</td>
</tr>
<tr>
<td>Ruetten et al.</td>
<td>2009</td>
<td>Prospective randomized controlled study</td>
<td>Germany</td>
<td>Full endoscopic</td>
<td>Swallowing difficulty (2), recurrent disc (2)</td>
</tr>
<tr>
<td>Tzaan</td>
<td>2011</td>
<td>Retrospective study</td>
<td>Taiwan</td>
<td>Full endoscopic</td>
<td>Recurrent disc (2)</td>
</tr>
<tr>
<td>Yang et al.</td>
<td>2014</td>
<td>Retrospective comparative cohort study</td>
<td>China</td>
<td>Full endoscopic</td>
<td>Hematoma (1), reoperation (1), headache (1)</td>
</tr>
<tr>
<td>Parihar et al.</td>
<td>2018</td>
<td>Retrospective study</td>
<td>India</td>
<td>Full endoscopic</td>
<td>C5 nerve deficit (1), hoarseness (1), swallowing difficulty (2), hematoma (16), incomplete decom (2)</td>
</tr>
<tr>
<td>Tacconi and Giordani</td>
<td>2019</td>
<td>Prospective study with meta-analysis</td>
<td>Italy</td>
<td>Full endoscopic</td>
<td>Esophageal injury (1), C7 nerve deficit (1)</td>
</tr>
<tr>
<td>Yu et al.</td>
<td>2019</td>
<td>Case series</td>
<td>China</td>
<td>Full endoscopic</td>
<td>mediastinal effusion (1), endplate collapse (2)</td>
</tr>
<tr>
<td>Ramirez León et al.</td>
<td>2020</td>
<td>Retrospective study</td>
<td>USA</td>
<td>Full endoscopic</td>
<td>Hematoma (3), carotid lesion injury (2), dysphonia (3), reoperation (3)</td>
</tr>
<tr>
<td>Ahn et al.</td>
<td>2020</td>
<td>Retrospective comparative cohort study</td>
<td>Korea</td>
<td>Full endoscopic</td>
<td>Swallowing difficulty (1), recurrent disc (2)</td>
</tr>
<tr>
<td>Ren et al.</td>
<td>2020</td>
<td>Retrospective study</td>
<td>China</td>
<td>Full endoscopic</td>
<td>Td: Recurrent disc (2), Tc: mediastinal effusion (1), endplate collapse (2), headache (1), hematoma (1)</td>
</tr>
</tbody>
</table>
### Table 3. Complications of full endoscopic posterior cervical surgery of reviewed study

<table>
<thead>
<tr>
<th>Study</th>
<th>Year</th>
<th>Design</th>
<th>Country</th>
<th>Approach</th>
<th>Complications (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ruetten et al.</td>
<td>2008</td>
<td>Prospective randomized controlled study</td>
<td>Germany</td>
<td>Full endoscopic</td>
<td>Transient hypesthesia (3), recurrence (3)</td>
</tr>
<tr>
<td>Huang et al.</td>
<td>2020</td>
<td>Prospective cohort study</td>
<td>China</td>
<td>Full endoscopic</td>
<td>Dura rear (2), hypesthesia (2)</td>
</tr>
<tr>
<td>Wu et al.</td>
<td>2021</td>
<td>Prospective study with Retrospective</td>
<td>Korea</td>
<td>Full endoscopic</td>
<td>Motor deficit (2), recurrence (1), neuropraxia(1)</td>
</tr>
<tr>
<td>Yang et al.</td>
<td>2014</td>
<td>Retrospective comparative cohort study</td>
<td>China</td>
<td>Full endoscopic</td>
<td>Neurologic deficit (1), reoperation (1)</td>
</tr>
<tr>
<td>Shu et al.</td>
<td>2019</td>
<td>Retrospective systematic review</td>
<td>China</td>
<td>Full endoscopic</td>
<td>Upper limb weakness (1)</td>
</tr>
<tr>
<td>Lee et al.</td>
<td>2018</td>
<td>Retrospective systematic review</td>
<td>Korea</td>
<td>Full endoscopic</td>
<td>Motor weakness (mild 2, severe 1), dura tear (1), dysthesia (1), hematoma (1), recurrence (1)</td>
</tr>
<tr>
<td>Zheng et al.</td>
<td>2018</td>
<td>Retrospective systematic review</td>
<td>China</td>
<td>Full endoscopic</td>
<td>Hematoma (1), reop. persistent pain (2), dura injury (1)</td>
</tr>
<tr>
<td>Tong et al.</td>
<td>2020</td>
<td>Retrospective comparative study</td>
<td>China</td>
<td>Full endoscopic</td>
<td>Nerve root injury (2)</td>
</tr>
<tr>
<td>Xiao et al.</td>
<td>2019</td>
<td>Retrospective comparative study</td>
<td>China</td>
<td>Full endoscopic</td>
<td>Pain (2), numbness (3), weakness (1)</td>
</tr>
<tr>
<td>Wang et al.</td>
<td>2021</td>
<td>Retrospective comparative study</td>
<td>China</td>
<td>Full endoscopic</td>
<td>Pain (1), dura injury (3), C5 palsy (4)</td>
</tr>
<tr>
<td>Yu et al.</td>
<td>2021</td>
<td>Retrospective comparative study</td>
<td>China</td>
<td>Full endoscopic</td>
<td>Dura injury (1)</td>
</tr>
<tr>
<td>Ma et al.</td>
<td>2020</td>
<td>Retrospective comparative study</td>
<td>China</td>
<td>Full endoscopic</td>
<td>Key hole: pain (1), Dura injury (2), weakness (1), disc recur (1) Delta: pain (1), numbness (1), disc recurred (1)</td>
</tr>
<tr>
<td>Ma et al.</td>
<td>2022</td>
<td>Retrospective comparative study</td>
<td>China</td>
<td>Full endoscopic</td>
<td>Hematoma (1), dural injury(1)</td>
</tr>
<tr>
<td>Ye et al.</td>
<td>2017</td>
<td>Retrospective study</td>
<td>China</td>
<td>Full endoscopic</td>
<td>Transient hypesthesia (1)</td>
</tr>
<tr>
<td>Yu et al.</td>
<td>2019</td>
<td>Retrospective study</td>
<td>China</td>
<td>Full endoscopic</td>
<td>Arm pain (1)</td>
</tr>
<tr>
<td>Kim et al.</td>
<td>2009</td>
<td>Retrospective study</td>
<td>Korea</td>
<td>Full endoscopic</td>
<td>Arm pain (1)</td>
</tr>
<tr>
<td>Zhong et al.</td>
<td>2022</td>
<td>Retrospective study</td>
<td>Korea</td>
<td>Full endoscopic</td>
<td>Arm pain (1)</td>
</tr>
<tr>
<td>Liu et al.</td>
<td>2021</td>
<td>Retrospective study</td>
<td>Italy</td>
<td>Full endoscopic</td>
<td>Transient hypesthesia (1)</td>
</tr>
<tr>
<td>Dalgic et al.</td>
<td>2022</td>
<td>Case series</td>
<td>Turkey</td>
<td>Full endoscopic</td>
<td>Pain (1), dura injury (3), disc recurred (1)</td>
</tr>
</tbody>
</table>

### Table 4. Complications of biportal endoscopic posterior cervical surgery of reviewed study

<table>
<thead>
<tr>
<th>Study</th>
<th>Year</th>
<th>Design</th>
<th>Country</th>
<th>Approach</th>
<th>Complications (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jung and Kim</td>
<td>2022</td>
<td>Retrospective study</td>
<td>Korea</td>
<td>Biportal endoscopic</td>
<td>Transient motor weakness (1)</td>
</tr>
<tr>
<td>Zhu et al.</td>
<td>2021</td>
<td>Technical note</td>
<td>China</td>
<td>Biportal endoscopic</td>
<td>Transient hypesthesia (1)</td>
</tr>
<tr>
<td>Kim et al.</td>
<td>2022</td>
<td>Technical note</td>
<td>Korea</td>
<td>Biportal endoscopic</td>
<td>Operation site pain and numbness (1)</td>
</tr>
<tr>
<td>Song and Lee</td>
<td>2020</td>
<td>Technical note</td>
<td>Korea</td>
<td>Biportal endoscopic</td>
<td>Dura tear (1)</td>
</tr>
</tbody>
</table>

### Table 5. Complications of full endoscopic thoracic surgery of reviewed study

<table>
<thead>
<tr>
<th>Study</th>
<th>Year</th>
<th>Design</th>
<th>Country</th>
<th>Approach</th>
<th>Complications (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ruetten et al.</td>
<td>2018</td>
<td>Retrospective comparative study</td>
<td>Germany</td>
<td>Full endoscopic transforaminal</td>
<td>Interlaminar: hematoma (1), transient dysesthesia (1) Extraforaminal: dura tear (1), hematoma (1), intercostal neuralgia (2), myelopathy (1) Transthoracic retropleural: dura tear (1), transient dysesthesia (1), myelopathy (1) Total: 19%</td>
</tr>
<tr>
<td>Gibson et al.</td>
<td>2021</td>
<td>Retrospective study</td>
<td>UK</td>
<td>Full endoscopic interlaminar</td>
<td>Dura tear (11; 2%), transient paresthesia (10; 2%), revision (7; 1.5%), neurologica injury (3; 0.6%), hematoma (3; 0.6%)</td>
</tr>
</tbody>
</table>

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at approximately 5% with both anterior and posterior approaches had an incidence equivalent to that expected from open cervical surgery.

According to the complication analysis of endoscopic spinal surgery, regardless of the cervical, thoracic or lumbar spine, regardless of the uniportal or biportal approach, main complications such as dural tears, postoperative hematoma, neurological irritation (dysesthesia), untreated pain are commonly reported.

1. Complications of Endoscopic Cervical Spinal Surgery

Regardless of the cervical anterior or posterior approach method, several literatures on the complications of full endoscopic cervical surgery have already been reported. According to the analysis of complications of endoscopic spinal surgery, Guo et al. reported total complication rate of 4.7% and a reoperation rate of 1.1% in cervical endoscopic surgery. In anterior full endoscopic cervical surgery, recurrent laryngeal nerve injury and swallowing dysfunction are unique complications of this method. In addition, numbness, hematoma, discitis, vascular injury, persistent pain were reported as complications.

In posterior endoscopic cervical surgery, transient dysesthesia, neck pain, and nerve (spinal cord and dura) injuries are comparatively common complications.

2. Complications of Endoscopic Thoracic Spinal Surgery

Gibson et al. reported complications of endoscopic thoracic surgery, in this study, dura tear (2%) and transient paresthesia (2%) were common complications, and revision (1.5%), neurological injury (0.6%), and hematoma (0.6%) were reported as complications.

In endoscopic transforaminal thoracic surgery, intercostal neuralgia is unique complication. Other common complica-
Complications and Management of Endoscopic Spinal Surgery

3. Complications of Endoscopic Lumbar Spinal Surgery

Regardless of the lumbar transforaminal or interlaminar approach method, literatures on the complications of full endoscopic surgery have already been reported. According to the analysis of the complications of endoscopic spinal surgery, dural tears, postoperative hematomas, neurological complications, lower condyle fractures, and epidural lipomatosis were reported. Lee et al. reported a meta-analysis that compared the trans-

Table 9. Complications of full endoscopic transforaminal decompression of reviewed study

<table>
<thead>
<tr>
<th>Study</th>
<th>Year</th>
<th>Design</th>
<th>Country</th>
<th>Approach</th>
<th>Complications (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kambin et al.</td>
<td>1996</td>
<td>Prospective study</td>
<td>USA</td>
<td>Full endoscopic transforaminal</td>
<td>Dysesthesia (4), infection (1)</td>
</tr>
<tr>
<td>Knight et al.</td>
<td>2014</td>
<td>Prospective study</td>
<td>UK</td>
<td>Full endoscopic transforaminal</td>
<td>Recurrent transient predominant symptom (15)</td>
</tr>
<tr>
<td>Li et al.</td>
<td>2019</td>
<td>Comparative study</td>
<td>China</td>
<td>Full endoscopic transforaminal</td>
<td>Dysesthesia (1), nerve injury (1), revision operation (2)</td>
</tr>
<tr>
<td>Tang et al.</td>
<td>2018</td>
<td>Retrospective study</td>
<td>China</td>
<td>Full endoscopic transforaminal</td>
<td>Dysesthesia (1), temporary pain aggravation (6), neck pain (1)</td>
</tr>
<tr>
<td>Zhang et al.</td>
<td>2020</td>
<td>Retrospective study</td>
<td>China</td>
<td>Full endoscopic transforaminal</td>
<td>Dysesthesia (3), dural tear (2)</td>
</tr>
<tr>
<td>Lewandowski et al.</td>
<td>2014</td>
<td>Retrospective study</td>
<td>USA</td>
<td>Full endoscopic transforaminal</td>
<td>None</td>
</tr>
<tr>
<td>Wen et al.</td>
<td>2016</td>
<td>Retrospective study</td>
<td>China</td>
<td>Full endoscopic transforaminal</td>
<td>Recurred pain (reop) (5), dural tear (1)</td>
</tr>
<tr>
<td>Lewandowski et al.</td>
<td>2018</td>
<td>Retrospective study</td>
<td>USA</td>
<td>Full endoscopic transforaminal</td>
<td>Irritation of dorsal root ganglion (12)</td>
</tr>
<tr>
<td>Lewandowski et al.</td>
<td>2018</td>
<td>Retrospective study</td>
<td>USA</td>
<td>Full endoscopic transforaminal</td>
<td>Dysesthesia (9), incisional pain (5), infection (2)</td>
</tr>
<tr>
<td>Yang et al.</td>
<td>2019</td>
<td>Retrospective study</td>
<td>China</td>
<td>Full endoscopic transforaminal</td>
<td>Dysesthesia (4), dural tear (1), urinary retention (1)</td>
</tr>
<tr>
<td>Youn et al.</td>
<td>2019</td>
<td>Retrospective study</td>
<td>Korea</td>
<td>Full endoscopic transforaminal</td>
<td>Dysesthesia (5)</td>
</tr>
<tr>
<td>Yeung et al.</td>
<td>2019</td>
<td>Retrospective study</td>
<td>China</td>
<td>Full endoscopic transforaminal</td>
<td>Dysesthesia (9), hematoma (1), other level pain (2), persistent pain (3), disc herniation (9)</td>
</tr>
<tr>
<td>Bao et al.</td>
<td>2019</td>
<td>Retrospective study</td>
<td>China</td>
<td>Full endoscopic transforaminal</td>
<td>Transient recurrence of symptoms (4), reoperation (2)</td>
</tr>
<tr>
<td>Lewandowski et al.</td>
<td>2019</td>
<td>Retrospective study</td>
<td>USA</td>
<td>Full endoscopic transforaminal</td>
<td>Durotomy (2), foot drop (2), disc reherniation (9), wound infection (1), discitis (1), COPD (1)</td>
</tr>
<tr>
<td>Li et al.</td>
<td>2020</td>
<td>Retrospective study</td>
<td>China</td>
<td>Full endoscopic transforaminal</td>
<td>Dural tearing (3), temporary leg numbness (5)</td>
</tr>
<tr>
<td>Martínez et al.</td>
<td>2020</td>
<td>Retrospective study</td>
<td>USA</td>
<td>Full endoscopic transforaminal</td>
<td>None</td>
</tr>
<tr>
<td>Lewandowski et al.</td>
<td>2019</td>
<td>Retrospective study</td>
<td>USA</td>
<td>Full endoscopic transforaminal</td>
<td>Dysesthesia (8), untreated pain (reop) (32)</td>
</tr>
<tr>
<td>Song et al.</td>
<td>2021</td>
<td>Retrospective study</td>
<td>China</td>
<td>Full endoscopic transforaminal</td>
<td>Dysesthesia (1), incomplete decompression (reop) (1)</td>
</tr>
<tr>
<td>Liu et al.</td>
<td>2020</td>
<td>Retrospective study</td>
<td>China</td>
<td>Full endoscopic transforaminal</td>
<td>None</td>
</tr>
<tr>
<td>Yeung and Lewandowski</td>
<td>2020</td>
<td>Retrospective study</td>
<td>USA</td>
<td>Full endoscopic transforaminal</td>
<td>Dysesthesia (17), recurrent HNP (9), hematoma (1), untreated pain (37)</td>
</tr>
<tr>
<td>Zhang et al.</td>
<td>2020</td>
<td>Retrospective study</td>
<td>China</td>
<td>Full endoscopic transforaminal</td>
<td>Dysesthesia (1), temporary pain aggravation (2)</td>
</tr>
<tr>
<td>Cheng et al.</td>
<td>2020</td>
<td>Retrospective study</td>
<td>China</td>
<td>Full endoscopic transforaminal</td>
<td>Dural tear (1), untreated pain (reop) (1), tibialis anterior weakness (1)</td>
</tr>
<tr>
<td>Nam et al.</td>
<td>2020</td>
<td>Case report</td>
<td>Korea</td>
<td>Full endoscopic transforaminal</td>
<td>Fracture (1)</td>
</tr>
<tr>
<td>Ahn et al.</td>
<td>2003</td>
<td>Technical note</td>
<td>Korea</td>
<td>Full endoscopic transforaminal</td>
<td>Missed foraminal dis fragment (reop) (1)</td>
</tr>
</tbody>
</table>

COPD, chronic obstructive pulmonary disease; HNP, herniation nucleus pulposus.

...tions include neurological injury, vascular injury, visceral injury, recurrence, dysesthesia, and incomplete decompression. In endoscopic interlaminar thoracic surgery, dural tears, transient paralysis, and dysesthesia were relative common complications. In thoracic spine endoscopic surgery, motor weakness due to the deterioration of myelopathy has been reported as a complication, requiring careful and meticulous techniques.

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foraminal decompression versus the interlaminar approach for lumbar lateral recess stenosis, in which the transforaminal approach had 3 times more complications (9.1%) than interlaminar decompression (3.4%).

Lin et al. reported a systematic review of unilateral biportal endoscopic spinal surgery (UBESS), reporting a mean incidence of complications of 6.7%. The most common complication was a dural tear. The total mean incidence of dural tears was 4.1% after the UBEBS procedure in 6 studies (range, 2.9%–5.8%).

Fan et al. reported complications and risk factors for percutaneous endoscopic transforaminal discectomy (PETD). In this study, the incidence of different types of complications was 9.76% (72 of 738). The complications and occurrence rates were as follows: 2.30% (17 of 738) of recurrence, 3.79% (28 of 738) of

### Table 10. Complications of full endoscopic interlaminar lumbar decompression of reviewed study

<table>
<thead>
<tr>
<th>Study</th>
<th>Year</th>
<th>Design</th>
<th>Country</th>
<th>Approach</th>
<th>Complications (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ruetten et al.</td>
<td>2009</td>
<td>RCT</td>
<td>Germany</td>
<td>Full endoscopic interlaminar</td>
<td>Dural tear (1), dysesthesia (3), urinary retention (1)</td>
</tr>
<tr>
<td>Komp et al.</td>
<td>2011</td>
<td>Prospective study</td>
<td>Germany</td>
<td>Full endoscopic interlaminar</td>
<td>Dural tear (2), dysesthesia (5), urinary retention (2), foot dorsiflexion paresis (1)</td>
</tr>
<tr>
<td>Komp et al.</td>
<td>2015</td>
<td>RCT</td>
<td>Germany</td>
<td>Full endoscopic interlaminar</td>
<td>Dural tear (2), dysesthesia (4), motor weakness (1), urinary retention (1)</td>
</tr>
<tr>
<td>Kamson et al</td>
<td>2017</td>
<td>Retrospective study</td>
<td>USA</td>
<td>Full endoscopic interlaminar</td>
<td>Reoperation (re herniation) (3), sympa thetical pain (2), urinary retention (1)</td>
</tr>
<tr>
<td>Lin et al.</td>
<td>2017</td>
<td>Case series</td>
<td>Korea</td>
<td>Full endoscopic interlaminar</td>
<td>Hematoma</td>
</tr>
<tr>
<td>Lee et al.</td>
<td>2018</td>
<td>Retrospective study</td>
<td>Korea</td>
<td>Full endoscopic interlaminar</td>
<td>Dural tear (6), dysesthesia (12), nerve injury (3) disc herniation (2)</td>
</tr>
<tr>
<td>Kim et al.</td>
<td>2017</td>
<td>Retrospective study</td>
<td>Korea</td>
<td>Full endoscopic interlaminar</td>
<td>Dural tear (3), untreated pain(reop) (2)</td>
</tr>
<tr>
<td>Kim et al.</td>
<td>2017</td>
<td>Retrospective study</td>
<td>Korea</td>
<td>Full endoscopic interlaminar</td>
<td>Dural tear (1), untreated pain(reop) (2)</td>
</tr>
<tr>
<td>Lee et al.</td>
<td>2018</td>
<td>Meta-analysis</td>
<td>Korea</td>
<td>Full endoscopic interlaminar</td>
<td>Dysesthesia (4), dural tear (5), hematoma (3), headache (3), reoperation (7)</td>
</tr>
<tr>
<td>Park and Lee</td>
<td>2019</td>
<td>Retrospective study</td>
<td>Korea</td>
<td>Full endoscopic interlaminar</td>
<td>None</td>
</tr>
<tr>
<td>Li et al.</td>
<td>2019</td>
<td>Comparative study</td>
<td>China</td>
<td>Full endoscopic interlaminar</td>
<td>Dysesetha (2)</td>
</tr>
<tr>
<td>Lim et al.</td>
<td>2019</td>
<td>Retrospective study</td>
<td>Korea</td>
<td>Full endoscopic interlaminar</td>
<td>Dural tear (7), hematoma (5), infection (1), untreated pain (reop) (6)</td>
</tr>
<tr>
<td>Lee et al.</td>
<td>2018</td>
<td>Retrospective study</td>
<td>Korea</td>
<td>Full endoscopic interlaminar</td>
<td>Dural tear (6), dysesthesia (12), nerve injury (3) disc herniation (2)</td>
</tr>
<tr>
<td>Cao et al.</td>
<td>2019</td>
<td>Retrospective study</td>
<td>China</td>
<td>Full endoscopic interlaminar</td>
<td>Untreated pain (3), spinal cord hypertension (1)</td>
</tr>
<tr>
<td>McGrath et al</td>
<td>2019</td>
<td>Retrospective study</td>
<td>USA</td>
<td>Full endoscopic interlaminar</td>
<td>Dysesthesia (3), disc herniation (1)</td>
</tr>
<tr>
<td>Huang et al.</td>
<td>2019</td>
<td>Retrospective study</td>
<td>Korea</td>
<td>Full endoscopic interlaminar</td>
<td>Dural tear (1), untreated pain (reop) (11 (2))</td>
</tr>
<tr>
<td>Hua et al.</td>
<td>2020</td>
<td>Retrospective study</td>
<td>China</td>
<td>Full endoscopic interlaminar</td>
<td>Dural tear (2), cauda equina syndrome (1)</td>
</tr>
<tr>
<td>Chiu et al.</td>
<td>2020</td>
<td>Retrospective study</td>
<td>China</td>
<td>Full endoscopic interlaminar</td>
<td>Medical problem (2)</td>
</tr>
<tr>
<td>Yang et al.</td>
<td>2020</td>
<td>Retrospective study</td>
<td>China</td>
<td>Full endoscopic interlaminar</td>
<td>Dural tear (2), medical problem (2), urinary retention (2)</td>
</tr>
<tr>
<td>Lim et al.</td>
<td>2020</td>
<td>Retrospective study</td>
<td>Korea</td>
<td>Full endoscopic interlaminar</td>
<td>Dural tear (5), hematoma (1), dysesthesia (8), untreated pain (reop) (1)</td>
</tr>
<tr>
<td>Ruetten et al</td>
<td>2020</td>
<td>Systematic review</td>
<td>Germany</td>
<td>Full endoscopic interlaminar</td>
<td>Wrong level surgery, epidural bleeding, insufficient decompression, dural tear, nerve injury, vessels injury gans</td>
</tr>
<tr>
<td>Zhao et al.</td>
<td>2019</td>
<td>Retrospective study</td>
<td>China</td>
<td>Full endoscopic interlaminar</td>
<td>Dural tear (1), Dysesthesia (2), untreated pain (reop) (1)</td>
</tr>
<tr>
<td>Yoshikane et al</td>
<td>2021</td>
<td>Retrospective study</td>
<td>Japan</td>
<td>Full endoscopic interlaminar</td>
<td>Dural tear (4), hematoma (3), untreated pain (reop) (2)</td>
</tr>
<tr>
<td>Yoshikane et al</td>
<td>2021</td>
<td>Retrospective study</td>
<td>Japan</td>
<td>Full endoscopic interlaminar</td>
<td>Dural tear (5), hematoma (1), motor weakness (6)</td>
</tr>
</tbody>
</table>
Complications and Management of Endoscopic Spinal Surgery

Ju CI, et al.

Persistent lumbosacral or lower extremity pain, 1.90% (14 of 738) of dural tear, 0.81% (6 of 738) of incomplete decompression, 0.41% (3 of 738) of surgical site infection, 0.27% (2 of 738) of epidural hematoma and 0.27% (2 of 738) of intraoperative posterior neck pain.

Ju et al. reported a study of narrative analysis, comparing the complications of the transforaminal and interlaminar approaches. They found that dural tears are overwhelmingly common (2.19%) in interlaminar decompression followed by epidural hematoma (0.76%) and transient dysesthesia, whereas in transforaminal decompression, dysesthesia (1.46%) was the most common, followed by untreated pain (1.20%) and dural tearing.

In UBESS, Liang et al. reported the overall complication rate was 5% and dural tears were the most frequent complications at 2%, followed by epidural hematoma with an incidence of 1%. The remaining complications included nerve root injury, inadequate decompression, and postoperative headache.

In addition, Wang et al. reported the results of a single-arm rate meta-analysis, which showed that the overall complication rate of unilateral biportal endoscopic treatment of lumbar spinal stenosis was 6.27%, the incidence of dural tear was 2.49%, the incidence of transient paresthesia was 0.14%, postoperative spinal epidural hematoma was 0.27%, and postoperative headache, inadequate decompression, root injury and infection were 0%.

Summing up several papers on complications of endoscopic spine surgery, the most common complications of endoscopic spine surgery are dural tears, epidural hematoma, transient dysesthesia, and incomplete decompression.

This study also discusses the treatment method for each complication, along with the thesis review.

4. Management of Complications of Endoscopic Spinal Surgery

1) Dural tear

Dural damage is the most common complication of endoscopic spinal surgery, and it can lead to serious complications if an accurate diagnosis and appropriate treatment are not performed. The overall rate of dural tears in endoscopic spinal surgery was 2.7%, range from 0% to 8.6%. The incidence of a dural tear was much greater in cases with lumbar stenosis (3.7%) than in lumbar discherniation (2.1%). The risk of dural tears is greater in bilateral decompression procedures than unilateral decompression.

Pan et al. reported that the incidence of dural rupture increased to 1.1% when percutaneous endoscopic lumbar discectomy (PELD) was switched from an “inside-out” technique to an “outside-in” technique. Dural injury by instruments or radiofrequency, spinal canal adhesions, large disc fragments, and a loose dura are risk factors for dural tears.

However, Klingler et al. reported that the occurrence of complications after durotomy in minimal invasive surgery is lower than after open surgery because of the preservation of the paraspinal musculature. The paraspinal musculature is not dissected during minimally invasive surgery and slides back to its original position after removal of the tubular retractor.

In UBESS, Liang et al. reported dural tears were the most frequent complication at 2%. Wang et al. reported that the incidence of dural tears was 2.49%. There are several main reasons for spinal dural tears caused by UBE spine endoscopic surgery. (1) Beginners easily make mistakes because the visual field under endoscopy is a 2-dimensional plane and is easily blurred. (2) UBE does not require retraction of the anatomical structure to expose the dura mater, which is quite different from other techniques. (3) Patients with complex conditions require operations of long duration, increasing the risk of spinal membrane tears. (4) During the operation, the injected saline squeezed both sides of the dura mater, causing the area to fold. The central area may be damaged during ligamentum flavum resection. (5) When using high-speed drills, the peripheral fibrous bands and vascular bundles of the dura may stretch around the drill neck, causing larger tears.

Several methods have been introduced for the treatment of incidental dural tears during endoscopic spinal surgery. An autologous muscle or fat graft in combination with fibrin glue or a fibrin-sealed collagen sponge seems to be a good and safe method for the management of dural tear in lumbar endoscopic spine surgery.

Kim et al. reported the incidence of incidental durotomy was 8.2% and classified the incidental durotomy during endoscopic decompression according to lumbar levels, 40.7% occurred at L3–4, 44.4% at L4–5, and 14.8% at L5–S1. They also divided incidental durotomy into 4 types: 29.6% are type 1 (peripheral type), 70% are type 2 (central type), 7.4% are type 3 (complex type), and 3.7% are type 4 (unrecognized). They recommended the endoscopic patch blocking dura repair technique should be considered in type 1 to type 3A of dural tears with a good prognosis and clinical outcome. However, open surgical repair is recommended in types 3B, 3C. and 4 dura tears with fair to poor outcome.

Nam et al. introduced double-Layer TachoSil packing technique for incidental durotomy in endoscopic surgery. A hemostatic agent, TachoSil (Nycomed, Linz, Austria), is used for con-
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Ju CI, et al.  reported that the total number of complications in biportal endoscopic surgery has not been described. When TachoSil packing is performed, the intradural TachoSil is inserted to avoid spilling, and the extradural TachoSil is sealed over the intradural TachoSil. Therefore, TachoSil did not cause a mass effect. Nevertheless, a thin layer of TachoSil must be applied; the application of larger quantities results in pooling that could lead to serious side effects such as compression of the spinal cord and nerve roots. If used incorrectly, excess TachoSil may cause additional iatrogenic dural tearing. In our experience, mild swelling of the TachoSil in the intradural space reinforces the dural repair site and prevents secondary rupture; it also ensures good adhesion of the edge of the TachoSil to the intact surrounding dura. Second, while maneuvering TachoSil intradurally, the cast side will dissolve in cerebrospinal fluid and adhere to nerve roots, which could be dangerous and difficult to reverse. Thirdly, thrombin is proinflammatory and could cause arachnoiditis and neuritis in the postoperative period if deployed intradurally.

2) Postoperative epidural hematoma

An epidural hematoma occurs mainly after an interlaminar approach. Recently, as endoscopic surgery for spinal stenosis and intervertebral discectomy has increased, the complication rate has also increased. It is also one of the most common complications in biportal endoscopic surgery.

The incidence of postoperative epidural hematoma is approximately 0.27%. Continuous saline irrigation is necessary during biportal endoscopic spine surgery. The use of an infusion pump during surgery may be an unavoidable risk factor. However, it may increase the epidural pressure and, subsequently, result in meningeal irritation, indicated by neck pain or headache. When the outflow of saline solution is blocked, the pump continues to infuse saline to increase the pressure in the surgical field, cover up bleeding points, and cause intraoperative hemostasis. Lack of saline solution may cause postsurgical epidural hematoma.

There are 2 possible mechanisms of increased epidural and intracranial pressure by continuous saline irrigation. The first is the direct pressure effect by continuous irrigation of saline. The second is direct cranial movement of irrigation fluid. Prolonged operating time or poor patency of the irrigation fluid can increase epidural pressure during biportal endoscopic surgery. In the biportal endoscopic approach, continuous saline is passed from the endoscopic portal to the working portal. The patency of saline outflow and constant flow is important for maintaining epidural pressure. An infusion pump pressure > 50 mmHg can increase the cervical epidural pressure in this surgery. Reducing the operation time and maintaining the pump pressure below 40 mmHg may be useful in reducing the complications caused by the increase in epidural pressure. Additionally, postoperative epidural Hemovac insertion may help to drain excessive irrigation fluid. Neck pain or headache can be improved with bed rest and conservative treatments.

Although symptomatic postoperative epidural hematoma is relatively rare (the incidence rate is 0.02% to 4.6%), it can lead to serious consequences such as cauda equina syndrome and even lower limb paralysis, which affects patients’ quality of life. Therefore, early detection and handling are important.

Ahn et al. reported that postoperative epidural hematoma is one of the complications that are considered to develop more often in biportal endoscopic surgery than in conventional spine surgery. The radiological thecal sac compression by hematoma was 39.8% of grade 1 (thecal sac compression less than a quarter), 30.1% of grade 2 (between a quarter and a half), 26.5% of grade 3 (between a half and three quarters), and 3.6% % of grade 4 (over three quarters) in biportal endoscopic surgery.

Kim et al. reported that the overall occurrence rate of postoperative hematoma was 23.6% after biportal endoscopic spinal surgery. Female sex, old age (> 70 years), preoperative anticoagulation medication, and usage of intraoperative water infusion pump were significantly correlated with the occurrence of postoperative hematoma. Although symptomatic postoperative hematoma was extremely rare (1.9%), radiologic hematoma confirmed by postoperative magnetic resonance imaging (MRI) was higher (23.6%). The perioperative risk factors of postoperative hematoma after biportal endoscopic spinal surgery include female sex, older age (> 70 years), preoperative anticoagulation medication, usage of intraoperative water infusion pump, and surgery requiring more bone work (laminecetomy or interbody fusion).

Additionally, Kim et al. reported that the total number of patients with hematoma was 39 (24.7%) according to T2-weighted axial postoperative MRI. The incidence of postoperative spinal epidural hematoma after biportal endoscopic spinal surgery according to postoperative MRI was higher than expected, regardless of the patients’ postoperative symptoms. Postoperative hematoma has a decisive influence on postoperative results, and revision surgery may be necessary if canal encroachment is > 50% with concomitant symptoms.

Symptomatic postoperative spinal epidural hematoma is a devastating complication that could develop after biportal en-
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The main reason for transient paresthesia is that palsy and pain are both caused by irritation of the instruments and improper operation. The dorsal root ganglion (DRG) lies in the intraforaminal region and is vulnerable to disc herniation, foraminal stenosis, and mechanical damage by operative instruments. Damage to the DRG brings symptoms different from those associated with primary pathology. As a unique complication of PETD, postoperative dysesthesia greatly affects recovery and the postoperative quality of life. Cho et al. applied the floating retraction technique to prevent postoperative dysesthesia and revealed that this technique was effective in 154 patients. Fluoroscopy is essential to locate guiding wire and working cannula to avoid mechanical stretch or damage to the upper DRG.

For the prevention of postoperative dysesthesia, the foraminoplasty is performed to expand the safety zone without causing an exiting nerve root irritation. Foraminoplasty is not always needed during the endoscopic transforaminal approach to prevent postoperative dysesthesia. However, it is an especially useful method for widening the safety zone in cases of narrowed intervertebral foramina, such as facet hypertrophy or superior articular process overriding. It is also a safe and effective technique for entering the epidural space without exiting nerve root injury, especially in cases of central disc herniation or a downward migrated disc herniation, which have a high risk of causing an exiting nerve root injury. To effectively remove herniated disc material, the insertion angle of the endoscope was modified depending on the type of disc herniation. Significantly, the closer the incidence angle is to that of the vertical axis, the wider the safety zone, thereby reducing the possibility of exiting nerve root injury; however, it is difficult to access the epidural space and to secure the field of view. On the other hand, if the angle of incidence is close to that of the horizontal axis, accessing the epidural space and securing the field of view is easier, but the safety zone is narrowed, which increases the possibility of exiting nerve root injury. Therefore it is important to determine the appropriate angulation based on the pattern of disc herniation. To reduce exiting nerve root irritation within the safety zone as much as possible. Keeping the endoscopic cannula steep and located in the inferior disc space rather than the superior disc space is important.

In biportal endoscopic surgery, the incidence of transient paresthesia is approximately 0.14%. The main reason for transient paresthesia after surgery is that palsy and pain are both caused by sensory nerves. The pain is transmitted by small unmyelinated fibers, and the conductive palsy is thick. The structure of unmyelinated fibers is relatively simple, and the postoperative recovery is faster, while myelin fibers need to undergo a lon-
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Moreover, recurrent disc herniation should be dis-  
covered. Most patients will relieve the palsy. However, because palsy is positively related to illness time and degree of stenosis, the recovery times of different patients are different.  

5) Incomplete decompression

Whether resection of the herniated disc is complete depends on the position of the working cannula, type of disc herniation, and size of the herniated fragments. Incomplete discectomy is particularly common in downward migration or high canal compromised disc herniation. Choi et al. retrospectively analyzed 10,228 patients treated by PETD, and found 283 cases of incomplete resection, among which 95 were caused by improper location. Regarding the type of herniation, there were 91 cases with central herniation (32.2%), 70 with migrated herniation (24.7%), 63 with axillary type herniation (22.3%), 18 with shoulder-type herniation (6.4%), and 12 with foraminal/extraforaminal herniation (4.2%). Lee et al. found that herniations with high canal compromise and high-grade migration make it harder for PELD to efficiently remove herniated disc. Herniated disc fragments should be adequately released from the annulus before they are grasped and removed. Detailed planning of the puncture route is the key for complete removal. A careful check for residual fragments is necessary, and placing the bevel of the working cannula toward the fragments helps achieve sufficient re-  

moval of the herniated disc. On the other hand, excessive resection of the herniated disc may increase the risk of dural tears and damage to the nerve root, thus, surgeons need to restore the normal motion and pulsation of the nerve root.  

In the transfornaminal approach, the foraminoplasty technique is a safe and reliable method for discectomy, and the migrated disc can be easily removed using a curved probe or forceps. Because the field of view of endoscopic surgery is narrow, it may not be possible to check the lesion area, and dura free pulsation must be checked to ensure sufficient decompression.  

During spinal stenosis decompression, unilateral and bilater-  
al decompression should be performed to sufficiently decom-  
press the superior articular process in the lateral recess area to confirm the traversing nerve root, and sufficient laminectomy is required for sufficient decompression.

Decompression is usually excellent in UBESS for lumbar spinal stenosis. However, decompression may be inadequate in patients with severe lumbar spinal stenosis. Deviations in the pre-operative assessment and intraoperative decompression range have been the main reasons for inadequate decompression. Choi et al. showed that for early cases, postoperative MRI revealed inadequate resection of the proximal and contralateral ligamentum flavum. These patients' acute neurologic symptoms were relieved, although they had complained of tiredness in the affected calf. Choi et al. reported that angled curettes were more useful in performing adequate flavectomy than Kerrison punch- 
es. Angled curettes, but not straight curettes or Kerrison punch- 
es, might scrape the ligamentum flavum under the lamina without excessive laminectomy. To decompress the contralateral side, Liang et al. reported that a wider interspinous gap should be created to allow for simultaneous insertion of an endoscope and an instrument into the small midline space, with partial resec-  

tion of the upper and lower ends of the spinous processes using a high-speed burr.

Intraoperative irregularities and thermal injuries from radio-  

frequency ablation have been the main causes of nerve root injury. The use of an arthroscopic radiofrequency ablation tip in the spinal canal can cause significant thermal damage to the neural structures. Therefore, it is important to be gentle during the procedure, to identify nerve structures carefully, and to reduce the voltage of the radiofrequency device if necessary.  

6) Recurrence of disc herniation

Recurrent lumbar disc herniation (LDH) is defined as a re-  
currence of disc herniation at the same site of a previous discec-  
tomy in a patient who has experienced a pain-free interval after surgery. However, the minimum length of the pain-free interval is debatable, ranging from any interval of pain resolution to 6 months. Moreover, recurrent disc herniation should be discriminated from incomplete discectomy or endoscopic operative failure.

The purpose of PELD is not to remove nucleus pulposus totally but to remove partially the herniated disc fragments and decompress nerve root. Therefore, recurrence of LDH sometimes occurs with aging, inappropriate weight-bearing, and other factors like male gender, obesity (body mass index [BMI] ≥ 25 kg/m²), old age (≥ 50 years), trauma history, and central disc herniation. But PELD also has some unique risk factors for LDH recurrence, such as surgeons' having less experience with PELD (≤ 200 cases) and performing operations in the early development stage of PELD. Especially, early recurrence after PELD is associated with several risk factors such as BMI, degeneration scale, combined herniation nucleus pulposus, and early ambulation. Preoperatively, surgeons should study imag-
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8. Postoperative Headache

With UBESS via the interlaminar approach, the use of high intraoperative water pressure can increase cerebrospinal fluid pressure and intracranial pressure, leading to postoperative headache and can even induce seizures. Therefore, we searched for the early symptoms of seizures after surgery, such as neck pain, headache, blurred vision, and drowsiness. To avoid the occurrence of postoperative headache, it is crucial to prevent high intraoperative water pressures. Rather than attempting to obtain a clear vision by increasing the infusion pressure, Kim et al. reported that it would be preferable to improve the outflow by applying an extension or crossection of the fascia incision via the working portal, which will allow for a clear view and prevent the occurrence of postoperative headache. Czigléczki et al. reported that irrigation could lead to meningeal irritation and postoperative headache; however, reducing the operative time can avoid such complications. Choi recommended that the irrigation pump pressure should be kept at < 30 mmHg when using the pump.

9. Postoperative instability and facet joint injury

Postoperative segmental instability or facet joint injury is another complication of biportal endoscopic laminotomy. In addition, iatrogenic inferior articular process fractures can occur during laminotomy, and these complications are similar to those from conventional or microscopic surgery. Therefore, preoperative instability is a contraindication of biportal endoscopic lumbar decompression.

10. Cervical and thoracic endoscopic spinal surgery

Cervical and thoracic endoscopic spinal surgery is currently performed in hospitals in the Far East, but is not popular in Europe or the United States. Attempts were made to remove cervical discs with minimally invasive anterior approaches in the 1990s, but the techniques used were not widely adopted because the inherent risks associated with the surgical approach and the lack of well-designed equipment.

Although it is well recognized that posterior cervical laminectomy for disectomy and root decompression with foramen widening will minimize blood loss and enhance patient recovery compared to anterior cervical surgery, the benefits regarding clinical outcomes are less well established.

This is because a variety of posterior surgical methods have been used by surgeons, from microsurgery with tubular retractors to purely endoscopic techniques. It is not clear endoscopic techniques lead to better surgical outcomes than the former.

Surgical complications of approximately 5% in both the anterior and posterior approaches were the same as expected in open cervical surgery, and there appeared to be a low rate of reoperation. The posterior approach may reflect the generally shorter clinical follow-up.

Choi et al. reported the 3 main complications of cervical endoscopic spinal surgery: (1) neurological injury like damage to the cervical cord or nerve root due to inadvertent use of forceps or laser (transient with laser), (2) vascular injury like ca-

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rotid vessels during percutaneous endoscopic cervical discectomy (PECD) and vertebral artery while foraminotomy. (3) visceral injury; mainly oesophagus because it is soft collapsible tube and highly prone to injury while needle insertion in PECD.

In the anterior cervical approach, the essential technical factor is the precise targeting of disc pathology. The surgeon should feel the carotid pulse and push the anterior neck down into the space between the carotid artery and tracheoesophagus until the fingertips touch the anterior surface of the vertebral body. The tracheal air shadow on the fluoroscopic view may be a good indicator of the position of tracheoesophagus. For the patient with a short and thick neck, the shoulder shadow may interfere with C6–7 or lower level. An oblique fluoroscopic view can be useful to approach the C6–7 level. Regarding selective discectomy, direct fragment removal with small instruments is difficult because of tenacious annular anchorage. Careful release of fibrotic adhesion around the herniated fragment is mandatory before the removal of the freely movable herniation fragment.

In the posterior cervical approach, a definitive dissection of bony structures and identification of the laminofacet junction (so-called “Y-point”) is essential for a safe and precise cervical foraminotomy. To prevent postoperative instability, the extent of facetectomy should be limited to no more than 50% of the facet joint. After adequate foraminotomy, the herniated foraminal disc fragment should be removed while preventing a dural tear. The dissection between the herniated disc and the neural tissues can be performed with a blunt dissector. The exposure of herniated fragment with firm nerve retraction can be achieved by rotating the bevel ended tip of the working cannula. After adequate nerve retraction, the herniated piece can be removed by endoscopic forceps and supplementary radiofrequency or laser. Epidural bleeding may occur from flourishing venous plexus. A gentle tamponade with hemostatic agents or hydrostatic pressure may be useful with a bipolar coagulator.

In thoracic endoscopic spinal surgery, 3 main complications of thoracic endoscopic surgery were reported: (1) neurological injury like damage to the spinal cord and its nerve roots, (2) vascular injury like damage to the inferior vena cava or thoracic aorta can be life threatening, (3) visceral injury like damage to the lung or mediastinal viscera. In endoscopic transforaminal thoracic surgery, intercostal neuralgia is a unique complication of insertion of a working cannula between the intercostal spaces. Above all, since thoracic surgery can cause serious neurological damage such as myelopathy, the operation must be performed very carefully and safely.

**DISCUSSION**

Recently, endoscopic spinal surgery has expanded from lumbar discectomy to lumbar spinal stenosis decompression and foraminal stenosis decompression as the transfominal and interlaminar approaches are advanced, respectively. In addition, endoscopic spinal surgeries have become possible from the lumbar spine to the cervical and thoracic spine, and various endoscopic surgical techniques are still being introduced and rapidly developing.

However, in spite of various advantages, endoscopic surgery does not yield good results for all spinal diseases, and it is important to select the appropriate surgical indications to obtain successful surgical results. The indications for endoscopic spinal surgery show slight differences depending on the interlaminar and transfominal approach.

Choi et al. reported a good indication of full endoscopic anterior cervical discectomy, in which disc herniation did not responding to conservative treatment and an annular tear with concordant pain on provocative discography. On the other hand, migrated disc herniation, calcified disc, collapsed disc space < 5 mm, instability, infection and past history of anterior cervical surgery were contraindications.

In full endoscopic posterior cervical foraminotomy, good indications were foraminal disc herniations (predominantly unilateral arm pain), single or multilevel foraminal stenosis (unilateral arm pain), persistent symptoms despite previous anterior cervical discectomy and fusion. On the other hand, axial neck pain, instability, and cervical kyphosis were contraindications.

Lewandrowski et al. reported a systematic review of the contraindications for full endoscopic transfominal decompression. In this article, more difficult central stenosis or complex foraminal stenotic lesions should be considered as alternative endoscopic approaches.

Also, Wagner et al. reported calcified disc, severe stenosis, cauda equina syndrome, painless weakness, severe fibrotic adhesion, pyogenic spondylodiscitis, and severe spinal infection were contraindicated in full endoscopic interlaminar decompression.

Ju et al. reported a systematic review article of contraindications and complications of full endoscopic lumbar decompression for lumbar spinal stenosis. In this study, considering the contraindications of transfominal and interlaminar lumbar decompression, the transfominal approach can be successful in the ipsilateral extraforaminal, foraminal, lateral recess, and central spinal canal. However, surgical access to the contralater-
al area is not possible owing to anatomical limitations. Therefore, in the case of the transforaminal approach, it is a major contraindication for multiple spinal stenosis, bilateral symptoms, and a high iliac crest. However, in the case of the interlaminar approach, access to the bilateral central stenosis and lateral recess is possible, but access to the foraminal or extraforaminal areas is difficult, thus, foraminal stenosis can be a contraindication. However, both the methods share similar contraindications. 

Heo et al.\textsuperscript{15} reported the contraindications of unilateral biportal endoscopic lumbar decompression to include trauma, infection, tumor, instability, high-grade spondylolisthesis, ischemic spondylolisthesis, and severe scoliosis.

For successful endoscopic spinal surgery, it is most important to understand the advantages and disadvantages of endoscopic approach methods and to select the most effective and convenient surgical approach for the disease. The endoscopic spinal surgery has developed rapidly as new delicate techniques have been introduced. The transforaminal endoscopic surgery developed into foraminoplasty with the spread of endoscopic drills, enabling decompression of foraminal stenosis at the surgical site, which was previously limited to discectomy. In addition, with the development of an interlaminar approach to drill-assisted laminectomy, bilateral and contralateral decompression has become possible. However, as the scope of endoscopic surgery is widen, high-level surgical skills are required and difficult, and the complications of endoscopic surgery are also increasing.

According to our study, the incidence of complications was similar between the transforaminal and interlaminar approaches, regardless of cervical, thoracic and lumbar endoscopic surgery. However, the incidence of some complications depends on the surgical approach and method.

In cervical endoscopic spine surgery, the anterior approach and posterior approaches are used. Since the anterior approach is similar to open surgery, there is an anatomically high risk of damage to the anterior structures of the spine, which can cause swallowing difficulties and complications such as hematoma and hoarseness. On the other hand, in the posterior approach, many complications such as nerve root injury, hematoma, and dysesthesia occur as the nerve root is exposed and needs to be managed during foraminotomy.

The surgical approach for the thoracic spine is subdivided into various methods due to its complex anatomical structure, however, in endoscopic surgery, it can be largely divided into transforaminal and interlaminar approaches.

In the full endoscopic thoracic transforaminal approach, it is necessary to enter between the ribs and access the epidural space through foraminoplasty, which can cause intercostal nerve injury from the moment the endoscope is inserted. Stimulation of or damage to the spinal cord during performance can cause serious complications that exacerbate myelopathy.

The interlaminar thoracic approach requires decompression of the spinal cord using a curet and Gerison punch after sufficient laminectomy as open surgery. In a state where sufficient laminectomy is not performed, it is dangerous because it can compress and damage the spinal cord during the process of inserting a curet, drill, or punch.

In particular, lesions that compress the anterior spinal cord, such as ossification of posterior longitudinal ligament, can exacerbate myelopathy during surgery, therefore, endoscopic thoracic spine surgery is a very dangerous and difficult, and open surgery should be actively considered if there is insufficient experience.

In lumbar endoscopic surgery, the full endoscopic interlaminar approach had a higher incidence of dural tear than the transforaminal approach, which might have been caused by medical instruments when dealing with the ligamentum flavum or adhered disc. According to our study, comparing the complications of the 2 methods, transforaminal approach had a high incidence of exiting nerve root injury, so dysesthesia was the most common, followed by untreated pain due to a high probability of incomplete surgery, and incidental dural tears which was less common. In contrast, the interlaminar approach requires decompression of nerves on both sides in the epidural space. The possibility of a dural tear and the incidence of epidural hematoma are high during instrument manipulation. The incidence of other complications was similar between the 2 methods.

Dural tear is the most frequently reported complication of endoscopic surgery in works of various literatures. Since nerve root herniation causes serious symptoms and secondary nerve damage, it is important to prevent nerve root herniation in dura defects. Until now, the gold standard treatment for dural damage is open dural repair, but recently, sealing dura defect by using TachoSil (collagen fleece) has been widely performed a lot in endoscopic surgery without open surgery requiring general anesthesia.

Hematoma is another common complication of the endoscopic spinal surgery. Intraoperative bleeding not only obstructs the surgical field of vision and delays the surgical time, but also can cause serious postoperative complications by unintentionally damaging structures during blind surgery. In general, electrical
Coagulation using radiofrequency is performed, however, it can be very difficult to control bleeding under a narrow endoscopic view.

In this case, it is easy to temporarily secure the surgical field using a hemostatic agent such as floseal, finding the bleeding site and cauterizing bleeding point. Even at the end of surgery, it is important to insert a hemostatic agent to prevent undetected bleeding during surgery. In patients with massive intraoperative bleeding or bleeding tendencies, it is important to insert a Hemovac to prevent hematoma so that unexpected bleeding is well drained and nerves are not compressed.

Nerve damage is a complication that occurs during surgery, and once it occurs, it cannot be treated surgically. Therefore, prevention is the most effective treatment option. In order to prevent this, accurate anatomical knowledge of endoscopic surgery and the safety of the approach must be considered, and careful and delicate surgery must be performed to avoid injury to the nerve during surgery.

Once nerve damage occurs, it takes a lot of time to recover even if it is reversible, and various treatments such as drug treatment and rehabilitation treatment must be performed because the symptoms vary depending on the degree and site of nerve damage.

Prevention is the best treatment for many other complications mentioned in this text. Even in a narrow space with a narrow field of view, it is necessary to obtain the same results as open surgery, therefore, a lot of experience and a long learning curve cannot be avoided.

In the last 5 years, many literatures related to endoscopic spinal surgery have been published. However, retrospective studies (level 3 evidence) are the mainstream, and level 1 evidence papers such as RCTs are absolutely lacking. In addition, there are many papers on full (uniportal) endoscopic spine surgery, however, papers on biportal endoscopic surgery are very rare, especially on the cervical and thoracic spine. For future endoscopic spinal surgery to have the same basis as open surgery, which is still the gold standard, more high-quality evidence such as RCT is needed. Based on these literatures, it is expected that meta-analyses on various topics will be conducted.

CONCLUSION

According to literature analysis, the endoscopic spinal surgery in lumbar, dura tear, postoperative hematoma, transient dysesthesia and untreated pain are relatively common. Additionally, various complications such as urinary retention, motor weakness, cauda equine syndrome, wound infection may occur. On the other hand, endoscopic cervical surgery, swallowing difficulty, hoarseness are common complication in anterior approach, dura tear, postoperative hematoma, transient dysesthesia and weakness are common in posterior approach. In summary, it is most important to understand the advantages and disadvantages of various endoscopic approach methods and to select the most effective and convenient surgical approach for the spinal disease.

NOTES

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The increase in the elderly population has resulted in a rapid increase in degenerative spinal diseases, and it is necessary to introduce a suitable spinal surgery method. The development of spinal endoscopic surgery is rapidly developing along with these demands, but related complications are also increasing due to the lack of educational courses and difficulties in training in spinal endoscopic surgery.1-3

In the March issue of Neurospine, the special issue of endoscopic spinal surgery was conducted with the theme of “The road to expansion and standardization of Endoscopic Spine Surgery”, in particular, “Complications and Management of Endoscopic Spinal Surgery” reported by Ju et al.4 can be said to be a very important and interesting study in terms of anticipating the expansion of spinal endoscopic surgery, and I was able to enjoy the authors’ reports and arguments with interest.

According to reports by Ju and Lee,4 endoscopic spinal surgery can also cause complications in all parts similar to open surgery, but, in cervical area, it is reported that serious complications occur less in the posterior compared to the anterior approach, and, compared to the uniportal approach, reports of complications related to the biportal approach are lacking.

In addition, the occurrence of overall complications occurs in less than 10%, and it is said that the incidence of life-threatening complications is less than that of open surgery. This is to say that the operation can be performed more safely compared to the existing open surgery, but, on the contrary, it also means that better treatment results can be derived through sufficient reports on complications related to endoscopic spinal surgery.

However, as the author said, some complications can be major complications that can lead to life-threatening complications such as lower extremity paralysis, so care must be taken in the decision and technique of endoscopic spinal surgery. Various techniques that can solve the problem have already been introduced, so even if complications occur, it is considered necessary to use them for appropriate treatment.5

Ju and Lee6 state that there are insufficient reports of complications related to current endoscopic spinal surgery in this study. Currently, the development of spinal endoscopic surgery is developing in a wide range of degenerative spinal diseases, and there is no doubt that it will become a major treatment technique for future spinal surgery and treatment. However, in order for this technique to be universalized, it is considered important to develop an understanding of complications and the ability to solve them through numerous
studies, as well as a sufficient educational process.

- **Conflict of Interest:** The authors have nothing to disclose.

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Biportal Endoscopic Transforaminal Lumbar Interbody Fusion Using Double Cages: Surgical Techniques and Treatment Outcomes

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Objective: To describe the surgical techniques and the treatment outcomes of biportal endoscopic transforaminal lumbar interbody fusion (BETLIF) using double cages.

Methods: This study included 89 patients with 114 fusion segments between July 2019 and May 2021. One pure polyetheretherketone (PEEK) cage and 1 composite titanium-PEEK cage were used for interbody fusion. Clinical outcomes measures included visual analogue scale (VAS) scores for lower back pain and leg pain, Oswestry Disability Index (ODI), and Japanese Orthopedic Association (JOA) scores. Computed tomography (CT) of the lumbar spine 1 year postoperatively was used to evaluate the Bridwell interbody fusion grades.

Results: There were significant improvement in VAS for lower back pain from 5.2 ± 3.1 to 1.7 ± 2.1, VAS for leg pain from 6.3 ± 2.5 to 1.7 ± 2.0, ODI from 46.7 ± 17.0 to 12.7 ± 16.1, and JOA score from 15.6 ± 6.3 to 26.4 ± 3.2. The p-values were all < 0.001. The average hospital stay was 5.7 ± 1.1 days. The CT studies available for 60 fusion segments showed successful fusion (Bridwell grade I or grade II) in 56 segments (93.3%). Significant cage subsidence of more than 2 mm was only noted in 3 segments (5.0%). Complications included 1 dural tear, 2 pedicle screws malposition, and 2 epidural hematomas, in which 2 patients required reoperations.

Conclusion: BETLIF with double cages provided good neural decompression and a sound environment for interbody fusion with a big cage footprint, a large amount of bone graft, endplate preservation, and segmental stability.

Keywords: Minimally invasive surgery, Biportal endoscopy, Interbody fusion, Fusion cage, Computed tomography, Treatment outcomes

INTRODUCTION

Lumbar interbody fusion (LIF) has been recognized as an effective surgical treatment for patients with refractory low back pain due to a variety of degenerative lumbar spinal disorders, including degenerative disc diseases and spondylolisthesis.1 LIF can be done via anterior or posterior approaches. The posterior approach is familiar to the spine surgeons and is capable of directly decompressing stenosis. Among the various LIF techniques via posterior approach, transforaminal lumbar interbody fusion (TLIF) has gained its popularity for easier access to the disc space, lower risk of neural injury, and unilateral approach for insertion of the fusion cage and bone graft as compared to posterior LIF.2 The fusion cages used in TLIF can be straight or crescent shapes made of different materials with equivalent clinical outcomes. However, pseudoarthrosis is still a big challenge, with an incidence ranging from 7% to 20%.3 Using a large-sized cage may improve the fusion rate, but it is limited by the transforaminal approach and the small annular window.

Minimally invasive TLIF (MIS-TLIF) with a muscle sparing...
Tubular retractor has evolved to reduce the approach related complications in traditional open surgeries, with decreased surgical morbidity, decreased length of hospital stay, and improved outcomes. However, MIS-TLIF still poses a great challenge for the surgeon in neural decompression, removal of disc, and endplate preparation due to limited anatomic visualization and decreased haptic feedback. Compared to the LIF via anterior approach, TLIF has a significant higher rate of cage subsidence, which may be attributed to the smaller cage footprint and endplate violation.

The biportal endoscopic technique is a revolutional minimally invasive technique that abandons the tubular retractor. It is performed through 2 independent portals with continuous irrigation of normal saline. The normal saline provides hydrostatic pressure to inhibit bleeding and carries away bone debris and oozing. The diameter of the endoscope is only 4 mm, thin enough to get access to the deep structures such as the contralateral lateral recess and the neural foramen. Combined with a high-definition endoscope, the biportal endoscopic technique provide a clear, bright, and magnified surgical field, enabling the surgeon to perform delicate surgical procedures with reduced risks of neural injuries.

Biportal endoscopic technique has been used for various MIS spinal decompression procedures, such as laminotomy for lumbar discectomy, unilateral laminotomy for bilateral decompression, and unilateral foraminotomy for decompression, all of which have demonstrated good clinical efficacy. Recently, the biportal endoscopy technique were applied to LIF surgery in several pioneer studies. These studies demonstrated the unique features of biportal endoscopic TLIF (BETLIF) including a clear and magnified surgical field, direct neural decompression, radical discectomy, and preservation of bony endplate. All these studies used a single TLIF cage for interbody fusion, and only 2 of them reported the fusion rate. Heo and Park reported a 78.3% successful fusion rate as evaluated by serial x-ray, while Kang et al. reported an 87.7% successful fusion rate as evaluated by computed tomography (CT) at 1 year postoperatively. However, there is still room for improvement. Additionally, since endplate preservation was repeatedly emphasized as an important feature of BETLIF, cage subsidence should be carefully evaluated.

In this study, we will describe our BETLIF technique, which uses 2 TLIF cages in a disc space. The purposes of this study are to evaluate the clinical and radiological outcomes, assessed using functional evaluation tools and CT, with a focus on the fusion rate and cage subsidence.

**MATERIALS AND METHODS**

1. **Patient Selection**
   This case series included 89 consecutive patients who received 114 segments of BETLIF with double cages between July 2019 and May 2021 after being approved by the Institutional Review Board of Far Eastern Memorial Hospital (112021-E). To increase the cage footprint, we intended to use 2 composite titanium-polyetheretherketone (Ti-PEEK) TLIF cages for interbody fusion. However, the cost of a composite Ti-PEEK TLIF cage is much higher than that of a pure PEEK TLIF cage, and it is not covered by the National Health Insurance (NHI) system in Taiwan. To compensate for the patient's expenses, we replaced one composite Ti-PEEK TLIF cage with one pure PEEK cage, which is covered by the NHI. That is the reason why we used 2 cages of different materials.

   The indications for BETLIF include mechanical lower back pain, radicular leg pain, or neurological symptoms/signs due to degenerative disc pathologies with persistent symptoms for more than 3 months and failure of conservative treatment. Double cages were used in all patients indicated for BETLIF, except for a few patients who could not afford the more expensive composite T-PEEK TLIF cage. Patients who had prior surgeries in their lumbar spines and patients who received BETLIF with a single cage were excluded from the study. The diagnoses were spondylolisthesis in 83 patients, degenerative disc disease in 4 patients, and degenerative scoliosis in 2 patients. All surgeries were performed by the author in a single medical center.

2. **Evaluation of Clinical Data and Outcomes**
   The demographic and clinical data were retrieved from medical chart reviews. Treatment outcomes were evaluated before the surgery, at 1 month, 3 months, 6 months, 1 year after the surgery, and then every year thereafter. The outcome measures included the visual analogue scale (VAS) for lower leg pain and back pain, the Oswestry Disability Index (ODI) for disability, and the Japanese Orthopedic Association (JOA) scores for functional recovery. All patients had plain anteroposterior (AP) and lateral x-rays, dynamic flexion-extension lateral x-rays before the surgery, at 1 month, 3 months, 6 months, 1 year after the surgery, and then every year thereafter. All patients had a lumbar spine magnetic resonance imaging study before the surgery. CT of the lumbar spine was arranged at 1 year after the surgery to evaluate the fusion status. Reconstruction images on the sagittal and coronal planes were used to evaluate the formation of bridging bone. Fusion results were classified into grade I to grade

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IV using the Bridwell interbody fusion grading system. Grade I or grade II fusion was defined as successful fusion. Cage subsidence was classified into “no subsidence,” “no more than 2 mm,” and “more than 2 mm,” depending on the depth of cage migration into the endplate on the sagittal or coronal CT images. Significant subsidence of more than 2 mm was considered clinically relevant.

Independent t-test was used to compare the continuous variables between groups. Chi-square test was used to compare categorical variables between groups. A p-value of < 0.05 was considered statistically significant.

SURGICAL TECHNIQUES

1. Anesthesia, Patient Positioning, and Draping

BETLIF is performed under endotracheal general anesthesia with the patient placed in the prone position on a Relton-Hall frame on a radiolucent spine table. The table should be adjusted to ensure free passage of the fluoroscope to obtain clear AP and lateral images. We also tilt the table head-up or head-down to keep the disc level of interest perpendicular to the floor for more ergonomic handling of the endoscope and surgical instruments.

Because the surgery is performed with continuous saline irrigation, a watertight draping is essential to prevent soaking and resultant hypothermia of the patient. We demonstrate the dam construct draping method with a transparent covering hood for the fluoroscope (Fig. 1).

2. Localization and Skin Marking

After determining the disc level of interest using the lateral fluoroscopic image, all the other localizations and skin markings are drawn using the AP images. The skin markings include the disc line, the medial and lateral pedicle lines, the inferior pedicle line of the upper vertebra, and the superior pedicle line of the lower vertebra, as well as the skin incisions (Fig. 2). The skin incisions are about 2.5 to 3 cm long for a 1-segment fusion and 4 to 5 cm long for a 2-segment fusion. The skin incisions are 1 or 1.5 cm parallel and lateral to the lateral pedicle lines, which are also used for insertion of the pedicle screws. The offset distance varies according to the patient’s body habitus and can be estimated on the axial MR images in preoperative surgical planning.

3. Approach and Creation of the Working Space

The approach is essentially the same as Waltse’s concept to minimize paraspinal muscle injury. After incising the deep fascia, we carefully dissect the intermuscular plane between the multifidus and longissimus dorsi down to the facet joint. Then, we use a dilator to bluntly dissect a small space over the lamina and facet joint. The endoscope is inserted into the working space through a separate small incision at the medial pedicle line. The triangulation of the endoscope and surgical instrument must be confirmed under fluoroscopy. With the inflow of normal saline, we use a radiofrequency wand (ArthroCare, Austin, TX, USA) to ablate the soft tissue to create the working space required for the following procedures.

4. Unilateral Laminotomy and Bilateral Decompression

We use the high-speed bur with a 4-mm coarse diamond ball tip (Primado II, NSK, Tokyo, Japan) as the main instrument for laminotomy. The starting point of unilateral laminotomy and bilateral decompression is the conjoined part of the spinous process and lamina (Fig. 3A). Use the high-speed bur to expose the cranial margin of the ligamentum flavum. Use the radiofreqeu-
cy wand to dissect the facet joint. Use the small caliber curved osteotome to chop off the inferior articular process into small pieces (Fig. 3B). Harvest these small bone chips as local autografts. Use the Penfield dissector to detach the ligamentum flavum from the undersurface of the lamina. Use the bur to proceed with the sublaminar decompression to the contralateral lateral recess. Make sure that the underlying dura is well protected by the ligamentum flavum. Then move to the caudal end, using the bur to expose the caudal margin of the ligamentum flavum and decompress the ipsilateral lateral recess. Use the osteotome to chop off the tip of the superior articular process as local autografts. Use the Penfield dissector to lift the ligamentum flavum off the dura. Use the pituitary clamp to remove the residual osteophytes and remnants of the ligamentum flavum. We prefer to use a 0° endoscope for initial laminotomy and contralateral decompression, then change to a 30° endoscope for the remaining procedures. The 30° endoscope provides a wider visual field and easier access to the disc space. Finally, use the bur to complete the total facetectomy and shape the transforaminal route (Fig. 3D).

5. Radical Discectomy and Endplate Preparation

The disk space must be large enough to accommodate 2 cages and a large amount of bone grafts. Therefore, the disk must be removed as radially as possible. Instead of using disk shavers or curettes for disk space preparation, we designed a new set of endplate strippers with 3 different angles to strip the cartilaginous endplate off the bony endplate (Fig. 4A). The different angles of the strippers are very helpful in accessing the deep contralateral corner in the disk space (Fig. 4B). The disk can be removed in large pieces along with the cartilaginous endplate and minimal injury to the bony endplate (Fig. 4C). We always insert the endoscope into the disk space to check the residual disk materials and ensure the integrity of the bony endplate (Fig. 4D).

6. Cages and Bone Grafts Insertion

The composite Ti-PEEK cage (Combo-T, A-spine, Taipei, Taiwan) is composed of a PEEK core covered by a Ti plate on its superior and inferior surfaces. When the cage is inserted into a collapsed disc space, disintegration of the Ti plate may occur if it encounters excessive shear stress parallel to its inter-

![Fig. 3. Illustrations and endoscopic images show the conjoined part of spinous process and lamina (A), use of the osteotome for resection of the inferior articular process (B), complete decompression and removal of the ligamentum flavum as a whole piece (C), resection of the superior articular process and creation of the transforaminal route (D).](https://doi.org/10.14245/ns.2346036.018)

![Fig. 4. (A) The endplate strippers. (B) An endoscopic photo shows using the endplate stripper to separate cartilaginous from the vertebral body. (C) The cartilaginous endplates removed in large pieces. (D) An endoscopic photo shows radical discectomy and preservation of the bony endplate.](https://www.e-neurospine.org)
Therefore, we usually insert the solid pure PEEK cage (Reborn, Baui, Taipei, Taiwan) first to avoid such a possible complication (Fig. 5A). The cage height is evaluated using serial cage trials of 1-mm increment starting from 7 mm. When the cage trial is difficult to retrieve by manual force, the same height of the fusion cage is determined. We do not use the cage to restore its original disc height because that may pose excessive stress on the bony endplate and lead to cage subsidence. The first cage is inserted vertically through Kambin’s triangle, which is usually big enough for the cage trials and cage implants with no need to retract the dura or the traversing nerve root (Fig. 5B). The remaining lateral portion of the ligamentum flavum serves as a good protector for the exiting nerve root if it has not been removed yet. The cage should be inserted as anteriorly as possible. The first cage also serves as a spacer to maintain the disc space for impacting bone grafts into the remaining disc space. Bone grafts can be impacted into the disc space using a specially designed funnel (Fig. 5C). Then the second cage is inserted obliquely at an angle of about 45° to the plumb line (Fig. 5D). For the bone graft materials, we use demineralized bone matrix putty (SurFuse, HansBiomed, Daejeon, Korea) inside the cages and the mixture of demineralized bone matrix putty, local autographs, and beta-tricalcium phosphate outside the cages.

We designed a cannulated dural anchor to protect the dura and the traversing nerve root while inserting the oblique cage (Fig. 6A). The surgeon gently retracts the dura and allows the assistant to tap the pin about 5 mm into the posterior annulus. The pin is made of shape memory alloy with a threaded anterior portion. The retractor can be easily removed by turning 180° and leaving the pin in situ to keep the dura retracted (Fig. 6B). The second cage is inserted obliquely into the disc space beside the pin. If indicated, the oblique cage can be inserted more horizontally to distract the contralateral disc space. Cage insertion is closely monitored under the endoscope (Fig. 6C). The final position of the cages is confirmed by fluoroscopy (Fig. 6D).

7. Final Check Point

Use the endoscope to check the adequacy of neural decompression, including the cranial and caudal portions of the central canal, the contralateral lateral recess and traversing nerve root, the ipsilateral lateral recess and traversing nerve root, and the ipsilateral exiting nerve root. Temporarily stop the irrigation to check the dural pulsation and identify active bleeders. Use the radiofrequency wand to coagulate the bleeders or use bone wax to seal the cancellous bone. A drain tube is mandatory to reduce the risk of epidural hematoma.
8. Insertion of Pedicle Screws and Reduction of Spondylolisthesis

We use cannulated transpedicle screws with long reduction barrels (Smartloc, A-spine) for fixation and reduction of spondylolisthesis. Insertion of the pedicle screws is guided by fluoroscopy through the same surgical wounds and the intermuscular planes bilaterally. The contralateral pedicle screws are inserted in the same way through another skin incision. We always contour the connecting rods to obtain better lordotic alignment. Reduction of spondylolisthesis can be achieved by securing the caudal pedicle screws first and then pulling up the cranial vertebra using the cantilever technique. After confirming the final position of the pedicle screws, we secure the entire construct and break off the barrels to complete the instrumentation. The wounds are closed in layers. The skin incisions are closed with nonabsorbable subcuticular sutures and then secured with adhesive gel.

9. Postoperative Care

The drainage tube is kept in place for 24 hours after surgery. Wound pain is managed with regular oral Acetaminophen every 6 hours and intravenous Morphine (5 mg) injection as needed. One or 2 intravenous methylprednisolone (500 mg) infusions may be given to patients with transient neurological complaints or significant lower back soreness. Ambulation with a lumbo-sacral orthosis is permitted if the patient can tolerate the pain. The patient is typically discharged from the hospital on the third or fourth day after surgery.

RESULTS

This study included 17 males and 72 females with an average age of 64.7 years (range, 35–85 years). These patients received 114 segments of BETLIF, including 1-segment fusion in 66 patients, 2-segment fusion in 21 patients, and 3-segment fusion in 2 patients. L4–5 was the most frequently involved level, followed by L3–4, L5–S, and L2–3. The average follow-up period was 15.5 months (range, 12–31 months). The average hospital stay was 5.7 ± 1.1 days (range, 3–7 days). No patient required a blood transfusion. At the final follow-up, the VAS for lower back pain improved from 5.2 ± 3.1 to 1.7 ± 2.1, and VAS for leg pain improved from 6.3 ± 2.5 to 1.7 ± 2.0. The ODI improved from 46.7 ± 17.0 to 12.7 ± 16.1. The JOA score improved from 15.6 ± 6.3 to 26.4 ± 3.2. All these improvements were statistically significant from baseline with p < 0.001. Complications included 1 dural tear (1.1%), 2 pedicle screw malposition (2.2%), and 2 epidural hematomas (2.2%). Reoperation was required in 2 patients for evacuating the epidural hematoma and adjusting the pedicle screw. There was no pedicle screw loosening nor posterior cage migration. The demographic data and clinical outcomes were summarized in Tables 1 and 2.

Forty-six patients with 60 fusion segments underwent CT

### Table 1. Demographic data (n = 89)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>17 (19.1)</td>
</tr>
<tr>
<td>Female</td>
<td>72 (80.9)</td>
</tr>
<tr>
<td>Age (yr)</td>
<td>64.7 (35–85)</td>
</tr>
<tr>
<td>Follow-up period (mo)</td>
<td>15.5 (12–31)</td>
</tr>
<tr>
<td>Diagnoses (n = 89)</td>
<td></td>
</tr>
<tr>
<td>Spondylolisthesis</td>
<td>83 (93.3)</td>
</tr>
<tr>
<td>Degenerative disc disease</td>
<td>4 (4.5)</td>
</tr>
<tr>
<td>Degenerative scoliosis</td>
<td>2 (2.2)</td>
</tr>
<tr>
<td>Segments of fusion (n = 89)</td>
<td></td>
</tr>
<tr>
<td>1-Segment fusion</td>
<td>66 (74.2)</td>
</tr>
<tr>
<td>2-Segment fusion</td>
<td>21 (23.6)</td>
</tr>
<tr>
<td>3-Segment fusion</td>
<td>2 (2.2)</td>
</tr>
<tr>
<td>Level distribution (n = 114)</td>
<td></td>
</tr>
<tr>
<td>L2–3</td>
<td>2 (1.8)</td>
</tr>
<tr>
<td>L3–4</td>
<td>27 (23.7)</td>
</tr>
<tr>
<td>L4–5</td>
<td>74 (64.9)</td>
</tr>
<tr>
<td>L5–S</td>
<td>11 (9.6)</td>
</tr>
</tbody>
</table>

Values are presented as number (%) or mean (range).

### Table 2. Summary for clinical outcomes

<table>
<thead>
<tr>
<th>Variable</th>
<th>Preoperative</th>
<th>Postoperative</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>VAS for back pain</td>
<td>5.2 ± 3.1</td>
<td>1.7 ± 2.1</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>VAS for leg pain</td>
<td>6.3 ± 2.5</td>
<td>1.7 ± 2.0</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>ODI</td>
<td>46.7 ± 17.0</td>
<td>12.7 ± 16.1</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>JOA score</td>
<td>15.6 ± 6.3</td>
<td>26.4 ± 3.2</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Complications</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dural tear</td>
<td>1 (1.1)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pedicle screw malposition</td>
<td>2 (2.2)</td>
<td>Revision to adjust the pedicle screw in 1 case</td>
<td></td>
</tr>
<tr>
<td>Epidural hematoma</td>
<td>2 (2.2)</td>
<td>Revision to evacuate the hematoma in 1 case</td>
<td></td>
</tr>
<tr>
<td>Reoperation</td>
<td>2 (2.2)</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Values are presented as mean ± standard deviation or number (%). VAS, visual analogue scale; ODI, Oswestry Disability Index; JOA, Japanese Orthopedic Association.
scan evaluation one year after surgery. Based on the Bridwell grading system, fusion results were grade I in 44 segments (73.3%), grade II in 12 segments (20.0%), and grade III in 4 segments (6.7%). Successful fusion was achieved in 56 segments (93.3%). Inside cage bridging bone (In-CBB) was observed in 44 segments (73.3%) and outside cage bridging bone (Out-CBB) was observed in 57 segments (95.0%). Of the 56 segments with successful fusion, 44 segments (78.6%) fused with both Out-CBB and In-CBB, 12 segments (21.4%) fused with only Out-CBB, and no segment fused with only In-CBB. Mild cage subsidence was observed in 11 segments (18.3%) and significant cage subsidence of more than 2 mm was observed in only 3 segments (5.0%). Pure PEEK cages had a significantly higher rate of subsidence than Ti-PEEK composite cages (p = 0.038) (Table 3).

### DISCUSSION

In this study, we present a minimally invasive technique for TLIF using biportal endoscopic technique and double cages. The treatment results show significant improvement in VAS score, ODI, JOA score, short hospital stay, and a low complication rate. No patient required blood transfusion. The radiological outcomes also show an excellent fusion rate with a very low incidence of cage subsidence.

Endoscopic LIF can be performed using uniportal or biportal endoscopic techniques.17 The uniportal endoscopic technique is more technically demanding than the biportal one because the surgical instruments are confined to the rigid working channel, and the surgeon’s hands, surgical instruments, and endoscopic vision all work on the same axis. In contrast, the biportal

### Table 3. Summary for radiological outcomes by computed tomography (CT)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Segments with CT</th>
<th>Total segments</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fusion segments</td>
<td>n = 46</td>
<td>n = 89</td>
<td>0.78</td>
</tr>
<tr>
<td>1-Segment fusion</td>
<td>34 (73.9)</td>
<td>66 (74.2)</td>
<td></td>
</tr>
<tr>
<td>2-Segment fusion</td>
<td>10 (21.7)</td>
<td>21 (23.6)</td>
<td></td>
</tr>
<tr>
<td>3-Segment fusion</td>
<td>2 (4.3)</td>
<td>2 (2.2)</td>
<td></td>
</tr>
<tr>
<td>Level distribution</td>
<td>n = 60</td>
<td>n = 114</td>
<td>0.88</td>
</tr>
<tr>
<td>L2–3</td>
<td>2 (3.3)</td>
<td>2 (1.8)</td>
<td></td>
</tr>
<tr>
<td>L3–4</td>
<td>13 (21.7)</td>
<td>27 (23.7)</td>
<td></td>
</tr>
<tr>
<td>L4–5</td>
<td>38 (63.3)</td>
<td>74 (64.9)</td>
<td></td>
</tr>
<tr>
<td>L5–S</td>
<td>7 (11.7)</td>
<td>11 (9.6)</td>
<td></td>
</tr>
<tr>
<td>Fusion results by Bridwell grading</td>
<td>n = 60</td>
<td>n = 114</td>
<td></td>
</tr>
<tr>
<td>Grade I</td>
<td>44 (73.3)</td>
<td>66 (74.2)</td>
<td></td>
</tr>
<tr>
<td>Grade II</td>
<td>12 (20.0)</td>
<td>24 (21.4)</td>
<td></td>
</tr>
<tr>
<td>Grade III</td>
<td>4 (6.7)</td>
<td>7 (6.1)</td>
<td></td>
</tr>
<tr>
<td>Grade IV</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td></td>
</tr>
<tr>
<td>Fusion rate</td>
<td>n = 60</td>
<td>n = 114</td>
<td></td>
</tr>
<tr>
<td>Fusion (grade I, II)</td>
<td>56 (93.3)</td>
<td>96 (84.2)</td>
<td></td>
</tr>
<tr>
<td>Nonfusion (grade III, IV)</td>
<td>4 (6.7)</td>
<td>9 (6.1)</td>
<td></td>
</tr>
<tr>
<td>Fusion by bridging bone distribution</td>
<td>n = 56</td>
<td>n = 114</td>
<td></td>
</tr>
<tr>
<td>Fusion with Out-CBB and In-CBB</td>
<td>44 (78.6)</td>
<td>88 (76.7)</td>
<td></td>
</tr>
<tr>
<td>Fusion with Out-CBB only</td>
<td>12 (21.4)</td>
<td>28 (24.2)</td>
<td></td>
</tr>
<tr>
<td>Fusion with In-CBB only</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td></td>
</tr>
<tr>
<td>Cage subsidence</td>
<td>PEEK (n = 60)</td>
<td>Composite Ti-PEEK (n = 60)</td>
<td>0.038</td>
</tr>
<tr>
<td>No subsidence</td>
<td>46 (76.7)</td>
<td>56 (93.3)</td>
<td></td>
</tr>
<tr>
<td>Subsidence ≤ 2 mm</td>
<td>11 (18.3)</td>
<td>3 (5.0)</td>
<td></td>
</tr>
<tr>
<td>Subsidence &gt; 2 mm</td>
<td>3 (5.0)</td>
<td>1 (1.7)</td>
<td></td>
</tr>
</tbody>
</table>

Values are presented as number (%). PEEK, polyetheretherketone; Ti, titanium; Out-CBB, outside cage bridging bone; In-CBB, inside cage bridging bone.
endoscopic technique has no rigid working channel. The endoscope and surgical instruments are handled independently by the surgeon's hands. Direct decompression of the central canal, bilateral lateral recess, and even bilateral neural foramen can be achieved under endoscopic guidance (Fig. 7). Traversing nerve root injury may be a concern when inserting the cage into the disc space; however, this concern can be solved by using a pin to gently retract the dura and the traversing nerve root.

CT scan is the most reliable imaging modality to evaluate fusion status. However, there are only limited studies using CT scans to evaluate fusion rates of endoscopic TLIF. The fusion rate in our series is as high as 93.3%. The high fusion rate is attributed to radical disc removal, increased cage footprint by using double cages, and a large amount of bone grafts in the disc space (Fig. 8).

To increase the contact surface between the graft and the vertebral bone, the removal of the disc should be as radical as possible to make room for bone graft and to expose the bony end-plate for bone ingrowth. The biportal endoscopic technique provides a magnified and bloodless surgical field that enables the surgeon to remove the disc efficiently, with no need to struggle with continuous oozing anymore.

The amount of bone graft in the disc space is one of the detrimental factors for successful interbody fusion. The bone graft inside the cages is usually of a small amount, or it would easily fall off when tapping the cage into the disc space. That makes bone graft outside the cage more important. However, because the outside cage bone grafts are usually inserted into the collapsed disc space before the cage, the amount of bone graft will be very small in the disc space. Sequential insertion of the double cages in our study allows more bone graft to be impacted in the disc space. We insert the first cage as the disc spacer, enabling the surgeon to impact more bone graft into the empty disc space before inserting the second cage. The postoperative CT scans show a substantial volume of fusion mass outside of the cages. A large amount of bone graft promotes bone fu-

Fig. 7. (A–C) Preoperative x-ray and magnetic resonance imaging (MRI) of the lumbar spine in a 64-year-old female patient with spondylolisthesis at L4–5 and associated severe canal stenosis. (D–F) Postoperative x-ray and MRI show restoration of the disc height, reduction of the spondylolisthesis, and good neural decompression with minimal soft tissue injury.
Cage subsidence is the most common complication following LIF. The incidence ranges from 15.9% to 70%, depending on the types of cages, surgical techniques, follow-up duration, and image evaluation tools. Mild cage subsidence is considered a normal phenomenon of spinal fusion with no correlation to the clinical outcomes. However, recent studies have observed that significant cage subsidence, more than 2 mm, is associated with postoperative disc height collapse and loss of lumbar lordosis, which may lead to recurrent symptoms and poor outcomes.

Endplate injury is recognized as a significant risk factor for cage subsidence. However, few studies describe practical techniques to prevent this complication during endplate preparation. Considering that using conventional serial disc shavers and curettes might be too aggressive and cause endplate injury, we designed a set of endplate strippers with different angles to strip the disc along with the cartilaginous endplate off the bony endplate. We can closely monitor this process using an endoscope to avoid bony endplate injury. At the end of the process, we routinely insert the endoscope into the disc space to evaluate the extent of endplate preparation, ensuring that the disc is removed thoroughly, and the bony endplate is well-preserved.

A larger cage footprint reduces the possibility of cage subsidence by providing better segmental stability. In posterior approach LIF, the size of the cage is limited by the presence of neural tissue in the path of the cage insertion. Overretraction of the neural tissue can lead to postoperative neurological symptoms or permanent neurological deficits. In our series, we use a “one vertical, one oblique” double-cage construct to double the footprint and reduce the risk of neurological complications from overretraction. Our newly designed cannulated dural anchor makes cage insertion much easier. This small pin not only prevents neural injury but also guides the insertion of the oblique

Fig. 8. Postoperative computed tomography scan 1 year after a 2-segment BETLIF for spondylolisthesis at L4–S in a 71-year-old female show solid interbody fusion at both the composite Ti-PEEK (A–C) and the pure PEEK cage sides (D–F) with no cage subsidence at all. BETLIF, biportal endoscopic transforaminal lumbar interbody fusion; Ti, titanium; PEEK, polyetheretherketone.
cage. All these features make cage insertion no longer a blind process. The fluoroscope is only used to confirm the final position of the cages. Our double-cage construct safely increases the cage footprint by twice and distributes the stress more evenly on the endplate.36,37

Ti alloy and PEEK are the most common materials used in interbody fusion cages. Ti alloy can enhance cell adhesion and bony ingrowth, but it can also increase subsidence caused by its stiffness relative to the vertebrae.38-41 In contrast, PEEK has an elasticity close to that of bone and shows less subsidence than Ti cages. However, as an inert compound, PEEK results in lower fusion rates and osteolysis at the interface.41-43 In our study, we used 1 composite Ti-PEEK cage and 1 pure PEEK cage for interbody fusion. The Ti interface showed better bony ingrowth and less osteolysis than the PEEK interface. The incidence of significant subsidence, more than 2 mm, was very low. However, the PEEK interface showed a significantly higher incidence of subsidence than the Ti interface, which contradicts the observations reported in the literature.

We always place the cages as anteriorly as possible and use the biplanar fluoroscope to confirm their final position. There are 2 major reasons for this. First, a posterior cage position is associated with cage subsidence and posterior cage migration.28,32,34,44-46 Second, an anterior cage position is helpful for restoring the lumbar lordosis. To place the cage anteriorly, the disc space must be cleared in advance. Special attention must be paid to avoid iatrogenic injury to the retroperitoneal organs such as the aorta and the vena cava. The process must be monitored using the endoscope or the fluoroscope to avoid such catastrophic complications.

The current study has several limitations. First, it is a retrospective study with a small sample size, short-term follow-up, and no control group to compare the treatment outcomes to BETLIF with a single cage. Second, all surgeries were performed by a single spine surgeon who is experienced in minimally invasive and endoscopic spine surgeries in a large medical center, and the results may differ if surgeries are performed by another surgeon with a different level of experience. Third, CT scans were not available for every patient due to the retrospective design of this study, and bias does exist.

CONCLUSION

Minimal invasiveness is an inevitable trend in every surgical field. However, smaller surgical wounds should not compromise treatment results. Although minimally invasive TLIF using biportal endoscopic techniques is feasible, fusion rate and cage subsidence remain significant challenges. By combining the advantages of the biportal endoscopic technique and the double-cage construct, it is possible to improve fusion quality to the next level of excellence, with a high fusion rate and a low incidence of cage subsidence. Nevertheless, further studies are necessary to determine the optimal cage materials and designs, the significance of bone graft amount for a successful fusion, and to refine the surgical techniques.

NOTES

Conflict of Interest: The authors have nothing to disclose.
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Biportal Endoscopic Posterior Cervical Foraminotomy for Adjacent 2-Level Foraminal Lesions Using a Single Approach (Sliding Technique)

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Objective: Endoscopic posterior cervical foraminotomy (PCF) using uniportal or biportal endoscopic approach has been performed for cervical foraminal stenosis or foraminal disc herniation. Two-level PCF is possible using a single biportal endoscopic approach. The purpose of this study was to present a technique of biportal endoscopic PCF for contiguous 2-level foraminal lesions using a single approach and its clinical results.

Methods: Patients who received 2-level PCF using a single biportal endoscopic approach were enrolled in this study. We analyzed their clinical data including age, sex, complications, and Neck Disability Index (NDI), and visual analogue scale (VAS) of neck and arm. Postoperative magnetic resonance image was taken on the first postoperative day to determine whether there was sufficient decompression.

Results: We successfully performed biportal endoscopic PCF for adjacent 2-level foraminal lesions using a single approach (sliding technique) in all 12 patients. There were cervical foraminal disc herniation with foraminal stenosis (5 cases) and 2-level foraminal stenosis (7 cases). Preoperative mean NDI and VAS of arm and neck significantly decreased at 12 months after surgery. Postoperative clinical outcomes were excellent in 5 patients, good in 6 patients, and fair in 1 patient. There was no major complication.

Conclusion: Two-level PCF could be performed using a single approach biportal endoscopic surgery with only 2 skin incisions. Clinical outcomes are favorable. This sliding PCF technique using biportal endoscopic approach might be an alternative surgical treatment for contiguous 2-level cervical foraminal pathologic lesions.

Keywords: Cervical vertebrae, Biportal, Foraminotomy, Endoscopy

INTRODUCTION

Posterior cervical foraminotomy (PCF) is a good surgical treatment option for cervical radiculopathy such as cervical foraminal stenosis and foraminal disc herniation. Minimal invasiveness, familiar surgical anatomy of posterior cervical approach, and motion preservation are advantages of PCF or discectomy. Recently, endoscopic PCF using uniportal or biportal endoscopic approaches have been attempted instead of microscopic PCF using tubular retractor systems.¹-³ Early recovery after surgery and minimal invasiveness are advantages of full endoscopic or biportal endoscopic PCF.⁴⁻⁵

 Compared with lumbar vertebrae, cervical vertebrae have a shorter interval between adjacent 2 segments (Fig. 1). A small dissection of multifidus muscle allows easy access to adjacent cervical segments without making an additional portal. Cervical lordotic curve also facilitates access to the adjacent cervical level. Therefore, 2-level PCF can be performed by a single endoscopic approach.⁶ Even in the biportal endoscopic cervical approach, 2-level PCF is possible using a single biportal endoscopic...
approach with only 2 skin incisions. Since a slight movement of the 2 portals allows direct access to adjacent foraminal lesion, PCF of 2 adjacent foraminal lesions with a single endoscopic approach is also called a “sliding technique” of PCF.

The purpose of this study was to present the technique of biportal endoscopic PCF for adjacent 2-level foraminal lesions using a single approach and clinical results of this technique.

MATERIALS AND METHODS

1. Patients and Clinical Data Analysis

Patients who received 2-level PCF using a single biportal endoscopic approach (sliding technique) were enrolled in this study. All enrolled patients were followed up for more than 12 months after surgery. Prospectively collected data were retrospectively reviewed. The study design of this study is a retrospective review.

This investigation was performed in accordance with Institutional Review Board of Wiltse Memorial Hospital, No. W-2022-RA3).

Indications of this sliding technique of biportal endoscopic PCF were unilateral symptomatic cervical radiculopathy due to 2-level cervical foraminal stenosis or foraminal disc herniation. Those with ossification of ligamentum flavum, cervical deformity, central canal stenosis, central disc herniation, segmental instability, or infectious disease were excluded.

Clinical data including age, sex, diagnosis, operation level, operation time, complications and estimated blood loss including postoperative blood drainage were analyzed. Analyses of clinical results were performed using Odom’s criteria (excellent, good, fair, and poor), Neck Disability Index (NDI), and visual analogue scale (VAS) of neck and arm. Blood samples were collected from patients before surgery and on the first day after surgery to measure C-reactive protein (CRP) and creatine phosphokinase (CPK) levels. Postoperative magnetic resonance imaging (MRI) was taken on the first postoperative day to confirm whether there was sufficient decompression or disc removal at symptomatic cervical foraminal area. Cervical flexion/extension dynamic x-rays were taken at 6 months and 12 months after surgery for evaluating instability at operation segments. Blood samples were collected from patients before surgery and on the first day after surgery to measure CRP and CPK levels to evaluate muscle injury of the operation area. CPK and CRP blood tests were also performed before and on the first day after surgery for single-level biportal endoscopic PCF patients who underwent surgery at the same time. Degrees of CPK and CRP elevation after surgery were compared between single-level PCF patients and 2-level PCF patients using the sliding technique. Since patient sample was small, nonparametric statistics were used. Statistical analysis was performed using Wilcoxon signed rank test, and Kruskal-Wallis test. Difference with a p < 0.05 was considered to be statistically significant. R 4.2.2 (R Foundation for Statistical Computing, Vienna, Austria) was used for all statistical analyses.

2. Surgical Technique

1) Surgical Instruments

A working sheath was needed to maintain the patency of continuous irrigation saline (Fig. 2B). Smooth drainage of irrigation can maintain a good endoscope view and prevent the rise of epidural pressure during a biportal endoscopic surgery. Radiofrequency probes were necessary for bleeding control and
soft tissue dissection.\textsuperscript{2} Water proof diamond drill was used for foraminotomy. We recommend the use of smaller size hooks or dissectors in biportal endoscopic cervical posterior approach when comparing instruments of lumbar surgery.

2) Making 2 portals

Two channels including an endoscopic portal and a working portal should be created under fluoroscopic C-arm view (Figs. 2, 3).\textsuperscript{3,4} When performing 2-level PCF at C5-6-7, 2 portals were made at C5 and C7 pedicle levels (Fig. 3). In anteroposterior x-ray view, 2 portals were lateral border of pedicle of C5 and C7. Usually, an endoscopic portal was made for the nondominant hand and a working portal was made for the dominant hand. Small stab skin incision was made about 10 mm in length for the working portal.\textsuperscript{5} We put in serial dilators under C-arm fluoroscopic monitoring. Finally, the working sheath with an optimal length was inserted at the working portal. An addition stab skin incision of 5 to 7 mm in length was made to create an endoscopic portal. A trocar of endoscopy was inserted for making an endoscopic portal under x-ray fluoroscopic monitoring. Two portals should contact over the facet joint. Continuous saline must be well drained from the endoscopic portal to the working portal.

3) Lamino-foraminotomy of first level (Supplementary video clip 1)

In many cases, the cranial lesion was easier to check the level. Thus, cranial lesion was operated first. However, this depends on the preference of the operator. Ipsilateral upper and lower laminae and facet joint were dissected and partially exposed using dissectors and radiofrequency (RF) probes. First, a surgical landmark of V-point consisted of inferior border of upper lamina and superior border of lower lamina (Fig. 4).\textsuperscript{2} After finding the V-point, laminotomy was performed using a drill and small

![Fig. 3. Skin incision points for 2-level posterior cervical foraminotomy using the sliding technique. In the case of C5-6-7 foraminal lesions, 2 portals were made at C5 and C7 pedicle levels (A, anteroposterior x-ray view; B, lateral x-ray view).](image)

![Fig. 4. V-point of posterior cervical foraminotomy. The V-point is the first surgical landmark.](image)

![Fig. 5. Intraoperative endoscopic images of biportal endoscopic posterior cervical foraminotomies at C5-6-7 left. (A) Left C6 nerve root was completely decompressed. (B) Intermediate laminae of C6 and 2 foraminotomy holes were seen while performing the sliding technique. (C) Left C7 nerve root was also fully decompressed after biportal endoscopic decompression using the sliding technique.](image)
sizes of Kerrison punches (1 or 2 mm). First, the lamina was thinned with a diamond drill. The lamina was then removed with a Kerrison rongeur. A sufficient foraminotomy was performed by medial facetectomy (removal of lateral mass). Medial facetectomy was done with a diamond drill and a Kerrison rongeur. After bone work, ligamentum flavum was exposed. If ligamentum flavum was partially removed, nerve root and dura were seen. If a patient had foraminal disc herniation, ruptured disc particles were removed through axilla area. A cervical nerve root of cranial level was completely decompressed (Fig. 5). After bleeding control, 2 portals were moved to the adjacent caudal level (Fig. 5).

4) Sliding moving of 2 portals to adjacent level (Supplementary video clip 1)

Two portals (endoscopic portal and working portal) were tilted vertically to caudal adjacent segment for foraminotomy (Figs. 5, 6). Multifidus muscle of adjacent level was dissected and ablated using RF probes. Laminae of lower level was relatively easily exposed using RF probes. Firstly, the V-point of lower adjacent level was confirmed. The same posterior foraminotomy was done. A cervical nerve root of contiguous caudal level was completely decompressed (Figs. 5, 7). After bleeding was meticulously controlled, a drainage catheter was inserted. A drainage catheter and its bag were removed at one or 2 days after surgery.

RESULTS

A total of 19 patients have been treated by this biportal endoscopic sliding technique from October 2019. After excluding 7 patients from this study due to a short follow-up period, 12 pa-
patients were treated with this technique. There were 2 females and 10 males. Their mean age was 57.8 ± 6.7 years. The mean follow-up period was 13.6 ± 1.9 months. We successfully performed biportal endoscopic PCF for adjacent 2-level foraminal lesions using the single approach (sliding technique) in all enrolled patients (n = 12). Postoperative MRI revealed well decompression of foraminal lesions after surgery (Fig. 7). Diagnoses included cervical foraminal disc herniation with foraminal stenosis (5 cases) and 2-level foraminal stenosis (7 cases). Operation levels involved C4-5-6 (2 cases), C5-6-7 (7 cases), and C6-7-T1 (3 cases). The average operation time was 91.4 ± 15.3 minutes. The mean postoperative estimated blood loss was 93.6 ± 22.3 mL (Table 1).

Preoperative mean NDI significantly decreased from 43.3 ± 11.1 to 10.3 ± 6.3 at 12 months after surgery (p < 0.05) (Table 2). Preoperative arm pain (VAS of arm) decreased significantly from 8.1 ± 1.1 to 1.2 ± 0.9 at 12 months (p < 0.05). Preoperative VAS of neck decreased significantly from 5.3 ± 2.1 to 2.3 ± 1.3 at 12 months after surgery (p < 0.05) (Table 2). According to Odom's criteria, postoperative clinical outcomes were excellent in 4 patients, good in 7 patients, and fair in 1 patient. Epidural injection was performed at 3 months after surgery in the patient with a fair outcome after surgery. There were 2 minor complications. One patient complained of temporary numbness of forearm, but recovered spontaneously. One patient developed small bullae on the chin area after surgery. It might be caused by a problem associated with the surgical position. However, it healed well without scarring. No instability was found on dynamic x-ray taken at 1 year after surgery. No patient underwent reoperation in this study. Preoperative and postoperative CPK and CRP blood levels were checked for 12 patients with 2-level PCF surgery and 18 patients with 1-level PCF surgery. Mean preoperative CPK blood level (normal range, 32–294 IU/L) increased from 113.3 ± 38.3 to 140.1 ± 50 IU/L postoperatively in patients with 1 level PCF, and from 122.9 ± 30.0 to 170.8 ± 4.1 IU/L postoperatively in patients with 2-level PCF. Mean preoperative CRP blood level (normal range, 0.5 mg/dL) increased from 0.02 ± 0.02 to 0.28 ± 0.17 mg/dL postoperatively in patients with one level PCF and from 0.11 ± 0.24 to 0.37 ± 0.37 mg/dL in patients with 2-level PCF. There was no significant difference in CPK or CPR blood level elevation between the 2 groups (p > 0.05).

### DISCUSSION

Biportal endoscopic PCF has been attempted for cervical unilateral radiculopathy caused by foraminal stenosis or disc herniations. The biportal endoscopic cervical approach can minimize injury to musculoligamentous structures with a clean, magnified surgical field. Contiguous 2-level cervical foraminal lesions could be treated using only 2 portals in the biportal endoscopic posterior cervical approach. The pivoting of 2 portals could provide access to 2 contiguous levels of cervical foraminal pathologic lesions. Even if the endoscopic surgical corridor to the surgical site is incorrectly created, it can be easily corrected to an appropriate surgical level without making a new skin incision under fluoroscopic guidance. Two-level PCF can be operated using a single endoscopic approach, including biportal or uniporal endoscopic surgeries.6 Indications for biportal endoscopic PCF were similar to those for conventional open PCF or minimally invasive approach with
tubular retractor systems. Cervical foraminal stenosis and foraminal disc herniations were indications for using a biportal endoscopic approach.3 Adjacent 2-level lesions could be treated using this sliding biportal endoscopic cervical approach (Fig. 7).6 Preoperative instability and tumor lesions were contraindications of this approach. This sliding technique can be used to perform adjacent 2-level PCF with or without discectomy. Usually, 3-level foraminotomies cannot be achieved using this sliding single biportal endoscopic approach. Cervical myelopathy cannot be treated by this approach.

The epidural vein was the main bleeding focus. Epidural vein bleeding must be prevented and controlled using RF probes. To prevent postoperative instability, it is recommended not to remove more than 1/2 of the lateral mass (the facet joint). Cervical nerve roots frequently consist of dual nerve roots including motor and sensory nerve roots.2 The possibility of dual cervical nerve roots should always be kept in mind to prevent motor nerve root injury. When finding or removing ruptured disc particles around the nerve root, it is strongly recommended to minimize nerve root retraction and manipulation as much as possible.4 If the axillary area of the cervical nerve root is very narrow, partial removal of the pedicle (pediculotomy) can make enough axillary space for disc exploration or removal. If dura tear or bleeding control is difficult, switching to microsurgery without delay is recommended. A face pillow must be used to avoid unnecessary pressure on the face, including eyeballs. If patients have a central disc herniation, an anterior cervical approach should be considered rather than a posterior endoscopic approach. Cervical myelopathy cannot be treated using this biportal endoscopic posterior foraminotomy. To create portals at the correct surgical site and avoid wrong-level surgery, intraoperative C-arm fluoroscope monitoring should be performed.4 If 2-level PCF is difficult with a single sliding approach using only 2 portals, making an additional portal should be considered. If 2-level PCF is difficult to perform with only 2 portals, it might be necessary to create an additional portal for complete decompression. If bleeding control is difficult and the surgical field is blurred, it might be necessary to switch from biportal endoscopy to conventional microsurgery. Three-level PCF is difficult to perform using only a 2-portal biportal endoscopic approach.

According to a systematic review paper, when PCF was compared with anterior cervical disectomy and fusion (ACDF), there was no significant difference in clinical outcome, complication rate, or reoperation rate. Compared to ACDF, PCF has advantages in that the cost is lower and the increase in ROM in the adjacent part is smaller. However, indication of PCF is narrower than that of ACDF. In this study, we did not experience revision surgery or major complications.

This study design was a retrospective review of cases series and not a randomized controlled trial. A small number of patients were enrolled in this study. Also, the follow-up period was as short as 12 months. To accurately analyze clinical results and advantages of this surgical technique, a large number of patients and a case control study are needed in the future. And, a long-term follow-up study of more than 2 years are required.

CONCLUSION

We successfully performed 2-level PCF using a single approach biportal endoscopic surgery with only 2 skin incisions. Two-level PCF can be sufficiently performed using 2 channels. The degree of muscle damage may be small. A 2-level biportal endoscopic PCF using a single approach might reduce skin wound size, number of portals, and operation time. This sliding PCF technique might be an alternative surgical treatment for contiguous 2-level cervical foraminal pathologic lesions. However, a randomized controlled trial should be required for accurate clinical research of this technique.

NOTES

Supplementary Material: Supplementary video clip 1 can be found via https://doi.org/10.14245/ns.2346144.072.

Video clip 1. Video clip of the sliding technique of 2-level posterior cervical foraminotomy. We performed a left-sided 2-level posterior cervical foraminotomy using the sliding technique in a patient with left-sided foraminal stenosis of C 5-6-7.

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Spinal Canal Remodeling and Indirect Decompression of Contralateral Foraminal Stenosis After Endoscopic Posterolateral Transforaminal Lumbar Interbody Fusion

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Objective: There is a lack of literature on indirect decompression in uniportal endoscopic posterolateral transforaminal lumbar interbody fusion (EPTLIF). Our aim is to evaluate the dimensions of the spinal canal and contralateral foramens before and after EPTLIF.

Methods: This is a retrospective study of patients who underwent EPTLIF in a tertiary spine centre over a 2-year period. The cross-sectional area of the spinal canal and the contralateral foramens at the level of fusion were measured on magnetic resonance imaging scan at 1-day postoperation and at the final follow-up. Patients were grouped according to the decompression performed as per the clinician’s judgement.

Results: One hundred fifty-two levels of fusion were performed in 120 patients. There was a statistically significant clinical improvement in visual analogue scale and Oswestry Disability Index scores postoperation. The measurements of the spinal canal area were 106.0 mm², 138.8 mm², and 195.5 mm²; while contralateral foraminal area were 73.2 mm², 104.4 mm², and 120.7 mm² at preoperation, 1-day postoperation, and at the final follow-up, respectively (p < 0.001). For the subgroup analyses, spinal canal area measurements for the bilateral decompression cohort (n = 35) were 57.0 mm², 123.9 mm², and 191.8 mm²; for the ipsilateral decompression cohort (n = 42) were 89.3 mm², 128.9 mm², 183.3 mm²; and for the cohort without any decompression and only cage inserted (n = 75) were 138.3 mm², 151.2 mm², and 204.1 mm² (p < 0.001). Contralateral foraminal area measurements were 73.3 mm², 106.4 mm² and 120.4 mm² in the bilateral decompression cohort; 69.5 mm², 99.0 mm², 116.9 mm² in the ipsilateral decompression cohort; and 75.1 mm², 106.5 mm², 122.9 mm² in the cohort without any decompression (p < 0.001).

Conclusion: Indirect decompression of both the spinal canal and the contralateral foramens can be achieved via EPTLIF. Decompression on an asymptomatic contralateral side is not necessary.

Keywords: Spinal diseases, Spinal stenosis, Endoscopy, Spinal fusion
to help preserve the normal anatomy and musculature of the lumbar spine in order to prevent the increased morbidity and reduce the risks of adjacent segment disease seen in traditional open methods such as the transforaminal lumbar interbody fusion (TLIF) technique described by Harms.

In cases with foraminal stenosis, direct decompression requires additional bone and soft tissue (on top of those required for fusion alone) would need to be removed. This may increase the instability of the adjacent level, resulting in a theoretical increased risk of adjacent segment disease. Over aggressive decompression may also result in iatrogenic injuries to the neural elements, dural tears, and epidural haematoma. This is especially seen in nonendoscopic minimally invasive surgical (MIS) techniques which has been shown to have a higher rate of nerve root injuries when compared to traditional open techniques.

There is a lack of literature on indirect decompression in uniporal endoscopic posterolateral transformaminal lumbar interbody fusion (EPTLIF). Our aim is to evaluate the dimensions of the spinal canal and contralateral foramen before and after EPTLIF, allowing direct assessment of the viability of indirect decompression using this technique.

**MATERIALS AND METHODS**

This is a retrospective study of all patients who underwent EPTLIF in a tertiary spine centre by a single fellowship-trained surgeon from 2020 to 2022. The inclusion criteria are patients who underwent EPTLIF for degenerative lumbar conditions such as lumbar spinal stenosis and spondylolisthesis with dynamic instability, without any contralateral radiculopathy. Cases who had previous spinal surgeries, spinal trauma, suspected spinal malignancies, inflammatory spinal conditions and spinal infection were excluded from this study.

All patients underwent a preoperative radiographs and magnetic resonance imaging (MRI) scans of the lumbar spine for preoperative assessment. Patients with corresponding MRIs and sufficient indications for lumbar fusion were counselled for surgery. The steps and techniques for surgery was as described in a technique paper published previously. Decision for bilateral foraminal decompression, ipsilateral foraminal decompression only or was performed based on the clinician's judgement and the patient's symptoms on presentation. Patients who presented with ipsilateral claudication with concordant MRI finding of severe bilateral lateral recess and foraminal stenosis underwent bilateral foraminal decompression EPTLIF. Patients who presented with ipsilateral claudication with concordant MRI of severe ipsilateral severe lateral recess and foraminal stenosis underwent ipsilateral decompression only EPTLIF. Patients who presented with ipsilateral claudication with concordant foraminal stenosis, spondylolisthesis and degenerative disc disease without significant central spinal canal stenosis underwent cage insertion alone without any decompression (no dural decompression was performed, the ligamentum flavum was preserved).

Demographic parameters including patient's age, sex, and the level of fusion were recorded. Clinical parameters such as the visual analogue scale (VAS) score, the Oswestry Disability Index (ODI) and the McNab criteria were measured at the preoperative review and postoperative review at 1 week, 6 months, and at the final follow-up. Additional MRI scans were also performed at the 1-day postoperative mark and at the final follow-up. Computed tomography scans were also performed at the 1-year mark for assessment of fusion at the level operated.

1. **Radiographic Analysis**

The preoperative and the 2 postoperative MRIs were reviewed in detail. The cross-sectional area of the spinal canal was measured from the axial cuts parallel to the adjacent end plates at the level of the disc fused. The cross-sectional area of the contralateral foramen was measured from the parasagittal cuts at the centre of the contralateral pedicle at the adjacent levels.

2. **Techniques**

1) **Facet resection and cage insertion alone without decompression**

EPTLIF had been described by Wu et al. We docked at the uniporal stenosis endoscope at laminofacet junction. After identification of the superomedial aspect of the inferior articular facet is often medial and deep to the midpont of the bony arch forms from the ipsilateral spinolaminar junction of the cephalad lamina to the most inferomedial rounded edge of the inferior articular process (IAP) and the superolateral edge of the inferior articular facet which articulates the superolateral edge of the superior articular facet, we perform complete resection of the inferior articular facet joint by drilling obliquely upwards and laterally from inferomedial rounded edge of the IAP to superolateral edge of the inferior articular facet for complete resection of inferior articular process. Once IAP is resected, ipsilateral superior articular process is removed. Ipsilateral ligamentum flavum overlying the disc space is removed. Care is taken to preserve the ligamentum flavum overlying the ipsilateral traversing nerve root as well as contralateral ligamentum flavum. Disc space is exposed after hemostasis, traversing nerve root protected by working retractor. We performed endplate
preparation under endoscopic guidance and insert 3-dimensional (3D)-printed titanium cage with autograft harvested from the facet joint through the single portal under fluoroscopic guidance with the nerve roots protected by Harrison's cage glider. Upon completion of cage insertion, percutaneous pedicle screws and rods are inserted to stabilize the fusion segment. In this technique, there is decreased risk in traversing nerve root injury as it is protected by ligamentum flavum and retractor tube (Fig. 1A, B).

2) Unilateral decompression

Similar steps to EPTLIF with facet resection with cage alone insertion without decompression are taken initially to remove facet. In edition for unilateral decompression, we drill the insertion of the ipsilateral ligamentum flavum at the proximal and distal insertion. We removed the ipsilateral flavum completely to expose ipsilateral traversing nerve root and disc end-plate preparation and cage insertion is similar to EPTLIF with cage alone cohort (Fig. 1C, D). Contralateral ligamentum flavum is preserved.

3) Bilateral decompression

In addition to the steps in EPTLIF with unilateral decompression. We perform lumbar endoscopic unilateral laminotomy with bilateral decompression with over-the-top decompression of contralateral ligamentum flavum and medial tip of superior articular process of the contralateral side to decompress the contralateral lateral recess and the foramen. After bilateral bony decompression is completed, both flava are removed and disc preparation is continued similar to other 2 cohorts of EPT-

Fig. 1. Cartoon and intraoperative picture demonstrating the 3 types of technique of EPTLIF. (A) Cartoon demonstrated EPTLIF with cage insertion and conservation of ipsilateral ligamentum flavum overlying traversing nerve root and contralateral ligamentum flavum (dotted yellow arrow). (B) Intraoperative picture demonstrated interbody cage placed lateral to ipsilateral ligamentum flavum. (C) Cartoon demonstrated EPTLIF with cage insertion and complete removal of ipsilateral ligamentum flavum overlying traversing nerve root while preserving the contralateral ligamentum flavum (dotted red arrow). (D) Intraoperative picture demonstrated interbody cage placed lateral to ipsilateral traversing nerve root with ligamentum flavum removed. (E) Cartoon demonstrated EPTLIF with cage insertion and complete removal of both ligamentum flavum (dotted red and blue arrows). (F) Intraoperative picture demonstrated contralateral decompression with removal of contralateral ligamentum flavum prior to placement of interbody cage on the ipsilateral side. EPTLIF, endoscopic posterolateral transforaminal lumbar interbody fusion.
LIF (Fig. 1E, F).

3. Statistical analysis

All collected data were tabulated using IBM SPSS Statistics ver. 23.0 (IBM Co., Armonk, NY, USA) with statistical significances set at p < 0.05. Baseline characteristics and radiographic parameters as described above for the entire cohort were tabulated and shown in Table 1.

The patient cohort was divided into 3 groups—those who underwent bilateral foraminal decompression, ipsilateral decompression, or cage insertion alone without any decompression. Subgroup analyses were performed within each group, and paired t-test were used for comparison to VAS and ODI at baseline. Changes in the clinical and radiographic parameters were also studied and shown in Table 2.

4. Ethical Statement

All procedures performed in studies involving human participants were in accordance with the ethical standards of the Ethics Committee of Nanoori Gangnam Hospital (2022-007) and the national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. All patients had given their informed consent for photographs, videos, and images for publication.

RESULTS

A total of 120 patients were recruited into this study. 152 levels of fusion were performed. The average age was 65.2 years. The mean follow-up period was 13.6 months. The most fused level was L4/L5 followed by L3/L4. There were 46 males and 106 females in the cohort. There was no significant difference between the groups when tested using chi-square test (Table 1).

Looking at the VAS and ODI measurements, there were no significant differences among the 3 groups at baseline. In the entire cohort as well as within the subgroups, there were significant improvements in the VAS as well as the ODI measurements at 1-week postoperation with continued trends of improvement at 6-week postoperation and at the final follow-up (Table 2, Fig. 2).

Looking at the MRI measurements, patients who underwent

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<td>Preoperative cross-sectional area of the contralateral foramen (mm²)</td>
<td>71.9 ± 27.1</td>
<td>73.3 ± 26.6</td>
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</table>

Values are presented as number or mean ± standard deviation. VAS, visual analogue scale; ODI, Oswestry Disability Index.
bilateral decompression had a smaller cross-sectional area of the spinal canal when compared with ipsilateral decompression; and patients who had cage insertion alone without any decompression have the largest cross-sectional area (p < 0.001). There were no significant differences in the contralateral foraminal cross-sectional area among the 3 groups at baseline. In the entire cohort as well as within the subgroups, there were significant improvements in the cross-sectional area of the spinal canal as well as the contralateral foraminal cross-sectional area among the 3 groups at baseline. In the entire cohort as well as within the subgroups, there were significant improvements in the cross-sectional area of the spinal canal as well as the contralateral foraminal cross-sectional area among the 3 groups at baseline. 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### DISCUSSION

Unilateral TLIF has also been shown to cause a contralateral radiculopathy with an incidence of up to 5.3%. This was attributed to undiagnosed contralateral foraminal stenosis, improper noncentral asymmetric cage placements, undersized cages, excessive compression to create lumbar lordosis and a
Fig. 2. (From left to right) Preoperative baseline magnetic resonance imaging (MRI), 1-day postoperative MRI, and MRI scans at the final follow-up of a patient who underwent endoscopic posterolateral transforaminal lumbar interbody fusion.

Fig. 3. (From left to right) Preoperative baseline, 1-day postoperative, and final follow-up axial and right parasagittal MRI in nondecompression left EPTLIF of L4/5. EPTLIF, endoscopic posterolateral transforaminal lumbar interbody fusion.
newly herniated disc due to insufficient disc removal and the use of unilateral cages pushing the disc material to the contralateral side. Some authors have even recommended for prophylactic decompression of the contralateral side in open cases where foraminal stenosis cannot be visualized without prior decompression. This can be circumvented using endoscopic-assisted techniques which allows direct visualization and assessment of the contralateral foramen. This not only reduces the risks of nerve injury, but allows assessment for contralateral compression and need for foraminotomy.

Newer techniques—especially with lateral approach techniques such as lateral lumbar interbody fusion, oblique lumbar interbody fusion (OLIF), and extreme lateral interbody fusion have been shown to achieve sufficient indirect decompression for fo-
Indirect decompression in endoscopic posterolateral fusion: Wu PH, et al.

Indirect decompression can be divided into segmental procedures and global spinal alignment procedures. Examples of segmental procedures include disc space utilization procedures (interbody cages), posterior segment distraction procedures (interspinous devices); and ligamentotaxis techniques to prevent infolding of ligaments that causes compression. With a clearer understanding of the anatomy of the lumbar spine, indirect decompression can be achieved while minimizing the soft tissue and bony injuries that lead to adjacent segment disease.

Castellvi et al.\textsuperscript{17} showed that indirect decompression of lumbar spinal stenosis can be achieved using with the lateral transpsoas interbody cages and percutaneous posterior instrumentation, resulting in increases in disc height, foraminal area, and canal area measured immediately postoperatively and were sustained at 1-year postoperation. VAS and ODI scores also showed corresponding improvements that were sustained at 1-year postoperation. Tseng et al.\textsuperscript{18} utilized OLIF for treatment of lumbar foraminal stenosis and showed that patients who did not undergo posterior decompression had better back pain VAS scores and ODI scores compared to those who underwent open posterior decompression at 12 months and 24 months postoperatively although there were no significant differences in disc height and foraminal height between the 2 groups. They suggested that the use of interbody cages and posterior instrumentation were sufficient for relieving symptoms in patients with lumbar foraminal stenosis and additional direct posterior decompression may deteriorate results in the follow-up period. Gajjar et al.\textsuperscript{19} showed further that severe degenerative lumbar central canal stenosis of Schizas grade C or D can be decompressed indirectly using OLIF. Rao et al.\textsuperscript{20} also showed significant indirect foraminal decompression based on the new pedicle-to-pedicle technique in anterior lumbar interbody fusions (ALIF) with up to a 67% increased cross-sectional area of the foraminal dimensions and that the posterior disc height correlated significantly with foraminal height for decompression purposes. Kim et al.\textsuperscript{21} analysed MRIs of patients who underwent unilateral MIS TLIF procedures pursuing indirect decompression of the contralateral foramen using cage distraction resulted in increased quantitative and qualitative dimensions of the spinal canal and the contralateral foramen.

Based on our results, this is the first time that such an effect can be seen in unilateral EPTLIF using similar cage techniques (in terms of cage sizing and placement) as well as not aggressively chasing the creation of lumbar lordosis. This becomes a balance of indirect decompression of the neural elements with obtaining sufficient correction of the sagittal imbalance. At the immediate postoperative MRI scans, there was a significant increase in the cross-sectional area of the spinal canal and the contralateral foramen regardless of whether any decompression was performed at all. The improvements in the radiological parameters were not only maintained but continues to improve with time due to subsequent remodeling as shown in the MRI scans at the final follow-up. There is significant change increment in axial cross-sectional cut in final follow-up compared to postoperative day one. In bilateral decompression, the axial cross-sectional area doubled in final follow-up. In ipsilateral decompression group, the cross-sectional area almost tripled in final follow-up and there is 5× increment in nondecompression group due to remodeling of spinal canal after EPTLIF. While foraminal height also remodeled with an average of 1.5× increment across all 3 groups. This remodeling pattern is concordant to the corresponding pattern in the patient-reported VAS and ODI scores at 1-week postoperation with continued trends of improvement at 6-week postoperation and at the final follow-up. Therefore, this technique can be used for indirect decompression of the central canal stenosis and contralateral foraminal stenosis and thus, able to reap the benefit of MIS approaches to preserve the anatomy of the spine and reduce the risk of adjacent segment disease while simultaneously avoiding iatrogenic injuries to the neural elements, dural tears, and epidural haematoma. This approach also allows for direct visualization of the contralateral foramen should the need arise and there are changes in neuromonitoring after the insertion of the interbody cage.

While there are studies on remodeling of spinal canal with the induced change of ligamentum flavum in ALIF,\textsuperscript{22} and oblique lateral lumbar interbody fusion,\textsuperscript{23} there is limited literature on remodeling after EPTLIF and other fusion methods, however our findings may provide an insight why patient generally feels better as the follow-up continued over a period of time as spinal canal area gets wider over time due to remodeling. More studies of such findings are required to understand this concept of spinal canal remodeling after fusion surgery.

In patients presented predominantly with claudication with minimal back pain, endoscopic foraminotomy is an alternative, minimally invasive technique compared to fusion designed to deal with foraminal stenosis.\textsuperscript{24} However, our cohort of patients had presented with back pain and claudication, we performed EPTLIF to our cohort of patients.

One of the potential advantages of ipsilateral decompression or no decompression alone over bilateral decompression is the reduction of operative time. However, we did not find any sta-
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There is an increasing interest in 3D-printed titanium cages in lumbar spinal fusion. We used 3D-printed titanium cages in our cohort of patients. One of the limitations of minimally invasive fusion is cage subsidence, the use of 3D-printed cage was associated with lower rates of subsidence. Kim et al. found that while there is no significant differences in overall fusion rate between PEEK and 3D-printed titanium cages, fusion grade was better in 3D-printed titanium cages. In our technique we performed fusion with straight cages. Choi et al. found that straight cages have lower subsidence rate compared to banana cages possibly due to more medial final position in banana cages. We felt that in EPTLIF, endoscopic direct visualization when we removed intervertebral disc, careful endplate preparation made with blunt endoscopic penfeel, and constant irrigation of inflammatory disc fragments with saline irrigation help in preparation of endplate without significant endplate violation to avoid subsidence. Together with 3D-printed cages potentially lower rate of subsidence, there is potential for better fusion rate. However, as our study is focus on MRI evaluation of spinal canal parameters, we did not evaluate further on fusion rate and subsidence which would be of academic interest in our future studies. Overall, minimally invasive transforaminal interbody fusion such as EPTLIF has promising results and potential in being treatment of choice for fusion with better understanding of technique and technology of interbody cages.

There are a few limitations of this study. The surgeon was not blinded to the patient’s symptoms and were given the option to decide if the patient requires bilateral decompression, ipsilateral decompression or cage insertion alone without any decompression during the surgery. At subsequent reviews, both the patient and the surgeon were not blinded as well when recording the patient-reported outcomes. Variabilities in measurements of the cross-sectional area of the spinal canal and the contralateral foramen is inescapable due to human error. Majority of our patients presented with spondylolisthesis, there is limitation in finding a difference during analysis in central and foraminal expansion between spondylolisthesis and spinal stenosis group. Our study is predominantly an MRI study, fusion rate and subsidence are not reflected in the study. Lastly, we did not include patients with bilateral lower limb radiculopathy that may benefit from bilateral decompressions. Future avenues of study could focus on patients with not only sagittal imbalance but also coronal deformity, as well as patients who underwent 3 or more level surgery.

CONCLUSION

Indirect decompression of both the spinal canal and the contralateral foramen can be achieved via EPTLIF. This radiological finding is supported by patient-reported outcome scores. Initial improvement (immediate postoperation) is not only maintained at the final follow-up, but there is continued improvement due to subsequent remodeling. Decompression on an asymptomatic contralateral side is not necessary unless it is accompanied by a very severe spinal stenosis due to the increased risks of injury in contralateral decompression.

NOTES

Conflict of Interest: Dr. Pang Hung Wu as first co-author declared his spouse is the director of Singapore based company
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Endocare PTE Ltd. which distributes orthopaedic and spine products including BESS, NSK drill, and Bonss energy system. No other co-authors have conflict of interest.

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Author Contribution: Conceptualization: PHW, HSK; Data curation: PHW, HSK; Formal analysis: PHW, HSK; Methodology: PHW, HSK; Project administration: PHW, HSK; Visualization: PHW; Writing - original draft: PHW, ETL, HSK; Writing - review & editing: PHW, HSK, GG, ITJ.

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The Use of Dual Direction Expandable Titanium Cage With Biportal Endoscopic Transforaminal Lumbar Interbody Fusion: A Technical Consideration With Preliminary Results

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Objective: Expandable cage technology has emerged for lumbar interbody fusion to restore intervertebral disc space height and alignment through a narrow surgical corridor. The purpose of this study is to present the technique of biportal endoscopic transforaminal lumbar interbody fusion (TLIF) using dual direction expandable cage and provide early clinical results.

Methods: We performed the biportal endoscopic TLIF using a dual direction expandable titanium cage for height restoration and a larger footprint in 10 patients. Clinical parameters including Oswestry Disability Index (ODI), visual analogue scale (VAS), and complications were retrospectively analyzed. Also, we investigated radiologic parameters using pre-operative and postoperative x-ray images.

Results: We successfully inserted dual direction expandable cages during biportal endoscopic TLIF. There was no significant subsidence or collapse of the expandable cages during the 6-month follow-up period. Lumbar lordosis and disc height were significantly increased after surgery. ODI and VAS scores were significantly improved at 6 months after surgery.

Conclusion: In this report, we describe the first use of a dual direction expandable interbody TLIF cage that expands in both width and height in biportal endoscopic TLIF surgery. Early clinical and radiographic outcomes of this TLIF technique may be favorable in early 6-month follow-up.

Keywords: Endoscopy, Lumbar vertebrae, Surgery, Biportal

INTRODUCTION

Minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF) has demonstrated comparable clinical outcomes and safety profile as compared to open conventional TLIF with significant improvement of pain and disability.¹² More recently, endoscopic techniques to perform TLIF surgery have been introduced with similar success as MIS-TLIF, especially with biportal endoscopic techniques.³⁴ The biportal endoscopic TLIF technique is similar to the MIS-TLIF technique in that the technique utilizes a posterolateral interlaminar approach, while visualizing the spinal anatomy with an endoscopic camera.⁷⁻⁹ Through the technique, direct decompression of the spinal canal can be achieved and interbody fusion can be completed through a transforaminal approach. This allows for restoration of intervertebral disc height and reduction of the spondylolisthesis, which has demonstrated significant correlation with clinical success.¹⁰,¹¹ The biportal endoscopic technique is less invasive as compared
to other MIS techniques with preservation of the lumbar musculoligamentous structures, which may reduce postoperative pain and facilitate recovery.\textsuperscript{5,7,8,12}

Expandable cage technology has been developed for interbody fusion and has demonstrated the ability to restore intervertebral disc height and correct alignment.\textsuperscript{13,14} However, subsidence of the vertebral endplates is a significant concern, especially with point loading of a narrow cage within the center of the intervertebral disc space.\textsuperscript{15,16} A narrow cage is typically utilized for a TLIF approach due to the narrow corridor available within the neural foramen to introduce the implant. With subsidence, collapse of disc height, loss of reduction, and malalignment may occur, which can lead to suboptimal clinical outcomes.

Recently, a novel dual direction expandable titanium TLIF cage has been developed that expands both in the medial to lateral dimension and in height. The cage can be placed through the neural foramen in the narrow, collapsed state. Once in the disc space, the medial to lateral expansion increases the surface area of endplate bony contact and provides contact with the apophyseal rings, which has been shown to be the strongest portion of the vertebral endplate.\textsuperscript{17,18} With these advantages, complete expansion with this dual expandable cage may lead to less subsidence and restore lumbar lordosis.

The purpose of this study is to present the technique of biportal endoscopic TLIF utilizing the dual direction expandable titanium TLIF cage and provide preliminary results.

MATERIALS AND METHODS

1. Patients and Clinical Data Analysis

We enrolled patients who were obtained single level biportal endoscopic TLIF using the dual direction expandable TLIF cage (Dual-X TLIF; Amplify Surgical, Inc., Irvine, CA, USA) in this study (Fig. 1). The design of this study was a retrospective analysis of prospectively collected data with description of surgical technique. After obtaining Institutional Review Board (IRB) approval from the hospital where the author was affiliated (IRB approval No. CA-TR-1), the investigations was performed. The design of this study was a technical report with preliminary data. The indications of this TLIF technique included degenerative spondylolisthesis, lumbar central stenosis, Lumbar foraminal stenosis and isthmic spondylolisthesis. We excluded the revision surgery, infection, trauma, and multilevel disease. Only patients who had full clinical and radiographic data for at least 6 months after surgery were included in the study.

We analyzed clinical data including Oswestry Disability Index (ODI), visual analogue scale (VAS) of back and leg, operation time, estimated blood loss, and complications. Estimated blood loss included postoperative blood drainage amount. We obtained lumbar radiographs, including anteroposterior (AP) and lateral x-rays including flexion and extension lateral views preoperatively, immediately postoperatively and 6 months after surgery. We measured disc height of operative segment (anterior height+posterior height/2), segmental lordotic angle of operative level, and lumbar lordotic angle using preoperative and postoperative x-rays. Significant cage subsidence was defined as a cage invading the vertebral body by more than 2 mm. Subsidence and collapse of the expandable cages were evaluated by disc height measurement.

Since the patient sample was small, nonparametric statistics were used. Statistical analysis was performed using Wilcoxon signed-rank test, and Kruskal-Wallis test. A $p < 0.05$ was considered to be statistically significant. R 4.2.2 (R Foundation for Statistical Computing, Vienna, Austria) were used for statistical analysis.
2. Surgical Procedure

The procedure utilizes biportal endoscopy, which consists of an endoscopic camera, endoscopic irrigation equipment, monitor, radiofrequency (RF) console with probes, high speed bur, bone cutting endoscopic shaver device, and standard surgical instruments.4,9,12

The dual direction expandable titanium TLIF cages start at a height of 7 mm that expand to 3-mm increments and width of 12 mm that expand to 21 mm with cage length options of 25 and 30 mm (Fig. 1). The cages are available in 0°, 8°, 12°, and 15° lordotic options. The cage is designed with a large center chamber for bone graft placement after expansion and an open structure design that allows bone graft to be placed through the cage and into the disc space. The cage is designed with 2 independent locking mechanisms to ensure that the cage remains expanded in both width and height. Initial locking occurs with an expansion locking mechanism and a secondary active locking occurs with insertion of a locking screw through the cage.

We preferred general endotracheal anesthesia for biportal endoscopic TLIF. After anesthesia, the patient is placed in the prone position on a Jackson table or a Wilson frame. Two incisions are made for the biportal endoscopic procedure (Fig. 2A). The first incision is made over the ipsilateral caudal pedicle below the disc space as the working portal, measuring approximately 2 cm (Fig. 2B). The surgical instruments, outflow cannula, interbody cage, and pedicle screw can all be introduced through this working portal. The second incision is for the viewing portal, which is a 5-mm stab incision made approximately 2 cm cephalad to the working portal and lateral to the pedicle (Fig. 2B). Two 18-gauge 90-mm length spinal needles are initially placed through the planned incision sites. Lateral fluoroscopic images are used to verify the correct spinal level and disc space as well as trajectories. Once the working portal incision is made, the lumbodorsal fascia is incised in the trajectory of the portal and serial dilators are inserted. The paraspinal musculature and adventitia are bluntly dissected off the cephalad and caudal laminae and a working space is created over the laminae. An outflow cannula is then placed in the working portal and the endoscopic camera is introduced after creating the viewing portal. After the endoscopic irrigation is started, the endoscopic camera and a RF probe are then triangulated over the cephalad lamina (Fig. 3A). Basically, our biportal endoscopic TLIF is similar to MIS-TLIF using tubular retractor systems. At this point, if patients have symptomatic central stenosis, a unilateral laminotomy with bilateral decompression can be performed as previously described (Fig. 3B).4,6 After the decompression is complete, a complete facetectomy is performed with a straight osteotome under direct visualization of the endoscope. The bone from the facetectomy can be harvested and processed as autograft for later in the procedure. Once the disc space is identified, and the annulus fibrosis is then incised by a blunt annular knife. Serial disc space shavers are then introduced into the disc space to remove the disc material and cartilaginous endplate. The disc material can then be further removed with a series of pituitaries and angled curettes under direct endoscopic visualization (Fig. 4A). The complete preparation of the bony endplates with bleeding bony surfaces can be verified directly by the endoscope (Fig. 4B). Prior to placing the final implant, serial trials are inserted.

Fig. 2. (A) Overview of biportal endoscopic approach. Intraoperative photograph depicting the endoscope placed in the viewing portal and the surgical instrument placed in the working portal. (B) Intraoperative anteroposterior fluoroscopy image depicting the location of the portals. The white line is the location of the viewing endoscopic portal and the black line is the location of the working portal.

Fig. 3. (A) Intraoperative fluoroscopy image showing the endoscopic camera and radiofrequency probe triangulated over the L4 lamina and disc space of L4–5. (B) Intraoperative endoscopic photograph showing the dura and traversing nerve root exposed after completion of the unilateral laminotomy and bilateral decompression.
into the disc space to determine the initial and final height that the disc space can accommodate. Only after proper trialing, the final implant is then selected.

Autograft can be introduced into the disc space using a specialized endoscopic funnel. The collapsed dual direction expandable cage is then inserted into the disc space with retraction of the thecal sac, traversing and exiting nerve root using specialized endoscopic retractors (Figs. 5, 6). A customized cage guidance helps to safely insert the cage into disc space. The cage is impacted to the anterior border of the disc space and across the midline under fluoroscopic guidance in both the AP and lateral projections (Fig. 5A, B). The cage is expanded initially in the medial to lateral direction (Fig. 5C). Once this is complete, the cage is then expanded to the final height position (Fig. 5D). After inserting the cage into the disc space, turning the insertion handle will initially expand the cage in the medial to lateral direction to the final width of 21 mm for increased surface area covered within the disc space. Once medial to lateral expansion is complete, then cage height expansion proceeds. The final height was previously determined by the trialing and the cage will expand in height by 3 mm to the final height with continued rotation of the insertion handle. Proper trialing and cage selection is paramount to prevent endplate damage and subsidence.

The secondary locking screw is then inserted and locked into final position. The inserter is then removed from the cage and fluoroscopic images are obtained in the AP and lateral projections.

Specialized bone graft cannulas are filled with allograft material such as demineralized bone matrix (DBM) putty and fiber and the cannulas are used to introduce the allograft material into the cage and disc space. The open architecture of the cage allows for the allograft to freely fill the cage and disc space. Typically, endoscopic fluid irrigation is paused during the insertion of the allograft material. A surgical drain is then placed into the laminotomy site to reduce the risk of epidural hematoma postoperatively. All endoscopic equipment is then removed, and percutaneous pedicle screws are placed in the standard fashion like MIS-TLIF (Fig. 6).

**RESULTS**

1. **Clinical and Radiological Results**

We successfully performed biportal endoscopic TLIF surgeries using dual direction expandable cages in 10 patients. All sur-
geries included biportal endoscopic unilateral laminotomy, bilateral decompression with TLIF and percutaneous pedicle screw fixation as described. The average age was 68.5 ± 5.4 years old with 6 females and 4 males. The diagnoses included degenerative spondylolisthesis with concomitant central stenosis (9 cases) and isthmic spondylolisthesis (1 case). The levels involved included L4–5 (8 cases), L5–S1 (2 cases). The average operation time was 151.4 ± 30.6 minutes. The mean postoperative estimated blood loss as measured by drain output was 156.6 ± 74.2 mL (Table 1).

Preoperative VAS of back decreased significantly from 6.9 ± 1.19 to 2.1 ± 1.85 at 6 weeks postoperatively, 1.3 ± 1.57 at 3 months postoperatively, and 1.25 ± 0.63 at 6 months after surgery (p < 0.05). Preoperative VAS of leg decreased significantly from 8.3 ± 1.16 to 0.55 ± 1.57 at 6 weeks postoperatively, 1.6 ± 1.65 at 3 months postoperatively, and 1 ± 0.94 at 6 months after surgery (p < 0.05).

Fig. 6. A 63-year-old female presented with low back pain, left lower extremity. Biportal endoscopic transforaminal lumbar interbody fusion with unilateral laminotomy with bilateral decompression using a dual direction expandable titanium cage was performed with a left sided approach. Preoperative anteroposterior (AP) (A) and lateral (B) x-ray images showing lower lumbar degenerative changes, facet arthropathy and grade 1 L4–5 spondylolisthesis with disc space narrowing. (C) Preoperative axial magnetic resonance imaging image demonstrating L4–5 severe central stenosis, facet and ligamentum hypertrophy. Intraoperative AP (D) and lateral (E) fluoroscopy images showed that dual expandable cage is inserted at L4–5 disc space. Intervertebral space is expanded after a cage insertion. Pedicle screws were placed with bone cement augmentation. Postoperative AP (F) and lateral (G) x-ray images taken 6 months after surgery revealed that the cage expansion was well maintained without subsidence or recollapse.
Preoperative ODI significantly improved from 55.2 ± 9.1 to 32.3 ± 17.3 at 6 weeks postoperatively, 29.1 ± 15.5 at 3 months postoperatively, and 26.6 ± 7.5 at 6 months after surgery (p < 0.05) (Table 2). There was one complication with an epidural hematoma causing a right ankle dorsiflexion weakness (G 3 of 5) postoperatively that required evacuation of the epidural hematoma on postoperative one day. After epidural hematoma removal, ankle weakness recovered well. Otherwise, there were no incidental durotomies, wound infections, implant failures, or medical complications in this clinical series.

Intervertebral disc height of operation segment was significantly widened and well maintained. The mean disc height of operation segment was significantly increased from 5.7 ± 2.7 mm to 13.2 ± 1.1 mm immediately after surgery, and 12.6 ± 1.1 mm at 6 months after surgery (p < 0.05). Also, preoperative segmental lordotic angle and lumbar lordotic angle were significantly increased and well maintained at 6 months after surgery (p < 0.05) (Table 3).

Postoperative radiographs at 6-month follow-up demonstrated no malposition or instrument failure with the cages or pedicle screws. There were no significant subsidence or recollapse of inserted cages.

**DISCUSSION**

With advancements in cage technology, many types of expandable cages have been developed for lumbar interbody fusion surgery. However, one of the main issues and criticisms of expandable TLIF cages is the point loading of the endplate due to the narrow cage geometry and differing modulus of elasticity of titanium to bone that may contribute to subsidence.15,16,19 This is especially true with osteopenic and osteoporotic bone, which is commonly seen in the older patient population that typically suffer from lumbar spondylolisthesis and stenosis.

The dual direction expandable titanium TLIF cage is a novel implant design that creates a wider footprint after placement within the disc space. Since the cage is initially in the collapsed and smaller state, it can be introduced endoscopically without difficulty. The wider footprint after initial expansion allows for greater surface area of vertebral endplate contact, which is advantageous for both disc height restoration and fusion purposes. The geometry of the cage contacts the anterior and posterior apophyseal ring, which is the stronger regions of the vertebral endplates, potentially reducing the risk of subsidence. With its open architecture, bone graft material such as flowable DBM allograft fibers can easily be packed into the cage and disc space after insertion of the cage. Alignment correction is achievable

<table>
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<tr>
<th>Characteristic</th>
<th>Value</th>
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<tr>
<td>Age (yr)</td>
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<tr>
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</tr>
<tr>
<td>L5–S1</td>
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<td>with central stenosis</td>
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<tr>
<td>Mean operation time (min)</td>
<td>151.4 ± 30.6</td>
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<tr>
<td>Mean estimated blood loss (mL)</td>
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Values are presented as mean ± standard deviation or number.

**Table 2. Clinical results**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Preoperative</th>
<th>Postoperative</th>
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<tbody>
<tr>
<td></td>
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<td>6 Weeks</td>
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<tr>
<td>VAS back*</td>
<td>6.9 ± 1.19</td>
<td>2.1 ± 1.85</td>
</tr>
<tr>
<td>VAS leg*</td>
<td>8.3 ± 1.16</td>
<td>0.55 ± 1.57</td>
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<tr>
<td>ODI*</td>
<td>55.2 ± 9.1</td>
<td>32.3 ± 17.3</td>
</tr>
</tbody>
</table>

Values are presented as mean ± standard deviation. VAS, visual analogue scale; ODI, Oswestry Disability Index. *p < 0.05.

**Table 3. Radiographic results**

<table>
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<th>Variable</th>
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<tr>
<td></td>
<td></td>
<td>Immediate</td>
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<tr>
<td>Disc height of operative segment (mm)*</td>
<td>5.7 ± 2.7</td>
<td>13.2 ± 1.1</td>
</tr>
<tr>
<td>Lordotic angle of operative segment (°)*</td>
<td>17.6 ± 7.7</td>
<td>21.1 ± 6.2</td>
</tr>
<tr>
<td>Lumbar lordotic angle (°)*</td>
<td>34.3 ± 6.2</td>
<td>41.1 ± 2.6</td>
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Values are presented as mean ± standard deviation. *p < 0.05.
with the various lordosis options available for the cage. When performing endoscopic TLIF, it can be difficult for the surgeon to insert a standard cage using a small skin incision. In addition, neural injury may occur when a large-sized cage is inserted through the neural foramen during endoscopic TLIF. However, using an expandable cage may make it easier and safer to insert the cage in endoscopic TLIF. When inserting a large interbody cage in MIS-TLIF or endoscopic TLIF, nerve root injury is a concern given the anatomical constraints. On the other hand, inserting a cage that is too small can result in fusion failure or cage pullout. The dual expandable cage is inserted in a small state and expanded to a large state in 2 dimensions within the disc space, which can prevent pullout and subsidence from occurring. Therefore, if a dual expandable cage is used in biportal endoscopic TLIF, the cage can be safely inserted without damaging the nerve root, and complications associated with cage implant failure can be minimized. Although the expandable cages have various advantages compared to the static cages, long-term research is needed. A comparative study using a large cohort and long-term follow-up is needed to elucidate the advantages of an expandable cages compared to a static cage.

Biportal endoscopic TLIF combines the advantages of endoscopic spine surgery and the enhanced visualization using the endoscope with the advantages of MIS-TLIF. Although the experience is still early with biportal endoscopic TLIF; several studies have demonstrated the clinical effectiveness and safety of the technique, demonstrating the technique is similar in the clinical outcomes as compared to MIS-TLIF at 1-year follow-up. Our early clinical experience of the initial 10 patients with at least 6-month follow-up demonstrated improvement of both back and leg pain as well as disability as compared to the preoperative state with no complications seen on postoperative radiographs. We did experience one case of epidural hematoma that necessitated reoperation with evacuation of the hematoma. Epidural hematoma is a known complication of biportal endoscopic TLIF due to more extensive bone work that leads to bony bleeding into a small, contained space within the spinal canal. Given this, the routine use of postoperative drains is advocated to reduce the risk of epidural hematoma in these cases.

The advantage of the biportal endoscopic TLIF is the minimally invasive nature of the surgery with very small incisions, minimal soft tissue trauma, yet without compromise of clinical effectiveness. The posterolateral interlaminar approach used in biportal endoscopic TLIF is very familiar to spine surgeons, whether they are trained in open or MIS surgery. Complete and thorough spinal canal decompression can be performed even with severe stenosis that is often seen concurrently with spondylolisthesis in these patients. In addition, there is less risk of damage to the exiting and traversing nerve roots with the translaminar approach as long as sufficient space is created with the laminotomy, decompression, and facetectomy. Another key advantage is the direct visualization and confirmation of a full endplate preparation using the endoscope and instruments such as angled curettes and pituitaries used within the disc space along with the endoscope. Proper and complete endplate preparation is a crucial step in achieving successful arthrodesis with the TLIF technique, whether it be open, MIS, or endoscopic. Prior studies have demonstrated that traditional TLIF techniques remove suboptimal disc material during the discectomy and the endplates may be insufficiently prepared during the procedure. This may lead to lower fusion rates and worse clinical outcomes over the long-term since successful arthrodesis has been correlated with clinical success. The verification of complete discectomy and endplate preparation with the endoscope may contribute to higher fusion rates based on the extent and completeness of the preparation. Multiple studies have shown that successful clinical outcomes after lumbar fusion are correlated with successful arthrodesis, disc height restoration, and alignment correction.

There were several limitations of this study. Since this study focused as a novel technical note of biportal endoscopic TLIF using the dual direction titanium expandable cage, the number of patients was small and follow-up period was short. This study is not a comparative study, but a preliminary study that described a small case series. Therefore, in order to fully investigate the clinical effects of expandable cages in biportal endoscopic TLIF, larger, long-term multi-center prospective studies and randomized case control studies are necessary.

**CONCLUSION**

In this study, we introduced the novel technique of inserting a dual direction expandable cage with biportal endoscopic TLIF. This is the first description of its kind in the scientific literature. We successfully performed the insertion of a dual direction expandable cage in biportal endoscopic TLIF. In the preliminary results, the radiographic and clinical outcomes may be favorable. All inserted expanded cages were well maintained without significant collapse or subsidence in our early experience. Biportal endoscopic TLIF using a dual direction expandable cage may be a successful alternative surgical option for treatment of lumbar degenerative disease.
NOTES

Conflict of Interest: The authors have nothing to disclose.

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Author Contribution: Conceptualization: DHH; Data curation: DYP, DHH; Formal analysis: DYP, DHH; Methodology: DYP, DHH; Visualization: DYP, DHH; Writing - original draft: DYP; Writing - review & editing: DYP, DHH.

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REFERENCES


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Endoscopic and Nonendoscopic Approaches to Single-Level Lumbar Spine Decompression: Propensity Score-Matched Comparative Analysis and Frailty-Driven Predictive Model

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2Bowers Neurosurgical Frailty and Outcomes Data Science Lab, Albuquerque, NM, USA
3School of Medicine, New York Medical College (NYMC), Valhalla, NY, USA

Objective: The endoscopic spine surgery (ESS) approach is associated with high levels of patient satisfaction, shorter recovery time, and reduced complications. The present study reports multicenter, international data, comparing ESS and non-ESS approaches for single-level lumbar decompression, and proposes a frailty-driven predictive model for nonhome discharge (NHD) disposition.

Methods: Cases of ESS and non-ESS lumbar spine decompression were queried from the American College of Surgeons National Surgical Quality Improvement Program database (2017–2020). Propensity score matching was performed on baseline characteristics frailty score (measured by risk analysis index [RAI] and modified frailty index-5 [mFI-5]). The primary outcome of interest was NHD disposition. A predictive model was built using logistic regression with RAI as the primary driver.

Results: Single-level nonfusion spine lumbar decompression surgery was performed in 38,686 patients. Frailty, as measured by RAI, was a reliable predictor of NHD with excellent discriminatory accuracy in receiver operating characteristic (ROC) curve analysis: C-statistic: 0.80 (95% confidence interval [CI], 0.65–0.94) in ESS cohort, C-statistic: 0.75 (95% CI, 0.73–0.76) overall cohort. After propensity score matching, there was a reduction in total operative time (89 minutes vs. 103 minutes, p = 0.049) and hospital length of stay (LOS) (0.82 days vs. 1.37 days, p < 0.001) in patients treated endoscopically. In ROC curve analysis, the frailty-driven predictive model performed with excellent diagnostic accuracy for the primary outcome of NHD (C-statistic: 0.87; 95% CI, 0.85–0.88).

Conclusion: After frailty-based propensity matching, ESS is associated with reduced operative time, shorter hospital LOS, and decreased NHD. The RAI frailty-driven model predicts NHD with excellent diagnostic accuracy and may be applied to preoperative decision-making with a user-friendly calculator: nsgyfrailtyoutcomeslab.shinyapps.io/lumbar_decompression_dischargedispo.

Keywords: Age, Endoscopic spine surgery, Frailty, Modified frailty index, National Surgical Quality Improvement Program, Risk analysis index

INTRODUCTION

Minimally invasive surgery (MIS) techniques have improved patient and surgeon satisfaction across the spectrum of spine pathologies.1,2 This group of techniques has minimized soft tissue manipulation, blood loss, and infection rates while allowing for expeditious recovery time.3,4 More recently, endoscopic spine surgery (ESS) was introduced as a minimally invasive treatment.
option for lumbar spine pathologies.\(^5\) ESS is defined by endoscope utilization for visualization in adjunct with tubular instruments through small incisions. This approach holds promise for minimizing tissue disruption and associated postoperative pain, further accelerating recovery.\(^6\)

ESS has been previously shown to decrease the risk of common surgical complications such as muscle crush injury from protractors, soft tissue stripping, and excessive bone loss.\(^7,8\) While the literature regarding ESS versus non-ESS (open or other MIS) spinal surgery is sparse, several studies have suggested MIS superiority.\(^9,13\) When comparing ESS to other MIS techniques, recent literature suggests ESS is better with the appropriate surgical indications.\(^14,15\) Of note, one recent study found no difference in early postoperative outcomes between endoscopic guided approaches and open approaches to single-level lumbar decompression.\(^16\) However, the significance of the study is questionable as the sample size was low and there was no adjustment for baseline measured differences.

Frailty, as measured by scales such as modified frailty index-5 (mFI-5) and risk analysis index (RAI) administrative-revised, have been shown to predict neurosurgical outcomes across the spectrum of neurosurgical subspecialties in the recent literature, and frailty assessment provides a reliable baseline of physiological reserve.\(^17-21\) Herein, the authors sought to supply data to support preoperative decision-making for minimally invasive spine surgery by analyzing outcomes across propensity score-matched ESS and non-ESS groups using data derived from a large, multicenter, surgical database. The intention was to identify whether any ESS benefits were present, with an emphasis on the hospital course. Furthermore, the authors sought to describe the impact of baseline frailty on patient outcomes using predictive analytics.

MATERIALS AND METHODS

1. Study Design
The present study was a retrospective observational analysis of a prospectively maintained, multicenter, international (49 USA, 11 countries), database. This manuscript was formatted in accordance with standardized reporting guidelines from the Equator Network: The STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) statement.

2. Data Source and Setting
The data source was the American College of Surgeons National Surgical Quality Improvement Program (ACS-NSQIP) database, 2017–2020. Characteristics of the ACS-NSQIPs database have been described previously.\(^22,23\) The study was considered exempt from continuing review by our Institutional Review Board (IRB-21-315) and conducted under the data user agreement between ACS and our institution.

3. Participants
Study participants included patients aged 18 or greater who underwent nonfuson single-level spine decompression at an NSQIP-participating institution. Cases were selected using Current Procedural Terminology (CPT) codes 62380 (endoscopic decompression of neural elements and/or excision of herniated disc) and 63030 (simple single-level lumbar decompression of neural elements and/or excision of a herniated disc, may include partial facetectomy, foraminotomy). Patients were excluded from the study if their age or discharge disposition were not reported.

4. Variables
Preoperative frailty, as measured by the mFI-5 and RAI, was the primary predictor variable. The RAI was computed using methodology previously described by Arya and Hall et al in the recalibration and external validation of the RAI for utilization with the ACS-NSQIP database (RAI-Rev).\(^24,25\) Demographic information (age, sex, race, ethnicity, body mass index [BMI]) and elective surgery status were also considered. The primary outcome was nonhome discharge disposition (NHD). “Home” included discharge home or facility which was home. Secondary outcomes included major complications (intubation over 48 hours, unplanned intubation, deep vein thrombosis/thrombophlebitis, pulmonary embolism, cerebrovascular accident/stroke, myocardial infarction, wound disruption, cardiac arrest requiring cardiopulmonary resuscitation), total operative time, unplanned readmission and reoperation, and 30-day mortality. Complications present at the time of admission (PATOS) were not considered to be surgical complications.

5. Statistical Analysis
Statistical analysis was performed with the open-source R ver. 2022.07.0+548 (R Foundation for Statistical Computing, Vienna, Austria) with adjunctive assistance from IBM SPSS Statistics ver. 28.0 (IBM Co., Armonk, NY, USA). Alpha was designated at 0.05, where \(p < 0.05\) was considered statistically significant. Baseline demographics, preoperative clinical characteristics, and outcomes were derived from the NSQIP database. Continuous variables were reported as mean with standard deviation (standard deviation). Proportions were reported
Table 1. Preoperative characteristics and frailty and postoperative complications and outcomes, endoscopic and nonendoscopic approaches to single-level lumbar spine decompression surgery, ACS-NSQIP 2017–2020

<table>
<thead>
<tr>
<th>Variable</th>
<th>All single-level, nonfusion, lumbar surgery (n = 38,686)</th>
<th>Endoscopic (n = 174)</th>
<th>Nonendoscopic (n = 38,512)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Preoperative characteristics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age (yr), median (IQR)</td>
<td>51 (38–64)</td>
<td>51 (38–64)</td>
<td>55 (40–66)</td>
<td>0.020</td>
</tr>
<tr>
<td>Female sex (biological)</td>
<td>17,009 (44.0)</td>
<td>16,938 (44.0)</td>
<td>71 (40.8)</td>
<td>0.400</td>
</tr>
<tr>
<td>Race</td>
<td></td>
<td></td>
<td></td>
<td>0.809</td>
</tr>
<tr>
<td>White</td>
<td>28,729</td>
<td>125</td>
<td>28,604</td>
<td></td>
</tr>
<tr>
<td>Black</td>
<td>2,547</td>
<td>12</td>
<td>2,535</td>
<td></td>
</tr>
<tr>
<td>Asian</td>
<td>71</td>
<td>0</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>7,339</td>
<td>37</td>
<td>7,302</td>
<td></td>
</tr>
<tr>
<td>Hispanic ethnicity</td>
<td>2,709 (7.0)</td>
<td>12 (6.9)</td>
<td>2,697 (7.0)</td>
<td>0.956</td>
</tr>
<tr>
<td>Body mass index (kg/m²)</td>
<td>29 (25–33)</td>
<td>29 (25–33)</td>
<td>30 (26–33)</td>
<td>0.80</td>
</tr>
<tr>
<td>Nonelective surgery</td>
<td>3,939 (10.2)</td>
<td>3,917 (10.2)</td>
<td>22 (12.6)</td>
<td>0.283</td>
</tr>
<tr>
<td>RAI, median (IQR)</td>
<td>16 (12–19)</td>
<td>17 (14–20)</td>
<td>16 (12–19)</td>
<td>0.016</td>
</tr>
<tr>
<td>RAI frailty tier</td>
<td></td>
<td></td>
<td></td>
<td>0.081</td>
</tr>
<tr>
<td>Robust (0–20)</td>
<td>28,288 (73.1)</td>
<td>115 (66.2)</td>
<td>28,173 (73.2)</td>
<td></td>
</tr>
<tr>
<td>Prefrail (21–30)</td>
<td>9,923 (25.7)</td>
<td>58 (33.3)</td>
<td>9,865 (25.6)</td>
<td></td>
</tr>
<tr>
<td>Frail (31–40)</td>
<td>452 (1.2)</td>
<td>1 (0.6)</td>
<td>451 (1.2)</td>
<td></td>
</tr>
<tr>
<td>Severely frail (≥ 41)</td>
<td>23 (0.1)</td>
<td>0 (0)</td>
<td>23 (0.1)</td>
<td></td>
</tr>
<tr>
<td>mFI-5, median (IQR)</td>
<td>0.6 (0.3–1.0)</td>
<td>0.6 (0.2–1.0)</td>
<td>0.6 (0.3–1.0)</td>
<td>0.160</td>
</tr>
<tr>
<td>mFI-5 frailty tier</td>
<td></td>
<td></td>
<td></td>
<td>0.640</td>
</tr>
<tr>
<td>Robust (0)</td>
<td>22,555 (58.3)</td>
<td>22,456 (58.3)</td>
<td>98 (56.3)</td>
<td></td>
</tr>
<tr>
<td>Normal (1)</td>
<td>11,365 (29.4)</td>
<td>11,316 (29.4)</td>
<td>49 (28.2)</td>
<td></td>
</tr>
<tr>
<td>Frail (2)</td>
<td>4,449 (11.5)</td>
<td>4,424 (11.5)</td>
<td>25 (14.4)</td>
<td></td>
</tr>
<tr>
<td>Severely frail (≥ 3)</td>
<td>317 (0.8)</td>
<td>315 (0.8)</td>
<td>2 (1.1)</td>
<td></td>
</tr>
<tr>
<td><strong>Postoperative complications</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operative time (min)</td>
<td>92 (65–119)</td>
<td>80 (58–110)</td>
<td>78 (60–111)</td>
<td>0.317†</td>
</tr>
<tr>
<td>Postoperative major complication</td>
<td>335 (0.9)</td>
<td>1 (0.6)</td>
<td>334 (0.9)</td>
<td>0.678‡</td>
</tr>
<tr>
<td>Unplanned reintubation</td>
<td>27 (0.1)</td>
<td>0 (0)</td>
<td>27 (0.1)</td>
<td>0.727</td>
</tr>
<tr>
<td>Sepsis</td>
<td>130 (0.3)</td>
<td>0 (0)</td>
<td>88 (0.2)</td>
<td>0.443</td>
</tr>
<tr>
<td>Septic shock</td>
<td>14 (0.0)</td>
<td>0 (0)</td>
<td>11 (0.0)</td>
<td>0.801</td>
</tr>
<tr>
<td>Pneumonia</td>
<td>61 (0.2)</td>
<td>0 (0)</td>
<td>52 (0.1)</td>
<td>0.599</td>
</tr>
<tr>
<td>DVT/thrombophlebitis</td>
<td>126 (0.3)</td>
<td>0 (0)</td>
<td>126 (0.3)</td>
<td>0.450</td>
</tr>
<tr>
<td>Pulmonary embolism</td>
<td>85 (0.2)</td>
<td>0 (0)</td>
<td>85 (0.2)</td>
<td>0.535</td>
</tr>
<tr>
<td>Myocardial infarction</td>
<td>37 (0.1)</td>
<td>0 (0)</td>
<td>37 (0.1)</td>
<td>0.682</td>
</tr>
<tr>
<td>Superficial SSI</td>
<td>304 (0.8)</td>
<td>0 (0)</td>
<td>304 (0.8)</td>
<td>0.239</td>
</tr>
<tr>
<td>Deep incisional SSI</td>
<td>93 (0.2)</td>
<td>0 (0)</td>
<td>91 (0.2)</td>
<td>0.516</td>
</tr>
<tr>
<td>Organ space SSI</td>
<td>125 (0.3)</td>
<td>0 (0)</td>
<td>93 (0.2)</td>
<td>0.452</td>
</tr>
<tr>
<td>Wound disruption</td>
<td>73 (0.2)</td>
<td>1 (0.6)</td>
<td>72 (0.2)</td>
<td>0.240</td>
</tr>
<tr>
<td>Cardiac arrest requiring CPR</td>
<td>16 (0)</td>
<td>0 (0)</td>
<td>16 (0)</td>
<td>0.788</td>
</tr>
<tr>
<td>Clavien-Dindo IV complication‡</td>
<td>276 (0.7)</td>
<td>0 (0)</td>
<td>276 (0.7)</td>
<td>0.262</td>
</tr>
</tbody>
</table>

(Continued)
as frequencies with a percentage of the cohort total. The Pearson chi-square test was used for categorical variables and the independent-samples t-test or Mann-Whitney U-test for the comparison of continuous variables. A predictive model was built using logistic regression for the primary outcome of NHD after single-level lumbar spine surgery. Discriminatory ability was assessed with receiver operating characteristic (ROC) curve analysis with computation of C-statistics (95% confidence intervals [CIs]) and interpreted using established epidemiological criteria per Hosmer-Lemeshow: outstanding (0.9–1.0), excellent (0.8–0.89), acceptable (0.7–0.79), poor (0.6–0.69), and no discrimination (0.5–0.59). The DeLong test assessed whether the area under the curve for RAI was statistically significantly different from that for chronological age and the mFI-5 score.

The R packages rms and shiny were used to generate an interactive calculator.

RESULTS

1. Participants

The study cohort included 38,686 patient cases with 174 (0.4%) treated ESS and 38,512 treated non-ESS. The study cohort was 44% female with median age, in years, of 51 (interquartile range [IQR], 38–64 years). The overall cohort was stratified by RAI frailty scoring into robust (RAI 0–20: N = 28,288 [73.1%]), normal (RAI 21–30: N = 9,923 [25.7%]), frail (RAI 31–40: N = 452 [1.2%]), and severely frail (RAI ≥ 41: N = 1 [0.1%]) (Table 1). After propensity score matching (1:1 nearest neighbor method, 0.1 caliper), a non-ESS cohort of 174 similar patients was compared to the original ESS cohort. Propensity matching calibration can be found in Fig. 1. There was a statistically significant reduction in total operative time (89 minutes vs. 103 minutes, p = 0.049) and hospital LOS (0.82 days vs. 1.37 days, p < 0.001) in patients treated endoscopically (Table 2). Other outcomes were extremely rare in the ESS cohort and thus limited statisti-

### Table 1. Preoperative characteristics and frailty and postoperative complications and outcomes, endoscopic and nonendoscopic approaches to single-level lumbar spine decompression surgery, ACS-NSQIP 2017–2020 (Continued)

<table>
<thead>
<tr>
<th>Variable</th>
<th>All single-level, nonfusion, lumbar surgery (n = 38,686)</th>
<th>Endoscopic (n = 174)</th>
<th>Nonendoscopic (n = 38,512)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of stay (day), mean ± SD</td>
<td>1.3 ± 2.8</td>
<td>0.8 ± 1.6</td>
<td>1.3 ± 2.8</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Length of stay (day), median (IQR)</td>
<td>-</td>
<td>1 (0–1)</td>
<td>0 (0–1)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Nonhome discharge disposition†</td>
<td>1,268 (3.3)</td>
<td>3 (1.7)</td>
<td>1,265 (3.3)</td>
<td>0.249</td>
</tr>
<tr>
<td>Unplanned readmission†</td>
<td>1,211 (3.1)</td>
<td>7 (4.0)</td>
<td>1,204 (3.1)</td>
<td>0.498</td>
</tr>
<tr>
<td>Unplanned reoperation†</td>
<td>1,039 (2.7)</td>
<td>4 (2.3)</td>
<td>1,035 (2.7)</td>
<td>0.752</td>
</tr>
<tr>
<td>Mortality within 30 days of operation†</td>
<td>11 (0)</td>
<td>0 (0)</td>
<td>11 (0)</td>
<td>0.824</td>
</tr>
</tbody>
</table>

Values are presented as number of patients (%) unless otherwise indicated.

ACS-NSQIP, American College of Surgeons National Surgical Quality Improvement Program; IQR, interquartile range; RAI, risk analysis index; mFI-5, modified frailty index-5; DVT, deep venous thrombosis; SSI, surgical site infection; CPR, cardiopulmonary resuscitation; SD, standard deviation.

†Pearson chi-square test or Fisher exact test.

3. Outcome Data

Postoperative outcomes within 30 days for both cohorts were reported before and after propensity matching. Prior to matching, major postoperative complications were seen in 0.6% of ESS patients and 0.9% of non-ESS patients (p = 0.678). Clavien-Dindo IV complications were seen in 0.0% and 0.7%, respectively (p = 0.272). The average LOS for ESS patients was 0.8 days compared to 1.3 days in the non-ESS cohort (p < 0.001). NHD was reported in 1.7% of the ESS cohort compared to 3.3% of the non-ESS patients (p = 0.249). Unplanned readmission was reported in 4.0% and 3.1%, respectively (p = 0.498), while unplanned reoperation was reported in 2.3% and 2.7%, respectively (p = 0.752). There were no fatalities in the ESS cohort, and 11 patients expired in the non-ESS cohort (p = 0.824). Complete postoperative complication data prior to matching can be found in Table 1.
4. Main Results – Frailty-Driven Predictive Model

Frailty, as measured by RAI, was a reliable predictor of the primary outcome of NHD with excellent discriminatory accuracy in ROC analysis: C-statistic: 0.80 (0.65–0.94) in ESS, C-statistic: 0.75 (0.73–0.76) overall cohort.

In the overall study cohort (ESS and non-ESS), a predictive model was built for the primary outcome of NHD disposition (Table 3). In the model, the independent predictors of NHD included indication for lumbar decompression, RAI score, non-elective surgery, BMI, and several abnormal preoperative labs (hypoalbuminemia, leukocytosis, low hematocrit). In ROC analysis, the frailty-driven model predicted the primary outcome of

![Fig. 1. Propensity score matching (1:1 nearest neighbor, caliper 0.1) diagnostics of endoscopic and nonendoscopic study cohorts. mFI-5, modified frailty index-5; RAI, risk analysis index; eCDF, empirical cumulative distribution function.](https://doi.org/10.14245/ns.2346110.055)
Table 2. Endoscopic and nonendoscopic cohorts propensity score matched (1:1, nearest neighbor) on baseline characteristics and frailty, comparison of postoperative outcomes, ACS-NSQIP 2017–2020

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Nonendoscopic (n = 174)</th>
<th>Endoscopic (n = 74)</th>
<th>p-value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>55 (42–68)</td>
<td>54 (41–67)</td>
<td>0.81†</td>
</tr>
<tr>
<td>Female sex (biological), n (%)</td>
<td>70 (40)</td>
<td>71 (41)</td>
<td>0.91†</td>
</tr>
<tr>
<td>Race, n (%)</td>
<td></td>
<td></td>
<td>0.97‡</td>
</tr>
<tr>
<td>White</td>
<td>125 (72)</td>
<td>125 (72)</td>
<td></td>
</tr>
<tr>
<td>Black</td>
<td>11 (6.3)</td>
<td>12 (6.9)</td>
<td></td>
</tr>
<tr>
<td>Asian</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>38 (22)</td>
<td>37 (21)</td>
<td></td>
</tr>
<tr>
<td>Nonelective surgery, n (%)</td>
<td>19 (11)</td>
<td>22 (13)</td>
<td>0.62‡</td>
</tr>
<tr>
<td>mFI-5, n (%)</td>
<td></td>
<td></td>
<td>0.95‡</td>
</tr>
<tr>
<td>Robust</td>
<td>96 (55)</td>
<td>98 (56)</td>
<td>&gt;0.99‡</td>
</tr>
<tr>
<td>Normal</td>
<td>49 (28)</td>
<td>49 (28)</td>
<td></td>
</tr>
<tr>
<td>Frail</td>
<td>28 (16)</td>
<td>25 (14)</td>
<td></td>
</tr>
<tr>
<td>Severely frail</td>
<td>1 (0.6)</td>
<td>2 (1.1)</td>
<td></td>
</tr>
<tr>
<td>RAI, n (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Robust</td>
<td>114 (66)</td>
<td>115 (66)</td>
<td></td>
</tr>
<tr>
<td>Normal</td>
<td>58 (33)</td>
<td>58 (33)</td>
<td></td>
</tr>
<tr>
<td>Frail</td>
<td>2 (1.1)</td>
<td>1 (0.6)</td>
<td></td>
</tr>
<tr>
<td>Severely frail</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>RAI, composite</td>
<td>17 (14–20)</td>
<td>17 (14–20)</td>
<td>0.78†</td>
</tr>
<tr>
<td>Total operation time (min)</td>
<td>88 (67–110)</td>
<td>78 (53–104)</td>
<td>0.049‡</td>
</tr>
<tr>
<td>Major complication occurrence, n (%)</td>
<td>2 (1.1)</td>
<td>1 (0.6)</td>
<td>&gt;0.99‡</td>
</tr>
<tr>
<td>Clavien-Dindo IV occurrence, n (%)</td>
<td>1 (0.6)</td>
<td>0 (0)</td>
<td>&gt;0.99‡</td>
</tr>
<tr>
<td>Extended length of stay, n (%)</td>
<td>42 (24)</td>
<td>33 (19)</td>
<td>0.24‡</td>
</tr>
<tr>
<td>Length of total hospital stay (day), mean ± SD</td>
<td>1.37 ± 2.67</td>
<td>0.82 ± 1.60</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Length of total hospital stay (day)</td>
<td>1 (0–1)</td>
<td>0 (0–1)</td>
<td>&lt;0.001†</td>
</tr>
<tr>
<td>Nonhome discharge disposition, n (%)</td>
<td>8 (4.6)</td>
<td>3 (1.7)</td>
<td>0.13‡</td>
</tr>
<tr>
<td>Mortality within 30 days of operation, n (%)</td>
<td>32 (0.1)</td>
<td>0 (0)</td>
<td>0.704‡</td>
</tr>
<tr>
<td>Unplanned reoperation, n (%)</td>
<td>4 (2.3)</td>
<td>3 (1.7)</td>
<td>&gt;0.99‡</td>
</tr>
</tbody>
</table>

Values are presented as median (interquartile range) unless otherwise indicated. ACS-NSQIP, American College of Surgeons National Surgical Quality Improvement Program; mFI-5, modified frailty index-5; RAI, risk analysis index; SD, standard deviation. †Wilcoxon rank sum test. ‡Pearson chi-square test or Fisher exact test.

NHD with excellent discriminatory accuracy as displayed in Fig. 2, C-statistic: 0.87; 95% CI, 0.85–0.88). The predictive model was deployed into a web application: nsyfryalitoucomeslab.shinyapps.io/lumbar_decompression_dischargedispo.

**DISCUSSION**

The present study analyzes a large modern series of 38,686 patients undergoing minimally invasive lumbar spine surgery in the 2017–2020 ACS-NSQIP database. In propensity-matched cohorts, ESS (vs. non-ESS) surgery reduced operative time and hospital LOS. Furthermore, the RAI frailty index predicted NHD destination with excellent diagnostic accuracy (0.75). A predictive model for NHD destination with RAI as the core predictor was proposed and enhanced with consideration of surgical indication, BMI, and several preoperative lab values. By contrast, a prior study of 34 patients undergoing single-level endoscopic lumbar surgery (ACS-NSQIP 2017) reported no differences in...
Table 3. Logistic regression predictive model for nonhome discharge after single-level lumbar decompression surgery (endoscopic and nonendoscopic)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>OR</th>
<th>95% CI</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diagnosis</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiculopathy with IVD</td>
<td>2.64</td>
<td>2.16–3.23</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Spinal stenosis</td>
<td>4.38</td>
<td>3.01–6.37</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Degenerative disease (includes spondylosis)</td>
<td>4.98</td>
<td>2.63–9.43</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Cauda equina</td>
<td>3.05</td>
<td>2.25–4.13</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Other</td>
<td>3.05</td>
<td>1.13–1.17</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>RAI-rev</td>
<td>5.58</td>
<td>4.56–6.83</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Nonelective surgery</td>
<td>1.05</td>
<td>1.04–1.06</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Body mass index</td>
<td>1.94</td>
<td>1.63–2.32</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Hypoalbuminemia</td>
<td>1.47</td>
<td>1.10–1.95</td>
<td>0.009</td>
</tr>
<tr>
<td>Leukocytosis</td>
<td>1.51</td>
<td>1.19–1.90</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Effect sizes are reported as odds ratios with 95% confidence intervals.
OR, odds ratio; CI, confidence interval; IVD, intervertebral disc disease; RAI, risk analysis index.

the rate of mortality, reoperation, readmission, complications, operative time, or LOS. The low sample size and lack of adjustment for baseline frailty in the prior paper may have contributed to the equivocal outcomes.

1. Interpretation

Here, the RAI was applied to effectively match 2 surgical cohorts on baseline characteristics, which further demonstrates its versatility. Recent literature suggests that RAI, as a metric of frailty, is a reliable, easily utilizable metric with benefits in preoperative decision-making. The disparity in results before and after propensity score matching highlights the importance of adjusting for baseline frailty for comparative analyses. The findings further underscore the importance of the continued study of ESS research with the design of high-powered randomized controlled trials to minimize confounders attributable to unmeasurable baseline differences. Despite the non-randomized study design, the results demonstrate that ESS for lumbar decompression is exceptionally safe and abbreviates patient recovery.

As discussed in the NSQIP series and systematic review by Chiu et al., the ESS literature is controversial regarding the safety and efficacy of ESS vs. non-ESS approaches to lumbar spine surgery. The literature suggests that ESS is associated with reduced patient time returning to work, increased recovery speed, and preservation of paraspinal muscles, reduced infection, and need for supportive care while also noting ESS to be associated with increased rates of incomplete decompression. Some studies report ESS as superior, inferior, or not statistically different than non-ESS techniques, resulting in unclear for any one method of preoperative decision-making. The limited sample size in most prior studies may explain some degree of ambiguity. As the present study found complications in both single-level non-ESS and ESS to be exceedingly rare, these previous studies may have been similarly unable to capture the granular differences in outcomes. The minuscule complication rate observed in the present cohort supports the trend in literature towards safe, minimally invasive, approaches to lumbar spine surgery.

While most patients rapidly recover from single-level lumbar decompression, there are certainly a group of patients with a complicated postoperative course warranting attention in the preoperative setting. The early identification of patients at high risk for delayed recovery is critical for the implementation of targeted interventions such as “enhanced recovery after surgery.” Thus, a predictive model was proposed that predicted NHD destination with excellent discriminatory accuracy. The C-statistic of 0.87 suggests most NHD can be anticipated preoperatively by considering RAI frailty score, surgical indication, the timing of surgery (elective vs. nonelective), BMI, and several

Fig. 2. Receiver operator characteristic curve analysis with excellent discriminative accuracy for the primary outcome of nonhome discharge after single-level lumbar decompressive surgery. (C-statistic: 0.87; 95% confidence interval [CI], 0.85–0.88; p < 0.001).

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www.e-neurospine.org
key lab values (serum albumin, leukocyte count, and hematocrit). A model with this level of diagnostic accuracy is superior compared to similar models in previous literature.\textsuperscript{36,37} The predictive model bears clinically translatable knowledge that may be used to reduce poor outcomes among spine surgery patients with augmentation of surgical decision-making or perioperative care.

2. Limitations

The endoscopic spine CPT code, introduced in 2017, was the first CPT code unique to minimally invasive spine surgery. Thus, the code is likely still underutilized and thus the present study may underestimate the total number of ESS (N = 174) performed at NSQIP-participating hospitals during the study period. Nationwide databases provide statistical power to enable complex analyses with widely generalizable results but are not without limitations. Database studies may include observer bias and data quality discrepancies. Patient case information such as the severity of disease, chronicity of disease, and unmeasured comorbidities or risk factors that may affect outcomes are omitted. Coding bias among the ICD and CPT systems may further influence the fidelity of the data. The coding systems reduce the granularity at which analysis may occur, for example, specific nonendoscopic techniques were not differentiated within the study cohort. Furthermore, The NSQIP does not include data beyond 30 days postoperatively, resulting in an inability to assess long-term outcomes.

3. Generalizability

The study population was derived from a multicenter, international (49 USA, 11 countries) database which significantly increases the generalizability of results. Although the specific approach for the nonendoscopic cases was not known, we expect the majority of single-level nonfusion decompression procedures from 2017–2020 to be minimally invasive.\textsuperscript{39,38} Clinically, the findings suggest that patients flagged as high risk for delayed recovery may benefit from minimally invasive approaches, which may include but are not limited to ESS. However, the present study was limited in granularity by available CPT codes which do not uniquely identify other types of MIS and thus require further in-depth analysis in a different study design.

CONCLUSION

The present study suggests that ESS is a safe and effective type of minimally invasive spine surgery in a large multicenter analysis from 2017–2020. After propensity score matching on baseline characteristics (particularly frailty measured by RAI-rev), endoscopic surgery was associated with reduced operative time, hospital LOS, and NHD disposition. Overall, the rates of delayed recovery and postoperative complications/morbidity after single-level lumbar decompression surgery were exceptionally rare. The RAI frailty index enhances preoperative risk stratification by predicting NHD with excellent diagnostic accuracy and may be translated clinically with a user-friendly calculator: nsgyfrailtyoutcomeslab.shinyapps.io/lumbar_decompression_dischargediso. The early identification of patients at high risk for delayed recovery is critical for the implementation of targeted interventions and anticipatory guidance.

NOTES

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Author Contribution: Conceptualization: AJK, KR, SFK, MHS, PCS, CAB; Data curation: AJK, KR, MHS, PCS; Formal analysis: AJK, KR, ACS; Methodology: AJK, KR, SFK, JV; Project administration: KR, SFK, MHS, PCS, CAB; Visualization: AJK; Writing - original draft: AJK, ACS, JV; Writing - review & editing: AJK, KR, ACS, SFK, JV, MHS, PCS, CAB

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REFERENCES


Biportal Endoscopic Posterior Thoracic Laminectomy for Thoracic Spondylotic Myelopathy Caused by Ossification of the Ligamentum Flavum: Technical Developments and Outcomes

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Objective: Advanced biportal endoscopic surgery techniques can be used to treat thoracic myelopathy secondary to ossification of the ligamentum flavum (OLF). This case series elaborates on a feasible biportal endoscopic technique for thoracic OLF removal and evaluates clinical and radiological outcomes.

Methods: A biportal endoscopic posterior thoracic laminectomy was performed to remove the thoracic OLF. Surgical techniques have evolved from inside-out piecemeal removal methods to outside-in en bloc removal methods. Preoperative computed tomography was performed to analyze dural ossification and OLF types. Intraoperative videos were reviewed to observe dural ossification and to determine the surgical method. Neurological outcomes were assessed using the Japanese Orthopaedic Association (JOA) score.

Results: Clinical symptoms and neurological function improved markedly after surgery (JOA score, preoperative: 12.6 ± 1.0, final follow-up: 15.6 ± 1.2). The mean operation time per segment was not short (106.6 ± 38 minutes). At early experience stages, inside-out piecemeal decompression was used and it caused intraoperative spinal cord injury. However, outside-in en bloc decompression technique did not induce neural complications. Postoperative segmental instability and correlated mechanical back pain were not observed.

Conclusion: The biportal endoscopic posterior thoracic approach is an attractive surgical option to treat thoracic spondylotic myelopathy secondary to OLF. Piecemeal inside-out decompression can induce irreversible spinal cord injury, especially in the early experience stages. Outside-in decompression is more efficient and safer than inside-out pattern procedures by minimizing dural manipulation. Nonetheless, this technique is technically demanding and should only be performed in selected patients after acquiring abundant experience with endoscopic spine surgeries.

Keywords: Endoscopy, Stenosis, Laminectomy, Thoracic vertebrae, Stenosis

INTRODUCTION

Thoracic myelopathy caused by ossification of the ligamentum flavum (OLF) is uncommon. Decompression surgery is required in patients with neurological symptoms of thoracic myelopathy. Traditional surgical techniques for the treatment of...
Biportal Endoscopic Thoracic Decompression

Kim JY, et al.

Thoracic OLF include open microscopic laminectomy. However, these techniques are traumatic to the normal structures of the thoracic vertebrae, and posterior instrumentation is necessary in cases of wide laminectomy.\(^1\) Compared to open laminectomy, minimally invasive surgery reduces perioperative morbidity.\(^2\)

Endoscopic spine surgery, including full endoscopy and biportal endoscopy, has evolved from lumbar discectomy to the current treatment of a wide range of degenerative diseases.\(^3-8\) Spinal endoscopic techniques have also been developed to reduce the need for additional instruments.\(^9,10\) Full endoscopic thoracic approaches have been used to treat thoracic stenosis and have shown good surgical outcomes.\(^11-15\) Biportal endoscopic surgery has also been described as a surgical technique to treat cervical and thoracic spondylotic myelopathy.\(^16-18\)

Additional pressure on a compressed spinal cord can induce irreversible neural injury. Therefore, a novel surgical technique that minimizes dural manipulation is necessary to safely remove thoracic OLF. Biportal endoscopic surgery is suitable for this requirement as it can perform delicate procedures intimated with the dura. A small-diameter endoscope can be used to visualize each corner of the spinal canal through a narrow extra space created by precise drilling.

We have developed a biportal endoscopic OLF removal techniques for treating thoracic myelopathy and analyzed the surgical outcomes according to different approaches.

**MATERIALS AND METHODS**

1. **Study Patients**

This prospective study analyzed patients who underwent posterior thoracic laminectomy using a biportal endoscopic system to treat thoracic spondylotic myelopathy due to OLF between January 2020 and December 2021 at 2 spinal centers. A single surgeon with 2 years of experience in biportal endoscopic lumbar spinal surgery performed all procedures. All consecutive patients who met the following inclusion criteria were included in this study.

1. The presence of myelopathy symptoms in the back and legs for more than 6 weeks failing to respond to conservative treatment.
2. Thoracic OLF, with or without spinal cord signal changes, confirmed using magnetic resonance imaging (MRI) and computed tomography (CT).
3. Posterior thoracic OLF removal performed for one or 2 consecutive levels.

Patients were excluded based on following criteria:
1. More than 3 consecutive levels of decompression surgery were necessary.
2. Thoracic OLF was accompanied by segmental instability at the operating level.
3. Thoracic OLF was accompanied by ossification of the posterior longitudinal ligament, involving more than 50% of the spinal canal and prominent disc herniation.
4. A broad extent of dural ossification was identified on the preoperative CT.

2. **Surgical Procedures**

Surgical methods were divided into 3 types: inside-out piece-meal, outside-in en bloc removal as a single flap, and bisection flaps. Inside-out piece meal removal referred to early exposure of the dura after partial laminotomy and flavectomy. Punches and dissectors were inserted into the space between the dura and the OLF to remove the ossified mass. Serial removal of the lamina and ossified flavum was repeated using a piecemeal removal pattern with a drill and punches. Outside-in decompression involved removing the lamina and ligamentum flavum by layer-by-layer drilling to expose the entire contour of the OLF (Fig. 1). The identified OLF was cut using a diamond drill and extracted with an en bloc pattern as a single piece (Fig. 1A-C) or bisected flaps (Fig. 1D-F). The 2 outside-in en bloc removal techniques consisted in the following steps (Supplementary video clip 1).

Patients underwent surgery under general anesthesia in the prone position on a chest bar or a radiolucent Wilson frame. The characteristics of the OLF determined the position of the surgeon. Under image intensification, 2 paramedian skin incisions were made at the medial border of the target-level pedicles to access the spinal canal bilaterally (Fig. 2A). A biportal endoscopic system (4 mm, 0° endoscope), a toolkit set, a customized scope retractor, and a working sheath (MD & Company, Seoul, Korea) were used for the procedure.\(^17,19,20\) The working sheath was essential for the smooth insertion of surgical instruments and drainage of irrigation fluid (Fig. 2B).

The ipsilateral target lamina, upper part of the lower-level lamina, facet joint, and the bilateral interlaminar window were exposed after soft tissue dissection using a radiofrequency probe and forceps. An ipsilateral laminotomy, including the spinous process base, was performed using an endoscopic diamond drill to expose the bilateral interlaminar window (Fig. 2C).

Cranial laminotomy was extended until the proximal end of the OLF was exposed through the space created by sublaminar

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drilling. The cranial end of the laminotomy could be determined by identifying the tip of the superior articular process (SAP) or by confirming the intervertebral foramen under C-arm guidance, as the extended-type OLF is usually located in the foraminal area (Fig. 2C). Subsequently, circumferential bony drilling was performed over the estimated boundary of the OLF, laterally with the bilateral medial facet joints (Fig. 2C, D). The medial region of the SAP should be exposed after the initial bony drilling because the OLF is commonly fused with the SAP. The midline of the ligamentum flavum was removed to divide the ossified mass into bilateral flaps. We confirmed the extent of OLF and dural ossification (Fig. 2E). After identifying the contour of the OLF, the remaining lamina and the bulky OLF were thinned using a diamond drill for easy manipulation during removal. The extended-type OLF commonly presents another bony ossification attached to the isthmic part, which is separated from the capsular OLF region. The extended part of the OLF was removed first and the capsular part was completely exposed (Fig. 2E). The capsular part of the OLF is fused to the SAP and is usually larger than the extended part. The bulky OLF was thinned using layer-by-layer pattern drilling (Fig. 2F). Subsequently, the medial part of the SAP was drilled bilaterally along the lateral dural border, until the epidural space was exposed (Fig. 2F). The secured OLF flap was removed from the bony edge using a fine dissector. The flap was gradually floated from the dura using a fine hook. Epidural dissection was performed safely using fine dissectors while holding the OLF flap with a scope retractor (Fig. 2G). Subsequently, the detached OLF flap was removed en bloc using forceps. A sufficiently decompressed thecal sac with free dural pulsation was also observed (Fig. 2G). The illustrated case shows the successful removal of bilateral OLF at the T11–12 level while preserving the facet joint (Fig. 2H).

If bisection of the ossified mass was difficult, the OLF and ligamentum could be lifted as a single flap (Fig. 1A–C). At this time, more attention should be paid to epidural dissection to prevent dural tear (Supplementary video clip 1).

A foamy hemostatic agent was used to achieve hemostasis of diffuse epidural bleeding. However, we recommend coagulating the epidural vessel if bleeding is noticeable, to prevent sur-
Surgical site hematoma (Fig. 2G). The skin wounds were closed by inserting a drainage catheter through the working portal. Blood loss during surgery was minimal, with a total surgical duration of 80 minutes.

3. Data Collection

1) Collection of clinical data

This study was approved by the Ethics Committee of Wiltse Memorial Hospital (IRB No. 2022-W13). Patient characteristics including sex, age, and symptoms were recorded. The level of

Fig. 2. Surgical steps are described with intraoperative photos and illustrations during the biportal endoscopic posterior thoracic laminectomy at the left T11–12 level. (A) Skin incision sites for the 2 portals on the C-arm image and on the patient's back (bold white line, endoscopic portal; bold yellow line, working portal, white dotted circles: pedicles). (B) Scope retractor and working sheath are essential for spinal cord decompression surgery. The scope retractor is installed outside of the trocar (red arrow). After ipsilateral laminotomy and spinolaminar junction drilling, the bilateral interlaminar space is widely exposed (upper figures). The medial facet joint is drilled to expose the bilateral superior articular process (SAP) and joint cartilages (right lower). Cranial laminotomy is performed until the tip of SAP (left lower) is identified. (D) Initial circumferential laminotomy is performed broadly over the ossification of the ligamentum flavum (OLF). The ossified mass is fixed to the lamina and SAP. The yellow dotted circle shows the margin of circumferential bony drilling. White asterisk: exposed epidural space. (E) If possible, split the midline ligamentum flavum to confirm the bilateral ossified mass and status of the dural compression (upper left). An extended ossified mass is commonly fused with lamina and is located at the cranial to the capsular part of the OLF (shown as red asterisks). This mass is removed first after marginal detachment (right upper and left lower).

(Continued)
Fig. 2. (F) The contour of the capsular ossified mass and the SAP are identified (right lower). The bilateral SAP is drilled along the lateral dural border until it appears as a thin paper (upper: ipsilateral, lower: contralateral). Black asterisk: exposed epidural space. (G) The secured OLF flap is detached and floated at the drilled border (right upper). The scope retractor (red arrowhead) elevates the ossified flap, and an epidural dissection is performed using a blunt hook (right upper). The ossified flap is removed after the epidural dissection is completed (left lower). Sufficiently expanded dura is observed, and the bleeding vessel is coagulated using the radiofrequency probe. Black asterisk: exposed epidural space; yellow asterisk: thick epidural. (H) Images from a 72-year-old woman who presented with symptoms of thoracic myelopathy. Preoperative magnetic resonance imaging (MRI) shows prominent OLF compressing the spinal cord at the T11–12 level (red arrowheads, upper figures). A preoperative axial MRI reveals a decompressed spinal cord at the bilateral spinal canal (left lower). Postoperative computed tomography shows laminectomy extent (right lower). The ipsilateral facet joint is preserved (shown as red asterisks). Blue dotted line: midline. S, superior; I, inferior; CL, contralateral; IL: ipsilateral; LF, ligamentum flavum. (Continued)

operation, operating time, and length of hospital stay, as well as any postoperative complications, were also documented. Physicians collected clinical information before, after and at the final follow-up in the ward and at outpatient departments. Visual analogue scale (VAS) for back and leg and MacNab criteria were used to assess clinical improvement. Neurological results were evaluated using the Japanese Orthopaedic Association (JOA) score.

2) Radiologic evaluations
Preoperative CT and MRI were obtained to analyze dural ossification\(^1\) (Fig. 3) and to categorize the Sato classification.\(^2\) On postoperative day 1, MRI was performed to analyze the suitability of neural decompression and complications. The endoscopic operating video was thoroughly reviewed to observe intraoperative dural ossification (Fig. 3) and to determine the OLF removal pattern. In the video, the procedures that caused spinal cord injury were analyzed. Statistical analyses were performed with SAS 9.4 (SAS Institute Inc., Cary, NC, USA).
RESULTS

We included 16 patients (9 men and 7 women) who underwent posterior thoracic laminectomy using the biportal endoscopic system. The mean age was 60.4 ± 9.7 years (Table 1). The mean duration of follow-up and hospital stays was 17.4 ± 4.4 months and 7.1 ± 2.9 days, respectively (Table 1). The operating levels are listed in Table 1. Eleven patients underwent single-level decompression and 5 underwent 2-consecutive-level operations. The mean operation time per segment was 106.6 ± 38 minutes (Table 1). All included patients had neurological deficits caused by thoracic spondylotic myelopathy, and the most common symptoms were mild sensory loss in the lower extremities and lack of gait stability (Table 1).

The type of OLF was classified using the Sato classification according to the progression of ligamentum flavum ossification. The lateral type refers to the ossification of only the capsular portion of the ligamentum flavum. The extended type refers to the extended ossification of the interlaminar portion. The enlarged type indicates anteromedial thickening and enlargement of the ossification. The fused type refers to fusion of the bilateral ossified masses at the midline. The tuberous type refers to anterior growth of the fused mass of ossification. Three patients had a lateral type; 10 patients had an extended type, 1 had an enlarged type, and 2 had a fused type. The tuberous type was excluded from this study.

Three patients presented a dural ossification “tram tract sign” on the preoperative CT. We analyzed the intraoperative videos and observed 5 cases of dural ossification. Two patients with observed intraoperative dural ossification did not show signs of dural ossification on preoperative CT. We detached the ossified dura from the inner layer of the dura under magnified endoscopic vision but did not observe any dural laceration.

We differentiated the 3 surgical approaches according to the OLF removal pattern. Three patients in the early experience stages underwent OLF removal using the “inside-out piecemeal removal” method. At the middle and late experience stages, “outside-in bisection” and “outside-in single piece” en bloc removal

![Preoperative and postoperative findings of the dural ossification in 2 cases. Case 1 (A-C) presented a symptomatic ossified ligamentum flavum at the T11–12 level. (A, B) Dural ossification (shown by the red arrowheads) was observed on the preoperative computed tomography (CT) and magnetic resonance imaging (MRI). (C) During the operation of this case, the inner layer is preserved (shown by the asterisk) after removing the outer layer of the ossified dura. A second case (D, E) did not present findings of dural ossification on the preoperative CT and MRI. (F) However, during operation, the dural ossification was observed, and the outer layer of ossified dura was peeled off from the inner layer (shown by the asterisk). The dural laceration did not occur due to the delicate working under magnified endoscopic vision.](https://doi.org/10.14245/ns.2346060.030)
techniques were performed in 7 and 6 patients, respectively. Of the 3 patients who underwent the “inside-out piecemeal removal” method, 2 exhibited spinal cord injury (Fig. 4A) and 1 presented insufficient decompression on the postoperative MRI (Fig. 4B). The 2 spinal cord injury patients could not stand alone without help and required a walking tool on the flat floor postoperatively. However, before surgery, they could walk without assistance even though they lacked gait stability. Of these, one patient recovered quickly from the illness and was able to walk without assistance even though they lacked gait stability. Of these, one patient recovered quickly from the illness and was able to walk without assistance; however, the other patient did not recover and needed walking assistance at the final follow-up. The patient with insufficient decompression showed marked improvement of myelopathy symptoms, but complained of persistent pain in the legs and back.

One patient who underwent a 2-level operation showed an asymptomatic subdural hematoma. We recommended 3 days of bed rest to prevent progression of the hematoma and the patient did not present any further neurologic symptoms (Fig. 4C).

One patient showed an epidural hematoma on postoperative MRI and was treated with conservative treatment. An uncontrolled epidural bleeding vessel was observed on the intraoperative video, which might cause the epidural hematoma (Fig. 4D).

Three patients with T2–3 and T3–4 level decompression had spinous process fractures on postoperative CT (Fig. 4E). One patient in the T2–3 level operation had an entirely removed facet joint (Fig. 4F). The upper thoracic vertebrae have smaller facet joints, lamina, and spinous processes. Therefore, preserving the midline bony structures was technically demanding, and excessive facet resection was inevitable for complete OLF removal. However, the patient did not complain of mechanical back pain during the follow-up period. Furthermore, none of the included patients showed any postoperative segmental instability on lateral flexion-extension x-ray images. Infused water-related complications were not observed, such as epidural fluid collection and increased intracranial pressure.

VAS scores for back and leg pain improved significantly after surgery (Table 2). Pain at the operating site was not noticeable.

### Table 1. Patient and surgical data (n = 16)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Sex, male:female</td>
<td>9:7</td>
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<tr>
<td>Age (yr)</td>
<td>60.4 ± 9.7</td>
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<tr>
<td>Follow-up duration (mo)</td>
<td>17.4 ± 4.4</td>
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<tr>
<td>Hospital stays (day)</td>
<td>7.1 ± 2.9</td>
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<tr>
<td>Operating time per segment (min)</td>
<td>106.6 ± 38</td>
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<td>Operating segments (n)</td>
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<tr>
<td>Single level</td>
<td>11</td>
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<tr>
<td>2 Levels</td>
<td>5</td>
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<tr>
<td>Operating levels (n)</td>
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<tr>
<td>T2–3</td>
<td>4</td>
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<td>1</td>
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<td>T8–9</td>
<td>2</td>
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<td>T9–10</td>
<td>3</td>
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<tr>
<td>T10–11</td>
<td>8</td>
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<tr>
<td>T11–12</td>
<td>2</td>
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</table>

### Preoperative neurologic symptoms

Motor dysfunction in lower extremities

- Lack of stability and reciprocation of gait 11
- Walk stairs with handrail 4
- Walk on flat floor with assistant 1

Sensory dysfunction in lower extremities

- Mild sensory loss 15
- Severe sensory loss 1

Sphincter dysfunction

- Minor voiding difficulty 8
- Severe voiding difficulty 1

### OLF type

- Sato classification†, A:B:C:D 3:10:1:2
- Dural ossification sign‡, tram tract sign 3

### Intraoperative video

- Intraoperative dural ossification (n) 5
- OLF removal pattern
  - Inside-out piecemeal 3
  - Outside-in bisection 7
  - Outside-in single piece 6

### Complications

- Spinal cord injury 2
- Insufficient decompression 1
- Excessive facet resection 1
- Operating level subdural hematoma 1
- Epidural hematoma 1
- Delayed spinous process fracture 3

Values are presented as numbers or mean ± standard deviation. OLF, ossification of the ligamentum flavum.

†Sato classification is based on the progression of ligamentum ossification. (A) The lateral type refers to ossification of only the capsular portion of the ligamentum flavum. (B) The extended type indicates the extended ossification of the interlaminar portion. (C) Enlarged type indicates anteromedial thickening and enlargement of ossification. (D) The fused type indicates fusion of the bilateral ossified masses at the midline. (E) The tuberous type refers to the anterior growth of the fused mass of ossification.

‡Preoperative computed tomography images were analyzed to identify dural ossification signs, tram tract sign, and comma sign.

### Table 2. Clinical outcomes

<table>
<thead>
<tr>
<th>Variable</th>
<th>Preoperative</th>
<th>Final follow-up</th>
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<tr>
<td>VAS back pain</td>
<td>5.6 ± 1.2</td>
<td>1.6 ± 0.6</td>
</tr>
<tr>
<td>VAS leg pain</td>
<td>6.3 ± 1.1</td>
<td>1.5 ± 0.6</td>
</tr>
<tr>
<td>JOA score</td>
<td>12.6 ± 1.0</td>
<td>15.6 ± 1.2</td>
</tr>
<tr>
<td>MacNab criteria</td>
<td>Excellent (5), good (10), fair (0), poor (1)</td>
<td></td>
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</tbody>
</table>

Values are presented as numbers or mean ± standard deviation. VAS, visual analogue scale; JOA, Japanese Orthopaedic Association.
Fig. 4. Cases of complications. (A) A 61-year-old woman underwent a biportal endoscopic thoracic laminectomy to remove the bilateral ossification of the ligamentum flavum (OLF). Postoperative magnetic resonance imaging (MRI, right upper) showing the complete removal of OLF, observed on the preoperative computed tomography (CT; left upper). In reviewing the intraoperative video, the punch compressed the dural sac during laminectomy (left lower), and the dissector severely pressed on to the spinal cord during contralateral dissection (right lower). These procedures were performed during the “inside-out piecemeal removal” method (open arrows: force to dural sac, yellow dotted line: compressed dural sac). (B) The postoperative MRI shows the residual ossified mass (red asterisks) at the left side of the T11–12 level (upper figures). Intraoperative photos reveal the residual ossified mass in the approaching side. Blue dotted line: midline. (C) An asymptomatic subdural hematoma is present on the postoperative MRI (red arrowheads). (D) A surgical site epidural hematoma (yellow arrowhead) is observed on the postoperative MRI (left). The intraoperative video reveals the bleeding epidural vein. An uncontrolled bleeding vessel might cause an epidural hematoma. (E) Spinous process fracture was found on the postoperative CT images (red arrows) after the left-side biportal endoscopic thoracic laminectomy at the T2–3 level. (F) The unilateral ossified mass was removed at the left T2–3 level using the biportal endoscopic posterior approach. Postoperative MRI showing the excessive facet resection at the approaching side (yellow asterisk). S, superior; I, inferior; CL, contralateral; IL, ipsilateral.
because of the well-preserved muscle ligament structures. Neurological function of thoracic myelopathy was improved and confirmed with an increase in the JOA score (preoperative JOA score: 12.6 ± 1.0, final follow-up: 15.6 ± 1.2; Table 2). The results of the MacNab criteria showed satisfaction with the surgery (8 excellent, 10 good, 1 poor). The patient with a severe spinal cord injury showed poor response.

**DISCUSSION**

In patients with cervical or thoracic spondylotic myelopathy, the compressed spinal cord is vulnerable to intraoperative injury even with slight pressure exerted by the surgical instruments. If piecemeal removal procedures are used in patients with myelopathy, repetitive insertion of instruments between the dura and the ligamentum flavum can cause irreversible spinal cord injury. In this study, 2 patients who underwent OLF removal using the “inside-out piecemeal removal” method experienced intraoperative spinal cord injuries (Supplementary video clip 2). In reviewing the operating videos, punches repeatedly pressed on the spinal cord during laminectomy and the dissectors pushed onto the dural sac during contralateral sublaminar dissection (Fig. 4A). Furthermore, early dural exposure limited the free use of instruments and may have induced insufficient decompression. One patient who underwent inside-out decompression showed a noticeable residual mass, which prevented the improvement of symptoms (Fig. 4B). Therefore, the surgical techniques commonly used in lumbar decompression surgery may not be suitable for thoracic decompression surgery.

Novel techniques that minimize dural manipulation are necessary for the safe removal of OLF. Recently, Kim et al. described biportal endoscopic en bloc removal techniques for treating cervical spondylotic myelopathy and cervical epidural cysts without complications. The key procedures of this technique include over-the-top decompression using layer-by-layer drilling and en bloc lesion removal; this technique was considered safe and efficient for removing thoracic OLF while minimizing dural manipulation. Full endoscopic surgery has also been used as an en bloc removal technique to treat thoracic OLF and has shown favorable surgical outcomes. In this study, no neurological complications occurred after using the outside-in decompression method.

Before thinning and completing marginal drilling of the OLF, any inserted instruments between the OLF and dura have a high risk of spinal cord compression. It is impossible to completely control the punch not to hit the dura while punching the hard bone (Supplementary video clip 2). Incidental pressing on the dura can induce irreversible spinal cord injury, even if only once. Therefore, we should try to eliminate the risk of spinal cord injury during OLF removal procedures, and outside-in en bloc removal can decrease the chance of spinal cord compression.

Outside-in decompression and en bloc OLF removal can be technically demanding and attention should be paid to critical surgical steps. First, in the initial laminotomy step, the circumferential drilling boundary contains the ossified mass. The cranial and lateral endpoints of bone drilling should be determined prior to bone work. As the capsular part of the ligamentum flavum is ossified, the ossified mass fuses with the SAP. Therefore, the medial aspect of the SAP should be exposed after drilling the facet joint. The SAP can be differentiated from the ossified

![Fig. 5.](https://doi.org/10.14245/ns.2346060.030)
mass by confirming joint cartilage (Fig. 5). If the joint cartilage is not visible during lateral laminotomy, drilling may be directed to the OLF and spinal cord. An ossified mass commonly extends to the neuroforaminal area as the foraminal extended ligamentum flavum becomes ossified (Fig. 2E). Therefore, cranial drilling must be extended to the foraminal level. The foraminal location can be confirmed by identifying the SAP tip (Fig. 2C) or by using an intraoperative x-ray image.

Second, the bulky OLF mass consists of hypertrophied SAP and an ossified ligamentum flavum. A diamond drill can slide along the outer surface layer of the OLF and can be peeled off in a layer-by-layer pattern. The thinned OLF is easy to manipulate and minimizes the risk of additional neural compression during the removal procedure (Fig. 1B, E). The thinned OLF can be cut into the SAP, which is covered by joint cartilage along the lateral border of the dural sac. This cutting location is critical for removing the OLF without any residual ossified mass, and the cutting tract is determined by an imaginary line of the dural lateral edge (Fig. 5).

Third, the half-and-half removal technique may be safer than the single-piece removal method for bilateral nonfused OLF. Smaller halved OLFs offer easier manipulation and reduce the risk of spinal cord compression. However, the midline portion of the OLF is fused to the lamina. Inserting the instruments into the epidural space to halve the ossified mass also exerts pressure on the vulnerable spinal cord. In this case, the single-piece removal technique could be a better surgical option than the half-and-half removal, although a more careful epidural dissection is necessary to prevent dural laceration (Fig. 1). If the OLF is elevated at the lateral border, the contralateral part of the OLF compresses the spinal cord due to the “seesaw phenomenon.” Resected OLF flap should be pulled outward from the medial edge using angled hooks or dissectors (Fig. 2G). Remaining attachments between the OLF and bony structures can induce the “seesaw phenomenon” while manipulating the OLF. Therefore, we should remove the OLF flap after completely detaching it from surrounding bony structures.

Fourth, if the thinned OLF severely adheres to the dura, the endoscope moves more medially to visualize the dissecting plane, and careful dissection is performed between the ossified outer dural layer and intact inner dural layer using the sharp hook or dissectors. This technique should be performed under clear, magnified endoscopic vision to prevent dural laceration. However, in the case of whole-layer dural ossification, the OLF should not be excessively separated from the dura but should be floated and left on the dura.

Two customized surgical instruments and an endoscopic diamond drill were essential for a successful operation (Fig. 2B). The working sheath maintained good saline outflow and kept the epidural water pressure low. A low epidural water pressure allows safer long-time surgery at the thoracic spinal level. The scope retractor was installed on the endoscopic trocar. It acts as a neural tissue protector during bony drilling and retracts the ossified mass while detaching it from the dura.

The upper thoracic vertebrae, such as the cervical vertebrae, have smaller laminae, facet joints, and short spinous processes. Therefore, during the removal of bilateral OLF from the unilateral side of the upper thoracic level, the preservation of the spinal process and the contralateral lamina may be technically more challenging than at the lower thoracic level. In this study, excessive facet resection and delayed spinous process fracture occurred at levels T2–3 and T3–4 levels; however, these complications did not induce noticeable surgical site pain. Biportal endoscopic surgery preserves muscle ligament structures and may maintain segmental stability.

Although this technique has remarkable advantages, biportal endoscopic removal of OLF from the thoracic vertebrae should be considered in selected patients after gaining significant experience with endoscopic spinal surgery. Open surgery with wide laminectomy should be considered first in patients with severe signs of dural ossification and Sato classification of tuberous type on the preoperative CT scan. Continuous high-pressure saline infusion may increase epidural pressure and induce spinal cord injury. The patency of the saline outflow should be monitored carefully and a saline infusion pressure below 30 mmHg is recommended. If incidental durotomy occurs during surgery, the hole should be repaired using a fibrin-sealant patch. However, if the endoscopic repair fails, open microscopic surgery should be performed to achieve complete dural repair. Intraoperative electrophysiological monitoring is necessary to prevent iatrogenic spinal cord during surgery.

CONCLUSION

The biportal endoscopic posterior thoracic approach is an attractive surgical option for treating thoracic spondylotic myelopathy secondary to ossified ligamentum flavum. Inside-out piecemeal decompression in the early experienced stages can induce irreversible spinal cord injury. Outside-in en bloc removal with bisected flaps or single piece is safer than inside-out piecemeal removal because it minimizes dural manipulation. However, this technique is technically demanding and should be per-
formed in selected patients after obtaining significant experience with endoscopic spine surgeries.

**NOTES**

**Supplementary Materials:** Supplementary video clips 1-2 can be found via https://doi.org/10.14245/ns.2346060.030.

**Supplementary video clip 1.** Biportal endoscopic posterior thoracic laminectomy at the left T10–11 level using the “outside-in single-piece removal” technique. SAP, superior articular process; OLF, ossification of the ligamentum flavum.

**Supplementary video clip 2.** Procedures causing spinal cord injury. Biportal endoscopic posterior thoracic laminectomy at the left T10–11 level using the “inside-out piecemeal removal” technique.

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**Author Contribution:** Conceptualization: JYK, JSH, CKL, DCL, SYC, CKP; Data curation: JYK, JSH, HJH; Formal analysis: JYK, JSH, CKL, HJH; Methodology: JYK, JSH, CKL, DCL; Project administration: JS Ha, CKL, DCL, SYC, CKP; Visualization: JY Kim, CKL, SY Choi, CKP; Writing - original draft: JYK, JSH; Writing - review & editing: JYK, JSH, CKL, DCL, HJH, SYC.

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Biportal Endoscopic Thoracic Decompression

Kim JY, et al.


Navigation-Assisted Full-Endoscopic Radiofrequency Rhizotomy Versus Fluoroscopy-Guided Cooled Radiofrequency Ablation for Sacroiliac Joint Pain Treatment: Comparative Study

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Objective: Sacroiliac joint (SIJ) pain is a common cause of chronic low back pain. Full-endoscopic rhizotomy of lateral branches of dorsal rami innervating SIJ is a potential option for patients’ refractory to medical treatment. The full-endoscopic rhizotomy is sometimes challenging under fluoroscopic guidance. This study is to evaluate the effectiveness of the navigation-assisted full-endoscopic rhizotomy for SIJ pain.

Methods: The study was a retrospective match-paired study that enrolled consecutive patients undergoing navigation-assisted full-endoscopic rhizotomy for SIJ pain. The patient demographics, clinical outcomes, and operative parameters of endoscopic rhizotomy were compared with conventional cooled radiofrequency ablation (RFA) treatment.

Results: The study enrolled 72 patients, including 36 patients in the endoscopic group. Thirty-six patients in the cooled RFA group were matched by age as the control. The follow-up time was at least 1 year. Patient characteristics were similar between the groups. The navigation-assisted endoscopic rhizotomy operation time was significantly longer than the cooled RFA. The visual analogue scale (VAS) for pain and Oswestry Disability Index (ODI) significantly decreased after each treatment. However, the between-group comparison revealed that the VAS and ODI of the patients after endoscopic rhizotomy were significantly lower than those after the cooled RFA group. There were no postoperative complications in the study.

Conclusion: Navigation-assisted full-endoscopic rhizotomy is an alternative to SIJ pain treatment. Integrating intraoperative navigation can ensure accurate full-endoscopic rhizotomy to provide better durability of pain relief than the cooled RFA.

Keywords: Endoscopic rhizotomy, Navigation, Sacroiliac joint, Radiofrequency ablation
INTRODUCTION

Sacroiliac joint (SIJ) pain is a common cause of chronic low back pain (CLBP). In about 25% of patients with CLBP, SIJ is the pain generator. The SIJ is a diarthrosis-amphiarthrosis joint between the sacrum and the ilium, which transfers weight from the axial skeleton to the lower extremities. The strong interconnecting ligaments surrounding the SIJ and the tight wedging of the sacrum between hip bones make the SIJ relatively immobile. The SIJ pain may result from capsular and ligamentous tension, hypo- or hypermobility, extrapleural compression, or shearing forces. The etiologies of SIJ injury could be traumatic or atraumatic. Because SIJ dysfunction lacks pathognomonic physical examination or radiographic findings, it is often overlooked and subsequently undertreated. The diagnosis of SIJ pain requires a combination of different modalities, including a comprehensive history and physical examinations. The provocative maneuvers and diagnostic injection are helpful to confirm the diagnosis. The first-line treatment can be analgesics, exercise programs, physical therapy, or chiropractic manipulation.

The interventional treatments are indicated for SIJ refractory to conservative treatment. The common interventions for SIJ pain include extra-articular or intra-articular injections and radiofrequency ablation (RFA) of lateral branch nerves innervating the SIJ. RFA is considered technically demanding, mainly due to variable patterns of SI joint innervation between patients. Besides, the efficacy of RFA for SIJ pain was short-lived in the previous study indicating the pain relapse due to nerve regrowth after lesioning rather than cutting nerve off. Recurrence may occur and require repeated treatment during the long-term follow-up period.

Recently, endoscopic RFA of the SIJ complex has been reported to treat SIJ pain successfully. Under endoscopic visualization, the posterior sacroiliac ligament and its overlying soft tissue were ablated using a bipolar radiofrequency probe through the endoscope’s working channel. Choi et al.13 used the bipolar radiofrequency to ablate the lateral branches of S1, S2, S3, and the L5 dorsal ramus innervating the posterior capsule of the SIJ. The clinical outcome was favorable in the preliminary study. Sometimes, it is challenging to identify anatomical landmarks such as the dorsal sacral foramen by fluoroscopy, especially when the patient had previous fusion surgery with instrumentation.

The computer-assisted navigation systems can provide reconstructed information in 3 dimensions, and surgeons can immediately interpret surgical anatomy on a navigation screen. The authors have reported an innovative technique of using full-endoscopic rhizotomy of SIJ innervation assisted with a navigation system. However, there is a lack of studies regarding the clinical efficacy comparing the innovative technique with the conventional one. In the current study, the authors reported the case series and comparative analysis with the cooled RFA treatment for SIJ pain.

MATERIALS AND METHODS

1. Patient Enrollment

The retrospective study was approved by the Institutional Review Board of Changhua Christian Hospital (No. 220306). The informed consent from all patients was collected before treatment. All the operations were performed by the same surgeon (first author). The authors collected medical records of consecutive patients who underwent the full-endoscopic rhizotomy of the SIJ pain for CLBP between January 2018 and August 2020. The diagnostic criteria included patients presenting CLBP with or without previous spine surgery that lasts more than 6 months refractory to conservative treatment; the pain was located in the area of the SIJ, approximately 1 to 3 cm inferior to the ipsilateral posterior superior iliac spine; the pain triggers at the inferomedial to the posterior superior iliac spine; physical exam shows more than 3 positive out of 6 provocative tests, including distraction, compression, thigh thrust, Gaenslen test, sacral thrust, and the drop test; double ultrasound guided SIJ injections relieved the pain over 50% temporarily. Radiological images were used to exclude other pain generators such as discogenic back pain or facet joint syndrome, and diagnostic blocks were performed for differential diagnosis. Patients with infection, malignancies, or instability were excluded. The age-matched control group was retrospectively collected from the patients undergoing the cooled RFA group in the prospective registry database. The diagnostic and exclusion criteria were the same in both groups, and the follow-up time was at least 1 year.


The patient was placed in a prone position on a radiolucent table in a hybrid operative room equipped with a 3-dimensional (3D) robotic C-arm system (ARTIS pheno, Siemens Healthineers, Erlangen, Germany). Patients were under local anesthe-
sia during all procedures. After sterile preparation and draping of the surgical site, the reference frame was firmly fixed on the skin with 2 layers of iodine-impregnated incision drapes. The robotic C-arm scanned the patient to obtain computed tomography of the surgical site. Intraoperative virtual images of the SI joints were processed and registered automatically into the image-guided surgery platform (BuzzTM Digital O.R., Brainlab, Munich, Germany).

Matching accuracy was confirmed by placing the navigation pointer on the reference frame. After confirming the matching accuracy, registration of a 5-mm obturator with trackers was done by inserting the corresponding size of the calibrating device. The navigation system helped to determine an entry point at the S1 foramen level. Injection of local anesthesia was done. A stab incision with a No.15 blade was made. Integrate the obturator with a working cannula (an inner diameter of 5.4 mm). The integrated obturator-working channel composite was inserted and docked at the lateral edge of the S1 foramen (Fig. 1). After removing the obturator, a 30° spinal endoscope with a 2.8 working channel and an outer diameter of 5.3 mm (Spinendos GmbH, Munich, Germany) was inserted. The endoscopic procedure was done under continuous saline irrigation. A bipolar coagulator (Vantage Biotech Co., Ltd., Taoyuan, Taiwan) was used for both hemostasis and ablation. The concordant pain response can help the surgeon locate the lateral sacral branch by stimulating the bipolar coagulator tip. The endoscopic micro punch can cut the nerve branch. Further ablation of the nerve stumps and surrounding soft tissues helped enhance the durability of rhizotomy (Fig. 2). The surgeon repeated the "cut-and-ablation" procedure at the lateral margin of the sacral foramen until the absence of triggered pain. After rhizotomies of the lateral sacral branch at the S1 level, the working cannula was shifted cranially and docked at the lateral border of the S1 superior articular process. The cut-and-ablation procedure was repeated for rhizotomy of the L5 dorsal ramus. Finally, the lateral branch rhizotomies at the S2 and S3 levels were conducted surrounding the lateral border of the sacral foramen. The pain relief was confirmed by direct compression of the trigger points."18 The wound was closed with a single suture.

3. Surgical Procedures: Cooled RFA

The patient was lying prone on a radiolucent table with a C-arm. Using an anteroposterior fluoroscopic view with tilt cranially (about 20°), the plane of the SI joint, the S1, S2, and S3 sacral

Fig. 1. The constructed intraoperative virtual images of the sacroiliac joints.
foramen were identified. Seven 25-gauge, 3.5-inch Quincke tip needles were inserted toward the lateral base of the S1 superior articular process for the L5 dorsal ramus and 7–10 mm away from the posterior sacral foramen of S1, S2, and S3.11 When the tip of the needle contacts the periosteum, needle position was confirmed by intraoperative fluoroscopy. The cooled radiofrequency probe (COOLIEF, Avanos Medical, Inc., Alpharetta, GA, USA) was inserted through the cannulated needles. The L5 dorsal ramus and the lateral sacral branches of S1–3 were ablated at a temperature of 80 degrees for 3 minutes.21 After removing the needles, the pain relief while pressing the trigger points was the end-point of the intervention.

4. Clinical Assessment
The authors collected patient data prospectively recorded by the clinical research coordinator in the registry database. Operative details such as operation time, blood loss, and complications were included. Visual analogue scale (VAS) score of the back and leg was used to evaluate pain severity. Functional disability was quantified by Oswestry Disability Index (ODI) scores. MacNab criteria were used to group patients according to satisfaction rate. The clinical research coordinator obtained patient-reported outcomes by questionnaire when patients visited the outpatient clinic preoperatively and at 1, 3, 6, and 12 months after the operation.

5. Statistical Analysis
The MedCalc ver. 20.110 (MedCalc Software Ltd., Ostend, Belgium) was the tool for statistical analysis and graphs. After finding out the normal distribution and the variances, the chi-square test, the Mann-Whitney U-test, and the independent t-test was done to compare both groups. Friedman test was done to compare the median values at different times of each group, and p-values below 0.05 were considered significant.

Table 1. Comparison of patients on demographic and procedural characteristics

<table>
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<th>Variable</th>
<th>RFA group (n = 36)</th>
<th>Endoscope group (n = 36)</th>
<th>p-value</th>
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<tr>
<td>Age</td>
<td>63.69 ± 2.42</td>
<td>62.27 ± 2.37</td>
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<tr>
<td>Sex</td>
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<td></td>
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<tr>
<td>Male</td>
<td>8 (22.2)</td>
<td>13 (36.1)</td>
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<tr>
<td>Female</td>
<td>28 (77.8)</td>
<td>23 (63.9)</td>
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<tr>
<td>Height (cm)</td>
<td>157.43 ± 1.32</td>
<td>158.54 ± 1.42</td>
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<tr>
<td>Weight (kg)</td>
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<td>63.92 ± 1.99</td>
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<td>BMI (kg/m²)</td>
<td>26.7 ± 4.34</td>
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<td>Alcohol</td>
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<td>Unilateral LBP</td>
<td>15 (42)</td>
<td>18 (49)</td>
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<tr>
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<td>20 (56)</td>
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<tr>
<td>Coccyx pain</td>
<td>1 (3)</td>
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<tr>
<td>Previous spine surgery</td>
<td>14 (38.9)</td>
<td>19 (54.2)</td>
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<td>Operation time (min)</td>
<td>39.08 ± 14.05</td>
<td>61.75 ± 23.55</td>
<td>&lt;0.001*</td>
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<tr>
<td>Opioid use</td>
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</tr>
<tr>
<td>Before</td>
<td>8 (22.2)</td>
<td>4 (11.1)</td>
<td>0.209</td>
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<tr>
<td>After</td>
<td>6 (16.7)</td>
<td>4 (11.1)</td>
<td>0.499</td>
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</tbody>
</table>

Values are presented as number (%) or mean ± standard deviation. RFA, radiofrequency ablation; BMI, body mass index; LBP, low back pain.

RESULTS
There were 40 consecutive patients undergoing the full-endoscopic rhizotomy between January 2018 and Aug 2020. Four patients did not have complete 1-year follow-ups and were excluded. The control group comprised patients undergoing cooled RF ablation for S1J pain. By matching age, 36 patients were enrolled in the cooled RF group. As for clinical presentation, most...
patients had unilateral or bilateral CLBP, except one patient in each group presenting coccyx pain. 46% of patients (33 of 72) had previous spinal surgery before SI joint pain. The demographic data of patients between the groups were similar (Table 1). No patients encountered intraoperative or postoperative complications such as infections, hematoma, and neurologic impairment in the study. The navigation-assisted endoscopic rhizotomy operation time was significantly longer than cooled RFA (Table 2). The VAS of low back pain was significantly higher in the endoscopic group. (RFA group: 6.28 ± 1.28, Endoscope group: 7.25 ± 1.66; p < 0.05)

After the operation, both groups showed statistically significant decreases in VAS of low back pain and ODI (p < 0.001). The improvement of SIJ pain and functional disability remained for the postoperative 1 year (Tables 3, 4). The full-endoscopic rhizotomy assisted with navigation was superior to cooled RFA regarding VAS reduction amplitude according to the between-group comparison at all follow-up times. The ODI scores at 1, 6, and 12 months were statistically significantly lower in the endoscopic group. During the 1-year follow-up, there was an upward trend of VAS and ODI in the cooled RFA group (Fig. 3). The Macnab criteria showed “excellent” in 86% and “good” in 11% of patients in the endoscopic group. On the contrary, the patients in the cooled RFA group reported “excellent” in 39% and “good” in 28% of patients (Fig. 4). Patients undergoing full-endoscopic rhizotomy assisted with navigation had a higher satisfaction at 1-year follow-up (Table 4).
Our mission is to find those pain generators to per...Therefore, the current series is essential to verify the roles of the new technologies.

The RFA has been an effective and standard treatment for SIJ pain. Ibrahim et al.\(^\text{21}\) reported favorable outcomes regarding pain relief and functional improvement for up to 2 years. However, the classic RFA technique used fluoroscopic guidance rather than the CT-based navigation system. Besides, their technique included the ablation of L4–5 and L5–S1 medial branches, which were not innervating the SIJ complex. According to cadaveric research, the SIJ is mainly innervated by the lateral branch of the L5 dorsal rami, S1, S2, and S3.\(^\text{11,17,23}\) Therefore, the current series omitted the ablation or rhizotomy of medial branches of L4–5 and L5–S1 dorsal rami. Simplified procedures can be efficient without compromising results.

There have been various RFA techniques for treating SIJ pain (3 puncture method, strip lesion, and leapfrog technique).\(^\text{24}\) Besides, 3 types of RFA have been applied for different purposes or target nerves, including pulsed, thermal, and cooled RFA.\(^\text{24-27}\) It is still being discussed which one has better efficacy over the others in treating SIJ pain. Shih et al.\(^\text{26}\) claimed that there were no statistically significant differences between different types of RFA in their study. Although RFA significantly improves SI joint pain, the efficacy of RFA decreases with pain relapse. Some researchers hypothesized that the recurrence of pain resulted from nerve regeneration after lesioning.\(^\text{12,24,26,27}\) Our results of the control group undergoing the RFA procedure also revealed similar trends. The pain and the functional disability relapsed gradually after 6 months to 12 months. Therefore, the authors emphasized the rhizotomy rather than ablation to resolve the SIJ pain.

The lateral branches of the nerve roots might be smaller in diameter when they are away from the sacral foramen. Therefore, we recommend docking the endoscope as close as possible to the sacral foramen to identify the nerve branches. When nerve branches cannot be found surrounding the sacral foramen, ablation with a bipolar tip along the lateral border of the foramen is an alternative.

The endoscope development allows us to visualize sensory nerve fibers with a diameter between 0.21 to 1.51 mm.\(^\text{28}\) The endoscopic procedure allows us to achieve maximum effect from the procedure, precisely targeting the L5 dorsal rami and lateral sacral branches from S1, S2, and S3 dorsal rami.\(^\text{13,22}\) In our study, the VAS score was significantly higher in the endoscopic group. However, the difference in pain severity did not reduce the efficacy and durability of the endoscopic rhizotomy. Most of the patients who have received the endoscopic treatment did not experience the recurrence of pain over one year. Only 8% (3 out of 36) of patients in the endoscopic group experienced the recurrence as opposed to a 61% of recurrence rate after 1 year from RFA. Besides, the patient-reported satisfactory results also favored endoscopic treatment. More than 90% of the patients undergoing the endoscopic rhizotomy reported excellent or good satisfaction in the current study.

The CT-based navigation system can improve the accuracy and safety of image-guided procedures. The benefits are not only for patients but also for the surgical team. The innervation pattern of the L5 dorsal rami and the lateral sacral branches from S1, S2, and S3 dorsal rami are unique and various in each individual.\(^\text{13,20}\) Our mission is to find those pain generators to perform the “cut-and-ablation” procedures at the pararapinal area until the triggered pain decreases.\(^\text{17}\) The conventional C-
arm fluoroscopy is often insufficient to visualize the sacral foramen. 3D robotic C-arm navigation system lets us identify the foramen quickly. Anatomical landmarks such as L5, S1, S2, and S3 foramina were visualized on the constructed intraoperative virtual images of the SI joints. Surgeons can check the orientation and localization of the target immediately without interruption by adjusting the fluoroscopic device. Besides, radiation exposure due to C-arm fluoroscopy is a critical issue for the health of medical staff. Before and during the procedure, all surgical team members were free from radiation exposure during navigation-assisted procedures. The surgical team members can also work with better ergonomics without wearing a lead apron.

The navigation-assisted endoscopic procedure took longer operation time compared to the RFA procedure in the current study. Though the average operation time in the navigation-assisted endoscopic procedure was 61.8 minutes, the time can be decreased to about 30 minutes in the unilateral SIJ procedure when familiar with the registration and integration of the navigation system. Besides, to conduct a rhizotomy, it is necessary to visualize the nerve branches with the endoscope. The nerve branches are often hidden between the soft tissues and the ligaments. Therefore, exploring the surgical field to find the nerve branches may cost time. Because patients were awake throughout the procedure, the surgeon can also use the bipolar coagulator to trigger the symptom to identify the pain generators. It is safer to monitor patients' intraoperative response. If the patients complain of excessive or radiating pain, the surgeon can hold on to the procedure and re-evaluate the surgical orientation. Estimated blood loss was minimal in the percutaneous procedures. The ambulatory surgery setting also avoided anesthetic risks. Therefore, no complications were noted, such as hematoma, motor nerve injury, or wound infections in the endoscopic procedures.

The current study supported that patients with failure after conservative treatment and relapsed symptoms after repeated SI joint injections are candidates for navigation-guided full-endoscopic rhizotomy. However, the navigation system might only be available in some hospitals. Fluoroscopy-assisted surgery can be an alternative imaging modality. From our experience, the ambulatory surgery setting enhances the application of the current technique. Patients with multiple comorbidities who cannot take general anesthesia for SI joint fusion or failure of previous RF ablation can benefit from the novel surgical treatment.

There were some limitations in the current study. First, this is a retrospective study with a small number of patients. Second, patients had diverse reasons for SI joint pain that other variables could confound. Third, most medical institutes do not offer a hybrid operation room or computer-assisted navigation system. Fourth, the imaging modalities were different between the group. The manipulated variables may affect perioperative parameters, such as surgical time. However, the bias resulting from the different imaging guidance was minor for the outcomes due to their assistant role. Finally, this is a pilot study for the current technique. Further prospective randomized studies or cohorts with long-term follow-ups are necessary to evaluate the applications of new techniques and technologies for SIJ pain.

**CONCLUSION**

The preliminary study indicates that navigation-assisted full-endoscopic rhizotomy is a feasible and effective alternative for SIJ pain treatment. Integrating intraoperative navigation with the endoscopic system ensures safe and accurate lesioning of target nerves without entering the foramen. The cohort of the current series proved the better durability of endoscopic rhizotomy compared with conventional RFA. Though long-term follow-up and randomized trials are necessary to confirm the superiority of the current endoscopic technique, it remains a potential to lead the trend of ambulatory surgery for SIJ pain treatment.

**NOTES**

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A Modified Endoscopic Access for Lumbar Foraminal Pathologies; Posterolateral “Intertransverse” Endoscopic Approach to Minimize Postoperative Dysesthesia Following Transforaminal Approach

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Objective: To present an innovative, modified endoscopic approach for foraminal/extraforaminal pathologies, to reduce postoperative dysesthesia (POD) following the conventional transforaminal endoscopic approach (the access angle more than 45° from the midline), since POD is one of the major documented disadvantages that may compromise patient satisfaction.

Methods: We introduce a modified posterolateral technique, termed the intertransverse approach, utilizing a steeper access angle less than 25° through the intertransversarii muscle and the intertransverse space with expanding Kambin triangle via lateral facetectomy/foraminoplasty, to reduce dorsal root ganglion/exiting nerve root irritation under direct visualization and lower the incidence of POD. Consecutive patients undergoing endoscopic spine surgery via the intertransverse approach for foraminal and/or extraforaminal disc herniations or bony stenosis were retrospectively reviewed. Clinical outcomes were reviewed with the primary outcome being POD.

Results: Twenty-two patients were included in the review. Patients showed significantly improved clinical outcomes (visual analogue scale leg and back pain and Oswestry Disability Index) postoperatively. There was a low rate of dorsal root ganglion (DRG)-related POD (9.1%, 2 of 22) that was minimal and resolved soon.

Conclusion: The inter-transverse endoscopic approach is feasible for lumbosacral foraminal and extraforaminal decompression with significantly improved clinical outcomes and the added advantage of a low rate of DRG-related POD compared to traditionally reported rates in the literature for the conventional transforaminal approach.

Keywords: Endoscopic lumbar discectomy, Decompression, Transforaminal approach, Intertransverse approach, Postoperative dysesthesia, Dysesthetic pain

INTRODUCTION

Full endoscopic lumbar discectomy is an established minimally invasive surgical technique providing adequate access and excellent visualization of lower lumbar herniated discs while causing less soft tissue trauma than traditional open discectomies with favorable outcomes compared to open discectomies. Conventional mainstay approaches for full endoscopic lumbar discectomy include the transforaminal and interlaminar approaches. The transforaminal approach, which is the most traditional endoscopic approach for lumbar disc herniations, allows for decompression of extraforaminal, foraminal, and lateral re-
cess pathologies. However, a transformational approach utilizes access through Kambin triangle, which is close to the nerve root and dorsal root ganglion (DRG).

One main disadvantage of the transforaminal approach includes postoperative dysesthesia (POD), with a reported incidence in the literature ranging from 9.3% to 26%.\(^1\) The cause of POD is still unclear but is thought to be a result of nerve root or DRG irritation from the endoscopic working sleeve.

We herein present a modification of the transforaminal approach to address foraminal and some extraforaminal pathologies, termed the ‘intertransverse approach’ with an advantage of decreased exiting nerve root and/or DRG irritation and easier access to the foraminal and extraforaminal area compared with the conventional transforaminal approach.

**MATERIALS AND METHODS**

Consecutive patients undergoing endoscopic spine surgery that included the intertransverse approach were retrospectively reviewed from March 2021 to August 2022. The study was approved by the Institutional Review Board (IRB) of Johns Hopkins University (IRB No. 00135145) with a waiver of patient consent. The inclusion criteria were foraminal and/or extraforaminal disc herniations or bony stenosis causing exiting nerve root compression and compatible radiculopathy. We excluded spondylolisthesis, history of prior lumbar surgeries, patients with spinal deformity, infection, trauma, or neoplastic disease processes. We also excluded patients who underwent a concomitant intertransverse and ipsilateral transforaminal approaches as it would be difficult to identify the cause of any POD. Demographics, perioperative and outcomes data were collected by query of our electronic medical record database. A total of 22 patients were included in the study cohort. Outcomes collected were age, sex, body mass index (BMI), operative time, length of stay, Oswestry Disability Index (ODI) and visual analogue scale (VAS) back and leg pain scores preoperatively, at 2–4 weeks, 6 weeks, 3 months, 6 months, 1 year, and at last follow-up. In addition, the incidence of POD and perioperative complications including reoperation during the follow-up period were collected.

POD was defined whenever there was pain which is different than the preoperative symptoms, uncomfortable sensation that could be described as burning, icy-hot, prickly, itchy-prickly, and intensely creepy-crawly at a proper DRG innervated region, as previously defined and used in the literature.\(^3\)

Continuous variables were expressed as mean ± standard deviation or as median with range. Categorical variables were expressed as frequencies and percentages. Continuous outcomes were compared with the t-test for means. Significance was set at 0.05. Statistical Analysis was performed using Microsoft Excel v16.65 (Microsoft, Redmond, WA, USA).

1. **Surgical Technique**

1) **Positioning of the patient and preparation**

Under general anesthesia, the patient is positioned prone over a radiolucent operative table. Electromyographic neuromonitoring is optional. The lumbar area is prepped and draped in a sterile fashion and a C-arm is positioned such that true anteroposterior (AP), lateral and 25° oblique views are available.

2) **Entry portal and trajectory angle**

On the AP view, the entry is located at the line connecting the tips of transverse processes above and below, and a line parallel to the intervertebral disc space (Fig. 1A). The entry point is located over the lateral aspect of the superior articular process on a 25° oblique view (Fig. 1B). Usually, the portal is located about 5–7 cm from the midline and at a 15°–25° angle from the vertical line (Fig. 2A, B). A 7-mm-sized transverse skin incision is made over the entry point. A discography needle is advanced until the tip of the needle touches the lateral aspect of the facet joint. Then a 6-mm obturator is placed after sequential dilation on a guide wire. Finally, a beveled working cannula is placed over the obturator, positioning the bevel towards the medial side (Fig. 3A, B).

![Fig. 1. Intraoperative fluoroscopic anteroposterior (A) and oblique (B) views show the location of the portal. (A) The entry is on the crossing point between the vertical line connecting the lateral borders of transverse processes and the intervertebral disc space. (B) On a 25° oblique view, the entry is over the lateral aspect of the facet joint and the disc space.](https://doi.org/10.14245/ns.2346076.038)
3) Lateral facetectomy/foraminoplasty; expanding the medial aspect of Kambin triangle

A 7-mm interlaminar spinal endoscope is introduced and the water inflow is opened. The posterolateral aspect of the facet capsule and attachment of longissimus muscle at the lateral aspect of the facet are dissected with a radiofrequency (RF) tip (Fig. 4A). Using a 3.5-mm endoscopic burr, the lateral aspect of the facet is drilled (i.e., superior articular process of the lower vertebra) to expand Kambin triangle. In cases with bony foraminal stenosis, the lateral aspect of the superior articular process is resected including the tip of superior articular process until the facet joint is exposed (i.e., lateral facetectomy). For soft disc herniation cases, the lateral aspect of the superior articular process is drilled to expand Kambin triangle without resection to the facet joint (i.e., foraminoplasty). The depth of drilling is usually 3–5 mm (1 to 1.5 times of drill diameter) but may vary depends on the hypertrophy of superior articular process (Fig. 4B, C).

4) Exposure of posterolateral annulus and exiting nerve root

Gradually, the beveled working cannula is advanced through the expanded Kambin triangle, until the posterolateral annulus is visible. Before exposing the annulus, the lateral facet capsule, foraminal ligament and intertransverse membrane are resected and shrunken using the RF tip. To make identification of the location of the disc or ruptured disc fragment easier, injection of diluted methylene blue in the disc space could be considered. The working cannula is still not touching the DRG or exiting nerve root. After cleaning the soft tissues at the foramen and extraforaminal area using an RF tip, the caudal aspect of DRG/...
exiting nerve root can be visualized without any root retraction or compression (Fig. 4D).

5) **Discectomy and/or foraminotomy**

After exposure of the posterolateral annulus, discectomy or additional foraminotomy is doable with variable sized endoscopic instruments, including pituitary rongeurs, Kerrison rongeurs and osteotomes. The additional foraminotomy can be performed for any ventral bony spurs arising from the endplates or the ventral aspect of the superior articular process which can cause compression of the exiting nerve root. After completion of the foraminal discectomy, exploration of the foramen, area under the exiting nerve root and lateral recess is possible by changing the angle of the working cannula (Figs. 5–7).

**RESULTS**

Twenty-two patients (12 men, 10 women) with a mean age of 62 ± 10 and mean BMI of 30.4 ± 6.0 kg/m² underwent endoscopic surgery that included the intertransverse approach. Indications for the intertransverse approach were foraminal/extraforaminal disc herniation in 14 patients (64%), bony foraminal...
stenosis in 4 patients (18%), and concomitant disc herniation and bony foraminal stenosis in 4 patients (18%). Twelve patients underwent stand-alone intertransverse approach (55%), with 10 cases involving single level and 2 cases involving 2 levels. The other 10 patients (45%) underwent a combination of intertransverse approach and concomitant interlaminar approach for a different level with intraspinal disc herniation or stenosis. The most common levels for the intertransverse approach in descending order are L4/5 (54%, n = 14/26), L3/4 (27%; n = 7/26), L2/3 (12%; n = 3/26), and L5/S1 (8%; n = 2/26).

Median operative time was 154 minutes (range, 59–286 minutes), and median operative time per level or approach was 82 minutes (range 59–129 minutes). Mean length of stay was 0.5 day ± 0.6.

### Table 1. Demographic and perioperative data

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>62 ± 10</td>
</tr>
<tr>
<td>Male sex</td>
<td>12/22 (55)</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>30 ± 6.0</td>
</tr>
<tr>
<td>Indication</td>
<td></td>
</tr>
<tr>
<td>Foraminal/extraforaminal disc herniation</td>
<td>14/22 (64)</td>
</tr>
<tr>
<td>Bony foraminal stenosis</td>
<td>4/22 (18)</td>
</tr>
<tr>
<td>Both</td>
<td>4/22 (18)</td>
</tr>
<tr>
<td>Intertransverse approach level</td>
<td></td>
</tr>
<tr>
<td>L2/3</td>
<td>3/26 (12)</td>
</tr>
<tr>
<td>L3/4</td>
<td>7/26 (27)</td>
</tr>
<tr>
<td>L4/5</td>
<td>14/26 (54)</td>
</tr>
<tr>
<td>L5/S1</td>
<td>2/26 (8)</td>
</tr>
<tr>
<td>Operative time (min)</td>
<td>154 (59–286)</td>
</tr>
<tr>
<td>Operative time/level (min)</td>
<td>82 (59–129)</td>
</tr>
<tr>
<td>Length of stay (day)</td>
<td>0.5 ± 0.6</td>
</tr>
</tbody>
</table>

Values are presented as or number (%), mean ± standard deviation, or median (range).

![Fig. 6. Foraminal stenosis at L3/4 with right sided decompression using an intertransverse approach. The red circle outlines the L4/5 right facet joint on the model for orientation. (A) Lateral facetectomy demonstrates the entry of the foramen at the disc level, lateral facet capsule and intertransverse membrane. (B) After removal of the intertransverse membrane and facet capsule the exiting nerve root can be visualized. (C) More foraminal decompression was achieved with drilling of the tip of the superior articular process, pars, and ligamentum flavum at the lateral recess.](image)

![Fig. 7. The preoperative (A, B) and the postoperative computed tomography (C, D) images of the patient in Fig. 6. The foraminal stenosis from osteophytes and disc was decompressed on both axial (C) and sagittal (D) images as seen in the area outlined in red (the target foramen).](image)
Modified Endoscopic Access to Minimize Postoperative Dysesthesia

Musharbash FN, et al.

A new technique from the transforaminal approach to reduce DRG/exiting nerve root irritation and lower the incidence of POD has been introduced. In this study, we modified the transforaminal approach via targeting the upper part of the pedicle of the lower lumbar vertebra and retracted the exiting nerve root towards the cranial part of the foramen to access the lateral recess.

During a transforaminal access to the epidural space, the working cannula in Kambin triangle can compress, irritate or injure the DRG or exiting nerve root sheath during the endoscopic procedure. Unlike the central and peripheral nervous systems which are protected by blood-brain and blood-nerve barriers respectively, the DRG lacks such a protective barrier. As such, it is more susceptible to the inflammatory mechanisms. Irritation of the DRG can lead to POD, which manifests as either spontaneous or evoked burning pain at a proper DRG innervated region, without motor weakness which differentiates it from nerve root injury.

The reported incidence is highly variable from 9.3% to 29%, but generally it is considered to be underreported given the lack of established diagnosis criteria. Several prior studies reported on the incidence of DRG-related dysesthesia after transforaminal approach. Lewandrowski et al. reported 451 consecutive patients undergoing transforaminal endoscopic decompression and found an incidence of 21.5% of dyesthetic leg pain which they report typically developed 5 to 10 days postsurgically, occurred at the same frequency in the different lumbar levels and without a predilection to 1- versus 2-level cases. The same author also showed that DRG-related dysesthesia leads to delayed return to work by a mean of almost 19 days. Kim et al. compared patients who underwent transforaminal foraminalotomy and disectomy with patients who underwent contralateral interlaminar foraminalotomy and disectomy and found a significant difference between the incidence of postoperative dysesthesias, with 26% in the transforaminal group compared to 14% in the contralateral interlaminar group.

Because of this well-known complication following conventional transforaminal approaches, there has been an effort to minimize the incidence of POD with modified transforaminal approaches in the literature. Cho et al. reported a ‘floating retraction technique’ specifically aimed at reducing postoperative DRG-related dyesthesia with good outcomes. They modified the transforaminal approach via targeting the upper part of the pedicle of the lower lumbar vertebra and retracted the exiting nerve root towards the cranial part of the foramen to access the lateral recess.

Although a conventional transforaminal approach could provide a good access to the lateral recess and epidural space either with inside-out or outside-in technique, direct visualization of the exiting nerve root and DRG at the foraminal/extraforaminal area could be limited because the working cannula is located through Kambin triangle.

There have been reports on posterolateral approaches to foraminal and extraforaminal pathologies in the literature with favorable outcomes. However, the access angles were about 45°–60° from the midline, which is similar to conventional transforaminal approaches. In this study, we introduced a modified technique from the transforaminal approach to reduce DRG/exiting nerve root irritation and lower the incidence of postoperative dyesthetic pain with better access to the foraminal and extraforaminal area. To accomplish that, we utilized a steeper access angle less than 25°, with the endoscopic portal being about 5–6 cm from the midline. Expansion of Kambin

The mean VAS leg pain score was as follows: preoperative, 6.9 ± 2.0; at 2–4 weeks, 2.3 ± 3.1; at 6 weeks, 3.0 ± 3.2; at 3 months, 1.6 ± 2.1; at 6 months, 1.9 ± 2.1; at 1 year, 2.0 ± 3.4; and at last follow-up, 2.0 ± 2.8 (p < 0.001, preoperative vs. at last follow-up).

The mean VAS back pain score was as follows: preoperative, 4.1 ± 3.5; at 2–4 weeks, 1.4 ± 3.1; at 6 weeks, 3.6 ± 2.9; at 3 months, 2.0 ± 2.5; at 6 months, 2.6 ± 2.3; at 1 year, 2.4 ± 2.4; and at last follow-up, 1.5 ± 2.0 (p < 0.01, preoperative vs. at last follow-up).

The mean ODI was as follows: preoperative, 42.7 ± 20; at 2–4 weeks, 12 ± 7.3; at 6 weeks, 19 ± 11; at 3 months, 4.7 ± 3.1; at 6 months, 3 ± 4.2; at 1 year, 12 ± 2.8; at last follow-up, 11 ± 8.2 (p < 0.01 preoperative vs. at last follow-up). Mean time to last follow-up was 4.5 ± 5.1 months.

POD occurred in 2 cases (9.1%). One in a patient who underwent a left sided L4/5 discectomy for a foraminal herniated disc using an intertransverse approach. The patient reported new onset “nerve pain” radiating down her left lower leg that began 4 days postoperatively and was associated with mild numbness in her left lateral calf. Her symptoms resolved after 2–3 weeks. The other was in a patient who underwent a right sided L3/4 discectomy for a foraminal herniated disc using an intertransverse approach, the patient had burning medial thigh dyesthestic pain that began 3–4 days after surgery that was very mild and did not require any additional medication or other treatment and resolved in 4–5 weeks.

DISCUSSION

Although conventional transforaminal endoscopic discectomy has demonstrated favorable clinical outcomes in the literature for the management of foraminal/extraforaminal disc herniations as well as paracentral disc herniations, the POD is not an uncommon complication that compromises patients’ satisfaction. This POD has been frequently reported in the literature with inside-out or outside-in technique, direct visualization of the exiting nerve root and DRG at the foraminal/extraforaminal pathologies. With POD occurring in 2–3% of patients undergoing transforaminal endoscopic discectomy with patients who underwent contralateral interlaminar foraminalotomy and discectomy and found a significant different between the incidence of postoperative dysesthesias, with 26% in the transforaminal group compared to 14% in the contralateral interlaminar group.

Because of this well-known complication following conventional transforaminal approaches, there has been an effort to minimize the incidence of POD with modified transforaminal approaches in the literature. Cho et al. reported a ‘floating retraction technique’ specifically aimed at reducing postoperative DRG-related dyesthesia with good outcomes. They modified the transforaminal approach via targeting the upper part of the pedicle of the lower lumbar vertebra and retracted the exiting nerve root towards the cranial part of the foramen to access the lateral recess.

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triangle could provide wide exposure of the DRG and exiting nerve root as well as the foraminal-extraforaminal area. Detailed exploration of the foramen for remaining soft disc herniation was possible with variable endoscopic hooks or dissectors and removal of osteophyte is doable using endoscopic burrs or osteotomes.

We termed this approach as “intertransverse” since the access is through intertransversarii muscle and the intertransverse space unlike a conventional transforaminal approach, which is through the quadratus lumborum muscle, lateral to the tip of the transverse process. The docking point of obturator and working cannula of intertransverse approach is at the posterolateral aspect of the facet, which is different than that of a transforaminal approach which is usually at the distal foramen under the transverse process (Fig. 2).

In our case series, patients had significantly improved clinical outcomes postoperatively but more importantly had a relatively low rate of POD (9.1%) compared to the literature regarding the transforaminal approach.1–7 We postulate that the dysesthetic pain could be avoided because of better visualization of the DRG and exiting nerve root from the posterior aspect like in an interlaminar approach, without contacting or irritation by the working cannula. It was unclear if the POD experienced by the 2 patients in our series were due to irritation of DRG by the procedure or due to postdecompression symptom that can also be seen similarly to open decompression surgeries. However, the intensity and duration were relatively mild and not disabling in nature. The disadvantages of the author’s technique should be less extent of access to the central part of the epidural space, unlike a conventional transforaminal approach because of the steeper access angle. The authors generally prefer an interlaminar approach for centrally located disc herniations to avoid the risk of dysesthetic pain from passing the working cannula through the foramen. But in most cases, lateral recess could be visible and disc fragment can be removed if it is not located too far centrally.

Limitations of this study include its retrospective nature. In addition, the presence of concomitant interlaminar approaches along with the intertransverse approach for different levels or sides further complicated the analysis of patient symptoms. However, in those patients who had postoperative pain, we were able to generally correlate the patient’s symptoms with the side or level of the approach to ascertain whether this constituted a DRG-related dysesthetic symptom. Thirdly, while the incidence of POD was low in our series relative to literature figures, we were unable to compare this in statistical fashion. Future work could compare a cohort of patients with stand-alone intertransverse approach versus stand-alone transforaminal approach.

CONCLUSION

The intertransverse endoscopic approach is feasible for lumbar-sacral foraminal and extraforaminal decompression with improved clinical outcomes and the added advantage of a low rate of DRG-related postoperative dyesthetic pain.

NOTES

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Author Contribution: Conceptualization: SHL; Data curation: FNM, SHL; Formal analysis: FNM; Methodology: FNM; Project administration: SHL; Visualization: SHL; Writing - original draft: FNM, SHL; Writing - review & editing: FNM, SHL.

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Looking Back on 2022 With Neurospine

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On behalf of the editorial office of Neurospine, we would like to extend our appreciation to all the readers who have supported the journal throughout the year. Neurospine was established in March 2018 through a collaboration of 3 leading spinal neurosurgery societies from Japan, Korea, and Taiwan. Since then, Neurospine has continued to enhance its academic impact, serving as a platform for sharing knowledge and information related to the management of spinal diseases. In this article, we aim to present the bibliometrics of Neurospine, including the submission and publication of manuscripts and the peer review process. We are looking forward to continued growth and serving the academic community to the best of our ability.

Keywords: Journal article, Journal impact factor, Peer review

INTRODUCTION

It has been another great year for Neurospine. We extend our heartfelt gratitude to all those who have contributed to its growth and development. We acknowledge the crucial role played by the editorial board, reviewers, staff, and readers, who have enabled us to serve as a platform for sharing knowledge and information related to spinal disease management. With all your help, the peer-reviewed articles published in Neurospine have provided a valuable resource for spine clinicians and researchers. As we reflect on Neurospine’s progress in 2022, we are reminded of the progress we have made and the opportunities that lie ahead for future growth.

HISTORY OF NEUROSPINE

Neurospine is an international, peer-reviewed, open-access journal that is published quarterly on the last day of March, June, September, and December. It was first established on March 31, 2004 under the name Korean Journal of Spine, and underwent a transformation in 2017 with the collaboration of 3 leading spinal neurosurgery societies from Japan, Korea, and Taiwan, during Asia Spine. Professor Ha Yoon was appointed as the editor-in-chief with the goal of establishing Neurospine as an international journal. He was supported by deputy editors Shih-Huang Tai and Makoto Taniguchi, Associate Editor Seung-Jae Hyun, and 32 editorial board members from around the world. An advisory board was also established, comprising leading journal editors, world spine society leaders, leaders of the 3 societies (Japan, Taiwan, and Korea), and former editors of the Korean Journal of Spine. The first issue of Neurospine was published in March 2018 and, as of the end of 2021, the journal had received 1,495 submissions and published 431 documents. Neurospine is indexed/tracked/covered by a number of databases, including Science Citation Index Expanded, PubMed, PubMed Central, Scopus, Directory of Open Access Journals, KoreaMed, KoMCI, EBSCO host, and Google Scholar. The annual Neurospine symposium, which was temporarily suspended due to corona-
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virus disease 2019, has resumed with the aim of strengthening
the capabilities of the editorial board and reviewers, and discuss-
ing the development of an efficient review system.

EDITORIAL DECISIONS

In 2022, a total of 545 papers were submitted to Neurospine. The submitted papers were analyzed by country, and the top 5 countries in order of submissions were China, the United States, Korea, Türkiye, and Japan (Fig. 1). As of the time of writing, 523 of the submissions have received a decision, with the remaining 22 still in processing. The submitted papers were initially evaluated by the editorial board, led by the editor-in-chief, and 64.4% (351 papers) were ultimately rejected. The remaining 35.6% (194 papers) were deemed to have relatively high academic value and underwent an additional peer review process. The editor-in-chief analyzed each paper and selected the appropriate editor, considering the unique characteristics of each submitted paper. The selected editor then chose peer reviewers from a specialty-based review board, taking care to avoid any conflicts of interest. Reviewers were sent an email containing the abstract of the paper in a blinded format and had up to 7 days to decide whether to accept the review.

REVIEWER INVITATION

A total of 801 review invitations were sent, and 546 (68.2%) were accepted. Of those, 70 invitations (8.7%) were declined, and 185 invitations (23.1%) did not receive a response. The acceptance rates varied by country, and the top 5 countries in order of acceptance rates were Korea, China, Japan, India, and Taiwan. On average, it took reviewers 5.5 days to accept review requests. Excluding former and current editors-in-chief and associate editors, the 3 editors who did the most editorial work in 2022 were Jae Keun Oh, Junseok Bae, and Dong Wuk Sohn, who were responsible for 21, 16, and 13 papers, respectively. Reviewers were given a maximum review period of 14 days after accepting a review request. Out of the 546 accepted invitations, 330 reviews (60.4%) were submitted on time and 173 (31.7%) were late. In 43 accepted reviews (7.9%), no results have been received yet. Three reviewers (Chi Heon Kim, Ikchan Jeon, and Su Hun Lee) were the most active in their respective roles. The average review period was 13.5 days.

PEER REVIEW AND PUBLICATION

At the time of this writing, 191 first reviews were finalized in 2022. Of these, 24 papers (12.6%) were accepted, 100 papers (52.4%) were recommended revision, and 67 papers (35.1%) were rejected. The average time from submission to the first decision was 45.4 days. Ninety-one papers underwent a second review, with 67 (73.6%) being accepted, 20 (22%) undergoing revision, and 4 (4.4%) being rejected. The average time from submission to the second decision was 85.5 days. Out of 15 third or further reviews, 14 (93.3%) were accepted, and 1 (6.7%) was rejected. The average time from submission to the final decision was 103.5 days. The average time from acceptance to publication was 71.2 days, and from submission to publication was 161.1 days (Fig. 2).

Neurospine published 123 articles in its quarterly issues in 2022. When classified by category, the published articles consisted of 72 original articles, 25 review articles, 1 technical note, 1 case report, and 21 editorials and letters.

HOMEPAGE OF NEUROSPINE

Neurospine can be accessed through its homepage at https://www.e-neurospine.org. On the homepage, visitors can find information on newly published articles, announcements of special issues, and access a bibliography of Neurospine papers that can be freely searched and downloaded. All papers published in Neurospine are open-access and free of article processing charges. The total number of visits to the site in 2022 was 1,800,011, with an average of 4,931.5 visits per day. The numbers of monthly visits are shown in Fig. 3. In 2022, the paper with the highest

Fig. 1. The distribution of manuscript submissions to Neurospine by country.
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CITATION REPORTS

According to the Journal Citation Reports by Clarivate Analytics, the 2021 Impact Factor of *Neurospine* was 3.374, a slight decrease from 3.492 in 2020. Unlike the Impact Factor, which does not include the current year, CiteScore, based on Scopus database by Elsevier, includes the results of the 4 years from 2018.

Fig. 2. The flowchart of the peer review process.

Fig. 3. The monthly number of visits to the *Neurospine* homepage.

number of views was “Superior and Middle Cluneal Nerve Entrapment as a Cause of Low Back Pain” by Isu et al. (Table 1). A total of 33,610 articles were downloaded in 2022, with “Pearls and Pitfalls of Oblique Lateral Interbody Fusion: A Comprehensive Narrative Review” by Kim et al. being the most downloaded paper (Table 2).
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Table 1. The top 3 most viewed articles in 2022

<table>
<thead>
<tr>
<th>Author</th>
<th>Title (yr)</th>
<th>DOI</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toyohiko Isu</td>
<td>Superior and Middle Cluneal Nerve Entrapment as a Cause of Low Back Pain (2018)</td>
<td><a href="https://doi.org/10.14245/ns.1836024.012">https://doi.org/10.14245/ns.1836024.012</a></td>
<td>5,110</td>
</tr>
</tbody>
</table>

Table 2. The top 3 most downloaded articles in 2022

<table>
<thead>
<tr>
<th>Author</th>
<th>Title (yr)</th>
<th>DOI</th>
<th>Count</th>
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</thead>
</table>

Fig. 4. The CiteScore from 2019 to 2021.

to 2021. *Neurospine* published 316 documents, were cited by 1,334 documents, and recorded a 2021 CiteScore of 4.2, showing a sharp increase compared to the previous years (Fig. 4). This corresponds to the ranks of #82/469 and #147/359 in the categories of “Surgery” and “Neurology (clinical),” respectively. Compared to the ranks of #150/422 and #202/343 in the last year, the journal advanced by 68 and 55 ranks, respectively.¹

The SCImago Journal Rank, which reflects the scientific influence of an average article in the journal, also increased steadily from 0.923 in 2019 to 1.107 in 2021 (Fig. 5).² A comparison between documents that have been cited at least once versus those not cited is shown in Fig. 6. Both groups have been increasing continuously in the most recent 3 years. The percentage of cited documents has remained stable, at approximately 60%, for the past 2 years. The proportion of self-cites relative to total cites is demonstrated in Fig. 7. While total cities showed persistent growth over the past three years, the number of self-citations has remained under 70. The self-citation rate was 8.45% in 2021.

CURRENT PROBLEMS AND FUTURE DIRECTION OF NEUROSPINE

In order to enhance its academic impact, *Neurospine* needs to consider increasing the frequency of publication. While other

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spine journals with similar impact factors publish between 12 and 24 issues annually, Neurospine publishes only quarterly issues, which may limit its reach. However, because expanding the publication frequency would require significant investments in financial and human resources, full support with the consensus of related societies would be necessary.

To streamline the submission and review process, Neurospine currently operates an online access system. However, the submission and review process still present certain challenges, which might be due to an inconvenient and outdated system. To address this, we plan to develop and distribute a unified template for article submissions in order to simplify the formatting process for authors. Additionally, the review system will continue to be improved to make the process more convenient for international authors and reviewers.

The rise and fall of academic journals depend heavily on the quality of the reviewers and editorial board members, as they play a crucial role in selecting high-quality papers that contribute to the advancement of the field. To attract competent and young reviewers and editorial board members from abroad, Neurospine will need to find effective ways to compensate those who contribute to the journal. This will be a crucial challenge for Neurospine to continue its growth.

**CONCLUSION**

We would like to extend our appreciation to all the readers who have supported Neurospine throughout the year. Your continued engagement and interest in the journal are critical to its success. We are committed to delivering the highest-quality content and providing a platform for the exchange of ideas in the field of Neurospine. We look forward to continued growth and
progress in the coming years and to serving the academic community in the best way possible.

NOTES

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Author Contribution: Conceptualization: DSR; Writing - original draft: DSR; Writing - review & editing: IBH.

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REFERENCES

Activating Endogenous Neurogenesis for Spinal Cord Injury Repair: Recent Advances and Future Prospects

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2Guangdong Cardiovascular Institute, Guangdong Provincial People’s Hospital (Guangdong Academy of Medical Sciences), Southern Medical University, Guangzhou, China
3Department of Gastrointestinal Surgery, The Third Affiliated Hospital of Sun Yat-sen University, Guangzhou, China
4Shantou University Medical College, Shantou, China
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6Southern Medical University, Guangzhou, China

After spinal cord injury (SCI), endogenous neural stem cells are activated and migrate to the injury site where they differentiate into astrocytes, but they rarely differentiate into neurons. It is difficult for brain-derived information to be transmitted through the injury site after SCI because of the lack of neurons that can relay neural information through the injury site, and the functional recovery of adult mammals is difficult to achieve. The development of bioactive materials, tissue engineering, stem cell therapy, and physiotherapy has provided new strategies for the treatment of SCI and shown broad application prospects, such as promoting endogenous neurogenesis after SCI. In this review, we focus on novel approaches including tissue engineering, stem cell technology, and physiotherapy to promote endogenous neurogenesis and their therapeutic effects on SCI. Moreover, we explore the mechanisms and challenges of endogenous neurogenesis for the repair of SCI.

Keywords: Spinal cord injury, Endogenous neurogenesis, Tissue engineering, Stem cells, Biomaterials

INTRODUCTION

Spinal cord injury (SCI) usually leads to permanent sensory, motor and autonomic dysfunction downstream of the injury level, often accompanied by complications such as muscle spasm, sexual dysfunction, and neuropathic pain. SCI seriously affects the patient’s physical and mental health and life expectancy, which brings a heavy economic burden to the patient’s family and society. To date, treatments of SCI focus on surgical decompression for stabilizing the lesion level and preventing further damage to the adjacent spinal cord, combined with post-operative rehabilitation to teach patients how to effectively cope with their disability. In sum, there is no clinically effective therapy for neural restoration and regeneration for SCI and the recovery from SCI has always been a global concern.

In the acute phase of SCI, ischemia, necrosis, edema, and oxidative stress can result in direct neuronal and glial cell necrosis and apoptosis. With disease progression, the lesion area continues to expand with infiltration of inflammatory factors, glial scarring, fibrous scarring, and formation of cavities, providing an unsuitable microenvironment for nerve regeneration. Additionally, neurons of the adult mammalian central nervous system...
system have demonstrated poor spontaneous regeneration and self-repair ability after SCI. In brief, the main difficulty of brain-derived descending corticospinal tracts (CST) passing across an injured area lies in the insufficient regeneration potential of endogenous nerve cells and the adverse microenvironment. In tetraplegics and paraplegics with complete SCI, brain-derived descending nerve fibers barely regenerate and traverse through the lesion area; thus, brain-derived descending neural information can hardly retransmit to target neurons to regulate limb movement. To promote CST regeneration, a large number of studies have been carried out using animal models of complete SCI, focusing on enhancing the intrinsic axonal regeneration kinetics of neurons, cell transplantation, and gene therapy. Of these, enhancing the regeneration of endogenous neural stem cell (NSC) has the potential to form a neural network, restricting tissue damage and neural loss after SCI. Due to the self-renewal and multipotent properties, NSCs can serve as reliable cell resources for the repair of SCI. After SCI, injury-activated NSCs migrate into the lesion area, where they may proliferate and differentiate into neurons. Some studies have proposed novel tissue engineering strategies involving growth-related factors, biomaterials and physiotherapy, achieved axon regeneration in CST in small rodent models and improvements in the microenvironment at site of injury. However, in adult mammals, CST regeneration is unable to penetrate the SCI area and reconnect target neurons which are caudal to the injury site. Therefore, a promising strategy is to trigger the neuronal differentiation of endogenous NSCs into interneurons at the injury site and to form a neural network that receives the neural information from CST and transmits this information to the caudal end of the injury site to restore the voluntary motor function. In this review, we focus on novel approaches and their mechanisms that trigger endogenous neurogenesis in SCI repair to achieve functional recovery.

ENDOGENOUS NEUROGENESIS IN SCI

NSCs transplantation is considered one of the most promising cell therapy for SCI repair. NSCs are primitive cells with self-renewal and multidirectional differentiation capabilities in the central nervous system and have the potential to proliferate and differentiate into neurons, astrocytes, and oligodendrocytes. However, the apoptosis of neurons is one of the main pathological mechanisms of secondary SCI injury. Therefore, researchers expect that inducing NSC proliferation and differentiation into neurons to compensate for the loss of neurons is an effective approach to reduce pathological damage and promote nerve regeneration. Ependymal cells (ECs), which line in the central canal of the spinal cord, have NSC-like potential (Fig. 1A). Normally, ECs function as a barrier to the brain and spinal cord and rarely undergo cell division. Following SCI, the injury-activated ECs massively migrate out of the central canal and demonstrate NSC-like potential during their migration to the injury epicenter. However, most injury-activated ECs start to divide rapidly and generate oligodendrocytes that myelinate axons and astrocytes at the site of the glial scar, but not neuron. Whereas astrocytes accumulate primarily at the edge of the lesion area, forming a dense glial scar. Although astrocytes in glial scar can generate inhibitory factors, such as chondroitin sulfate proteoglycans that prevent axons from penetrating the scar, numerous beneficial effects of the scar have been discovered. Astrocytes in the glial scar restrict secondary enlargement of the lesion, infiltration of inflammation-associated cells, and prevent further cell death (Fig. 1B). In addition, the neuronal differentiation of endogenous ECs into oligodendrocytes may guide neural fiber regeneration and remyelination, playing a crucial role in the repair of motor and sensory function. Apart from preserving spinal cord integrity, restricting inflammatory cell infiltration, and providing neurotrophic support for neurons, endogenous NSCs also have the potential to differentiate into functional interneurons. Lin showed that the interneuronal networks formed by NSCs can effectively transmit neural information across the injury site, restoring motor functions. Therefore, how to effectively induce the ECs as abundant and reliable neuronal sources is a major concern in SCI repairing.

Some studies have been designed to promote endogenous neurogenesis (Table 1), in which neurons can transmit ascending and descending impulses, and transfer neural information to propriospinal nerve endings. Although descending nerve fibers cannot regenerate and penetrate across the lesion area, it may be feasible to trigger endogenous neurogenesis by transplantation of functional biomaterials which provides a neuronal network able to transmit neural information across the lesion area, improving both motor and sensory functions (Fig. 1C). Previously, endogenous neurogenesis was defined as the activation of endogenous NSCs, and the generation of new neurons. Recently, some researchers supplemented the endogenous neurogenesis as follows: injury-activated endogenous NSCs migrated to the lesion area and then differentiated into mature neurons. The mature neurons then were able to connect with host
spinal cord, forming functional neuronal relay (Fig. 1D).15,40 Although the endogenous ECs have been reported to differentiate into neurons which is an appealing candidate for SCI repairing, the efficiency of neuronal differentiation is far from satisfactory.41 Physiologically, endogenous NSCs mostly differentiate into oligodendrocytes and astrocytes and the number of differentiated interneurons is relatively small, especially in adult mammals.35 To improve the efficiency of designed neuronal differentiation of ECs, a variety of bioactive materials has been applied to stimulate SCI repair.

**BIOMATERIALS FOR TRIGGERING ENDogenous NEUROGENESIS**

After SCI, a cascade of pathophysiological progress, such as inflammation, neural death and reactive astrocytes may result in cystic cavity and glial scar formation.42 The cavity and glial scar block the transduction of electrical signal and stimulation of spinal cord tissue, inhibiting the proliferation and neuronal differentiation of endogenous NSCs.43 Considering the rapid achievements in biomaterials, scientists have developed novel biomaterials which mimic the mechanical properties of the spinal cord targeting SCI repair.28,44 The hybrid hydrogels, with highly porous structure, facilitate the transportation of nutrients and in particular, some hydrogels seamlessly integrate with the host tissue by filling the lesion cavity and conforming to the shape of the defect.45 Moreover, the designed hydrogel promotes axon regeneration via remodeling of the extracellular matrix (ECM) through minimally invasive injection to prevent secondary damage.46 These biomaterials have achieved therapeutic effects in repairing SCI, improving the microenvironment and eliminating secondary damage. However, some studies suggest that better recovery may be obtained if the biomaterial can activate and guide endogenous NSC differentiation into neurons.

![Image of spinal cord and biomaterials](https://doi.org/10.14245/ns.2245184.296)
Table 1. Summary of endogenous neurogenesis strategies and their effectiveness for spinal cord injury repair

<table>
<thead>
<tr>
<th>Publication</th>
<th>Species</th>
<th>Treatment</th>
<th>Autonomous locomotor recovery</th>
<th>Electrophysiological improvement</th>
<th>Proposed mechanism</th>
<th>Synapse-like structure in the injured site</th>
<th>Pathway</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transplanting biomaterials mimicking the mechanical property of spinal cord</td>
<td></td>
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<tr>
<td>Li et al.46</td>
<td>Rat 2020</td>
<td>Injectable nanofiber-hydrogel composite</td>
<td>Yes</td>
<td>NR</td>
<td>Supporting proregenerative macrophage polarization, angiogenesis, axon growth, and neurogenesis in the injured tissue</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Zhao et al.47</td>
<td>Rat 2021</td>
<td>Gelatin and hyaluronic acid-based hydrogels made of principle components of extracellular matrix</td>
<td>Yes</td>
<td>NR</td>
<td>Improving endogenous NSC migration and neurogenesis, neuron maturation and axonal regeneration.</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Zhu et al.48</td>
<td>Mouse 2021</td>
<td>Mg/Al layered double hydroxide nanoparticles</td>
<td>Yes</td>
<td>Yes</td>
<td>Accelerating NSCs migration, neural differentiation, Ca(2+) channel activation, and inducible action potential generation</td>
<td>NR</td>
<td>Inhibiting inflammation through transforming growth factor-β receptor 2</td>
</tr>
<tr>
<td>Zhou et al.49</td>
<td>Rat 2018</td>
<td>Biocompatible conducting polymer hydrogel</td>
<td>Yes</td>
<td>NR</td>
<td>Activating endogenous NSC neurogenesis in the lesion in vivo</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Luo et al.50</td>
<td>Rat 2022</td>
<td>Injectable, self-healing and electro-conductive hydrogels</td>
<td>Yes</td>
<td>NR</td>
<td>Activating endogenous NSC neurogenesis, and inducing myelinated axon regeneration into the lesion</td>
<td>NR</td>
<td>Activation of the PI3k/Akt and MEK/ERK pathways</td>
</tr>
<tr>
<td>Ma et al.51</td>
<td>Rat 2021</td>
<td>Poly (lactic-co-glycolic acid) shell-ensheathed decellularized spinal cord scaffolds</td>
<td>Yes</td>
<td>NR</td>
<td>Creating a favorable microenvironment for migration, residence, and neuronal differentiation of endogenous NSCs and presenting mild immunogenic property, polarizing macrophages to the M2 phenotype</td>
<td>NR</td>
<td>NR</td>
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<td>Growth factor-loaded biomaterials</td>
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<tr>
<td>Yang et al.52</td>
<td>Rat 2015</td>
<td>NT-3-coupled chitosan biomaterial</td>
<td>Yes</td>
<td>NR</td>
<td>Attracted NSCs to migration, differentiation, and formation of functional neural networks</td>
<td>Yes</td>
<td>NR</td>
</tr>
<tr>
<td>Li et al.53</td>
<td>Rat and canine 2016</td>
<td>NT-3/fibroin coated gelatin sponge scaffold</td>
<td>Yes</td>
<td>NR</td>
<td>Improved tissue regeneration, reduced cavity areas and abrogated the inflammatory response</td>
<td>NR</td>
<td>Eliciting inflammatory response by reducing TNF-α and CD68 positive cells</td>
</tr>
<tr>
<td>Xie et al.54</td>
<td>Rat 2018</td>
<td>Sodium hyaluronate-CNTF scaffold</td>
<td>Yes</td>
<td>Yes</td>
<td>Facilitate NSCs migration, differentiation, forming synaptic contact, and receiving glutamatergic excitatory synaptic input</td>
<td>Yes</td>
<td>NR</td>
</tr>
<tr>
<td>Shang et al.55</td>
<td>Rat 2019</td>
<td>bFGF controlled release system</td>
<td>Yes</td>
<td>NR</td>
<td>Reduce microglial activation, promote revascularization, elicit endogenous neurogenesis and promote regrowth of transected axons</td>
<td>Yes</td>
<td>NR</td>
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<tr>
<td>Biomaterials releasing drugs</td>
<td></td>
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<tr>
<td>Li et al.56</td>
<td>Rat and canine 2017</td>
<td>Cetuximab in modified linear ordered collagen scaffolds</td>
<td>Yes</td>
<td>NR</td>
<td>Neuronal regeneration, including neuronal differentiation, maturation, myelination, and synapse formation</td>
<td>Yes</td>
<td>NR</td>
</tr>
<tr>
<td>Fan et al.57</td>
<td>Rat 2017</td>
<td>EGFR antibody with a collagen-binding domain</td>
<td>Yes</td>
<td>NR</td>
<td>Promoted neuronal differentiation and neurite outgrowth under myelin</td>
<td>NR</td>
<td>NR</td>
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</table>

(Continued)
<table>
<thead>
<tr>
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<th>Pathway</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yin et al.</td>
<td>Canine</td>
<td>Taxol-modified collagen scaffold</td>
<td>Yes</td>
<td>Yes</td>
<td>Increased neurogenesis, axon regeneration and reduce glial scar formation</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Yang et al.</td>
<td>Rat</td>
<td>LDN193189, SB431542, CHIR99021 and P7C3-A20 in an injectable collagen hydrogel</td>
<td>Yes</td>
<td>NR</td>
<td>Induced neurogenesis, increase neuronal differentiation of spinal cord NSCs and inhibited astrogliogenesis</td>
<td>NR</td>
<td>NR</td>
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<tr>
<td>Biomaterials with exogenous stem cells</td>
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<tr>
<td>Yuan et al.</td>
<td>Rat</td>
<td>DNA hydrogel-carrying exogenous NSCs</td>
<td>Yes</td>
<td>Yes</td>
<td>Enabling sufficient migration, proliferation, and differentiation of both implanted and endogenous NSCs</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Li et al.</td>
<td>Canine</td>
<td>Collagen-based biomaterial loading with human umbilical cord-derived mesenchymal stem cells</td>
<td>Yes</td>
<td>NR</td>
<td>Fascinated newborn neurons matured into 5-HT positive neurons and the regenerated axon with remyelination and synapse connection</td>
<td>Yes</td>
<td>NR</td>
</tr>
<tr>
<td>Wang et al.</td>
<td>Rat</td>
<td>Modified scaffolds loading NSCs overexpressing NGF</td>
<td>Yes</td>
<td>NR</td>
<td>Modulating the microenvironment and enhancing endogenous neurogenesis</td>
<td>NR</td>
<td>Activating TrkA, upregulating CREB and microRNA-132 around the lesion focus.</td>
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<tr>
<td>Physiotherapy</td>
<td></td>
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<tr>
<td>Xu et al.</td>
<td>Rat</td>
<td>Electroacupuncture on Governor Vessel acupoints</td>
<td>Yes</td>
<td>NR</td>
<td>Activating the intrinsic growth ability of injured spinal neuron</td>
<td>Yes</td>
<td>GV-EA activating CGRP/RAMP1/alphaCaMKII pathway</td>
</tr>
<tr>
<td>Xu et al.</td>
<td>Rat</td>
<td>Fire needle</td>
<td>Yes</td>
<td>NR</td>
<td>Promoting endogenous NSCs proliferation differentiating into neurons</td>
<td>NR</td>
<td>Activation of Wnt/β-catenin and inhibiting the overexpression of ERK.</td>
</tr>
<tr>
<td>Combinatorial treatments</td>
<td></td>
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<tr>
<td>Li et al.</td>
<td>Rat</td>
<td>TrkC-modified NSC-derived neural network tissue in the NF-GS</td>
<td>Yes</td>
<td>NR</td>
<td>Establishing favorable microenvironment and supporting the long-time survival of both exogenous neurons and endogenous newborn neurons</td>
<td>Yes</td>
<td>NR</td>
</tr>
<tr>
<td>Liu et al.</td>
<td>Rat</td>
<td>Combining thermosensitive polymer electroactive hydrogel loaded with NGF with electrical stimulation</td>
<td>Yes</td>
<td>NR</td>
<td>Promoted the neuronal differentiation of NSCs and axonal growth</td>
<td>NR</td>
<td>NR</td>
</tr>
</tbody>
</table>

NR, not reported; NSCs, neural stem cells; MEK/ERK, mitogen-activated protein kinase kinase/extracellular signal-regulated kinase; TNF-α; tumor necrosis factor-α; CNTF, ciliary neurotrophic factor; NT-3, neurotrophin-3; bFGF, basic fibroblast growth factor; EGFR, epidermal growth factor receptor; 5-HT, 5-hydroxytryptamine; NGF, nerve growth factors; CREB, cAMP-response element binding protein; GV-EA, electroacupuncture on Governor Vessel acupuncture points; NF-GS, NT-3/fibroin coated gelatin sponge scaffold; TrkC, tropomyosin receptor kinase C.
while improving the microenvironment for nerve regeneration.\textsuperscript{47}

Recent studies have reported that a series of novel hydrogels could trigger endogenous neurogenesis without the need for additional therapeutic agents and lead to the recovery of motor function. Li et al.\textsuperscript{48} designed an injectable nanofiber-hydrogel with interfacial bonding properties, providing mechanical strength and porosity at the lesion area. In addition to providing mechanical support to the constrained spinal cord, the composite material also promoted neurogenesis, proregenerative macrophage polarization, and angiogenesis. After treating with nanofiber-hydrogels, the immature neurons at the injury site gradually increased over times and at 28 days the number of immature neurons was 2-fold higher than in controls. Therefore, the designed nanofiber-hydrogel was able to promote the harsh microenvironment at the injury site, which supported the neuronal differentiation and survival of NSCs.

Zhao et al.\textsuperscript{49} developed gelatin and hyaluronic acid-based hydrogels which were constituted of principal ECM. The transplantation of the hybrid hydrogel eliminated the inflammatory responses and suppressed the formation of glial scar. Moreover, the hybrid hydrogel effectively contributed to endogenous neurogenesis, improving NSC migration, neuron maturation, and axonal regeneration. Zhu et al.\textsuperscript{50} developed Mg/Al layered double hydroxide nanoparticles to repair the completely transected SCI. They found that the application of nanoparticles accelerated NSC migration and neuronal differentiation, activated the L-Ca (2+) channel, and induced action potentials. By implantation of the layered double hydroxide, they observed BrdU-labeled endogenous NSCs and neurons in the injured area, with an improved electrophysiological and behavior performance in the SCI rat. Further analysis demonstrated that layered double hydroxide inhibited inflammation through the transforming growth factor-\(\beta\) receptor 2 and activated neural cell proliferation.

Apart from mimicking the physical strength, researchers were also interested in developing high-conductivity biomaterials which somehow contributed to endogenous neurogenesis.\textsuperscript{50} Zhou et al.\textsuperscript{51} developed a biocompatible conducting polymer hydrogel, mimicking mechanical properties of the spinal cord and demonstrating high conductivity. In vitro, conducting polymer hydrogel promoted NSCs differentiation into neurons and suppressed the differentiation into astrocytes. In vivo, the conducting polymer hydrogel could trigger endogenous neurogenesis at the lesion site, improving locomotor functions in rats. Luo et al.\textsuperscript{52} also employed an injectable, self-healing, and electro-conductive hydrogels to treat SCI. These hydrogels, composed of natural ECM and polypyrrole, exhibit similar mechanical and electrical properties to the natural spinal cord. In vitro, conductive injectable hydrogels effectively promoted neuronal differentiation, axonal growth, and inhibited astrocyte differentiation. In vivo, the conductive hydrogels activated endogenous NSC neurogenesis and triggered the regeneration of myelinated axons at the site of lesion through the PI3k/Akt and MEK/ERK (mitogen-activated protein kinase kinase/extracellular signal-regulated kinase) pathways.

Recently, Ma et al.\textsuperscript{53} investigated novel tissue scaffolds, which not only met the mechanical properties of pathological spinal cord tissue but also comprised a proregenerative matrix. To construct poly (lactic-co-glycolic acid) shell-ensheathed decellularized spinal cord scaffolds (PLGA-DSCS), researchers removed the inhibitory components and preserved the permissive matrix by electrospinning and chemical extraction strategies. The decellularized spinal cord (DSC) scaffold was mechanically enhanced with a thin PLGA. In vitro, the DSC scaffolds allowed robust neurogenesis and promoted NSC differentiation into neurons. In vivo, the PLGA-DSCS implanted at the injury area created a favorable microenvironment for migration, residence, and neuronal differentiation of endogenous NSCs. Furthermore, PLGA-DSCS presented a mild immunogenic property, polarizing macrophages into the M2 phenotype. Therefore, the PLGA-DSCS could have significant therapeutic effects on neural regeneration and function recovery.

The biomaterials discussed above could integrate with the host tissue by filling the lesion cavity and somehow promoting the endogenous neurogenesis.\textsuperscript{37} For example, the hybrid hydrogels were able to provide mechanical support and high conductivity for the lesion area and the physical characteristics of hydrogels endured in the harsh microenvironment, eliminated inflammatory processes and glial scar formation to facilitate generation of NSC progeny leading to significant recovery of motor function.\textsuperscript{47} The modified DSC, which is composed of a proregenerative matrix was able to create a favorable microenvironment for neural regeneration.\textsuperscript{53} However, the efficiency of neuronal differentiation of ECs is currently unsatisfactory.\textsuperscript{54} To better modulate the microenvironment and guide the directional differentiation in the injury site, functional neurotrophic factors may be a promising strategy.

**BIOMATERIALS LOADED WITH NEUROTROPHIC FACTORS TO ACTIVATE ENDOGENOUS NEUROGENESIS**

Neurotrophic factors have been reported to modulate various...
aspects of neural activity. Numerous neurotrophic factors, such as neurotrophin-3 (NT-3), brain-derived neurotrophic factor (BDNF), nerve growth factor (NGF), ciliary neurotrophic factor (CNTF) and basic fibroblast growth factor (bFGF), play a crucial role in neural proliferation, migration, neuronal differentiation and synaptogenesis. In vitro, NT-3 promotes the neuronal differentiation and formation of synapses from NSC-derived neurons, demonstrating the potency of synaptic transmission. Similarly, NGFs have been reported to promote axonal sprouting, guide axon regeneration and myelination after nerve injury and the upregulated NGF at the perilesion site contributing to repair and synaptic plasticity after SCI. Furthermore, CNTF is able to promote the survival and axonal growth of neurons and achieved a promyelinating effect in vitro. These bioactive factors could ameliorate the harsh microenvironment and improve the NSC-like potential of ECs after SCI. Transplantation of the mentioned neurotrophic factors may create a pro-regenerative microenvironment, thus increasing endogenous repair in both rats and nonhuman primates with SCI. However, the release of neurotrophic factors suffers from the short half-lives observed under physiological conditions and limited administration in vivo. Normally, neurotrophic factors diffuse rapidly at the site but are unable to maintain a suitable concentration. To improve the adverse microenvironment conditions, it is necessary to elicit endogenous neurogenesis and to promote axon growth, scientists have designed numerous functional biomaterials combined with neurotrophic factors to achieve long-term release (Fig. 2B). The novel strategies are focused not only

Fig. 2. Therapeutic strategies to trigger endogenous neurogenesis. (A) Transplantation of biomaterials that mimic the mechanical properties of the spinal cord. (B) Transplantation of functional biomaterials loaded with neurotrophic factors. (C) Transplanting functional biomaterials for sustained small molecule drugs release. (D) Transplantation of exogenous stem cells. (E) Physiotherapy. MSC, mesenchymal stem cell; NSC, neural stem cell.
on supporting NSC-derived neuron differentiation and increasing remyelination, but also on improving the formation of synaptic connections between propriospinal nerve fibers and neurons at the injury site.\(^{61}\)

NT-3 is a crucial growth factor, distributed in both the central and peripheral nervous systems.\(^{56}\) \textit{In vitro}, NT-3 could activate the tropomyosin receptor kinase C (TrkC) receptor, facilitating NSCs proliferation. \textit{In vivo}, NT-3 has been confirmed to promote neurogenesis in the spinal cord and axonal growth in the CST.\(^{65}\) Thus, researchers have developed innovative and functional biomaterials able to load NT-3 for the repair of SCI. Yang et al.\(^{60}\) constructed a 14-week slow-release preparation of NT-3 in a biodegradable chitosan material. After transplanting this material to the injury area, the slow release of NT-3 improved the harsh microenvironment and attracted endogenous NSCs able to migrate into the SCI site and differentiate into neurons. Most importantly, endogenous neurons derived from NSCs connected with propriospinal neurons and formed functional neural networks, leading to both sensory and motor recovery in experimental animals. Similarly, Li et al.\(^{64}\) developed a gelatin sponge scaffold coated with NT-3/fibroin (NF-GS) to achieve a controlled artificial release lasting 28 days. \textit{In vivo}, NF-GS improved the concentration of NT-3 and exhibited proper biocompatibility. NF-GS improved tissue regeneration and reduced cavity areas in the lesion area. The axon extensions with myelin sheath penetrated the glial scar and some of the cells traversed the NF-GS. Furthermore, NF-GS abrogated the inflammatory response by reducing tumor necrosis factor-\(\alpha\) and CD68-positive cells.

CNTF is a potent survival factor for neurons and oligodendrocytes and it promotes neurotransmitter synthesis and neurite outgrowth. Xie et al.\(^{66}\) developed a sodium hyaluronate-CNTF scaffold that was capable of releasing CNTF for up to 105 days. The designed scaffold could activate endogenous NSCs from the ependymal layer and promote migration of the NSCs to the injury site. Furthermore, the endogenous NSCs could differentiate into mature neurons, forming synaptic connections and receiving excitatory input from the glutamatergic synapse. The electrophysiological results of the regenerated neural network, recorded by a planar multielectrode dish system, suggest that functional synapses could be established between endogenous NSC-derived neurons and the host spinal cord.

bFGF plays a crucial role in modulating neuronal differentiation and repairing damage. Thus, Shang et al.\(^{57}\) also investigated bFGF controlled release system for spinal cord regeneration. Under physiological conditions, these scaffolds had proper mechanical properties, enabling the release of bFGF for up to 6 weeks. After implantation, these scaffolds could facilitate revascularization, stimulate endogenous neurogenesis and axon growth and inactivate microglia. Similarly, endogenous neurons connected to each other or with propriospinal neurons through a synapses-like connection. The functional neural networks established between the lesion area and the host spinal cord eventually resulted in recovery from locomotion.

In summary, the above studies demonstrate that functional biomaterials were able to achieve slow release of neurotrophic factors \textit{in vivo}. Furthermore, the loading of designed functional biomaterials with neurotrophic factors could trigger endogenous neurogenesis of NSCs by creating a regenerative microenvironment, reducing inflammation, improving the migration of NSCs, promoting neuronal differentiation and neurite outgrowth, and generating functional synapses with the propriospinal nerve fibers of the host.\(^{66}\) Without transplanting exogenous stem cells, endogenous NSCs differentiated into interneurons and functioned as neuronal relays that reconnect with the original downstream targets. Although neurotrophic factors could effectively promote the microenvironment in the area of the injury and modulate the activity of endogenous NSCs, it has proven difficult for neurotrophic factors to fulfill slow-release and maintain long-term activity. Therefore, researchers are interested in finding bioactive materials that intelligently control the release of factors.

### BIOMATERIALS WITH SUSTAINED SMALL MOLECULE DRUGS RELEASE THAT TRIGGER ENDGENOUS NEUROGENESIS

In addition to growth factors, a series of small molecule drugs are associated with modulating the survival, proliferation, and neuronal differentiation of NSCs, inhibiting inflammation, and promoting angiogenesis \textit{in vivo}. For example, the anticancer drug taxol has the potential to reduce scar formation, decrease axonal degeneration and stabilize microtubule.\(^{69}\) Cetuximab, an epidermal growth factor receptor (EGFR) antagonist, induces significant neuronal differentiation, generating \textit{de novo} neuron formations, and reducing astrocytic differentiation of neural progenitor cells in acute SCI.\(^{70}\) To achieve sustained-release of small molecule drugs that promote endogenous neurogenesis after SCI, researchers have developed functional collagen scaffolds that have demonstrated good biodegradability and excellent biocompatibility (Fig. 2C).

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Li et al. implanted cetuximab, an EGFR signaling antagonist, in modified linear ordered collagen scaffolds. After transplantation to injury sites in canine, low-dose cetuximab effectively improved migration and encouraged the neuronal production of endogenous NSCs at the site of injury and inhibited the expression of chondroitin sulfate proteoglycans in the glial scar. Furthermore, neurons derived from endogenous NSCs demonstrated myelination and synapse formation which could connect with host spinal neurons to restore locomotion. In summary, cetuximab-modified linear ordered collagen scaffolds may provide a suitable microenvironment for endogenous neurogenesis and enable neuronal relays after acute SCI. In one study, Fan et al. engineered a collagen-binding EGFR antibody by fusing the EGFR antibody with a collagen-binding domain to achieve its sustained-release from the collagen scaffold. In vitro, the engineered collagens promoted neuronal differentiation and neurite outgrowth under myelin. After transplantation into rat models with SCI, endogenous NSCs for injury-activated neurogenesis were observed, and endogenous NSCs could differentiate into functional neurons and reconnect the 2 injured stumps.

In other studies, the same researchers also investigated the taxol-modified scaffold for SCI repair in canine models. After the complete transection of 1 cm of spinal cord, a linear-order collagen scaffold was implanted that allowed the slow release of taxol into the injured area. In addition to stabilizing microtubules, taxol demonstrated therapeutic effects in restricting scar formation and significantly promoting neurogenesis and axon regeneration after severe spinal cord transection in a canine model. In vitro, taxol promoted the neuronal differentiation of NSCs through the p38 MAPK signaling pathway. Therefore, the taxol-modified scaffold provided a suitable microenvironment for neuronal differentiation of endogenous NSCs and the extension of neuronal axons resulted in significant promotion of locomotion and motor-evoked potentials.

Other attempts, including small molecules, have great therapeutic potential for repairing the spinal cord. Yang et al. loaded functional small molecules including LDN193189, SB431542, CHIR99021, and P7C3-A20 into an injectable collagen hydrogel. The small molecules could induce neurogenesis, increase neuronal differentiation of spinal cord NSCs and inhibit astrogliogenesis at the injury site. Neuronal regeneration at lesion sites leads to recovery from locomotion.

Altogether, the above studies demonstrate that biodegradable and biocompatible materials loaded with small molecule drugs are able to achieve the slow-release of growth factors in vivo. Furthermore, these designed functional biomaterials could create a suitable microenvironment, promoting neuronal differentiation and synapse formation with the propriospinal nerve fibers of the host, leading to better locomotion and electrophysiology. However, for severe SCI or extensive defects, mammals may suffer massive neuron apoptosis within the area of the lesion and the transplantation of biomaterials may not trigger quantitative endogenous neurons to repair impaired neuron circuits. A promising solution is represented by the transplantation of exogenous stem cells. These strategies may induce many more endogenous stem cells to participate in the repair process and restore the defected neural circuit through the synergistic effects of both endogenous and exogenous stem cells.

### EXOGENOUS STEM CELLS THAT TRIGGER ENDOGENOUS NEUROGENESIS

Transplantation of exogenous stem cells is an attractive strategy for repairing SCI. In the 1980s, transplantation of embryonic spinal cord tissue at the injured site promoted the regeneration of the descending nerve fibers of the brain, resulting in locomotion recovery. In this section, we focus on the therapeutic effects of exogenous stem cells on endogenous NSCs migration and neuronal differentiation and on generating functional synapses with host neurons (Fig. 2D).

Yuan et al. designed a DNA hydrogel with high permeability, self-healing, and proper mechanical support for repairing a completely transected spinal cord in rat models. The DNA hydrogel-carrying exogenous NSCs promoted the formation of a renascent neural network, enabling sufficient migration, proliferation, and neuronal differentiation of both implanted and endogenous NSCs. After 8 weeks of transplantation the rats showed better hindlimb function and detectable motor-evoked potentials through synapses of the regenerated neural networks. Furthermore, the hydrogel DNA network offered a regenerative microenvironment by expressing quantitative growth factors including BDNF, GDNF, NGF, and NT-3.

Focusing on chronic SCI in large animals, Li et al. investigated a collagen-based biomaterial loaded with human umbilical cord-derived mesenchymal stem cells in a chronic SCI canine model. Two months after SCI, the glial scar tissue was removed and the biomaterials named the “NeuroRegen scaffold” were transplanted into the lesion area. The implantation of the “NeuroRegen scaffold” facilitated locomotor recovery and endogenous neurogenesis in the center of the lesion area. Additionally, some of the de novo neurons matured into 5-hydroxy-
tryptamine positive neurons and the regenerated axon fibers demonstrated remyelination and synapse connections in the injured area at 1 year after injury. The implantation of the “NeuroRegen scaffold” also reduced the formation of glial scar at the lesion level one year after implantation.

Previous studies have showed that NGF was a crucial growth factor regulating neuronal regeneration. Wang et al. designed modified scaffolds loading NSCs overexpressing NGF for targeted delivery of NGF to the site of the injury. Four weeks after transplantation, NGF-NSCs attenuated damage in the center of the lesion and NGF-NSCs that survived in the core of the lesion maintained high levels of NGF release. The NGF-NSC graft modulated the microenvironment around the lesion core by reducing oligodendrocyte loss, reducing astrocytosis and demyelination, protecting neurons, and increasing the expression of multiple growth factors. Most importantly, in the subacute stage of traumatic SCI, the neuroprotective effect of NGF-NSCs may be mediated by activating TrkA, upregulating cAMP-response element binding protein, and microRNA-132 expression around the epicenter of the injured site. In summary, the exogenous stem cells achieved functional recovery by modulating the microenvironment and enhancing endogenous neurogenesis in rats.

In summary, exogenous stem cell-seeded biomaterials promoted the migration, proliferation, and neuronal differentiation of endogenous NSCs. The researchers also observed the formation of synaptic connections and the formation of neural circuits through implanted and endogenous stem cells. The therapeutic effects of exogenous stem cells targeting endogenous neurogenesis may be attributed to the creation of a favorable microenvironment for axon regeneration, by secreting multiple growth factors to guide migration. To endow host propriospinal neurons with better integration capability with exogenous-derived and endogenous-derived neurons, combination with physiotherapy strategies can improve intrinsic growth capacity, activate endogenous neurogenesis and improve the rigid microenvironment.

**PHYSIOTHERAPY STRATEGIES FOR ACTIVATING ENDOGENOUS NEUROGENESIS**

Physiotherapy has previously been regarded as a symptomatic treatment for SCI. Current advanced physiotherapy strategies which include epidural electrical stimulation (EES) and brain-spine interface can restore leg motor functions after SCI. EES following activity-specific stimulation protocols can mimic the natural activation of motor neurons by multielectrode paddle. Three patients following an activity-specific stimulation program were able to complete standing, walking, swimming, and controlling trunk movements in a single day. Although physiotherapy has shown sustained progress in improving motor skills, little is known about the functional effects of physiotherapy on neuroprotection, modulating environment and triggering endogenous neurogenesis.

To improve the hostile microenvironment and poor intrinsic growth capacity, Xu et al. have reported that the application of electroacupuncture on Governor Vessel acupuncture points (GV-EA) could promote neuronal survival and axonal regeneration after SCI. In GV-EA, needles are inserted at GV acupuncture points where a small low-frequency pulsed current can be delivered, ventilating the meridians to promote blood flow. The study suggests that GV-EA could stimulate cells in the dorsal root ganglion to release calcitonin gene-related peptide (CGRP) from the afferent terminals in the spinal cord. However, in vivo and in vitro results demonstrated that CGRP could trigger NT-3 synthesis and secretion by CGRP/receptor activity-modifying protein (RAMP)/calcium/calmodulin-dependent protein kinase (alphaCaMKII) pathway. Furthermore, the mentioned effect could be interrupted by dorsal rhizotomy and blocking the CGRP/RAMP1/alphaCaMKII pathway. Therefore, GV-EA could activate intrinsic growth and promote the survival, axonal growth, and synaptic maintenance of spinal cord neurons in the injured area by increasing NT-3 production (Fig. 2E).

Fire needle acupuncture, known as fire needle, is a physiotherapy technique that combines acupuncture and cauterization with heated needle therapy. Xu et al. found that fire needle improved locomotor function in SCI rats and increased nestin, Gal-C expression while inhibited glial fibrillary acidic protein expression after SCI. These findings indicated that fire needle promoted endogenous NSC migration, proliferation, and differentiation into neurons at the injured site and inhibited differentiated NSCs into astrocytes. Increased Wnt3a, GSK3β, β-catenin, and ngn1 expression and down regulation of ERK1/2 and of cyclinD1 gene and protein expression were observed in the fire needle group. Therefore, endogenous neurogenesis could be mediated by activation of Wnt/β-catenin and inhibition of the ERK pathway.

In conclusion, electrical stimulation has the potential to promote the survival and neuronal differentiation of endogenous NSCs, and contributes to the activation of the propriospinal neuronal network, axonal growth and formation of synaptic connections at the injured site. Electrical stimulation also trig-
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The application of multiple therapeutic strategies, including exogenous cell transplantation, the delivery of neurotrophic factors or small molecule drugs, and neuromodulation by physiotherapy can achieve more effective repair. The combination of multiple treatments is considered an ideal approach that may provide new insights for clinical treatments.

COMBINATION TREATMENTS

In the literature, some studies describe the therapeutic effects aimed at repairing SCI. For example, biomaterials mimicking the physical characteristics of the spinal cord can compensate for tissue loss, create a better microenvironment, and eliminate secondary damage. Neurotrophic factors and small molecule drugs overcome the harsh microenvironment and promote synapse formation with the propriospinal nerve fibers of the host. The transplantation of exogenous stem cells has offered cell sources, and secreted growth factors able to guide cell migration and to create a favorable microenvironment. Physiotherapy strategies can activate the propriospinal neuronal network, and integrate regenerated neurons with the spinal cord fiber. Most importantly, all these strategies somehow trigger endogenous neurogenesis, promoting the migration, proliferation, and neuronal differentiation of endogenous stem cells at injury site. In fact, the efficiency of repairing SCI using a single treatment without combining other therapeutic agents was low.

The following issues or limitations should be carefully considered: (1) improvement of the microenvironment of the impaired spinal cord; (2) triggering of the migration, proliferation and neuronal differentiation of endogenous or exogenous stem cells in the replacement of dead neurons; and (3) promotion the integration of regenerated cells. Therefore, the combination of multiple therapeutic strategies may be the key to SCI repair.

To promote tissue repair efficacy, Li et al. combined slow neurotrophic factors release and exogenous cell transplantation strategies, and transplanted a TrkC-modified NSC-derived neural network tissue in the NF-GS. The NF-GS created an NT-3-enriched microenvironment and the NSCs overexpress TrkC, NT-3 receptor, thus creating a functional neuronal population-dominated neural network. In addition to providing a regenerative niche for long-term survival of the exogenous neural network at the injured site, the novel strategy allowed for the sustained differentiation of endogenous NSCs into neurons. Transplantation of the NT-3-releasing scaffold at the lesion site established a favorable microenvironment and supported long-term survival of exogenous neurons and endogenous de novo neurons. This could compensate for the loss of neurons and could lead to an increase in neuronal population at the injury site bringing structural repair to the sensorimotor pathways.

A combination of scaffold-based biochemical and electrical stimulation signals may be useful to repair SCI. Liu et al. investigated a novel approach that combined thermosensitive polymer electroactive hydrogel (TPEH) loaded with NGF with electrical stimulation. The designed hydrogel was able to achieve the sustained-release of NGF for 24 days and demonstrated high conductance on electrical stimulation. In vitro, the TPEH with NGF improved the neuronal differentiation of NSCs and axon growth. In vivo, electrical stimulation and TPEH with NGF promoted endogenous neurogenesis and led to improved motor function.

Current combinatorial treatments focus on providing a regenerative environment to support the long-time survival, proliferation and neuronal differentiation of NSCs. However, we still have limited knowledge about the remodeling and integration of synapses with propriospinal neurons. The application of neuroregulatory technology, including EES, and transcutaneous spinal cord stimulation, can excite the spinal neural network and regulate synaptic plasticity. Therefore, tapping its full potential for better integration with host nerve tracts will require a combination of neuroregulatory techniques with biomaterials.

CHALLENGES AND FUTURE PERSPECTIVES

With recent advances in the understanding of the repair mechanism of tissue engineering along with physiotherapy, endogenous neurogenesis has become a significant mechanism for SCI research. Despite some attempts to achieve functional recovery by targeting endogenous neurogenesis, challenges and obstacles remain. For large mammals, it is still challenging to ensure that endogenous NSCs survive, proliferate, and differenti-
ate into neurons in adequate quantities.\textsuperscript{96} Considering the obstacles mentioned above, combination therapy may be the most appropriate approach. In the future, combination treatments will be designed as selective approaches that may interact to catalyze with each other.\textsuperscript{97} For instance, transplantation of biomaterials creates a favorable microenvironment for axon regeneration, promotes exogenous neuronal differentiation, and facilitates synapse formation with the endogenous newborn neurons that contribute to neurological recovery. In turn, neuromodulation techniques could theoretically excite spinal neural networks, strengthen synaptic connections, promote plasticity, and facilitate integration into the central nervous system.\textsuperscript{98} To reach their full potential, combinatorial treatments must adhere to the strict temporal window and select an appropriate SCI model.

Apart from revealing the mechanisms and effects underlying endogenous neurogenesis through combination treatments, efforts should be made to further expand the applications in clinical practice: (1) Differences in neuroanatomy (distribution of CST) and size gaps between humans and rodents hinder clinical trials. In rodents, the lesion site is about a few millimeters long, whereas human injuries can span centimeters.\textsuperscript{99} To conduct neural information through lesion area, the functional recovery of SCI patients needs more endogenous newborn neurons and longer-distance axon growth. Despite being costly and time-consuming, SCI models of non–human-primate and large mammals provide numerous advantages for evaluating treatment efficacy before clinical trials due to their similar neuroanatomical and functional characteristics.\textsuperscript{100} (2) It is important to note that SCI patients exhibit variability in the neurological level of injury, lesion severity, treatment duration, and types of early treatment, making injuries unreproducible.\textsuperscript{101} Possible solutions may be aligning the animal models closely with clinical

Fig. 3. Schematic illustration of combined strategies using exogenous stem cell-seeded biomaterials and physiotherapy for the repair of spinal cord injury.
conditions. (3) Immunosuppression is often required in SCI patients who receive NSCs transplantation. The application of immunosuppressants increases the risks of malignancies, infection, and other side effects in humans. The possible solutions include the use of low-immunogenic biomaterials or endogenous NSCs. (4) The exogenous stem cells have the potential to form ectopic aggregates as stem cells migrate and proliferate in the central nervous system. Engineered neural network tissues provide terminally differentiated cells and a stable matrix that successfully mitigates the migration of stem cells. Although no severe adverse events including cancer, infections, and allergic reaction have been identified in some Phase I-II clinical trials, long-term side effects require constant monitoring. (5) The majority of SCI patients can be classified as chronic SCI which is still understudied and its treatments remain more challenging than acute/subacute SCI. In the future, clinical trials will shift their focus to the treatment of chronic SCI.

CONCLUSION

Currently, triggering endogenous neurogenesis represents a potentially practical and feasible strategy for SCI repair. In this review, promising therapeutic strategies, including implantation of biomaterials alone, implantation of biomaterials loaded with neurotrophic factors or small molecule drugs, transplantation of exogenous stem cells, physiotherapy, and combination treatments have been proposed. The current evidence suggests that these strategies may provide a more supportive microenvironment and trigger the migration, proliferation and neuronal differentiation of endogenous NSCs. However, the efficiency and therapeutic effects of single strategies for SCI repair are relatively low and functional recovery is currently unsatisfactory. To better cope with SCI repair, combinatory strategies may be the optimal choice. The combination of physiotherapy with bioactive materials loaded with exogenous stem cells (Fig. 3) can be a promising approach which can trigger endogenous neurogenesis to reconstruct the neural circuits and regulate neuroplasticity for better integration with host nerve tracts. In the future, more clinical studies will be required to ensure the safety of combination therapy and to translate this combination treatment modality into a wide range of clinical settings.

NOTES

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Reduction of Lower Cervical Facet Dislocation: A Review of All Techniques

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Objective: The surgical treatment of lower cervical facet dislocation is controversial. Great advancements on reduction techniques for lower cervical facet dislocation have been made in the past decades. However, there is no article reviewing all the reduction techniques yet. The aim is to review the evolution and advancements of the reduction techniques for lower cervical facet dislocation.

Methods: The application of all reduction techniques for lower cervical facet dislocation, including closed reduction, anterior-only, posterior-only, and combined approach reduction, is reviewed and discussed. Recent advancements on the novel techniques of reduction are also described. The principles of various techniques for reduction of cervical facet dislocation are described in detail.

Results: All reduction techniques are useful. The anterior-only surgical approach appears to be the most popular approach. Moreover, many novel or modified reduction and fixation methods have been introduced in recent years.

Conclusion: The selection of surgical approach depends on a combination of factors, including surgeon preference, patient factors, injury morphology, and inherent advantages and disadvantages of any given approach.

Keywords: Lower cervical spine, Facet dislocation, Techniques, Review

INTRODUCTION

Lower cervical facet dislocation is a common spinal trauma caused by flexion-distraction force that usually results in damage to the 3-column structure, as well as vertebral dislocation, facet locking, and intervertebral disc destruction (Fig. 1). The treatment of lower cervical facet dislocation is generally recognized as reduction, decompression, fixation, and fusion. Early reduction can reduce the compression of the spinal cord, which is particularly important for patients with incomplete spinal cord injury. Since Walton et al. first reported closed reduction by manipulation of cervical spine deformity caused by facet dislocation in 1893, great advancements have been made in reduction techniques, especially in recent years. In the present study, we review all reduction techniques, including traditional, popular, and novel techniques. In general, the reduction techniques are categorized into 4 main types: closed reduction, anterior alone, posterior alone, and combined approach techniques.

CLOSE REDUCTION TECHNIQUES

Close reduction was the initial technique for lower cervical facet dislocation. After Walton et al. first described closed reduction by manipulation of cervical facet dislocation in 1893, Crutchfield et al. introduced tongs for in-line traction-reduction in 1933. Thereafter, closed reduction of the cervical spine using head traction has been used for many years and reported as an effective treatment for many cervical facet dislocations. Although the technique of manipulation varies from surgeon to surgeon, the basic procedure is a gradually traction, followed by anterior rotation and lateral flexion away from the side of the dislocated facets. While the locked facets have been disen-
gaged, rotation is carried out in the opposite direction. As soon as a click is heard or felt, the neck is extended (Fig. 2).

Although the principle of closed reduction is basically the same, there are also some differences and controversies in various literature views. Firstly, the weights required to be traction reported in the previous literature were different. Reindl et al. reported that all patients were treated with Gardner-Wells traction, starting with 5 kg+2.5 kg/level of injury below C1. This was followed by addition of 2.5 kg every 30 minutes until reduction was achieved, to a maximum of 50% estimated body weight for 1 hour. In the cases report of Tumialán et al., an initial traction weight of 9.1 kg was applied, followed by an increase of 4.5 kg per hour. Once 27.2 kg was reached, the lateral radiograph was suggestive of reduction. Miao et al. retrospectively analyzed 40 patients. The initial traction weight was 5 kg, and if the weight reached 15 kg, closed reduction could be completed in most patients (38 cases, 95%). This difference may depend on the state of the articular process after facet dislocation. If the facets are fractured, the reduction may occur with lower weights, and good alignment will be achieved easily. Otherwise, if the facets are locked, too many weights are necessary, a reduction may be severe. Moreover, if the dislocation is delayed, closed reduction is almost impossible.

Secondly, there is still some controversy as to whether or not anesthesia is performed during traction-reduction. The observations of Evans and Kleyn popularized reduction under anesthesia, although other authors condemned the procedure as potentially dangerous compared with craniocervical traction-reduction. In 1994, a cohort study performed by Lee et al. found a higher rate of success and a lower complication rate with traction-reduction as opposed to manipulation under anesthesia. In 1999, a prospective observational study by Vaccaro et al. assessed the safety of awake closed reduction maneuvers in 11 patients with cervical spine dislocations. The results showed that none of the patients in their study suffered from neurological worsening during or after closed reduction. Suitably, Vaccaro et al. stated in the conclusion of the article that the implications related to the “neurologic safety of awake closed reduction traction reduction remains unclear.” However, there were also many authors who believed that manipulation under anesthesia was still a frequently practiced technique, usually used after fail-

Fig. 1. Imaging studies of the illustrative case with C5–6 bilateral facet dislocation. Preoperative lateral radiograph (A), and sagittal computed tomography (CT) (B) showing a C5–6 dislocation and vertebral translation (arrows). (C) T2-weighted sagittal magnetic resonance imaging showing C5–6 intervertebral disc herniation (arrow) and spinal cord compression. (D-F) Sagittal CT and 3-dimensional reconstruction of the patient showing C5–6 bilateral facet dislocation (arrows).

Fig. 2. Illustrations of closed reduction. (A) Lateral image of facet dislocation. (B) The weight of in-line traction is increased gradually under fluoroscopy monitoring, until the articular process is completely unlocked. (C) While maintaining the traction, manually push the upper vertebrae in a caudad direction to achieve reduction.
Reduction of Lower Cervical Facet Dislocation

Liu K, et al.

The need for magnetic resonance imaging (MRI) before reduction is a matter of debate. Some investigators believed that disc disruption in association with facet fracture-dislocation increases the risk of spinal cord injury by disc material after reduction. Rizzolo et al. found evidence of disc disruption/herniation in 42% of patients studied with prereduction MRI. Darsaut et al. recommended MRI-guided reduction due to their observation of an incidence of 88% cervical disc disruption before closed reduction. Hart et al. also believed that prereduction MRI was crucial, basing his argument on the supine cost incurred if the diagnosis was missed even rarely. So, they recommend the use of prereduction MRI to assess for ventral cord compromise caused by traumatic disc disruption. On the other hand, some authors have found no relationship between findings on prereduction MRI, neurological outcome, or findings on postreduction MRI. et al. based his opinion that MRI was unnecessary in many cases on extensive clinical experience and prospective clinical data. A basic animal research has demonstrated that a relatively brief window of 1 to 3 hours is available, after which injury to the spinal cord caused by mechanical compression may become irreversible. The use of prereduction MRI may delay reduction of the spinal deformity and therefore may delay decompression of the compromised spinal cord. Moreover, prereduction MRI assessment requires the transport of a patient with a highly unstable cervical spine fracture to the MRI suite. Many laboratories work also suggested that early reduction of fracture-dislocation injuries may improve neurological outcome.

In previous reports, the success rate of closed reduction ranged from 30% to 100% (Table 1). Those who failed closed traction reduction should perform open reduction as soon as possible. Many papers reported that closed reduction attempts could not be successful in all cases. Some surgeons suggested that closed reduction was only suitable for conscious and cooperative patients, and for severely injured uncooperative patients, rapid open surgical reduction should be selected. Besides, even after a closed reduction, open surgery with stabilization of the dislocated level is necessary. Since closed reduction requires close neurologic monitoring, imaging to monitor progress is not always feasible. Some surgeons prefer to make an open reduction and stabilization surgery at the same sitting for those patients who failed closed reduction. Hart et al. believed that early reduction of fracture-dislocation injuries may improve neurological outcome.

OPEN SURGICAL REDUCTION TECHNIQUES

The surgical treatment of patients with lower cervical facet dislocation is indicated to improve neurologic deficit, to restore spinal mechanics through correction of a deformity, to stabilize unstable lesions, and to facilitate the patient’s comfort. There are many ways of surgical reduction, including anterior approach, posterior approach, and combined anterior-posterior approach. The choice of surgical way depends on many factors, including the patient’s neurological status, whether it is combined with traumatic disc herniation, the success of closed reduction, unilateral or bilateral facet dislocation, whether there is a vertebral fracture or accessory fracture, and the surgeon’s experience and habits.

1. Anterior-Only Approach Techniques

Anterior-only approach surgery is mainly suitable for patients with structural injuries on the ventral side of the spinal cord, especially for the patients with traumatic disc herniation. Anterior-alone approach is surgically less traumatic owing to its blunt interplane dissections. Infection rate is lower compared with the posterior approach (0.1% to 1.6% vs. 16%). Direct access to the injured intervertebral disc enables decompression via discectomy.

Anterior stand-alone interbody bone grafting and fusion of lower cervical spine fracture dislocation was recognized and widespread following reports by Bailey and Badgley (1960), Cloward (1961), and Verbiest (1962). It was further refined by Bohler (1964), Orozco (1970), Tschern (1971), Senegal (1971), and Gassman and Seligson (1983) with the introduction of plate and screws to tackle earlier complications related to secondary deformity and graft extrusion. In 1973, Cloward reported a new surgical technique and instrument they called "cervical dislocation reducer," which treated a patient with an unusual
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<td>Evans 1961</td>
<td>17 Patients treated by induction of anesthesia and intubation, sometimes with manipulation under anesthesia. Pre-MRI.</td>
<td>Fig. 2</td>
<td>No neurological deterioration noted. All (100%) successfully reduced. 2 Unchanged, 2 died, 13 improved.</td>
<td>Reduction under anesthesia safe and effective.</td>
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<td>Burke and Berryman 1971</td>
<td>41 Patients treated by MUA, light traction followed by induction of anesthesia and intubation, followed by manipulation under anesthesia if necessary. 32 patients treated with traction. 3 treated by traction after traction for stabilization, not reduced. C7-T1 not attempted.</td>
<td>Fig. 2</td>
<td>37 of 41 (90.2%) successfully reduced by MUA. 21 of 25 (84%) reduced with traction alone before anesthetic. 7 Patients were judged too sick manipulation failed for anesthesia and underwent traction for stabilization, not reduced. 2 Cases of neurological deterioration: 1 overdistraction and 1 unrecognized injury.</td>
<td>MUA and traction both safe if proper diagnosis and careful attention paid to radiographs.</td>
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<td>Shrosbree 1979</td>
<td>216 Patients treated by manual traction, tong traction, and open Reduction. Used traction (no weight specified) followed by manipulation under anesthesia if traction failed. Pre-MRI.</td>
<td>Fig. 2</td>
<td>70 of 95 unilaterals reduced (74%), 77 of 121 bilaterals reduced (64%). No neurological morbidity reported. Patients who were successfully reduced improved more often than patients who were not successfully reduced (41% vs. 32% unilateral, 16% vs. 0% bilateral).</td>
<td>Traction followed by manipulation is safe and usually effective, and reduction seems to improve outcome.</td>
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<td>Sonntag 1981</td>
<td>15 patients of bilateral locked facets. Retrospective series. Weight used ranged from 25 (11.3 kg) to 75 lb (34 kg). No MRI done.</td>
<td>Fig. 2</td>
<td>10 of 15 (66.7%) successfully reduced by traction: 6 were reduced with manual manipulation (traction, flexion), 4 were reduced with progressive weight application with administration of sedatives and muscle relaxants.</td>
<td>Stepwise algorithm (traction, manual manipulation, operative reduction) is indicated. Closed reduction by weight application is the preferred method for reduction of deformity.</td>
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<td>Kley 1984</td>
<td>101 patients treated by traction. Unilateral and bilateral, all with neurological involvement. If injury &lt; 24 hr, MUA attempted initially; if reduction fails with maximum of 18-kg weight, MUA performed.</td>
<td>Fig. 2</td>
<td>82 of 101 successfully reduced (4 open reduction, 6 partial reduction accepted, 9 no further attempt owing to poor condition of patient). 37 of 45 incomplete lesions improved, 7 of 56 complete lesions improved. No neurological deterioration.</td>
<td>Traction followed by MUA is safe, usually (80%) effective, and may result in improved neurological function.</td>
</tr>
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<td>Maiman et al. 1986</td>
<td>28 Patients. Variety of treatments offered. 18 Patients had attempt at closed reduction (maximum weight, 50 lb [22.7 kg]). No MRI done.</td>
<td>Fig. 2</td>
<td>10 of 18 reduced with traction. No patient treated by authors deteriorated. 1 Referred patient had an overdistraction injury.</td>
<td>Mixed group of patients and treatments. In general, traction seemed to be safe.</td>
</tr>
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<td>Sabiston et al. 1988</td>
<td>39 patients (Retrospective series). Unilateral and bilateral. All acute injuries. Up to 70% of body weight used.</td>
<td>Fig. 2</td>
<td>35 of 39 patients (90%) successfully reduced. No neurological deterioration. Failures due to surgeon unwillingness to use more weight.</td>
<td>Closed reduction with up to 70% of body weight is safe and effective for reducing locked facets.</td>
</tr>
<tr>
<td>Star et al. 1990</td>
<td>57 Patients (retrospective series). Unilateral and bilateral. Early rapid reduction attempted in all patients. No MRI done before reduction. 1 Patient was a delayed transfer weights up to 160 lb (72.6 kg) (began at 10 lb [4.5 kg]).</td>
<td>Fig. 2</td>
<td>53 of 57 (93%) reduced. No patient deteriorated a Frankel grade. 2 Patients lost root function, 1 transiently. 45% Improved 1 Frankel grade by time of discharge, 23% improved less substantially. 75% of patients required &gt; 50 lb (22.7 kg).</td>
<td>Closed reduction is safe and effective for decompressing cord and establishing spinal alignment.</td>
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(Continued)
Table 1. Summary of close reduction techniques for lower cervical facet dislocation (Continued)

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<td>Hadley et al.,1992</td>
<td>68 Patients (retrospective series). Facet fracture dislocations only. Unilateral and bilateral. 66 Treated with early attempted closed reduction (2 late referrals). Average weights used for successful reduction were between 9 (4.1 kg) and 10 lb (4.5 kg) per cranial level.</td>
<td>Fig. 2</td>
<td>58% of patients had successful reduction. Overall, most patients (78%) demonstrated neurological recovery by last follow-up (not quantified). 7 patients deteriorated during “treatment” (6 improved following ORIF; 1 permanent root deficit following traction)</td>
<td>Early decompression by reduction led to improved outcomes based on fact that patients who did best were reduced early (5–8 hr). No comparison possible between closed reduction and ORIF because of small numbers. 1.2% Permanent deficit (root) related to traction.</td>
</tr>
<tr>
<td>Mahale et al.,1993</td>
<td>341 Patients treated for traumatic dislocations of cervical spine. 15 Suffered neurological deterioration. Variety of treatments used to reduce deformity (4.3%).</td>
<td>Fig. 2</td>
<td>Complete injuries: 6 after OR, 1 after manipulation. Incomplete injuries: 1 after OR, 3 after manipulation, 2 after traction, 1 during application of cast. Radiculopathy: 1 (occurred when tongs slipped during traction). Deterioration delayed in 11 patients.</td>
<td>Numbers of patients subjected to each treatment arm not given. Purely a descriptive article. Neurological deterioration can occur and the early use of MRI or CT myelography is recommended.</td>
</tr>
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<td>Rizzolo et al.,1994</td>
<td>24 Patients (all awake). Prospective study. No fractured facets. All acute injuries. Weights up to 140 lb (63.5 kg) used. No CT or MRI done.</td>
<td>Fig. 2</td>
<td>All 24 reduced. No incidence of neurological deterioration. Manipulation used in addition to weights in 9 patients (when facets perched). Time required ranged from 8 to 187 min.</td>
<td>Reduction with weights up to 140 lb is safe and effective in monitored setting with experienced physicians.</td>
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<td>Lee et al.,1994</td>
<td>210 Patients. Manipulation under anesthesia in 91. Rapid traction-reduction in 119. Retrospective historical cohort. Groups similar except traction group had longer delay to treatment. Weights up to 150 lb (68 kg) used. No CT or MRI done.</td>
<td>Fig. 2</td>
<td>Reduction successful: MUA, 66/91 (73%); RT, 105 of 119 (88%). All failures in RT group were due study to associated fractures or delayed referral. Time to reduction (RT), 21 min. No loss of Frankel grade in either group. 6 MUA and 1 RT had deterioration on ASIA score.</td>
<td>Traction superior to MUA. Both rapid traction and the use of weights up to 150 lb (68 kg) are safe.</td>
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<td>Vital et al.,1998</td>
<td>168 Patients (retrospective series). Unilateral and bilateral. Employed manipulation under general anesthesia in minority of cases. Used relatively light weights (maximum, 8.8 lb [4 kg] plus 2.2 lb [1 kg], per level for maximum of 40 lb [18.1 kg]). All patients operated on immediately after reduction or after failure of reduction. MRIs not done before reduction (although disks noted in 7 patients?)</td>
<td>Fig. 2</td>
<td>43% Reduced by traction without anesthesia (time, 2 hr). 30% Reduced by manipulation under anesthesia. 27% reduced intraoperatively. 5 Patients did not reduce (delayed referral, surgical error). Authors observed no cases of neurological deterioration.</td>
<td>Authors promote their protocol as a safe and effective means for reduction and stabilization of fractures.</td>
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<td>Grant et al., 1999</td>
<td>82 Patients (retrospective series). All closed C-spine injuries with malalignment included. Unilateral and bilateral locked facets. Early rapid closed reduction attempted in all patients. MRI scans obtained after reduction. ASIA and Frankel grades determined on admission at 6 and 24 hr. Weight up to 80% of patient’s body weight.</td>
<td>Fig. 2</td>
<td>Successful reduction in 97.6%. Average time to reduction, 2.1 ± 0.24 hr. Overall, ASIA scores improved by 24 hr following reduction. 1 Patient deteriorated 6 h after reduction (probable root lesion). 46% had disk injury on MRI; 22% had herniation. Disk injury on MRI correlated with cord edema on MRI. Successful reduction in 97.6%.</td>
<td>Closed reduction is effective and safe despite high incidence of MRI-demonstrable disk injuries/herniations.</td>
</tr>
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<td>O’Connor et al., 2003</td>
<td>21 Patients (retrospective case series).</td>
<td>Fig. 2</td>
<td>11 of 21 patients reduced successfully. 1 Patient with transient neurological deficit.</td>
<td>Anterior translation correlates to neurological deficit.</td>
</tr>
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<td>Greg Anderson et al., 2004</td>
<td>45 Patients (of 132), retrospective study to determine a statistical model to predict neurological outcomes.</td>
<td>Fig. 2</td>
<td>88% Successfully reduced with closed reduction. No patient deteriorated neurologically.</td>
<td>Age and initial motor score predict neurological outcome. Timing of reduction did not correlate to outcome.</td>
</tr>
<tr>
<td>Reindl et al., 2006</td>
<td>41 Patients, retrospective case series of patients treated with anterior fusion for cervical dislocations.</td>
<td>Fig. 2</td>
<td>33 of 41 cases reduced successfully. 1 Patient deteriorated during surgery but recovered at 1 year.</td>
<td>Closed reduction successful in most cases. Anterior surgery sufficient for stabilization.</td>
</tr>
<tr>
<td>Darsaut et al., 2006</td>
<td>17 Patients, prospective nonconsecutive series. Reduction under MRI.</td>
<td>Fig. 2</td>
<td>Reduction successful in 11 of 17. 10 of 11 reductions achieved spinal canal decompression.</td>
<td>Traction reduction achieves patients spinal cord decompression.</td>
</tr>
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<td>Tumialán et al., 2009</td>
<td>Case report. MRI and CT done before reduction. Weights up to 60 lb (27.2 kg) used (began at 20 lb [9.1 kg]).</td>
<td>Fig. 2</td>
<td>Successful closed reduction of spondyloptosis of C7 on T1.</td>
<td>Traction reduction of spondyloptosis is safe.</td>
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<td>Miao et al., 2018</td>
<td>40 Patients (retrospective case series). Without vertebral body fracture. MRI and CT done before reduction. Weight ranged from 7–15 kg (began at 5 kg).</td>
<td>Fig. 2</td>
<td>38 of 40 patients completely reduced. Surgery significantly improved neurological function in all patients.</td>
<td>Stepwise algorithm (traction, manipulation, anterior approach operative) is indicated. Closed reduction successful in most cases. Anterior approach surgery sufficient for decompression and stabilization.</td>
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MUA, manipulation under anesthesia; MRI, magnetic resonance imaging; ORIF, reduction and internal fixation; OR, operating room; CT, computed tomography; RT, rapid traction-reduction; ASIA, American Spinal Injury Association.
cervical dislocation successfully. De Oliveira's intervention was performed through an anterior approach using interbody disc spreaders in 1979. Since then, due to the unique advantages of anterior-only surgery, it has become widely popular, and the techniques and instruments have undergone continuous improvement.51-53

In 2000, Ordonez et al.54 reviewed the previous experience and introduced the reduction techniques in detail with the anterior surgical approach in 10 patients with either unilateral or bilateral cervical facet dislocation. After a standard anterior approach discectomy to the cervical spine, vertebral body posts (Caspar or equivalent devices) were placed at approximately a 10° to 20° divergent angle with respect to each other. Angling the vertebral body posts allows for the application of a bending moment when distraction was applied. While the locked facets were disengaged, dorsally directed pressure to the rostral vertebral body into normal alignment could be applied using manual pressure or a curette (or similar device) (Fig. 3).

This technique was improved and supplemented in reports by Reindl et al.52 in 2006 and Ren et al.55 in 2020. There was still application of the Caspar retractor system with pins at the level above and below the subluxation or dislocated segments. The pins were placed in a convergent manner to apply a slight amount of kyphosis during the distraction maneuver. If this was not effective, a laminar spreader (Reindl) or a periosteal detacher (Ren)

Fig. 3. Illustrations of the reduction principle of the Caspar pins or the intervertebral distractor. (A) Placing Caspar pins at approximately a 10° to 20° with respect to each other in the sagittal plane. (B) Permitting the creation of a kyphosis utile the inferior articular process of dislocated vertebrae was just right on top of the superior process of inferior vertebrae, which in turn disengages the facets. (C) An assistance of dorsal force is applied to the rostral vertebra. (D) A disc interspace spreader is used to reduce deformities by placing the spreader in the disc interspace at an angle. (E) Distraction to disengage the facet joints. (F) Rotation to reduce the deformity (dotted vertebra) is then performed.

Fig. 4. Illustrations of the reduction principle of the laminar spreader. (A) Insertion of the laminar spreader which is inserted as far posteriorly as possible but not beyond the posterior wall of the upper vertebra into the cleared disc space. (B) Following by gradual distraction of the disc space under fluoroscopic guidance. (C) Once the facet joints are cleared, the spreader is pushed in a caudal direction to achieve posterior translation of the upper segment.
was inserted at the affected disc space. Distraction and cephalad rotation of the instrument were then used to unlock the dislocated facets (Fig. 4).

In 2014, Du et al.\textsuperscript{56} reported that 17 patients monitored by spinal cord evoked potential were successfully reduced using a trial-model device as a lever. With spinal cord evoked potential monitoring, standard transverse incision was performed. After removal of disc and opening the posterior longitudinal ligament, anterior decompression of spinal cord was completed. Skull traction was maintained until the inferior articular process of dislocated vertebrae was just right on top of the superior process of inferior vertebrae. Then they poked the inferior vertebrae to unlock the facet dislocation (Fig. 5).

Unfortunately, for some patients with delayed treatment or osteoporosis, the distraction force of conventional techniques may not be able to completely disengage the locked facets. In 2017, Zhang\textsuperscript{57} reported the successful reduction of 4 patients with unilateral facet dislocation using the anterior pedicle distraction reduction technique who failed to use the vertebral distractor reduction technique. After anterior discectomy, a pedicle distractor (anterior screw tapper) was implanted from the anterior approach along the axis of the pedicle under fluoroscopy monitoring. The trial model used as a fulcrum was placed into the intervertebral, and the distractor could directly act the force on the locked facet. Then pressed down the spreader to pry and disengage the facet. When the inferior articular process of dislocated vertebrae was just right on top of the superior process of inferior vertebrae, the upper vertebrae was pushed in a caudad direction to achieve reduction (Fig. 6).

In 2017, Li et al.\textsuperscript{58} believed that the conventional anterior approach techniques still had many disadvantages. Attention should be paid to intervertebral instrument insertion depth and the prevention of secondary spinal cord injury caused by instantaneous springing at the time of reduction. They reported a new anterior cervical distraction and screw elevating-pulling reduction technique. The 1st vertebral body superior of the involved segment and the 2nd vertebral body inferior thereto was drilled. After Caspar pins were driven into the drilled holes, Caspar vertebral body retractor was installed and used for longitudinal distraction until a certain tension of surrounding soft tissues was reached. An anterior cervical titanium plate with a length equal to the distance of distraction by the retractor was placed between 2 Caspar pins. Then a half-thread cancellous bone screw of appropriate size was driven into the middle of the plate to pull the

![Fig. 5. Illustrations of the reduction principle of the trial-model device. (A) Insert the trial-model device after removal of the involved intervertebral disc. (B) The weight of traction is increased gradually until the inferior articular process of dislocated vertebrae was just right on top of the superior process of inferior vertebrae. (C) Poke the inferior vertebrae to unlock the facet dislocation (reduction by leverage).](image)

![Fig. 6. Illustrations of the reduction principle of anterior pedicle distractor. (A) After anterior discectomy, a pedicle distractor (anterior screw tapper) is implanted from the anterior approach along the axis of the pedicle under fluoroscopy monitoring. The trial model used as a fulcrum is placed into the intervertebral as far posteriorly as possible but not beyond the posterior wall of the upper vertebra. (B) Press down the spreader to pry and disengage the facet. (C) Push the upper vertebrae in a caudad direction to achieve reduction, when the inferior articular process of dislocated vertebrae was just right on top of the superior process of inferior vertebrae.](image)
dislocated vertebrae until it was pressed against the titanium plate (Fig. 7).

Moreover, Kanna et al. also believed that the simultaneous application of traction and reduction maneuver using the same instrument (Caspar distracter or interbody spreader) did not allow un-locking of the facets. Repeated reduction attempts could be dangerous to the neural tissue and surrounding vascular structures. Hence, they introduced a modified anterior reduction technique used separate instruments in 2017, one for maneuvering the vertebral body and another for interbody distraction, to consecutively treat cervical facet dislocations. After identifying the subluxate segment, Caspar pins were placed on adjacent vertebral bodies parallel to the vertebral endplates in the cranio-caudal plane and gently distracted under fluoroscopy monitoring. In the medio-lateral plane, it was essential to place the pins perpendicular to the plane of displacement in uni-facetal subluxation. Anterior cervical discectomy was performed ensuring complete decompression beyond the posterior longitudinal ligament and till the uncovertebral joints on either side. At this stage, the Caspar pin distracters were used for distraction, and an interbody spreader was placed between the vertebral bodies to sustain the distraction. And then the Caspar distracter was now removed leaving the Caspar pins in the vertebral body. The interbody spreader acted only as the distracter while the Caspar pins were used as “joy sticks.” The pins were moved to provide a transverse rotation or flexion-extension moment, depending on the side of facet subluxation (Fig. 8).

Even if the reduction techniques all above failed, Liu and Zhang also proposed a novel anterior-only surgical procedure including kyphotic paramedian distraction with Caspar

Fig. 7. Illustrations of the reduction principle of screw elevating-pulling. (A) Drill the holes of the Caspar vertebral body retractor to be installed in the 1st superior and the 2nd inferior vertebrae body of the involved segment. (B) Under intraoperative fluoroscopic monitoring, gradually distract until the facet joints are cleared. An anterior cervical titanium plate with a length equal to the distance of distraction by the retractor was placed between 2 Caspar pins, and then implant a suitable length of half-thread cancellous bone screw into the middle vertebral body. (C) Pull the dislocated vertebrae until it was pressed against the titanium plate.

Fig. 8. Illustrations of the reduction principle of the separate instruments. (A) Placement of Caspar pins parallel to the endplates in the sagittal plane and perpendicular to the vertebral body in the axial plane. (B) The Caspar pin distracters are used for distraction, and an interbody spreader is placed between the vertebral bodies to sustain the distraction. (C) The Caspar distracter is removed leaving the Caspar pins in the vertebral body. The interbody spreader act as a distracter while the Caspar pins are used as “joy sticks.” The pins are moved to provide a transverse rotation or flexion-extension moment to reduce.
pins and anterior facetectomy in 2019. The successful rate of reduction was reported to be 100%. Kyphotic Paramedian Distraction with Caspar Pins: The level of the injured cervical spine was exposed through a standard Smith-Robinson approach. Two Caspar pins were placed at approximately a 10° to 20° with respect to each other in the sagittal plane. But the entry point and direction of the upper pin should be biased toward the dislocation side to provide greater distraction forces on the dislocated joint. Thus, the distraction was presented in a kyphotic paramedian manner, which mimicked segmental flexion to help facet subluxation (Fig. 9). This technique could reduce most lower cervical facet dislocations. Anterior facetectomy: This procedure was applied after the failure of the kyphotic paramedian distraction technique. Anteromedial foraminotomy was performed by resection of posterior foraminal portion of the uncovertebral joint. After the nerve root was retracted in a cephalad direction in the neuroforamina, the edge of the dislocated superior facet was broken to achieve reduction. The Caspar retractor was pushed in a posterior direction to achieve posterior translation of upper segment and the broken lower segment (a part of the superior facet) (Fig. 10).

Although anterior-only approach surgery has many advantages (Table 2), for some patients with delayed dislocations, it is difficult to open the facet joints directly with anterior-only approach techniques. In order to release the facet joints, the weight of traction is often given too much to them, which may cause secondary iatrogenic injury to the spinal cord. Especially, for patients with severe vertebral fractures or osteoporosis, they cannot even withstand the force of distracting provided by the spreader. Johnson et al. described a 13% radiographic failure rate for anterior plate fixation in patients with flexion injuries of the subaxial cervical spine in 2004. They postulated that facet fractures might have an impact on the stability of anterior plate fixation. Amorosa and Vaccaro recommended that for patients with severe posterior column injury, the stability was not good enough after anterior surgery alone, which needed to add posterior fixation. Alternatively, the anterior pedicle screw and plate fixation reported by Zhang et al. can also be used, so

Fig. 9. Illustrations of the reduction principle of kyphotic paramedian distraction with Caspar pins. (A) Direction of the upper pin place at the dislocation side in the axial plane. (B) Placing Caspar pins at approximately a 10° to 20° with respect to each other in the sagittal plane. (C) After anterior discectomy, gradual distraction (arrow) under fluoroscopy until disengagement of locked facets was observed on the lateral view. Application of dorsal and rotational force to the rostral vertebra to achieve reduction.

Fig. 10. Illustrations of the reduction principle of anterior facetectomy. (A) Facet locking remains after the kyphotic paramedian distraction. (B) An anteromedial foraminotomy by resection of the posterior foraminal area of uncovertebral joint. Resection of the edge of the dislocated superior facet after the nerve root was retracted cephalad in the neuroforamina. (C) Application of the dorsal and rotational force (arrow) to the rostral vertebra to achieve reduction.
Table 2. Summary of anterior reduction techniques for lower cervical facet dislocation

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</table>
| Cloward | Case report. 1973  
Before the operation, skull traction reduction failed. | Fig. 3 | Successful reduction of spondyloptosis of C7 on T1. | The author describes a method and an instrument for reduction of dislocated cervical vertebrae. |
| de Oliveira et al., 1979 | 12 Patients (retrospective series).  
Firstly, skull traction failed to obtain reduction. Unilateral and bilateral. | Fig. 3 | All 12 (100%) reduced by using Harrington distractor.  
No neurological deterioration occurred. | Reduction of interlocking facets can be easily and safely achieved through an anterior approach if technical details are correctly.  
The ventral surgical procedure is safe and effective. MRI provides an effective means by which to identify traumatic disc herniations, but not necessarily be predictive of the development of disc herniation during attempted closed or open dorsal reduction of cervical facet dislocations. |
| Ordonez et al., 2000 | 10 Patients (retrospective series).  
Ligamentous injury with minimum or no bone disruption.  
MRI and CT done before operation. Unilateral and bilateral. | Fig. 3 | 9 of 10 (90%) reduced by using Caspar pins and a curette or disc interspace spreader.  
8 of 10 revealed satisfactory sagittal plane alignment: 1 residual unilateral perched; 1 dorsal elements splayed and slight focal angulated.  
4 No changed in neurological status and 6 improved. | Reduction of interlocking facets can be easily and safely achieved through an anterior approach if technical details are correctly. MRI provides a means to identify traumatic disc herniation and to guide the surgical approach. |
| Reindl et al., 2006 | 41 Patients (retrospective case series).  
Firstly, Gardner-Wells traction was used to obtain reduction. Both anterior and posterior structures disrupted. CT done before operation. | Fig. 4 | 6 of 8 (75%) reduced by using Caspar pins and a laminar spreader.  
2 of 8 anterior open reductions failed requiring posterior surgery.  
1 Patient deteriorated during surgery but recovered at 1 year. | The author supports a protocol based on anterior surgery. Closed reduction successful in most cases. It is proposed that facet dislocation associated with a pedicle fracture may be an indication for an initial posterior approach. |
| Du et al., 2014 | 17 Patients (retrospective case series).  
Under spinal cord evoked potential monitor. Unilateral and bilateral. | Fig. 5 | All 17 (100%) reduced by using Intraoperative skull traction and a trial-model device. | Anterior cervical surgery monitored by spinal cord evoked potential is effective and safe. |
| Zhang et al., 2016 | 8 Patients (retrospective case series).  
Unilateral and bilateral; with or without facet fracture. Delayed management (7–52 days). Failed in the conventional anterior reduction. | Fig. 10 | All 8 (100%) reduced by anterior facetectomy reduction. No neurological deterioration occurred. | Anterior facetectomy reduction represents a safe and efficacious option for the treatment of cervical facet dislocation. |
| Zhang, 2017 | 15 Patients (case series).  
Unilateral. Delayed management (7–18 days). MRI and CT done before operation. | Fig. 6 | All 15 (100%) reduced: 5 with Gardner-Wells traction, 6 with vertebra spreader, 4 with anterior pedicle distraction. No neurological deterioration occurred. | Stepwise algorithm (closed reduction for patients without traumatic disc herniation, conventional anterior open reduction, anterior pedicle distraction) is indicated. Anterior pedicle spreader reduction represents an efficacious option for the delayed treatment of unilateral cervical facet dislocation. |
| Li et al., 2017 | 86 Patients (retrospective study).  
Distraction-flexion injury with bilateral facet locking. No facet fracture. MRI and CT done before operation. | Fig. 7 | All 86 (100%) reduced: 44 with conventional anterior cervical reduction, 42 with distraction and screw elevating-pulling reduction. No neurological deterioration noted. | Anterior cervical distraction and screw elevating-pulling reduction is a safe and effective operation method for cervical spine fractures and dislocations. |

(Continued)
Table 2. Summary of anterior reduction techniques for lower cervical facet dislocation (Continued)

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<td>Kanna et al., 2018</td>
<td>39 Patients with cervical type C injury. Retrospective series.</td>
<td>Fig. 8</td>
<td>All 39 (100%) reduced: 5 unchanged, 4 died, 30 Improved. One facet was fractured in 17 and both in 5 patients. 13 Patients had a traumatic disc prolapse. No neurological deterioration noted. One patient had a partial loss of reduction.</td>
<td>The modified anterior reduction technique is safe and effective for sub-axial cervical dislocation (AO type C injuries).</td>
</tr>
<tr>
<td>Liu and Zhang, 2019</td>
<td>63 Patients (retrospective series).</td>
<td>Fig. 9</td>
<td>All 63 (100%) reduced: 52 with kyphotic paramedian distraction using Caspar pins, 11 with anterior facetectomy. No neurological deterioration noted.</td>
<td>A novel anterior-only reduction procedure including kyphotic para-median distraction with Caspar pins and anterior facetectomy is indicated.</td>
</tr>
<tr>
<td>Ren et al., 2020</td>
<td>102 Patients (retrospective series).</td>
<td>Fig. 4</td>
<td>99 of 102 (97.1%) reduced by using Caspar pins and a periosteal detacher. 3 of 102 patients needed additional posterior reduction. No neurological deterioration noted.</td>
<td>The anterior reduction and fusion is effective and safe.</td>
</tr>
</tbody>
</table>

CT, computed tomography; MRI, magnetic resonance imaging.

2. Posterior-only Approach Techniques

Posterior surgery is advocated because of its ease of reduction and restoration of the cervical spine alignment. After cervical spine trauma, the biomechanical advantages of posterior fixation and the high stability of cervical pedicle screw fixation have been reported. Especially for patients with posterior column damage, posterior fixation can provide higher stability than anterior fixation. For patients with old facet dislocation, severe vertebral fractures, osteoporosis, ankylosing spondylitis, or comminuted fractures of the facet joint, it may be broken up, the ventral margin of the involved superior facet, or even the whole facet, might have to be removed to complete the reduction. Subsequently, using the same principle of exposure, pedicle screws and so on. In 1967, Alexander et al. first reported the reduction technique assisted by small hammerwork, and placement of a lateral mass plate or pedicle screw rod system. Especially for the reduction techniques with instrument-assisted manipulation, a partial or complete facetectomy, reduction and fusion of the facet joint, which was located near the inferior edge of the rostral facet, care must be taken not to place the tip of the curette more deeply than the inferior edge of the rostral facet to avoid injuring the exiting nerve root, which was located near the inferior edge of the facet. With gentle pressure and a twisting maneuver, the curette tip would slide between the two becomes wider and adhesions could not be broken up, the ventral margin of the involved superior facet, or even the whole facet, might have to be removed to complete the reduction. Subsequently, using the same principle of exposure, pedicle screws and so on. In 1967, Alexander et al. first reported the reduction technique assisted by small hammerwork, and placement of a lateral mass plate or pedicle screw rod system. 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Especially for the reduction techniques with instrument-assisted manipulation, there were various instruments, including facecto...
edge of the rostral facet. The handle of the curette was then gently pulled caudally so that the rostral facet is levered up and over the caudal facet (Fig. 12).

Some authors who considered that some patients of cervical facet dislocation might combine with traumatic disc herniation, proposed that neurological damage would occur if we reduced the injured spine without adequate distraction force. In 2001, Fazl and Pirouzmand described a new technique for dorsal reduction of facet dislocations by use of a modified interlaminar spreader. As the same principle, Nakashima et al. reported the use of bone-holding forceps for posterior reduction in the treatment of 40 patients with cervical fracture-dislocations and traumatic disc herniation in 2010. Firstly, axial traction was gently applied to the injured cervical spine using the Mayfield head
holder before operation. After exposure, in cases of dislocation or subluxation, a distraction force was gradually applied between the spinous processes, using bone-holding forceps, to reduce anterior translation of the proximal vertebra. When the inferior articular process of dislocated vertebrae was just right on top of the superior process of inferior vertebrae, a dorsal force was pulled to the rostral vertebra to achieve reduction (Fig. 13).

If reduction could not be achieved, especially for old cervical subluxation, a high-speed burr might be used to release the locked facets by resection of the tip of the superior articular process of the distal segment. In 2014, Barrenechea reported a 1-stage posterior technique utilized in the reduction of high-grade lumbar spondylolisthesis to reduce an old cervical subluxation. Under neurophysiologic monitoring, the patient was placed in a Mayfield head holder with her neck slightly extended. After opening and exposing the posterior elements, the locked C5–6 facets

Fig. 12. Illustrations of the reduction principle of spinal curette. (A) A curette is placed between the locked facets and the curette is turned so that the cup side docks with the inferior edge of the facet. (B) The curette is gently pull caudally so that the inferior facet is levered up and over the superior facet. (C) Application of dorsal and rotational force to the rostral vertebra to achieve reduction.

Fig. 13. Illustrations of the reduction principle of bone-holding forceps. (A) Two bone-holding forceps were fixed between the spinous processes of the 2 dislocated vertebrae. (B) A distraction force was gradually applied between the spinous processes, using bone-holding forceps, until the inferior articular process of dislocated vertebrae was just right on top of the superior process of inferior vertebrae. (C) Application of a dorsal force to the rostral vertebra to achieve reduction.
Reduction of Lower Cervical Facet Dislocation

Liu K, et al.

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www.e-neurospine.org

Fig. 14. Illustrations of the principle of lifting reduction. (A) Perform a wide bilateral foraminotomy using a high-speed drill to refracture the partially ossified facets and place 6 lateral mass screws. (B) Securing a rod across one side of the screws. (C) Use a rod reducer to bring the middle screw head back toward the rod, thus realign the lateral mass screw heads and reduce the subluxation.

appeared ossified. They performed a wide bilateral foraminotomy using a high-speed drill to refracture the partially ossified facets. And then, they placed 6 lateral mass screws (2 on C4, 2 on C5, and 2 on C6) followed by securing a rod from C4 to C6, spanning the C5 lateral mass screw. Reassembling the technique utilized in the reduction of high-grade lumbar spondylolisthesis with "reduction screws," they used a rod reducer to bring the C5 screw head back toward the rod, thus realigning the lateral mass screw heads and reducing the subluxation (Fig. 14).

Compared with anterior techniques, posterior techniques can directly release the locked facets, which is easier to reduce, and can also remove the compression on the dorsal side of the spinal cord (Table 3). Moreover, posterior pedicle screw fixation has better biomechanical stability which can provide more favorable conditions for long-term bone graft fusion. However, the posterior-only surgery has its serious drawbacks: (1) The herniated intervertebral disc and other soft tissues on the ventral side of the spinal cord cannot be removed before reduction; (2) During the reduction of the posterior approach, the compressive materials may enter the spinal canal and compress the spinal cord, which bring iatrogenic surgical complications; (3) Patients with intervertebral disc destruction may be at risk of poor fusion rate and internal fixation failure due to lack of support for the anterior-middle column. Thus, a further anterior procedure should be considered in cases with canal compromise with traumatic intervertebral disc herniation.

3. Combined Approach Techniques

Combined anterior and posterior fixation/fusion is the most definitive operation to maintain cervical stability after a fracture or dislocation, and this has been demonstrated by many authors in biomechanical experiments or clinical studies. Therefore, it has been more recommended for the treatment of a bilateral dislocation than anterior or posterior fixation/fusion alone, which are more accepted in unilateral dislocation.

Because of reduction via the posterior approach is less challenging than that via the anterior approach, almost all the reduction techniques used by the authors are from the posterior approach mentioned before, and the only difference is the sequence of the surgical approach. There are many ways of combined approach surgery, including anterior-posterior, posterior-anterior, anterior-posterior-anterior, and posterior-anterior-posterior approaches. In 2008, Liu et al. reported a novel operative approach for the treatment of old distractive flexion injuries of subaxial cervical spine. They firstly performed facetectomy and released sufficient soft tissue for reduction, fixed with spinous process wire, and used morselized autogenous cancellous graft harvested from the posterior iliac process to posterior element fusion through a posterior approach. And then an anterior approach surgery was performed for decompression, fusion and internal fixation. Thereafter, there have been more authors who recommend posterior-anterior order used posterior lateral mass screws or pedicle screws for fixation. In recent years, with the advancement of minimally invasive techniques, some authors have used minimally invasive techniques to achieve posterior release and reduction. In 2019, Shimizu et al. reported a fluoroscopy-assisted posterior percutaneous reduction technique for the management of unilateral cervical facet dislocations. The reduction instrument and principle were the same as those reported by Alexander et al. in 1967, except that Shimizu et al. employed...
Table 3. Summary of posterior reduction techniques for lower cervical facet dislocation

<table>
<thead>
<tr>
<th>Study</th>
<th>Cases description</th>
<th>Reduction technique</th>
<th>Results</th>
<th>Conclusions</th>
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<tbody>
<tr>
<td>Alexander et al.†, 1967</td>
<td>Technique note. The operation is indicated only for failed reduction or successful reduction but unstable.</td>
<td>Fig. 12</td>
<td>The reduction is brought about by a small sharp periosteal elevator.</td>
<td>The sooner reduction is carried out after the injury, the easier it will probably be.</td>
</tr>
<tr>
<td>Sonntag†, 1981</td>
<td>15 Patients (retrospective series). Closed reduction is unsuccessful. Bilateral.</td>
<td>No specified</td>
<td>All 15 reduced: 6 with manual reduction, 4 with traction, 5(33.3%) with posterior surgery (no specific technique mentioned). 2 of 5 by posterior operation had increasing neurological deficits.</td>
<td>Steppwise algorithm (traction, manual manipulation, posterior reduction) is indicated.</td>
</tr>
<tr>
<td>Fazl and Pirouzmand†, 2001</td>
<td>52 Patients (technique note). Unilateral and bilateral.</td>
<td>Fig. 13</td>
<td>All 52 (100%) reduced by using a modified interlaminar spreader. No neurological deterioration noted.</td>
<td>This new technique provides a feasible and reliable approach to open reduction of cervical facet dislocations.</td>
</tr>
<tr>
<td>Nakashima et al., 2010</td>
<td>40 Patients (retrospective series). With traumatic disc herniation. Axial traction was gently applied. MRI and CT done before operation.</td>
<td>Fig. 13</td>
<td>All 40 (100%) reduced by using bone-holding forceps or high-speed burr. No neurological deterioration observed. 25% of total cases and 75% of incomplete paralysis cases improved postoperatively by ≥ 1 grade in the ASIA impairment scale.</td>
<td>A 2-step algorithm is proposed. However, the incidence of neurological deterioration after posterior open reduction was zero, even in cases with traumatic cervical disc herniation.</td>
</tr>
<tr>
<td>Bunyaratavej and Khao-roptham†, 2011</td>
<td>5 Patients (retrospective series). Closed reduction is unsuccessful. No anterior compression. Unilateral. MRI and CT done before operation.</td>
<td>Fig. 12</td>
<td>All 5 (100%) reduced by using small straight spinal curettes. No neurological deterioration occurred.</td>
<td>The reported technique is safe and effective. The exiting root and vertebral artery may be at the risk of injury if the curette is placed too deeply during the reduction maneuver. The presence of facet fracture, disk herniation or bone fragments in a neuroforamina are contraindications from this technique.</td>
</tr>
<tr>
<td>Barrenechea†, 2014</td>
<td>Case report. A 2-month standing C5/6 facet dislocation. Without traction.</td>
<td>Fig. 14</td>
<td>The patient was reduced by a posterior technique resembling used in the reduction of high-grade lumbar spondylolisthesis.</td>
<td>This technique could be added into the decision-making option for cases without disk herniation.</td>
</tr>
<tr>
<td>Park et al., 2015</td>
<td>21 Patients (retrospective series). Closed reduction is not attempted. Unilateral and bilateral. With 3 lb (1.4 kg) or 5 lb (2.3 kg) of traction. MRI and CT done before operation.</td>
<td>Fig. 12</td>
<td>All 21 (100%) reduced (7 with traumatic disc herniations) by using a Kocher clamp and a curet. All patients improved neurologically. Disc fragments were successfully removed from the 7 patients with herniated discs.</td>
<td>Posterior open reduction followed by pedicle screw fixation or posterolateral removal of herniated disc fragments is a good treatment option for cervical facet dislocations.</td>
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MRI, magnetic resonance imaging; CT, computed tomography; ASIA, American Spinal Injury Association.

inserted the elevator into the locked facet percutaneously through a small incision above the facet with fluoroscopic assistance, and reduction was achieved by lever action without complications. Subsequently, Yang et al.† reported 4 cases of old subaxial cervical facet dislocations unlocked by the posterior approach under endoscopy followed by anterior decompression, reduction, and fixation.

However, cases have been reported of patients who were neurologically intact before intraoperative reduction, but who experienced a deficit after the reduction. Some authors recommend anterior discectomy first, and if the reduction can be obtained by means of the anterior incision, the anterior column can be grafted and fused using standard techniques. If required, this procedure can be followed by posterior fusion and instrumentation. There have been many studies of anterior-posterior surgery in recent decades. Feng et al.† described a surgical
technique of anterior decompression and nonstructural bone grafting followed by posterior reduction and fixation in 2012. The patients were firstly placed in the supine position. After discectomy through a standard Smith-Robinson’s anterior cervical approach, the Caspar distraction pins were placed divergently in a rostrocaudal fashion and the disc space was distracted 1 to 3 mm to restore near-normal disc height and to correct the kyphosis. A layer of absorbable gelatin sponge was gently filled into one-third of the posterior disc space to protect the exposed spinal cord and prevent dislocation of cancellous bone graft. Afterwards, a layer of morselized cancellous bone grafts from the iliac crest was placed in two-thirds of the anterior disc space, restoring proper intervertebral height and lordosis. Then a layer of gelatin sponge was placed on the surface of bone graft, and the longus colli muscle was opposed over the sponge and stitched carefully. The anterior wound was closed and turn to prone position, and then the posterior reduction and internal fixation of the lateral mass screws were performed (Fig. 15).

On the other hand, if the reduction cannot be succeeded through the anterior approach, a posterior approach must be used to obtain the reduction, which leaves a question of how to address the anterior fusion and instrumentation. Often, after posterior reduction and fusion, the anterior column is approached again to place a bone graft in the disc space and affix a plate, requiring yet a third procedure to complete the treatment. This technique was rarely used in the past because of its complicated procedures and complications. Bartels and Donk reported the anterior-posterior-anterior approach and posterior-anterior-posterior approach for the treatment of delayed traumatic bilateral cervical facet dislocation in 2002.

In order to avoid the third procedure, some authors applied some new means of anterior bone grafting. In 2001, Allred and Sledge described a technique for grafting and instrumentation of the anterior cervical spine before reduction using tricortical iliac crest bone graft secured with a buttress plate. In 2013, Song et al. considered that the buttress plate did not provide safety from graft motion or impingement of the spinal cord since it did not completely fix the interbody graft. Therefore, they reported a modified technique using a prefixed polyetheretherketone cage and plate system. Similarly, Wang et al. reported a novel surgical approach, which was successfully applied to treat 8 cervical facet dislocation patients. After anterior discectomy, a suitable peek frame cage, containing the autologous iliac bone particles or tricalcium phosphate bone substitute, was inserted in the position to fill the interspace. And then, by using 2 screws, an appropriate anterior peek composite buttress plate was added to fix the cage to the lower vertebral body. The anterior wound was closed, and the patient was placed carefully in the prone position for the posterior manipulation. Reduction of the facet dislocations was gradually achieved by gentle distraction of the involved spinous processes with tooth forceps and prying the locked facets with a reset handle, as well as positioning the patient’s neck progressively into extension at the same time. Finally, posterior internal fixation was performed using mass screws or pedicle screws (Fig. 16).

Combined approach surgery has the both advantages of anterior-only approach and posterior-only approach (Table 4). However, the sequence of combined approach is still controversial. The sequences and techniques of surgical decompression and fixation need to be determined according to the specific condi-
Fig. 16. Illustrations of the procedure of the new cage and plate system. (A) The cage containing autologous iliac bone particles or tricalcium phosphate bone substitute placed in the interspace after discectomy and fixed anteriorly with a peek composite buttress plate. (B) Posterior reduction of the facet dislocations was gradually achieved by gentle distraction of the involved spinous processes with tooth forceps and prying the locked facets with a reset handle. (C) Posterior internal fixation was performed using mass screws or pedicle screws after reduction.

Fig. 17. Synthesized diagrammatic flow chart depicting clinical heterogeneity within the treatments of lower cervical dislocation.

tions of the patient. The procedure is more complicated than anterior-only or posterior-only approach, which requires a higher physical condition of patient and results in a higher risk of postoperative infection. Furthermore, multiple changes of position may even cause secondary spinal cord injury.
Table 4. Summary of combined reduction techniques for lower cervical facet dislocation

<table>
<thead>
<tr>
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<tr>
<td>Cybulsky et al., 87 1992</td>
<td>21 Patients (retrospective series). Four-column cervical spine injuries.</td>
<td>No specified</td>
<td>All patients underwent a posterior wiring procedure with bone graft supplementation first. Persistent postoperative instability was identified in each patient.</td>
<td>Combined posterior and anterior fusion or anterior fusion with halo orthosis is required to render the 4-column-injured cervical spine stable.</td>
</tr>
<tr>
<td>Allred and Sledge, 102 2001</td>
<td>4 Patients (retrospective series). Dislocation with a prolapsed disc.</td>
<td>Fig. 16</td>
<td>All 4 patients were treated by using bone graft from the iliac crest with an anterior cervical buttress plate, and subsequent posterior reduction and fusion. No neurologic deterioration occurred.</td>
<td>The reported technique was used successfully in the treatment of patients with irreducible dislocations of the cervical spine.</td>
</tr>
<tr>
<td>Bartels and Donk, 101 2002</td>
<td>3 Patients (case report). Older (&gt; 8 weeks) facet dislocation. Bilateral.</td>
<td>Fig. 15</td>
<td>2 Patients reduced by anterior-posterior-anterior procedure, and the other 1 reduced by posterior-anterior-posterior procedure. No complications occurred.</td>
<td>For delayed (&gt; 8 weeks) traumatic bilateral cervical facet dislocation, the authors propose the following surgical treatment algorithm: (1) complete release of the facets with no attempt at reduction; (2) anterior microdiscectomy with reduction and anterior plate fixation; and (3) posterior (lateral mass or pedicle) fixation.</td>
</tr>
<tr>
<td>Wang et al., 96 2003</td>
<td>3 Patients (retrospective series). Unilateral and 1 bilateral.</td>
<td>Fig. 2</td>
<td>2 Patients with unilateral dislocation reduced by traction, followed by anterior-posterior procedure for fixation and fusion. 1 Patient with bilateral dislocation reduced and fixed by posterior surgery. No complications occurred.</td>
<td>The authors described the use of a minimally invasive approach by means of the tubular dilator retractor system to instrument and fuse the posterior cervical spine.</td>
</tr>
<tr>
<td>Payer, 97 2005</td>
<td>5 Patients (retrospective series). Bilateral. Plain radiographs and CT done before operation.</td>
<td>Fig. 10</td>
<td>All 5 reduced by immediate anterior open reduction and combined anteroposterior fixation/fusion. No surgical complication occurred.</td>
<td>Immediate open anterior reduction of bilateral cervical locked facets and combined antero-posterior fixation/fusion was safe and reliable.</td>
</tr>
<tr>
<td>Liu et al., 90 2008</td>
<td>9 Patients (retrospective series). Old distractive flexion injuries.</td>
<td>Fig. 12</td>
<td>All 9 reduced by a novel posterior-anterior procedure. Neck pain significantly remitted and neurologic function improved. All patients maintained the anatomic reduction until fusion, except for one who lost partial reduction but achieved fusion ultimately.</td>
<td>Using the posterior-anterior procedures, anatomic reduction was successfully achieved for old distractive flexion injuries of subaxial cervical spine.</td>
</tr>
<tr>
<td>Schmidt-Rohlfing et al., 92 2008</td>
<td>Case report. Unilateral fracture-dislocation C7-T1. Involving all 3 columns.</td>
<td>Fig. 12</td>
<td>The patient was successfully reduced by posterior approach, and then followed by anterior bone graft and instrumentation. No complications occurred.</td>
<td>The authors felt that three-column lesion at the cervicothoracic junction necessitated combined posterior-anterior stabilization.</td>
</tr>
<tr>
<td>Feng et al., 100 2012</td>
<td>21 Patients (retrospective series). Accompanied by traumatic disc herniation. 13 Unilateral and 8 bilateral.</td>
<td>Fig. 15</td>
<td>All 21 reduced by an anterior-posterior procedure (anterior discectomy and nonstructural bone grafting, posterior reduction and fusion). No instrument failure and no complications occurred.</td>
<td>Anterior decompression and nonstructural bone grafting and posterior fixation provide a promising surgical option for treating cervical facet dislocation with traumatic disc herniation.</td>
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(Continued)
Table 4. Summary of combined reduction techniques for lower cervical facet dislocation (Continued)

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<tr>
<td>Song et al., 2013</td>
<td>Case report. Bilateral. Fracture-dislocation with a prolapsed disc.</td>
<td>Fig. 16</td>
<td>The patient was successfully treated by using a prefixed polyetherether-ketone cage and plate system (anterior-posterior procedure). No instability or complications.</td>
<td>The author reported a prefixed polyetherether-ketone cage and plate system for the treatment of irreducible bilateral cervical facet fracture-dislocation.</td>
</tr>
<tr>
<td>Wang et al., 2014</td>
<td>8 Patients (retrospective series). Bilateral and unilateral. With traumatic disc herniation. 4 Accompanied with facet fractures.</td>
<td>Fig. 16</td>
<td>All 8 patient was successfully treated by using a new anterior-posterior procedure (after anterior discectomy, a peek frame cage composite buttress plate was used, and subsequent posterior reduction and fusion). No neurological deterioration or instrument failure occurred.</td>
<td>The reported surgical approach is an efficient and safe way for the treatment of traumatic cervical facet dislocations.</td>
</tr>
<tr>
<td>Ding et al., 2017</td>
<td>17 Patients (retrospective series). Old facet dislocations. 10 Unilateral and 7 bilateral. 8 With traumatic disc herniation.</td>
<td>Fig. 15</td>
<td>All 9 reduced by an anterior-posterior procedure (anterior discectomy and morselized bone grafting, posterior reduction and fusion). No neurologic deterioration and no procedure-related complications.</td>
<td>Anterior release and nonstructural bone grafting combined with posterior reduction and fixation provided a safe and effective option for treating old lower cervical dislocations.</td>
</tr>
<tr>
<td>Miao et al., 2018</td>
<td>24 Patients (retrospective series). 16 Unilateral and 8 bilateral. Skull traction was performed with spinal cord evoked potential monitoring.</td>
<td>Fig. 2</td>
<td>All 24 successfully treated by immediate reduction under general anesthesia and combined anterior and posterior fusion. No major complications occurred.</td>
<td>Immediate reduction under general anesthesia and combined anterior and posterior fusion can be used to successfully treat distraction-flexion injury in the lower cervical spine.</td>
</tr>
<tr>
<td>Shimizu et al., 2019</td>
<td>Case report. Unilateral cervical dislocation. Fluoroscopy-assisted</td>
<td>Fig. 12</td>
<td>The patient was achieved posterior percutaneous reduction with an elevator. No complications or neurological deterioration observed.</td>
<td>This novel reduction technique, which contains posterior percutaneous approach and subsequent ACDF, could be a useful option for the management of cervical facet dislocations.</td>
</tr>
<tr>
<td>Yang et al., 2019</td>
<td>4 Patients (retrospective series). Old subaxial cervical facet dislocations.</td>
<td>Fig. 12</td>
<td>All 5 reduced by using the procedure of posterior unlocking combined with anterior reduction. No neurological deterioration or iatrogenic injury occurred. The neck visual analogue scale score and disability index were improved.</td>
<td>For patients with old SCFD, the unlocking of facet joints via the posterior approach under endoscopy followed by anterior decompression, reduction, and fixation is an alternative technique.</td>
</tr>
</tbody>
</table>

CT, computed tomography; MRI, magnetic resonance imaging; ACDF, anterior cervical discectomy and fusion; SCFD, subaxial cervical facet dislocation.

**CONCLUSION**

Although there were many treatment strategies and algorithms in the past, the optimum treatment strategy and algorithm of cervical facet dislocation is still a matter of debate (Fig. 17). Despite agreement in the literature over the role of closed reduction and surgical treatment of these injuries, there are still areas of debate including indications for MRI and MRI timing. The selection of surgical approach depends on a combination of factors, including surgeon preference, patient factors, injury morphology, and inherent advantages and disadvantages of any given approach.42,107

**NOTES**

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Reduction of Lower Cervical Facet Dislocation

Liu K, et al.


Reduction of Lower Cervical Facet Dislocation

Review Article

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The Incidence, Changes and Treatments of Cervical Deformity After Infection and Inflammation

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A healthy cervical spine with normal movement is the basis of many daily activities and is essential for maintaining a good quality of life. However, the alignment, fusion, and structure of the cervical spine can change for various reasons, leading to cervical deformity, mainly kyphosis. Approximately 5%‒20% of spinal infections in the cervical spine cause cervical deformity. The deformity can recover early; however, the disease's long-term existence or the continuous action of abnormal stress may lead to intervertebral fusion and abnormal osteophytes. Many gaps and controversies exist regarding infectious cervical deformities, including a lack of clear definitions and an acceptable classification system thereby requiring further research. Moreover, there is no consensus on the indications for postinfectious cervical deformity associated with Mycobacterium tuberculosis, Staphylococcus aureus, and Brucellosis. Therefore, we reviewed and discussed the incidence, clinical manifestations, changes, and treatment of infectious and inflammatory secondary cervical deformities from common to rare to provide a theoretical basis for clinical decision-making.

Keywords: Cervical deformity, Infection, Cervical spine tuberculosis, Staphylococcus aureus, Brucellosis

INTRODUCTION

The cervical spine is a complex and vital spinal alignment that transmits axial load from the skull, maintains horizontal gaze and average head and neck movement, protects vital neurovascular structures and achieves a maximum range of motion compared to that of the rest of the spine. Therefore, a healthy cervical spine with normal movement is the basis of many daily activities and is essential for maintaining a good quality of life.

The alignment, fusion, and structure of the cervical spine can change for various reasons, causing cervical deformity, especially kyphosis. Cervical kyphosis can be congenital, surgical, or traumatic. In addition, cervical degenerative changes, tumors, ankylosing spondylitis, and other factors may cause cervical kyphosis.

Infection is also a cause of cervical kyphosis, although spinal infection is not very common, accounting for 2%‒7% of systemic skeletal infections. However, with the aging of the population and increased number of immunosuppressant users, the incidence of spinal infections has increased, with 5%‒20% accounting for cervical spine infections. In addition, factors that impair a patient's immune system, such as malignant tumors, malnutrition, diabetes, and acquired immune deficiency syndrome (AIDS), are risk factors for cervical spine infection, similar to those of other infectious diseases.

The deformity can recover early, but the disease's long-term existence or the continuous action of abnormal stress may cause intervertebral fusion and osteophytes. This may result in kyphosis, and the anterior edge of the spinal cord will show neurological symptoms due to compressions, such as Hoffman's sign and tendon hyperreflexia. Some patients have permanent neurological impairment despite antibiotic treatment. In addition, the cervical spine may impinge on the spinal cord owing...
to kyphosis during extension and flexion, resulting in cervical spinal cord injury.11

Many gaps and controversies exist regarding infectious cervical deformities, including a lack of clear definitions and an acceptable classification system thereby requiring further research. Moreover, there is no consensus on the indications for conservative treatment, surgical methods, or postoperative drug treatment for its various types. Therefore, this article reviewed and discussed the primary classification, clinical manifestations, diagnosis, and treatment of infectious secondary cervical kyphosis to provide a theoretical basis for clinical decision-making.

CERVICAL DEFORMITY ASSOCIATED WITH MYCOBACTERIUM TUBERCULOSIS

1. Mycobacterium tuberculosis

Mycobacterium tuberculosis (MTB), the etiologic agent of tuberculosis (TB), is a severe global public health challenge, causing significant morbidity and mortality worldwide.12 In India, Charaka and Sushruta named it “Yakshama” in the oldest medical paper ever written from 1,000 to 600 BC.13 DNA evidence suggests that MTB was contemporary with early hominids in East Africa; therefore, it has coevolved with Homo sapiens.14 MTB is mainly found inside immune cells that house or destroy most other bacteria.15 MTB can counteract a complex and dynamic range of host defenses, including acidification, reactive oxygen, nitrogen intermediates, and antimicrobial peptides.16 In addition, MTB can escape into the cytoplasmic matrix and may encounter additional environmental pillars.17

2. Cervical Spine Tuberculosis

Spinal tuberculosis is considered secondary, caused by the hematogenous dissemination of TB from the primary lesion.18 It mostly affects the thoracolumbar junction, followed by the lumbar and cervical vertebrae.19 In 2011, Sabat et al.20 reported Os odontoideum at the craniocervical junction (CVJ), a rare preference site for MTB. Cervical tuberculosis has a greater likelihood of neurological deterioration, instability and progressive malalignment owing to its smaller canal dimension, proximity to the vertebral artery and other vital structures, unique faceted architecture, higher mobility, and lordotic alignment.21,22 Managing cervical spine tuberculosis (CSTB) with kyphosis and delayed presentation is a great challenge.23 With the accumulating evidence, more surgeons have focused on cervical tuberculosis deformity changes in recent years. Many surgical strategies and approaches have been undertaken to treat CSTB kyphosis.

3. Epidemiology

In 2021, the World Health Organization (WHO) estimated 10 million new TB cases. They mostly occurred in the WHO regions of Southeast Asia (43%), Africa (25%), and the Western Pacific (18%). Among all patients with TB, 8.0% were people living with human immunodeficiency virus/AIDS. The global number of TB deaths has increased from 1.2 to 1.3 million compared to that in 2019 (Global tuberculosis report 2021. Geneva: WHO; 2021. License: CC BY-NC-SA 3.0 IGO). Of the 6.3 million new TB cases confirmed by the WHO in 2017, 16% were extrapulmonary, ranging from 8% in the Western Pacific region to 24% in the Eastern Mediterranean region (Global tuberculosis report 2018. Geneva: WHO; 2018. License: CC BY-NC-SA 3.0 IGO).

According to the National Tuberculosis Clinical Center in China, skeletal tuberculosis is the main form of extrapulmonary tuberculosis in hospitalized patients, accounting for 41% of all extrapulmonary TB cases.24 However, spinal TB remains the most common form of skeletal TB, representing 50%–62.2% of all osteoarticular locations.25,26 CSTB is divided into CVJ tuberculosis (CVJT) and subaxial cervical tuberculosis (SACTB) constituting 0.3%–1% and <3% of all spinal TB cases, respectively.27 Three patients (5%) who underwent ambulatory chemotherapy for spinal tuberculosis developed a deformity exceeding 60°.28 The deformity was the chief complaint in 22 of the 27 patients (81.5%) who underwent cervical dorsal junction operation.29

4. Pathophysiology

CSTB in adults is more localized and less purulent than in pediatric patients.30 Tuberculosis is characterized by granulomatous inflammation. Granulomas are organized aggregates of lymphocytic infiltrates and epithelioid cells, which may coalesce to form classic Langhans giant cells, eventually leading to affected tissue necrosis and cold abscesses formation.31 Regarding the deformity of CVJT, the disease progresses to involve the atlantoaxial joint by destructive necrosis and inflammation, resulting from the extension of the inflammatory reaction.32 Regarding the deformity of SACTB, the cervical spine eventually develops instability and deformity due to progressive destruction of the vertebral body caused by TB.33

5. Clinical Presentation

CSTB involves the anterior part of the cervical vertebral body, with fewer posterior elements.34 CSTB kyphosis tends to be less of a concern than that of chest or thoracolumbar spine TB be-
cause the weight transmission line in the cervical spine is posterior to the vertebral body, and vertebral loss is well tolerated in the cervical spine.36 Regarding the deformity of CVJTB, severe torticollis is a characteristic presentation of atlantoaxial TB, which was occasionally reported as occipital condyle syndrome or post-infectious atlantoaxial rotary instability.33,37 Regarding the deformity of SACTB, Luan et al.38 measured the local kyphosis angle of 25.1° ± 8.3° in 23 SACTB patients. In contrast, Chen et al.39 measured the local kyphosis angle of 73.6° ± 13.1° in 10 patients with upper thoracic or cervicothoracic junction. Cervical spine immaturity and flexibility are the reasons why children are prone to rapid and severe malformation progression after a vertebral collapse. An unstable spine was classified as retropulsion, subluxation, lateral translation, or toppling.40 Children younger than 8 years had more significant deformities at presentation than that of older children and adults, meaning they were more prone to collapse in the acute phase of the disease and the progression of the deformity after widespread disease. Before age 8, the fulcrum of normal cervical motion is in the C2–3 disc space, where kyphosis progresses owing to gravity, macrocephaly, and increased flexion moments.30

A medical team in China reported that the prevalence of neurological deficits was 73.8% in SACTB and 45% in CVJTB.41 In the early stage, abscess, inflammatory tissue, sequestrum, and instability lead to direct compression causing a neural compromise in the active stage.42 At the healed stage, myelomalacia, traction, or compression injury to the cord at the apex of the deformity, pseudoarthrosis, and intervertebral instability contribute to neurological deficit.43 The Japanese Orthopedic Association (JOA) score was 11.5 points on average, and the mean visual analogue scale score was 4.5, indicating that patients with CSTB kyphosis often experience limitations in neck mobility and pain.44 Tenderness had a high sensitivity of 97.6% for identifying abscess, which meant that if there was an abscess, tenderness was likely to occur at the abscess location.45 The systemic complaints were also a common presentation in CSTB patients with a cervical deformity, such as fever (18%), night sweats (24%), cervical lymphadenopathy (17%), dysphagia (5%), wheezing (7.5%), and airway impairment.29,45

6. Sagittal Alignment Changes of CSTB Deformity

As early as 1995, spine surgeons were aware of the importance of cervical and thoracic sagittal alignment in the adolescent population,46 which prompted researchers to study the complex area of cervical alignment further. For asymptomatic normal children, Lee et al.47 proposed that the C2–7 Cobb angle of Asian asymptomatic children was -4.8° ± 12°, showing a large variation in the cervical spine curvature. We believe that cervical lordosis is a normal physiological curvature; however, studies have found that kyphosis or a straight neck is common in asymptomatic children.48

The C2–7 Cobb angle (8.15° ± 26.62° vs. -3.00° ± 15.96°) of patients with CSTB deformity who underwent surgery was more significant than those who could be treated conservatively. At the same time, there was no significant difference in the C2–7 sagittal vertical axis (SVA) (16.10 ± 7.74 mm vs. 16.18 ± 13.22 mm) between them.49 The whole sagittal alignment changes in patients with CSTB kyphosis who underwent staged combined posterior anterior surgery were reported by Luan et al.50 The SVA (35.19 ± 10.69 mm) and coronal balance distance (22.58 ± 7.59 mm) was greater than the normal values, indicating a coronal and sagittal imbalance. Surgery can improve the cervical spine sagittal alignment; the C0–2, C2–7, and local Cobb angles, T1 slope, C2–7 SVA, and CGH–C7 SVA were corrected remarkably after surgery.51

7. Management of Cervical Deformity Associated With Mycobacterium tuberculosis

1) Multidrug antitubercular treatment

The fundamental principle in treating spinal tuberculosis is obtaining culture samples to develop optimal protocols.51 Prompt antitubercular chemotherapy is required to prevent complications.52 Multidrug antitubercular treatment (ATT) is the mainstay treatment for complicated and uncomplicated CSTB,44 and the development and combination of anti-TB chemotherapy have made it possible to reduce mortality. Multidrug ATT remains the cornerstone of spinal tuberculosis treatment is essential, as varying categories of bacilli exist in a lesion.53 The first-line ATT include isoniazid, rifampicin, pyrazinamide, ethambutol, and streptomycin. The WHO recommends 9 months of treatment via 2 phases—intensive phase (isoniazid, rifampicin, pyrazinamide, ethambutol, or streptomycin administered for 2 months) and continuation phase (isoniazid and rifampicin for 7 months).54 There is still no consensus on the definition of the healing standard of spinal tuberculosis, and the time to stop ATT treatment. The consensus of Chinese experts for the diagnosis and treatment of tuberculosis recommends the anti-tuberculosis treatment of 12–18 months,55 while India's guidelines for the diagnosis and treatment of tuberculosis recommend the anti-tuberculosis treatment of 10–16 months.56 Kanamycin, amikacin, capreomycin, levofloxacin are recommended, as the second-line ATT drugs, are recommended to be used judiciously.
ly due to more side effects and cost.\textsuperscript{37}

However, it is inadequate for treating CSTB kyphosis in the
presence of spinal instability, progression of neurological de-
cits, and conservative treatment failure.\textsuperscript{28} CSTB kyphosis man-
agement is divided into conservative and surgical treatments,
which are challenging and controversial. The spinal immobi-
lization was also considered for patients with CSTB kyphosis
during the chemotherapy to obtain the stability and prevent long-
term deformity.\textsuperscript{33,39}

At least 2–4 weeks of antituberculosis therapy (isoniazid 300
mg, rifampicin 450 mg, ethambutol 1,200 mg, and pyrazinamide
1,500 mg) is recommended before spinal tuberculosis patients
undergo surgery. Its duration may make it possible to stabilize the
disease status and restore body temperature, erythrocyte sedi-
mation rate (ESR), C-reactive protein levels (CRPs), and other indi-
cators to their acceptable ranges.\textsuperscript{60} The symptoms of TB poison-
ing were significantly controlled, when ESR $<$ 50 mm/hr, and
CRP $<$ 30 mg/L, surgical treatments of CSTB would be performed.

2) Surgical treatments and technique of CSTB kyphosis

The operation of cervical deformity after infection and in-
flammation were outlined in Fig. 1. Indications for surgery of
patients with CSTB include progressive neurological worsen-
ing, significant static neurological deficits, kyphotic deformity,
spinal instability, bowel bladder involvement, no response to
chemotherapy, and large paraspinous abscess.\textsuperscript{24,36,38,50,61}

Regarding atlantoaxial TB, atlantoaxial and occipitocervical
fusion are the most preferred globally.\textsuperscript{62} If atlantoaxial TB is ir-
reducible or rotatory, posterior distraction with stabilization or
a combined anteroposterior approach should be undertaken.
Transoral debridement, lesion drainage, fusion with bone graft
with stabilization via external fixation, and other minimally in-
vasive surgeries are the primary surgical treatments.\textsuperscript{60} Twenty
patients with atlantoaxial TB who underwent anterior transoral
debridement combined with posterior fixation and fusion were
analyzed to find that the satisfaction rate was 100%, and no se-
vere complications were documented during follow-up.\textsuperscript{61}

Fig. 1. From common to rare: causes and indications of the operation of cervical deformity after infection and inflammation.
### Table 1. Basic characteristics of comparison studies that evaluated the efficacy of different surgical approaches in CSTB patients

<table>
<thead>
<tr>
<th>Study</th>
<th>Year</th>
<th>Illness</th>
<th>Object</th>
<th>Comparison</th>
<th>No. of patients</th>
<th>Mean age (yr)</th>
<th>Preoperation cervical kyphosis (°)</th>
<th>Postoperation cervical kyphosis (°)</th>
<th>Inclusion criteria</th>
<th>Result</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yin et al. (2017)</td>
<td>2017</td>
<td>CSTB</td>
<td>To evaluate the clinical outcomes of 3 surgical techniques in CSTB patients, and to determine the most appropriate approach for CSTB patients.</td>
<td>Anterior group</td>
<td>37</td>
<td>36.9±16</td>
<td>14.5±7.5</td>
<td>4.6±1.8</td>
<td>Patients diagnosed with CSTB and confirmed by laboratory and radiographical exams. Patients conservatively treated were excluded from the cohort.</td>
<td>All patients showed improvements in neurological status and clinical outcomes. ESR returned to normal in all patients. Kyphosis deformity in all patients was significantly restored.</td>
<td>All 3 surgical methods were viable management options for CSTB. Individualized surgical strategies should be formulated according to the different characteristics of CSTB patients.</td>
</tr>
<tr>
<td>Zeng et al. (2015)</td>
<td>2015</td>
<td>CTSTB</td>
<td>To compare the efficacy and feasibility of 3 surgical techniques for the treatment of CTSTB</td>
<td>Anterior group</td>
<td>20</td>
<td>53.4±5.2</td>
<td>21.4±8.1</td>
<td>9.4±4.8</td>
<td>Patients diagnosed with CTSTB by nonspecific laboratory findings and by radiological findings.</td>
<td>Three surgical approaches all improved the kyphosis deformity and neurological function significantly. A-P group experienced longer mean operation time, more blood loss, and longer hospitalization days. Complications were most prevalent in the anterior group.</td>
<td>The anterior approach should be limitedly used for severe CTSTB. The A-P approach had got satisfactory clinical and radiographic outcomes, but with larger trauma and more complications, which should be reservedly performed for mild CTSTB. Posterior surgery can significantly improve clinical results and obviously relieve postoperative complications.</td>
</tr>
<tr>
<td>Wu et al. (2020)</td>
<td>2020</td>
<td>CTSTB</td>
<td>To evaluate the efficacy of three surgical approaches for the treatment of CTSTB.</td>
<td>Anterior group</td>
<td>33</td>
<td>23.85±14.92</td>
<td>13.82±4.92</td>
<td>8.15±2.40</td>
<td>Patients diagnosed with CTSTB. Patients were excluded because of conservative therapy, complicated spinal tumor, active pulmonary tuberculosis, and poor tolerance or compliance.</td>
<td>Three surgical strategies significantly improved kyphosis. There were significant differences before and after treatment for VAS, NDI, and JOA score.</td>
<td>Anterior approach surgery for the treatment of CSTSTB showed excellent efficacy and fewer complications. The choice of operation for CSTSTB should be selected based on the pathological changes, scope, and general physical condition of the patient.</td>
</tr>
<tr>
<td>Zhu et al. (2018)</td>
<td>2018</td>
<td>CTSTB</td>
<td>To explore the selection of surgical treatment approaches for CTSTB through a 10-year case review.</td>
<td>Anterior group</td>
<td>19</td>
<td>35.4</td>
<td>34.7±6.8</td>
<td>10.2±2.4</td>
<td>Patients diagnosed with CTSTB.</td>
<td>The kyphosis angle and NDI and JOA scores were significantly changed. No severe postoperative complications occurred, and patients' neurologic function was improved in various degrees.</td>
<td>Single-stage cervical anterior approach with or without partial manubriotomy is capable of complete debridement for tuberculosis lesions, which is relatively simple, and induces less morbidity. The manner of fixation should be selected based on the anatomical relation of the suprasternal notch and the diseased segments as revealed on sagittal MRI images.</td>
</tr>
</tbody>
</table>

CSTB, cervical spinal tuberculosis; A-P group, anterior combined with posterior approach; ESR, erythrocyte sedimentation rate; CTSTB, cervicothoracic tuberculosis; VAS, visual analogue scale; NDI, neck disability index; JOA, Japanese Orthopedic Association; MRI, magnetic resonance imaging.
Regarding SACTB, 1-stage anterior debridement, instrumentation and fusion, and single posterior instrumentation followed by chemotherapy are practical to correct the cervical deformity of the patient, whose JOA score improved to 9–12 postoperatively. In 2020, Jia et al. retrospectively analyzed the safety and efficacy of early surgical management of spine tuberculosis in patients with neurological deficits. They found that standard anti-TB treatment for < 4 weeks may relieve spinal cord compression and benefit early recovery. Anterior debridement and bone grafting with fusion using internal fixation combined with anti-TB chemotherapy could eradicate the lesion, decompress spinal cord compression, and correct kyphotic deformity to restore spinal sagittal balance. Using titanium cages, plates, and screws for spinal fixation stabilizes the spine and corrects the deformity. Studies have reported no risk of graft rejection or inflammation. Pan et al. suggest that more attention should be paid to realigning the cervical spine, particularly to restore the C2–7 SVA, the most influential factor correlated with outcome improvement when debridement, decompression, and reconstruction were performed. Fifteen articles with a total of 456 patients were evaluated in a meta-analysis, and the results showed that radical debridement might cause progressive kyphosis during children’s growth.

3) Surgical approaches for CSTB kyphosis

Direct access to the lesion, better decompression, and tissue sampling in the anterior approach provides biomechanically robust options for stabilization in the posterior approach. Anterior debridement and decompression followed by bone grafting and instrumentation have been widely applied as the gold standard treatment. Garg et al. presented an anterior-posterior-anterior procedure for severe, rigid, posttubercular cervical kyphosis, which included an anterior approach to osteotomize the fused vertebral body mass and decompress the spinal cord, a posterior approach to osteotomize the fused facets and decompress the cord dorsally, and an anterior approach to replace the corpectomy cage with a larger one supplemented.

For the choice of surgical approach, spine surgeons mainly focus on the anterior, posterior, and posterioranterior combined approaches. Table 1 summarizes the four studies that evaluated the efficacy of different surgical approaches in CSTB patients. The average operation time, blood loss, and length of hospital stay for patients with CSTB who underwent the posterioranterior combined approach were greater than those who underwent the anterior or posterior approach. Zhu et al. compared patients with CSTB who underwent a single-stage anterior- or debridement and instrumentation approach with or without additional posterior fusion and reported that either approach could complete debridement for tuberculosis lesions. Yin et al. found that postoperative deformities and neurological deficits significantly improved as did the visual analog pain scale at the last follow-up in the anterior, posterior instrumentation, anterior, and posterior groups (p < 0.05). Direct access to the lesion enables better decompression, and tissue sampling in the anterior approach provides biomechanically robust options for stabilization in the posterior approach. Complications were most common in the anterior and posterioranterior combined approaches and least common in the posterior approach.

There was no significant difference among the three approaches in correction loss and bone fusion at the last follow-up (p > 0.05).

CERVICAL DEFORMITY ASSOCIATED WITH STAPHYLOCOCCUS AUREUS

1. Epidemiology

Staphylococcus aureus is the main pathogenic bacterium causing cervical spine infection, with an insidious onset and a lack of specificity in clinical manifestations. Pathogens can reach and infect related vertebrae in three ways: (1) hematogenous spread from the source of infection, (2) external infection caused by trauma (injury or surgery), and (3) diffusion of neighboring tissues. S. aureus has the unique ability to invade, customize, and grow in the bones. Once the bone is infected, it activates osteoclasts, increases bone resorption, and destroys the vertebral body bone, further destroying the vertebral body and causing cervical instability. In severe cases, this can lead to cervical kyphosis. S. aureus vertebral infections are common in the lumbar vertebrae but are rare in the cervical vertebrae, accounting for only 11% of spinal infections. Other pathogenic bacteria include Escherichia coli, Streptococcus, Pneumococcus, Salmonella, etc. E. coli can be found in patients with urinary tract infections but rarely invades the cervical spine. Streptococcus and Anaerobes are commonly found in patients with diabetes, AIDS, malignant tumors, malnutrition and other diseases that damage the immune system.

2. Pathophysiology and Clinical Presentation

The rich blood supply of the spine makes the spine highly susceptible to infection. Since the arteries of one segment can supply both the lower part of the upper vertebra and the upper part of the lower vertebra, spinal infections usually involve 2 adjacent vertebrae. The spinal venous system has slow blood
flow, which can be stagnant or retrograde, so the pathogenic bacteria can also spread through the venous system. In addition, the prevertebral pharyngeal vein can be a potential route for bacterial transmission during head and neck infections, thereby invading the cervical vertebra. As the most dominating pathogen of cervical spine infection, *S. aureus* has multiple pathogenic mechanisms during bone infection. An article from the University of Rochester, USA, published in Nature, identified intra-cellular infections within osteoblasts, osteoclasts, and osteocytes as possible sources of *S. aureus* persisting during osteomyelitis. *S. aureus* can also achieve immune escape by invading the osteocyte-lacunar tubule network. In addition, *S. aureus* has the unique ability to chronically infect the bone marrow by forming robust SACs during osteomyelitis and soft tissue. SACs at the bone infection site are often used to diagnose and classify osteomyelitis stages because they can significantly increase the severity of the infection by restricting blood flow to the area.

The possible multiple pathogenic mechanisms of bone infection by *S. aureus* were showed in Fig. 2.

Neck or back pain, including fever, chills, weight loss, and other common symptoms associated with bacterial infection, are the general manifestations of cervical *S. aureus* infection. Within 2 weeks to 3 months after infection, the affected vertebral endplate is irregularly destroyed or loses its normal contour, which may progress to vertebral collapse in the later stage, leading to local kyphosis of the cervical spine. In 2010, Walter et al. presented five patients with cervical suppurative infection, one of whom had a 2.7° cervical kyphosis, while the other four patients had varying degrees of loss of lordosis (0.2°–3.1°). However, Abumi et al. reported a case of cervical kyphosis caused by a suppurative infection of the cervical spine, with a local kyphosis Angle of 35° at the affected site. In addition, in the study of O'Shaughnessy et al. of patients with rigid cervical kyphosis, they included a patient with cervical kyphosis secondary to a suppurative infection, with a kyphosis angle of 38°. With the progress of cervical kyphosis, patients often complain of different degrees of neurological symptoms such as upper limb numbness and pain, lower limb numbness, walking instability due to changes in the cervical spine force line, pathological changes in soft tissues around the forehead caused by infection, and spinal nerve roots compression.

### 3. Diagnosis

The diagnosis of cervical kyphosis secondary to infection is based on clinical features, imaging, bacteriology, and pathology. The literature shows that 42.6%–81.3% of the patients with suppurative spondylitis do not have an increase in white blood cells, so it can be used as a general examination but has little effect on...
A Review About Postinfectious Cervical Deformity

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4. Management of Cervical Deformity Associated With Staphylococcus Aureus

1) Antibiotic treatment of suppurative cervical spondylitis

The diagnosis of the pathogen should be confirmed as soon as possible. According to the results of CT-guided needle biopsy and blood culture, the pathogen and drug sensitivity should be determined. And Broad-spectrum antibiotics should be used in patients with unknown pathogenic bacteria. It was believed that antibiotics such as rifampicin and levofloxacin can be used when spinal stability is not destroyed. Rifampicin can eliminate S. aureus in osteoblasts. Studies have shown that rifampicin and levofloxacin have good therapeutic effects against S. aureus, the most common pathogen, and rifampicin is considered to be able to completely eliminate S. aureus in osteoblasts. Most studies recommend 6 to 8 weeks of intravenous antibiotics followed by 6 weeks of oral antibiotics. However, Seyman et al. found that intravenous antibiotics for more than 6 weeks, followed by oral antibiotics for another 8 weeks, could significantly reduce the recurrence of infection.

2) Surgical approaches for kyphosis associated with S. aureus

Medical therapy alone is less effective when patients present with progressive neurological impairment, with or without cervical instability (cervical kyphosis), and surgical treatment is needed. The objectives of surgical treatment include deformity correction, horizontal gaze restoration, the release of neurospinal compression, and restoration of sagittal balance. Table 2 summarizes the three studies that evaluated the efficacy of different surgical approaches in patients with cervical spine infection. Anterior debridement with bone graft fusion can be performed for cervical kyphosis with focal infection. Talia et al. indicated that 1-stage debridement and fusion has the dual benefits of eliminating infection and stabilizing the spine. And the implantation of titanium cages after debridement is safe and effective. Hann et al. also proposed that cervical kyphosis without ankylosis should be preferentially treated with anterior release and bone grafting, with or without posterior fusion. However, when the infection involves multiple segments, complete lesion removal, and the anterior bone graft fusion destroy the growing ability and stability of the anterior spine. The combination of the anterior and posterior approaches can remove the lesion and resolve spinal instability, preventing the recurrence and aggravation of cervical kyphosis caused by the imbalance of anterior and posterior cervical growth in the long term after the operation.

3) Surgical treatments and technique of kyphosis associated with S. aureus

In the study by Papavero et al., 23% of cervical spine surgery patients underwent revision surgery due to infection. Therefore, it is crucial to avoid the recurrence of infection after surgery. Chen et al. describe a case of cervical kyphosis secondary to pyogenic infection who underwent anterior C5 and C6 vertebral resection due to progressive kyphosis and neurological impairment. In addition, it is the first report on the use of antibiotic polymethylmethacrylate (PMMA) strut in suppurative spondylitis. The PMMA strut mixed with antibiotics was inserted into the injured cavity before the end of the surgical procedure, and the wound was closed primarily without drainage. Antibiotics mixed with PMMA strut are released into the surrounding soft tissue, increasing the local antibiotic concentration. After the surgery, the patient’s cervical spine was stable, and the symptoms were relieved. During follow-up, no recurrence of infection occurred in the patients, but 9.8% of the patients experienced subsidence of the struts.

Annular osteotomy is required for rigid cervical kyphosis,
Table 2. Basic characteristics of comparison studies that evaluated the efficacy of different surgical approaches in pyogenic infection patients

<table>
<thead>
<tr>
<th>Study</th>
<th>Year</th>
<th>Illness</th>
<th>Object</th>
<th>No. of patients</th>
<th>Mean age (yr)</th>
<th>Preopera-</th>
<th>Postopera-</th>
<th>Inclusion criteria</th>
<th>Result</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>O'Shaughnessy et al.</td>
<td>2008</td>
<td>Fixed cervical kyphosis with myelopathy</td>
<td>To investigate clinical and radiographic outcomes following the surgical treatment of fixed cervical kyphosis with myelopathy</td>
<td>16</td>
<td>52</td>
<td>+38</td>
<td>-10</td>
<td>Fixed kyphosis is defined as patients with less than 50% reduction of the deformity on dynamic flexion-extension radiographs and segmental ankylosis visualized on thin-cut CT scan.</td>
<td>The mean preoperative cervical Cobb angle as measured from the C2-7 was +38° and improved to -10° at final follow-up. The mean Nurick score improved from 2.4 before surgery to 1.5 at the time of follow-up. Solid bony arthrodesis and maintenance of correction occurred in all patients; The treatment of fixed cervical kyphosis with myelopathy using circumferential spinal osteotomies and instrumented reconstruction is technically demanding; however, restoration and maintenance of a neutral or lordotic cervical profile and excellent clinical outcomes are achievable.</td>
<td></td>
</tr>
<tr>
<td>Mavrogenis et al.</td>
<td>2016</td>
<td>Spondylodiscitis</td>
<td>To evaluate the outcome of a series of patients with spondylodiscitis aiming to answer when and how to operate on these patients.</td>
<td>153</td>
<td>57</td>
<td>/</td>
<td>/</td>
<td>Patients with infections of the spine from variable pathogens</td>
<td>Orthopedic surgical treatment was necessary for 5 Staphylococcus aureus of the 153 infectious patients. Improvement or recovery of the neurological status was observed post-operatively in all patients with preoperative neurological deficits. Complications related to spinal instrumentation were not observed in the respective patients. The anterior approach provides direct access and improved exposure to the most commonly affected part of the spine. Spinal instrumentation is generally recommended for optimum spinal stability and fusion, without any implant-related complications.</td>
<td></td>
</tr>
<tr>
<td>Talia et al.</td>
<td>2015</td>
<td>Vertebral osteomyelitis and epidural abscess</td>
<td>Aims to assess the results of single-stage instrumentation and fusion at the time of surgical debridement of spinal infections; vertebral osteomyelitis or epidural abscess.</td>
<td>7</td>
<td>69</td>
<td>/</td>
<td>/</td>
<td>Patients with vertebral osteomyelitis and epidural abscess</td>
<td>There was a significant reduction in pain scores compared to preoperatively. All patients with neurological deficits improved post-operatively. Despite introduction of hardware, no patients had a recurrence of their infection in the 12-month follow-up period. Single-stage debridement and instrumentation appeared to be a safe and effective method of managing spinal infections. The combination of debridement and fusion has the dual benefit of removing a focus of infection and stabilising the spine. The current series confirms that placing titanium cages into an infected space is safe in a majority of patients. Stabilisation and correction of spinal deformity reduces pain, aids neurologic recovery and improves quality of life.</td>
<td></td>
</tr>
</tbody>
</table>

CT, computed tomography.
where the Cobb angle changes by <10° between flexion and extension. In the study of Abumi et al.,54 13 patients with rigid cervical kyphosis underwent circular osteotomy and posterior fusion, and the kyphotic angle was corrected from +31° preoperatively to +1° at the last follow-up. No complications related to internal fixation and bone graft occurred in all patients after the operation. Brian et al.75 also performed circular osteotomy for rigid cervical kyphosis patients in the study. The average improvement was 48°, from +38° to -10°, accompanied by a low incidence of internal fixation-related complications. Although this is a successful surgical strategy, the high risks associated with osteotomy limit the application of this technique.

Nerve injury is the most severe complication of the surgical treatment of cervical kyphosis. Therefore, intraoperative electrophysiological detection plays an essential role in reducing the occurrence of nerve injury.95 Once there is a change in the somatosensory evoked potential and motor evoked potential, the compression site of the spinal cord should be actively searched for decompression. Supposing that the high spinal cord tension leads to electrophysiological changes, the scope of distraction should be appropriately reduced to avoid the excessive pursuit of the kyphosis correction effect. It has been shown that excessive pursuit of kyphosis correction cannot effectively increase surgical efficacy but can increase the risk of surgical complications such as nerve injury.96 In recent years, with the continuous progress of minimally invasive techniques, surgeons have treated cervical spinal epidural abscesses with local kyphosis using minimally invasive endoscopic surgery.97 Nevertheless, minimally invasive endoscopic cases with moderate-to-severe spinal deformities have not been reported.

The use of postoperative antibiotics remains controversial. Shiban et al.98 suggest oral antibiotic treatment for 3 months after CRP being reduced by more than half, and clinical symptoms are significantly relieved. If inflammation markers do not show signs of infection on reexamination after 3 months of oral antibiotics and no recurrence occurs within 12 months after surgery, the infection is considered completely cleared.

**CERVICAL DEFORMITY ASSOCIATED WITH BRUCELLOSIS**

1. Epidemiology

Brucellosis is a systemic disease caused by certain species of Brucella that can be transmitted to humans through infected animals or dairy products. Brucellosis can damage various tissues and organs, especially the reticuloendothelial and musculoskeletal systems, leading to arthritis, bursitis, and spondylitis.99 Osteoarthritis accounts for 20%–60% of the cases, and spondylitis was about 8%–13%.100 The infection occurs most frequently within the spine in the lumbar and thoracic regions and, more rarely, in the cervical location.101,102

2. Pathophysiology and Clinical Presentation

After invading the human body through damaged skin, gastrointestinal mucosa, or the respiratory tract, Brucella bacteria can grow and reproduce in nearby lymph nodes and are then killed by macrophages. Those that fail to be killed continue to grow and multiply to form infection foci and eventually break through the lymph node barrier into the blood to develop bacteremia, followed by violation of the reticuloendothelial system. Brucella spondylitis occurs alternately with three pathological changes: exudation, hyperplasia, and granuloma.103 When Brucella invades the cervical spine, the patient may develop neck stiffness, flexion immobilization, and reduced range of motion with common symptoms such as fatigue, fever, and night sweats.104,105 With the increasing number of osteoporosis patients, cervical kyphosis is more likely to occur when combined with brucellosis, which challenges its treatment.106

3. Changes in Cervical Deformity Associated With Brucellosis

Brucella spondylitis was first reported by Tekkok et al.,107 but it is more common in the lumbar spine and rarely occurs in the thoracic or cervical spine.108 There are two main types of Brucella infection: focal and diffuse. The diffuse type can lead to the softening of the involved vertebral endplate and the instability of the intervertebral disc, and segmental cervical kyphosis may occur with the progression of the disease.109 A study in 2022 involving 22 patients with Brucella cervical infection showed a mean kyphotic Cobb Angle of 11.5° in 22 included patients. The mean kyphosis angle of these 22 patients improved from 11.5° preoperatively to 0.2° postoperatively. At the last follow-up, 15 of the 20 patients with neurological dysfunction had fully recovered. No implant failure or pseudarthrosis was reported, and bone fusion was achieved in all patients.106

4. Diagnosis

Brucella spondylitis can present with elevated white blood cell count and ESR. However, routine clinical and laboratory evaluations cannot precisely diagnose vertebral involvement in brucellosis, and x-rays do not reveal spondylitis or spinal discitis at an early stage. Therefore, CT, MRI, and bone imaging tech-
Techniques are required for further diagnosis. Its imaging features present as endplate lesions resembling Schmorl nodes and disc gas. With the progress of the disease, the affected part may appear endplate destruction, intervertebral space narrowing, and even collapse of the vertebral body, and then local cervical kyphosis. It is worth noting that there are about 3 months from the involvement of the cervical spine to the occurrence of vertebral body collapse.

The etiological diagnosis included blood cultures and specific serological tests (Rose Bengal, agglutination, and Coombs) against Brucella. Because Brucella can migrate into cells over time, the positive rate in blood cultures of patients with acute and chronic brucellosis is 40%-70% and 25%, respectively, which means that the longer the disease course, the lesser the likelihood of a positive blood culture result.

5. Management of Cervical Deformity Associated With Brucellosis

When cervical brucella has not yet caused kyphosis or nerve compression, conservative treatment with bed rest and wearing a cervical collar can be adopted, and antibiotic therapy should be carried out following the principle of “long-term, sufficient, and combined.” A recent study showed that a long-term (at least 24 weeks) triple antibiotic regimen of doxycycline, rifampicin, and aminoglycosides was effective. All patients achieved complete remission with no recurrence or sequelae. But Ulu-Kilic et al. suggest that the duration of treatment appears to be more important than the choice of antibiotic.

Surgery is necessary for patients with multiple vertebral involvements, neurological dysfunction, or significant cervical kyphosis. Khan et al. reported a patient with an epidural abscess and secondary cervical kyphosis caused by Brucella infection, who underwent an anterior approach alone. Postoperative follow-up results showed that the patient developed cervical kyphosis, one of the drawbacks of anterior approach alone surgery. However, the patient did not have neck pain or neurological impairment. The authors believed that if the kyphosis developed, additional posterior fixation surgery should be considered.

It was suggested by Li et al. that patients with cervical kyphosis should undergo anterior debridement, decompression, bone graft fusion, and internal fixation combined with posterior bone graft fusion. After surgery, all patients were treated with an antibiotic therapy of doxycycline 100 mg twice a day + gentamicin 5 mg/kg one a day + rifampicin 10 mg/kg up to 900 mg for at least 3 months. Clinical and radiographic results showed satisfactory surgical results without internal fixation failure and good bony fusion. de Divitiis O and Elefante also concluded in a review of brucellosis that surgery is the best treatment for patients with cervical kyphosis secondary to brucellosis, and a satisfactory prognosis can be achieved in all patients with drug therapy.

CONCLUSION AND PROSPECT

In conclusion, early detection, diagnosis and treatment should be advocated for treating cervical infection. Early anti-infection therapy and debridement can often achieve good results. However, as the disease progresses, a cervical infection may cause cervical kyphosis and neurological impairment. Due to its possible injury to the spinal cord and neurological function, the method and timing of surgery for postinfectious cervical kyphosis are still controversial, which is the mainstream research direction in the future. Given the development of minimally invasive technology, its advantages of less trauma and low surgery risk will make it widely used in treating infectious cervical kyphosis. This review describes the common and rare postinfectious cervical kyphosis and reviews the relevant literature comprehensively, which provides theoretical guidance for the clinical decision-making of the disease. However, further exploration of personalized treatment for patients is still needed in future clinical work.

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A Review About Postinfectious Cervical Deformity

Han B, et al.

2014;20:O75-82.


INTRODUCTION

The cervical spine functions to position the head over the body in space and to maintain horizontal gaze.\(^1\) Under physiologic conditions, these functions occur without excess recruitment of soft tissue structures or fatigue of cervical musculature.\(^2\) As cervical alignment deviates from normal, increased energy is required to maintain horizontal gaze.\(^3\) Cervical spine deformity (CSD) is associated with increased disability, decreased health-related quality of life (HRQoL), and myelopathy.\(^4,5\) and cervical alignment is closely related to global sagittal alignment.\(^7\)

Causes of cervical deformity are numerous, and are broadly categorized as congenital, traumatic, inflammatory, infectious, degenerative, and iatrogenic.\(^8-10\) The most common cause of deformity is iatrogenic, and relates to patient positioning, hardware placement, size and quantity of bone graft used, and technical error.\(^8\) The natural history of cervical degenerative disc disease may also be accelerated after cervical spine surgery, leading to increased adjacent segment degeneration and deformity.\(^11,12\) More recent literature has highlighted the concept of reciprocal change, when unfused spinal regions adapt after primary deformity fusion in other regions such as the thoracolumbar spine.\(^13,14\) Applications of techniques to prevent cervical deformity therefore apply to a wide range of procedures to treat different spine pathology.

Several radiographic alignment parameters aid in measuring and defining CSD. Cervical lordosis (CL) is the cobb angle from the anterior and posterior tubercles of C1 or the inferior endplate of C2 and inferior endplate of C7, with normal C1–7 lordosis measuring approximately 40° and normal C2–7 measuring approximately 10° (Fig. 1).\(^7\) Translation of the head in the sagittal plane refers to the cervical sagittal vertical axis (cSVA), the distance of a plumbline from the center of C2 to the posterosuperior corner of C7 (Fig. 1). The average cSVA in healthy individuals is about 1.5 cm, and values greater than 4 cm are associated with disability and negative HRQoL.\(^15,16\) The chin-brow vertical angle (CBVA) is the angle between a line...
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from the chin to the brow and the vertical axis and helps infer horizontal gaze (Fig. 1). The CBVA is positive when the head is facing down and negative when the head is facing up. The CBVA is a primary target for cervical deformity correction, as restoration to physiologic values between +10° and -10° correlates with improved outcomes.\textsuperscript{17,18} The last major angle defining cervical alignment is T1 slope, a line parallel to the superior endplate of T1 and the horizontal. The T1 slope closely relates to the overall CL and is similar to the association of lumbar lordosis and pelvic incidence.\textsuperscript{1} Staub et al.\textsuperscript{19} proposed that normative CL may be predicted using the formula $\text{CL} = \text{T1 slope} - 16.5^\circ \pm 2^\circ$. Table 1 depicts normative values for the discussed radiographic parameters.\textsuperscript{15,20,21}

Recent efforts to classify CSD have provided systems that may improve communication, research, and treatment algorithms. The Ames-Misclassification includes a “Deformity Descriptor” based on the location of the deformity with 5 modifiers.

Table 1. Normative values for various cervical alignment radiographic parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1–7 lordosis (°)</td>
<td>41.8</td>
</tr>
<tr>
<td>C2–7 lordosis (°)</td>
<td>9.6</td>
</tr>
<tr>
<td>cSVA (mm)</td>
<td>15.6 ± 11.2</td>
</tr>
<tr>
<td>CBVA (°)</td>
<td>Between -10 and +10</td>
</tr>
<tr>
<td>T1 slope (°)</td>
<td></td>
</tr>
<tr>
<td>20-39 Years</td>
<td>-22</td>
</tr>
<tr>
<td>40-59 Years</td>
<td>-21.1</td>
</tr>
<tr>
<td>&gt; 60 Years</td>
<td>-31.6</td>
</tr>
</tbody>
</table>

cSVA, cervical sagittal vertical axis; CBVA, chin-brow vertical angle.

Fig. 1. Pictorial representations of commonly used angular measurements to describe cervical alignment. CBVA, chin-brow vertical angle; cSVA, cervical sagittal vertical axis; CL, cervical lordosis. Adapted from Passias et al. Neurosurgery 2018;83:651-9, with permission of Wolters Kluwer Health, Inc.\textsuperscript{7}

Fig. 2. Cervical deformity classification system developed by Ames et al.\textsuperscript{22} CBVA, chin-brow vertical angle; mJOA, modified Japanese Orthopaedic Association; PI, pelvic incidence; LL, lumbar lordosis.
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ers: C2–7 SVA, CBVA, T1 slope minus CL (T1–CL) mismatch, myelopathy (modified Japanese Orthopedic Association score), and thoracolumbar deformity (Scoliosis Research Society-Schwab classification) (Fig. 2).22 The Kim-International Spine Study Group classification uses dynamic radiographs to define 3 distinct groups: “flat neck,” “focal deformity,” and “cervicothoracic deformity,” each with unique drivers of CSD and surgical treatment strategies (Fig. 3).23 The Cervical Spine Research Society (CSRS)-Europe system classifies CSD into 4 groups based on cervical alignment, regional balance, and global balance; this system has practical implications for myelopathy, osteoporosis, and treatment approach.24

Cervical deformity based on abnormal radiograph parameters correlates with disability and negative HRQoL.3,4,25-27 The strongest predictors of disability and poor HRQoL are decreasing T1–CL, high C2–7 SVA, and high CBVA.3,25,26,28 As a kyphotic deformity ensues, the spinal cord drapes over the posterior aspect of the vertebral bodies, leading to compression of the spinal cord and its ventral blood supply.29,30 This process can lead to neuronal loss, demyelination, and ultimately development of myelopathy. Two important considerations about the cervical deformity literature, though, are the radiographic correlations to outcome are not as strong as those in the lumbar spine, and additionally the majority of studies are on primary, rather than iatrogenic deformity. Therefore, the relationship between iatrogenic deformity and HRQoL is not as clear. Nevertheless, considering the most common cause of CSD is iatrogenic, it is paramount for spine surgeons to recognize pitfalls in surgical techniques that may lead to postoperative CSD. Furthermore, surgical correction of iatrogenic CSD has a high incidence of complications.31,32 Overall complication rate has been cited as high as 56.5% if a 3-column osteotomy is involved, with neurologic deficits and postop mortality cited as high as 17.4% and 9.2%, respectively.33 These findings further emphasize the importance of preventing iatrogenic cervical deformity after spine surgery. The aim of this review is to discuss current concepts and techniques to prevent postoperative CSD.

PREVENTING CERVICAL DEFORMITY AFTER ANTERIOR CERVICAL PROCEDURES

Lack of preoperative radiographic assessment/planning and positioning are the first parts of anterior cervical procedures that may contribute to iatrogenic sagittal, coronal, and axial deformity. Obtaining appropriate preoperative flexion/extension films and entire spine films in addition to advanced imaging (computed tomography/magnetic resonance imaging) will mitigate against missing instability or thoracolumbar issues that may affect outcome. For positioning, a bump is often placed under the patient’s neck to drop the scapulae and head to increase exposure. In doing so, hyperlordosis may occur. Fusion

![Fig. 3. Different morphologic groups of cervical deformity. Adapted from Kim et al. J Neurosurg Spine 2019;1-7, with permission of Elsevier.23 TS, T1 slope; CL, cervical lordosis; cSVA, cervical sagittal vertical axis.](https://doi.org/10.14245/ns.2244780.390)
in excessive lordosis may cause posterior neck and interscapular pain in addition to nerve root symptoms from narrowing of the neuroforamen. It is imperative to adequately inspect the patient both clinically and radiographically prior to beginning a fusion procedure. Adjusting the bump to create neutral to slightly lordotic alignment is desirable. If excess lordosis is noted intraoperatively, the technique of placing converging Caspar pins may help reduce the lordosis once the pins are parallelized and distracted (Fig. 4). Coronal malalignment may occur from over tensioning of one shoulder when the shoulders are taped down. Extra caution and inspection must be done to ensure the head is not tilted towards one side. Axial malalignment can also occur and may be difficult to detect, because it usually occurs during retraction after the patient has been draped. Several methods can mitigate this, such as taping the forehead to stabilize head rotation prior to draping, use of Gardner-Wells tongs, or using commercially available head holders that utilize a chin strap to maintain rotation. Positioning is a seemingly benign event that can lead to poor outcomes, and it is critical for the entire surgical team to be cognizant of the patient’s position both clinically and radiographically prior to fusing any motion segments.

Asymmetric exposure of the disc and vertebral bodies may lead to subsequent asymmetric discectomy/corpectomy. Placing a graft eccentrically may then induce a coronal deformity. It is therefore recommended that complete anterior exposure of the disc to the margins of the transverse foramina and to the uncovertebral joints be performed. These osseous structures provide reliable landmarks in each patient to aid in execution of a symmetric discectomy. If Caspar pins and distraction are used to aid in decompression, misplaced pins may lead to sagittal, coronal, and axial malalignment as demonstrated in Fig. 5. Lastly, performing multiple corpectomies with a single, straight graft will leave the patient in neutral alignment. Therefore, depending on the pattern of compression, performing skip decompressions instead will produce multiple points of fixation where lordosis can be restored.

Table 1 summarizes several tips and techniques for preventing iatrogenic cervical deformity after various spine surgeries.

### PREVENTING CERVICAL DEFORMITY AFTER POSTERIOR CERVICAL PROCEDURES

Like anterior procedures, positioning is crucial for posterior procedures. The head is often fixed in a tong or halo device.
which can be adjusted to flex or extend the neck. Ensuring proper position of the neck clinically and radiographically, particularly if a fusion procedure is to be performed, is essential. Not only can the neck be fixed with improper sagittal alignment from the head positioner, but axial and coronal malalignment can also occur.31 In heavier patients who have redundant skin folds on the posterior neck, the skin should be manually retracted to inspect the actual position of the posterior neck prior to final positioning, as these redundant skin folds can often make the neck appear to be in neutral alignment when it is in fact too flexed or extended. As with anterior procedures, the shoulders are usually taped during posterior procedures to aid in radiographic imaging of the cervical spine. Asymmetric taping of may lead to a coronal malalignment. We recommend that prior to beginning the procedure the entire surgical team agree that the neck is positioned adequately both clinically and radiographically. The above nuances are particularly essential when performing an occipital-cervical fusion where no compensation can occur postoperatively. Choice of fixation device, such as Mayfield vs. Gardner Wells tongs becomes an important choice. Mayfield tongs can aid in locking in the exact alignment, however if any adjustments need to be made this can prove challenging intraoperatively. Additionally, the position afforded by Mayfield tongs is generally one of extension and lordosis, which may make other aspects of the surgery challenging. A mitigating strategy is to use Gardner-Wells tongs and bivector traction to be able to perform decompression and osteotomies in flexion and fix the patient in adequate extension. This also allows for mobility of the spine during the procedure to ensure good motion post laminoplasty.

The facet joints and posterior tension band are critical for stability, particularly in the sagittal plane.34,35 Foraminotomies may destabilize the spine if more than 50% of the facet is resected.34 Surgeons must be cognizant of the entire margin of the facet, particularly if the foraminotomy is performed through a minimally invasive retractor that may obscure visualization. Laminectomies remove the tension band, and postlaminectomy kyphosis can occur in up to 21% of patients.36,37 Kaptain et al.36 performed a study of 46 patients undergoing laminectomy alone for cervical spondylotic myelopathy, and found that patients with a straight spine preoperatively (within 4° of neutral) had the highest incidence of postoperative kyphosis (30%). Outcomes, however, were not found to correlate with development of postoperative kyphosis. Instrumented fusion may reduce loss of lordosis and improve neurologic and functional outcomes after laminectomy.38 Even if instrumented fusion accompanies a laminectomy, patients can still experience postoperative kyphotic deformity. If patients have a high preoperative cervical kyphosis, fusion in a lordotic position may lead to hardware failure and recurrence of the kyphotic alignment. These patients must therefore be considered for anterior-posterior procedures.33

Laminoplasty is a motion preserving technique that has become widely popular for posterior decompression of the cervical spine. Postlaminoplasty kyphosis is a complication that occurs in about 10% of cases and is very technique dependent.39 During posterior cervical dissection, care must be taken not to violate the facet capsules as the dissection is taken out laterally. The semispinalis cervicis muscle is a strong, dynamic stabilizer that inserts on the spinous process of C2. It has been clearly shown that disruption of this muscular attachment contributes strongly to postlaminoplasty kyphosis.40-42 When performing laminoplasty, it is essential to preserve, or repair, the C2 muscular attachments. Preoperative cervical kyphosis and increased T1 slope correlate with increased postlaminoplasty loss of lordosis.43 Lee et al.44 performed a radiographic analysis and determined that there was a weak but statistically significant correlation (r = 0.3) between increasing T1 slope and loss of CL. They also determined that preoperative T1 slope > 29° was the most sensitive and specific threshold value for predicting a postoperative kyphotic change ≥ 5, though the sensitivity and specificity were only 63% and 69%, respectively. It is very important to understand though, that there were no clinical outcomes measured, and additional studies have found no correlation between clinical outcomes and loss of lordosis after laminoplasty. Laminoplasty should not be performed if preoperative kyphosis is > 13°.45

For any posterior cervical procedure, not only are the muscular attachments of C2 important, but the entire posterior soft tissue envelope serves as a tension band. The impetus for laminoplasty versus laminectomy alone is to leave a osseous shell for reattachment or scarring of the soft tissue envelope which provides the benefit of a soft tissue tension structure. Closure of cervical procedures should therefore be performed meticulously and in several layers to fortify the soft tissue tension band.

**CERVICAL DEFORMITY AFTER ADULT THORACOLUMBAR SPINAL DEFORMITY CORRECTION**

Patients with positive sagittal imbalance secondary to adult thoracolumbar spinal deformity may use compensatory mech-
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Anisms to maintain horizontal gaze. These include pelvic retroversion, hip extension, knee flexion, ankle dorsiflexion, a loss of thoracic kyphosis, and cervical spine hyperextension. Studies demonstrate how surgical correction of thoracolumbar deformity affects unfused cervical alignment. Smith et al. studied 75 patients with a positive sagittal imbalance (SVA > 5 cm) who underwent a lumbar pedicle subtraction osteotomy and found that there was a statistically significant reduction in cervical hyperlordosis from 30.8° to 21.6°. The authors also demonstrated that a correction of the SVA to less than 5 cm was associated with the greatest correction of CL. Passias et al. expanded on this concept by studying the incidence of cervical deformity after adult spinal deformity correction. The authors observed a 63% incidence of postoperative cervical deformity in the 215 patients studied. Independent predictors of postoperative cervical deformity included diabetes and increased preoperative T1 slope minus cervical lordosis (T1–CL). An upper instrumented vertebra lower than T4 protected against postoperative cervical deformity. Despite the high incidence of postoperative cervical deformity, clinical outcomes were similar between those who developed cervical deformity and those who did not. Whether the postoperative cervical deformity requires revision surgery has yet to be determined. Additional studies have demonstrated that high preop C2–T3 Cobb angle and increased number of Smith–Peterson osteotomies (SPOs) are risk factors for postoperative cervical deformity after thoracolumbar deformity correction.

While the concept of cervical deformity after thoracolumbar ASD deformity correction has been well studied, optimal strategies to prevent development of cervical deformity have yet to be identified. Future work should aim to elucidate such strategies. Future studies must also determine the impact of cervical deformity after adult thoracolumbar deformity correction on clinical outcomes. The current knowledge of the interplay between cervical reciprocal changes and potential for cervical deformity development after ASD surgery is nonetheless useful when counseling patients undergoing ASD corrective surgery.

AVOIDING DISTAL MALALIGNMENT AFTER CERVICAL DEFORMITY CORRECTION

A relevant complication following cervical deformity correction is distal junctional kyphosis (DJK), defined as kyphosis > 10° between the superior endplate of the most caudal level included in the correction, and the inferior endplate of the next caudal vertebrae. While the radiographic incidence of DJK can be up to 32.2% after adult cervical deformity correction, a much smaller percentage (as low as 6%) of patients are actually symptomatic. Preoperative T1–CL > 36.4°, thoracic kyphosis < 50.6°, and CL < 12° are all predictors of postoperative DJK after cervical deformity correction, and future studies may investigate these as targets to minimize postoperative DJK. An important technical aspect of deformity correction that requires clarification is the effect of lower instrumented vertebra on incidence of DJK. One study found that patients with a primary thoracic driver of cervical deformity without inclusion of the thoracic apex in the correction tended to have higher incidence of DJK and worse clinical outcomes. Further studies should expand on these findings as that may be an important technique for prevention of postop DJK.

Lafage et al. recently developed a cervical score based on the difference between postoperative alignment and age adjusted targets. The score consisted of T1–CL, T1 slope, and SVA, therefore incorporating both cervical and overall sagittal alignment. Points are assigned to each measurement based on how much they differ from age adjusted targets, and the total score is the sum of the points for each measurement. Importantly, positive scores suggest under correction, while negative scores suggest overcorrection. Of the patients studied, 21% experienced mechanical failure, defined as either requiring a revision for mechanical failure or developing radiographic DJK. The authors found that the mean cervical score in those experiencing mechanical failure was 4 (under correction), compared to a score of 1 for those who did not experience mechanical failure. This differs from the thoracolumbar literature on PJK that suggests that overcorrection of thoracolumbar deformity contributes to PJK. The cervical score not only takes into account cervical alignment, but also global alignment through the SVA. Surgeons must therefore consider global alignment during deformity correction, and how compensatory mechanisms after cervical deformity correction may affect global alignment. Additionally cervical deformity must be corrected within the range of age adjusted targets to best prevent DJK.

To summarize, the current literature suggests the optimal strategies to prevent postoperative cervical deformity after cervical deformity correction include restoring horizontal gaze, including the primary driver apex in the construct, and achieving adequate correction and global sagittal alignment.
PREVENTING CERVICAL DEFORMITY AFTER CERVICAL TUMOR RESSECTION

CSD after cervical spine tumor resection occurs for many of the same reasons as after posterior approach to the cervical spine for laminectomy or laminoplasty, namely large resection of the posterior elements including the facets and detachment of the semispinalis cervicis from C2 spinous process. Tumor surgery also faces the additional challenges of possible weakness from compression of the tumor, and postoperative radiation, both of which contribute to a high incidence of postoperative deformity, particularly in adolescents. The incidence of CSD after cervical spinal cord tumor (CSCT) resection ranges from 0%–41% according to a meta-analysis by Noh et al. The authors identified younger age, C2/C3/laminectomy at the cervicothoracic junction, and increasing number of laminectomy levels as 3 main risk factors for postoperative deformity after CSCT resection. Young, skeletally immature patients may be at increased risk due to soft tissue laxity, and abnormalities that may develop from resection of elements of the spine that may still be growing. Instrumented fusion is not required in all CSCT patients, and overutilization of instrumented fusion may add additional time, costs, and complications. Young patients (age < 33) with preoperative cervical deformity who undergo a C2 laminectomy, ≥ 3 level laminectomy, cervicothoracic junction (CTJ) laminectomy should undergo a concomitant instrumented fusion.

CONCLUDING REMARKS

CSD is a debilitating problem that often occurs iatrogenically. Surgical intervention to treat CSD can lead to high morbidity and complications, and therefore surgeons must implement every technique possible to try to mitigate or prevent iatrogenic cervical deformity. During anterior procedures performed for degenerative cervical conditions, the clinical and radiographic cervical alignment must be optimized prior to fusing any segments. This requires proper positioning, adequate exposure, symmetric discectomy, and placement of pin distractors if used. Posterior cervical procedures similarly rely on adequate positioning to avoid iatrogenic deformity. Resecting greater than 50% of a facet joint and violating the posterior tension band should be avoided if possible. If multilevel laminectomies must be performed, then instrumented fusion should be considered. If nonfusion procedure like laminectomy is chosen, surgical dissection must preserve the C2 muscular attachments and must also not be performed on any patient with preoperative kyphosis of 13°. Surgeons must be aware of the concept of reciprocal change and compensatory cervical response to adult thoracolumbar or lumbar deformity correction. Increased preoperative T1–CL, high preoperative C2-T3 cobb angle, and increased number of SPOs are all risk factors for developing cervical deformity after thoracolumbar deformity correction. Future studies should aim to identify strategies that protect against developing iatrogenic cervical deformity after thoracolumbar deformity correction. After cervical deformity correction, horizontal gaze should be restored with adequate correction of global sagittal balance and inclusion of the primary driver of the cervical deformity in the correction construct. Tumor surgery resection from a posterior approach follows similar principles, but cervical deformity occurs at an increased incidence compared to when the posterior approach is performed for degenerative conditions. Instrumented fusion may be warranted in younger patients due to the risk of post laminectomy kyphosis, particularly if C2 laminectomy, CTJ laminectomy, or ≥ 3 level laminectomy is performed.

Further research is required to elucidate factors which may contribute to iatrogenic cervical deformity and to develop strategies to minimize these complications. Additionally, the relationship between radiographic iatrogenic deformity and impact on clinical outcome must be clarified.

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Clinical Characteristics and Treatment Outcomes of Long-Level Intramedullary Spinal Cord Tumors: A Consecutive Series of 43 Cases

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Objective: Long-level intramedullary spinal cord tumors (LIMSCTs) cause complex treatment issues. However, LIMSCTs have rarely been analyzed separately. The authors reported a large case series of LIMSCTs and analyzed the clinical characteristics and treatment outcomes.

Methods: The medical data of patients with LIMSCTs at our institution between January 2015 and December 2019 were retrospectively reviewed. Demographics, tumor size and location, pathology, extent of resection, and neurological functional status were collected.

Results: A total of 43 consecutive cases were included. Twenty-three cases (53.5%) of LIMSCTs were ependymal tumors. All patients with ependymal tumors achieved gross total resection (GTR). In ependymal tumor cases, 3 cases (13%) of ependymal tumors experienced postoperative neurological deterioration, and 66% of them showed an improvement at follow-up; 25.6% were low-grade astrocytic tumors. The rates of GTR, subtotal resection (STR) and partial resection (PR) were 63.6%, 27.3%, and 9.1%, respectively. Twenty-seven percent cases showed postoperative neurological worsening, and 33% of them had an improvement at follow-up; 20.9% were high-grade astrocytic tumors. The excision rates were 44.4% for GTR, 44.4% for STR, and 11% for PR, respectively. Fifty-five percent cases showed postoperative neurological worsening, and none of them had an improvement at follow-up.

Conclusion: In this series, all LIMSCTs were gliomas. Aggressive tumor resection did not increase the risk of long-term functional deterioration in ependymal tumors and low-grade astrocytic tumors, but in high-grade astrocytic tumors, patients had a higher risk of neurological deterioration and difficulty in recovery. In ependymal tumors and low-grade astrocytic tumors, patients can achieve long-time survival after performing aggressive tumor resection.

Keywords: Intramedullary tumors, Long level, Ependymoma, Astrocytoma, Outcome

INTRODUCTION

Long-level intramedullary spinal cord tumors (LIMSCTs) are defined as tumors that involve at least 5 spinal vertebral segments.¹ Generally, most intramedullary tumors present clinically due to nerve compression rather than tumor invasion.² In rarer cases, intramedullary tumors can be long-segmental localized. Long-level lesions gradually progress neurologically. Patients may suffer from weakness, sense disorders, and sphincter defects and eventually become significantly disabled, morbidly ill, and even die.

Given that patients with long-level intramedullary lesions suffer more neurological deterioration and postoperative complications, some surgeons may choose conservative manage-
Clinical Experience of Long-Level Intramedullary Tumors

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These conservative protocols cannot prevent disease progression. In addition, several studies have also noted that aggressive resection increases the overall survival of patients with intramedullary tumors, and the earlier the radical resection of intramedullary tumors is performed, the greater the chance of preserving the patient’s neurological function. To date, the optimal management for LIMSCTs remains unclear.

In this study, we reported our experience with LIMSCTs, which has rarely been discussed separately in previous literature. Based on a series of 43 patients treated in our institution, we analyzed the tumor characteristics, extent of resection and clinical outcomes and attempted to provide answers on optimal treatment strategies for LIMSCTs.

MATERIALS AND METHODS

1. Study Patients

This study was a retrospective analysis of data from surgical cases who underwent microsurgical LIMSCT resection at Beijing Sanbo Brain Hospital between January 2015 and December 2019. The collective patient databases were analyzed to determine cases of intramedullary tumors in which the tumor involved at least 5 spinal vertebral levels or longer. Patients with terminal filum tumors or cauda equina tumors were excluded. Data were collected from our computerized database, follow-up appointments and telephone interviews.

A total of 43 cases were included in this analysis. Patient data, including age, sex, symptoms, tumor size and location, pathology, extent of resection, neurological functional status, and follow-up outcomes, were recorded. We used the modified McCormick Scale (MMS) to evaluate the neurological function of each patient at the first presentation, postoperation, and follow-up visits. The location of each LIMSCT was categorized as cervical, cervicothoracic (tumor that involved C7 and T1 level), thoracic, thoracolumbar (tumor that involved T12 and L1 level), and holocord involvement (tumor involved cervical, thoracic, and lumbar levels).

This study protocol was approved by the University Institutional Review Board (SBNK-YJ-2020-006-03). Informed written consent was obtained from all participants.

2. Histological Evaluation and Pathological Findings

All histological specimens were reviewed by senior neuropathologists at our institution. Specimens were independently reviewed by one neuropathologist and then examined by another to confirm the diagnosis. We used the World Health Organization (WHO) 2016 classification of central neural system tumors for diagnosis and classification. For patients who underwent operation before 2016, tumor specimens were assessed according to the same classification system to maintain unified histological grading criteria.

3. Surgical Technique

Our operative technique has been described previously in detail. Laminoplasty that spanned the length of the intramedullary lesion was performed in all patients. A C1 laminectomy was performed for tumor sections at the C1 level. In each case, the medial facet joint was exposed, and an effort was made to maintain the facet joint capsules. Bilateral laminectomies were performed using an ultrasonic bone scalpel. The spinous processes, interspinous ligaments, and ligamentum flavum of the planned laminoplasty section were kept intact. Using intraoperative neuro-monitor mapping, a midline dural and spinal cord incision was performed sparing the whole length of the tumor. The tumor was approached gently and resected piecemeal. After removing the tumor, the dura was closed via 5-0 absorbable sutures. Mini titanium plates were used to fix the laminae. Finally, the paraspinal muscles were sutured, and the skin incision was closed. In addition, 3 patients who suffered from LIMSCT complicated with scoliosis were treated by a 1-stage operation of tumor resection and scoliosis correction. Gross total resection (GTR) was attempted in all patients. GTR is defined as excision of ≥ 95% of the tumor, as evidenced by a clean operative field at the end of the surgery or absence of residual enhancement signal on postoperative magnetic resonance imaging (MRI). The procedure was considered a subtotal resection (STR, 80%–95% resection) if a small tumor piece was deliberately left in place due to intraoperative conditions or a retained fragment was detected on postoperative MRI. Partial resection (PR) was defined as less than 80% tumor removal, which was rare in this case series. Intraoperative neuropsychological monitoring, including motor evoked potentials (MEPs) and somatosensory evoked potentials (SEP), was performed in all patients. The warning criteria were set for a 50% amplitude reduction of SEP or a 50% amplitude reduction of MEP. The permanent 75% amplitude reduction of MEP was used to stop the operation.

4. Statistical Analysis

Statistical analyses were performed using GraphPad Prism ver. 8.0 (GraphPad Software Inc., La Jolla, CA, USA). Percentages were calculated for categorical data, and medians and in-
terquartile ranges (IQRs) were calculated for continuous data. The Mann-Whitney test was used to compare nonparametric data between the groups. For percentage analysis, the chi-square test was used. Kaplan-Meier analysis for overall survival was performed with log-rank tests. The differences were considered statistically significant if the p-value was < 0.05.

RESULTS

1. Demographic and Clinical Characteristics

A total of 43 consecutive cases underwent LIMSCT resection in the study period (Table 1). Twelve of them (27.9%) were pediatric patients (age ≤ 18 years), whereas 31 patients (72.1%) were adults. Nineteen patients (44.2%) were female, and 24 patients (55.8%) were male.

The most common presenting symptoms in this series were combined symptoms (65.1%) followed by sensory dysfunction (20.9%) and motor deficits (14.0%). In 19 cases (44.2%), the prodrome time persisted for ≤ 1 year from the initial symptomatology to surgical treatment. In 13 patients (30.2%), the prodrome time lasted 1 to 3 years. In 11 patients (25.6%), the prodrome time lasted > 3 years. The major sensory symptoms included pain, extremity numbness, and dysesthesia. Major motor deficits included extremity weakness, motor loss and muscle atrophy. The median preoperative MMS score in our series was 2 (IQR, 2–3).

2. Tumor Location, Resection, and Pathology

Based on preoperative imaging, patients most commonly presented with a lesion that involved the cervicothoracic spine. Thirteen tumors (30.2%) were located in the cervical spine, 21 tumors (44.8%) were located in the cervicothoracic spine, 4 tumors (9.3%) were located in the thoracic spine, 4 tumors (9.3%) were restricted to the thoracolumbar spine, and 1 tumor (2.3%) had a holocord tumor (Fig. 1A).

In total, 23 cases (53.5%) were ependymal tumors, and 20 cases (46.5%) were astrocytic tumors. The detailed distribution of histopathological diagnosis was subependymoma in 2 cases (4.6%), ependymoma in 21 cases (48.8%), pilocytic astrocytoma (PA) in 3 cases (7%), diffuse astrocytoma in 8 cases (18.6%), anaplastic astrocytoma in 2 cases (4.6%), glioblastoma in 3 cases (7%), and diffuse midline glioma in 4 cases (9.3%) (Fig. 1B, C). Overall, GTR was achieved in 34 cases (79.1%), and STR was achieved in 7 cases (16.3%). Only 2 patients (4.6%) underwent PR. All patients with ependymoma achieved GTR. The rates of GTR, STR, and PR of low-grade astrocytomas (WHO grade I and II) were 63.6%, 27.3%, and 9.1%, respectively. The excision rates for high-grade astrocytomas (WHO grade III and IV) were 44.4% for GTR, 44.4% for STR, and 11% for PR. High-grade tumors had a significantly lower possibility of achieving complete tumor resection than low-grade tumors (p = 0.004).

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Age</strong></td>
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</tr>
<tr>
<td>Pediatric (≤ 18 yr)</td>
<td>12 (27.9)</td>
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<tr>
<td>Adult (&gt;18 yr)</td>
<td>31 (72.1)</td>
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<tr>
<td><strong>Sex</strong></td>
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<tr>
<td>Male</td>
<td>24 (55.8)</td>
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<tr>
<td>Female</td>
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<tr>
<td><strong>Clinical symptom</strong></td>
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<tr>
<td>Sensory</td>
<td>9 (20.9)</td>
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<tr>
<td>Motor</td>
<td>6 (14.0)</td>
</tr>
<tr>
<td>Combined</td>
<td>28 (65.1)</td>
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<tr>
<td><strong>Symptom duration in years</strong></td>
<td></td>
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<tr>
<td>≤ 1</td>
<td>19 (44.2)</td>
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<tr>
<td>1–3</td>
<td>13 (30.2)</td>
</tr>
<tr>
<td>&gt; 3</td>
<td>11 (25.6)</td>
</tr>
<tr>
<td><strong>Classification of tumor (extent of resection)</strong></td>
<td></td>
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<tr>
<td>Ependymal tumor WHO I and II (GTR 100%)</td>
<td>23 (53.5)</td>
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<tr>
<td>Astrocytic tumor WHO I and II (GTR 63.6%, STR 27.3%, PR 9.1%)</td>
<td>11 (25.6)</td>
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<tr>
<td>Astrocytic tumor WHO III and IV (GTR 44.4%, STR 44.4%, PR 11.1%)</td>
<td>9 (20.9)</td>
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<tr>
<td><strong>Extent of tumor involvement (spinal levels)</strong></td>
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<tr>
<td>5</td>
<td>16 (37.2)</td>
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<td>6–8</td>
<td>23 (53.5)</td>
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<td>11–13</td>
<td>3 (7.0)</td>
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<td>Holocord</td>
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<td><strong>Preoperative MMS score</strong></td>
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<tr>
<td><strong>Length of stay in days</strong></td>
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<td><strong>Postoperative adjuvant therapy</strong></td>
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<tr>
<td>Radiotherapy</td>
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<tr>
<td>Combined</td>
<td>4 (9.3)</td>
</tr>
<tr>
<td><strong>Follow-up length in months</strong></td>
<td>34 (25–60)</td>
</tr>
</tbody>
</table>

Values are presented as number (%) or median (interquartile range). LIMSCT, long-level intramedullary spinal cord tumor; WHO, World Health Organization; GTR, gross total resection; STR, subtotal resection; PR, partial resection; MMS, modified McCormick Scale.
3. Surgical-Related Outcomes and Neurological Function

No patient died because of operative-related procedures. The median length of hospitalization was 20 days (IQR, 17–25 days). As reported in previous studies, the modified MMS was used to best express the change in operation-induced neurological function. Overall, most patients (27 cases, 62.8%) had only a minor neurological deficit (MMS II) at presentation. In contrast, 8 cases (18.6%) had MMS III, and 5 cases (11.6%) had MMS IV. The median preoperative MMS score was 2 (IQR, 2–3), and the postoperative MMS score was 3 (IQR, 2–3).

Overall, no significant difference was noted between the pre- and postoperative MMS scores (p=0.1067). In ependymal tumor cases, 3 cases experienced postoperative neurological deterioration, and 2 of them showed an improvement at the last follow-up. Of the low-grade astrocytic tumor cases, 3 cases showed postoperative worsening in their neurological status, and one of them had an improved grade at the last follow-up. Of the high-grade astrocytic tumor cases, 5 cases experienced postoperative functional worsening. Unfortunately, functional improvement was not observed in those patients. No further
neurological functional decrease in MMS was found in the follow-up duration (Fig. 2). Three patients encountered postoperative pneumonia. These complications were successfully treated by subsequent management.

All 43 patients had clinical follow-up, and the median follow-up duration was 34 months (IQR, 25–60 months). In the whole group, 39 patients (90.7%) remained alive at the time of this study. Four patients died of disease progression and respiratory failure, including 2 WHO grade IV astrocytic tumors (a 6-year-old girl died 20 months after surgery, and a 13-year-old boy died 24 months after surgery), one WHO grade III astrocytic tumor (a 34-year-old woman died 6 months after surgery) and one WHO grade II astrocytic tumor (a 2-year-old girl died 30 months after surgery). One patient with diffuse midline glioma was alive despite recurrence after adjuvant therapy at the 21-month follow-up. The remaining patients were progression-free during the follow-up period. Survival was statistically correlated with tumor pathological grade \((p = 0.004)\). The following variables did not affect mortality independently: age, tumor location, tumor span, and extent of tumor resection. Four patients (9.3%) with astrocytic tumors who underwent incomplete tumor resection received adjuvant radiation therapy (3 cases of WHO grade II and 1 case of WHO grade III). Three patients (7.0%) with WHO grade IV astrocytic tumors who underwent complete tumor resection underwent adjuvant chemotherapy. Four patients (9.3%) with WHO grade IV astrocytic tumors with incomplete resection received combined therapy. The major determinant of overall survival was the WHO grade of the tumor in LIMSCTs (Fig. 3). An illustrative case of LIMSCT is presented in Fig. 4.

**DISCUSSION**

Generally, intramedullary tumors comprise approximately 20%–30% of all primary spinal cord tumors. Some rare cases present with neurological defects due to a long-level extent of tumor involvement, which complicates the management strategies. However, the clinical characteristics and surgical outcomes for LIMSCTs have rarely been studied before. In this study, we presented a series of 43 consecutive patients who had LIMSCT and underwent tumor resection at our institution. To our knowledge, this represents the largest series of patients with LIMSCT involvement who underwent tumor resection.

The general characteristics of long-segment intramedullary neoplasms are somewhat different from those of general intramedullary neoplasms. According to other papers, intramedullary tumors are more common in adults and less common in children.

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**Fig. 3.** Kaplan-Meier analysis for overall survival with regard to ependymal tumor WHO grades I and II, astrocytic tumor WHO grades I and II, and astrocytic tumor WHO grades III and IV. WHO, World Health Organization.

**Fig. 4.** (A) A 48-year-old female patient. Preoperative imaging indicated a long-level intramedullary tumor. (B) Gross total resection was achieved, and the pathology result was ependymoma WHO grade II. (C) Thirty-month follow-up imaging showed no tumor recurrence. WHO, World Health Organization
children. Only approximately 10%–13% of intramedullary tumors occur in children.\textsuperscript{7,12} However, in this series, approximately 30% of patients with long-segment intramedullary tumors were children, which was significantly greater than that generally noted for intramedullary tumors. The possible explanation for this finding is that the pathological properties of intramedullary tumors in children are often poor, and the degree of malignancy is high. Malignant tumors are more likely to grow rapidly and infiltrate the spinal cord. In addition, children often have higher neurological adaptability, and early numbness and weakness do not receive sufficient attention. Therefore, the proportion of children with long-segment intramedullary tumors is higher than that noted for general intramedullary tumors.

In our series, most LIMSCTs involved the cervicothoracic and cervical levels. All the long-segment intramedullary tumors were gliomas, and no other types were observed. Ependymal tumors and astrocytic tumors occurred in 53.5% and 46.5% of all patients, respectively. All patients with ependymal tumors were adults, whereas pediatric patients exhibited a higher proportion of astrocytic tumors. This finding is compatible with previous studies.\textsuperscript{19,20} Ependymomas are the most frequent tumors, representing half of the patients in this series. Many studies have demonstrated the characteristics of ependymomas.\textsuperscript{21,22} Typically, intramedullary ependymomas are solitary tumors located centrally in the spinal cord. Ependymomas rarely show infiltrative growth. The relatively well-defined interface between the lesion and the surrounding spinal cord tissue facilitates the aggressive resection of ependymomas. In this study, we achieved GTR in all patients with long-level ependymomas. No recurrence was observed at the last follow-up of each patient. Interestingly, 2 patients were diagnosed with subependymoma in this study. Subependymomas are indolent, benign tumors that have been described as having a distinct pathological pattern.\textsuperscript{23} Jain et al.\textsuperscript{24} concluded that surgical treatment can provide long-term tumor control. In the current case of subependymoma, the patient received GTR and achieved long-term progression-free status at the 50-month follow-up duration. Compared with ependymal tumors, preserving the functional status in patients with astrocytic intramedullary tumors is comparatively difficult. Astrocytomas are infiltrating tumors. Therefore, aggressive resection cannot be achieved in most cases.\textsuperscript{25–27} In this series, we were able to achieve GTR in 63.6% of patients with long-level low-grade astrocytic tumors and in 44.4% of patients with high-grade astrocytic tumors. Considering the long-level extent of tumor involvement, the clinical outcome is still encouraging. The medical prognosis is relatively poor in astrocytic tumors, especially those with high histological grade. Overall survival was mainly affected by the WHO grade of the tumor in LIMSCTs.

Despite their rarity, intramedullary tumors can lead to severe neurological function defects prior to medical treatment.\textsuperscript{28,29} In addition, patients may have no specific complaints or even remain asymptomatic for a long period, which increases the difficulty of early diagnosis.\textsuperscript{2,7} In our current series, most patients experienced combined symptoms of both sensory and motor defects. Neuropathic pain, numbness and muscle weakness were the most frequent complaints in our patients. There is a high index of suspicion for intramedullary tumors when patients experience intractable pain. Although there was a trend that patients with LIMSCTs had a longer prodrome duration compared to other studies, neurological function grade was not statistically associated with the length of prodrome time. Most patients showed a relatively mild neurological defect (MMS grade II) when they presented to our institution. However, 5 patients experienced severe dysfunction (MMS grade IV) due to rapid deterioration. Previous studies have indicated that early removal of an intramedullary tumor increases the possibility of preserving neurological function.\textsuperscript{3,10} In our experience, all patients with ependymoma achieved GTR. The rates of GTR, STR, and PR of low-grade astrocytomas were 63.6%, 27.3%, and 9.1%, respectively. The above excision rates for high-grade astrocytomas were 44.4% for GTR, 44.4% for STR, and 11% for PR. In this case series, intraoperative neurophysiological monitoring, including MEPs and SEPs, was performed in all patients. The warning criteria were set for a 50% amplitude reduction of SEP or a 50% amplitude reduction of MEP. The permanent 75% amplitude reduction of MEP was used to stop the operation.\textsuperscript{14–16} When there were significant changes in MEP, the operation was suspended temporarily. Warm saline solution was used to irrigate the surgical field, and the blood pressure was increased to at least 60 mmHg. Several literatures have studied and reviewed different monitoring techniques.\textsuperscript{14} It is showed that intraoperative neuromonitoring facilitates more aggressive tumor resection given its high sensitivity and specificity and the D-wave signal also exhibits potentials for the prediction of the neurological status.\textsuperscript{14,31,32} However, the optimal criteria for monitoring techniques remains controversial and a small tumor piece may be deliberately left in place due to intraoperative conditions. After aggressive tumor resection, disease recurrence is rare. In the ependymal tumor group (WHO grade I and II), 13% of patients experienced postoperative neurological deterioration, and 66.6% of them showed an improvement at the last
follow-up. In the low-grade astrocytic tumor group (WHO grade I and II), 27.3% of patients showed postoperative worsening in their neurological status, and one-third of them had improved their grades at the last follow-up. In the high-grade astrocytic tumor group (WHO grade III and IV), 55.6% of patients experienced postoperative functional worsening. Sadly, functional improvement was not observed in those patients. Our results indicated that low-level ependymal tumors and low-grade astrocytic tumors achieve a relatively better functional grade after tumor resection, whereas long-level high-grade astrocytic tumors are associated with a poor postoperative neurological status. The functional outcome was not affected by the extent of tumor resection in low-grade ependymal tumors and astrocytic tumors. During the follow-up period, no further functional aggravation was witnessed. In addition, high WHO grade tumors were significantly related to high mortality, which should not be neglected. For the treatment of high-grade gliomas, some institutions prefer conservative treatment strategies, such as biopsy with adjuvant therapy. \(^{33}\) For a sensitive patient population, adjuvant therapies and immunotherapy may represent alternative options. \(^{34,35}\) However, the role of adjuvant therapies for high-grade intramedullary tumors still needs to be discussed. \(^{36,37}\) Tumor resection remains the mainstay of spinal cord tumors. \(^{7,38}\) In this study of LIMSCTs, we found that long-level tumor extent did not affect the benefits of surgical management. In contrast, the limitation of conservative treatment strategies is that the process cannot prevent tumor progression and finally cause intractable deterioration in patients with intramedullary tumors. \(^{6,39-41}\) Therefore, we strongly advocate that GTR, or even STR, should be attempted in patients with LIM-SCTs, especially in ependymal tumors and low-grade astrocytic tumors, and a beneficial outcome can be expected.

In our case series, no postoperative progressive spinal scoliosis or kyphosis was observed. Three cases of long-segment intramedullary low-grade astrocytomas complicated with severe preoperative scoliosis were treated via a 1-stage operation. Laminectomy was performed for the entire tumor area, and complete resection of the tumor was performed; transpedicular screws were used to correct scoliosis. Patients achieved long-term tumor-free survival, and neurological function was basically preserved at the last follow-up. No serious short- or long-term complications resulted from the primary procedure. The correction of scoliosis prevents the development of spinal deformities and facilitates a return to normal life. Specifically, we encountered a unique case of primary holocord PA. PA is a subtype of glioma with a well-circumscribed, slow-growing, and cystic nature. \(^{42}\) Primary holocord PAs are extremely rare. \(^{43}\) We performed spinal internal fixation and posterior spinal fusion as well as laminoplasty. Even after performing spinal fixation, laminoplasty is still recommended. The reinsertion of the lamina plays an important role in reconstructing posterior spinal alignment, avoiding epidural scarring, preventing cerebrospinal fluid leakage, and facilitating reoperation if tumor recurrence occurs. \(^{44,45}\)

There were several limitations in this study. In addition to the nature of a retrospective study, all of the patients in this study underwent surgery in a single institution, which limited the generalizability. Additionally, the limited population of patients with LIMSCTs also leads to bias. Moreover, the true disease progression rate may be underestimated based on a mean follow-up duration of 37 months. To counter these limitations, further prospective randomized studies with large populations of patients with LIMSCTs are needed.

**CONCLUSION**

In the current case series, all LIMSCTs were gliomas, among which ependymoma was the main proportion type, and no other tumors were observed. LIMSCTs are most common in adults, whereas the proportion of children is increasing compared to general intramedullary tumors. All ependymal tumors achieved GTR, whereas astrocytic tumors exhibited a lower rate of complete tumor resection, especially in high-grade tumors. Aggressive tumor resection did not increase the risk of long-term neurological functional deterioration in low-grade ependymal tumors and astrocytic tumors. However, in high-grade astrocytic tumors, patients had a higher risk of neurological deterioration and difficulty in recovery. With attempting GTR, patients can expect a low disease progression rate in low-grade ependymal tumors and astrocytic tumors, and complete tumor removal remains the primary goal of treatment. We believe this protocol provides a good review of clinical characteristics and treatment outcomes for patients with LIMSCTs.

**NOTES**

**Conflict of Interest:** The authors have nothing to disclose.

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Author Contribution: Conceptualization: T Fan; Data curation: DZ, XZ, CL, YW, KW; Formal analysis: DZ, XZ, CL, YW, KW; Funding acquisition: TF; Methodology: DZ, WF; Project administration: TF; Visualization: DZ, WF; Writing - original draft: DZ; Writing - review & editing: TF, WF.

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Yinqian Wang: 0000-0001-5004-9417
Kun Wu: 0009-0003-6663-0101

REFERENCES
The Accuracy and Safety of a Pedicle Screw Using the Freehand Technique in Minimally Invasive Scoliosis Surgery

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Objective: The safety and clinical usefulness of minimally invasive scoliosis surgery (MISS) has been reported in various studies. However, freehand pedicle screwing in MISS remains technically challenging. The purpose of this study is to evaluate the accuracy and safety of pedicle screw placement using the freehand technique in adolescent idiopathic scoliosis (AIS) patients treated with MISS compared to conventional open scoliosis surgery (COSS).

Methods: We included 76 patients who underwent deformity correction for AIS. Computed tomography scans were used to assess screw violations divided into 2 groups according to the surgical technique: MISS or COSS. Anterior violations were classified into grade 0, 1 (no contact with internal organs), and 2 (contact with internal organs). Medial and lateral violations were classified into grade 0, 1 (< 2 mm), and 3 (≥ 2 mm). Grade 2 were considered critical violations.

Results: A total of 630 and 1,174 pedicle screws were inserted in the MISS and COSS groups, respectively. The overall critical violation rates of the MISS and COSS groups were 16.8% (106 screws) and 14.0% (165 screws) (p = 0.116). Medial critical violations on the left side in the middle thoracic region frequently occurred in the MISS group compared to the COSS group (p = 0.003). There were no statistical differences in the complications.

Conclusion: Pedicle screw placement using the freehand technique in MISS for AIS patients provided similar accuracy and safety compared to COSS. Pedicle screws inserted on the left side of the middle thoracic region exhibited more medial critical violations in the MISS group.

Keywords: Accuracy, Safety, Pedicle screw, Freehand technique, Minimally invasive scoliosis surgery

INTRODUCTION

In recent decades, spine surgeries with minimally invasive surgical techniques have been applied to various spinal fields including scoliosis surgery.¹ In minimally invasive scoliosis surgery (MISS), pedicle screw insertion and correction maneuvers are performed through small 2 incisions 4 cm in length and previous studies reported that MISS for adolescent idiopathic scoliosis (AIS) showed acceptable radiological and clinical effects.²³ The freehand technique of pedicle screw insertion is preferable to decrease the radiation exposure that takes place more in MISS surgery due to its narrow surgical fields. However, the freehand technique of pedicle screwing in MISS has many difficulties in identifying the entry point compared to open surgery because of the limited visualization of anatomical structures underneath uncised skin. Maintaining accurate 3-dimensional trajectory in MISS also is difficult due to the limited retraction of surrounding soft tissue that interferes with
proper direction orientation and positioning of probing instruments for pedicle screwing.

To the best of our knowledge, there have been few studies on the accuracy of pedicle screwing using the freehand technique in MISS.

Therefore, the authors intended to primarily examine the differences in the accuracy and safety of freehand pedicle screwing and complications in MISS through a comparative study with conventional open scoliosis surgery (COSS). Second, differences in the accuracy and safety of inserted screws with the freehand technique according to the anatomical region of the spine in MISS were evaluated.

**MATERIALS AND METHODS**

1. **Study Design**
   
   This is a retrospective comparative study conducted at a single institution. This study was approved by the Institutional Review Board of Korea University Guro Hospital (2022GR0135). Written informed consent was obtained from the patients. From 2014 to 2020, among the 350 patients who underwent deformity correction surgeries for AIS with typical right thoracic curve, 76 patients who underwent pre- and postoperative computed tomography (CT) scans are included in this study. The patients with neuromuscular scoliosis, syndromic scoliosis, and idiopathic scoliosis with atypical curve such as left thoracic curve were excluded. Of them, 28 patients underwent surgeries using minimally invasive surgical techniques (MISS group) (Fig. 1), while 48 patients underwent surgeries using conventional techniques (COSS group). In all patients, sex, age, height, and weight were measured to identify individual characteristics between the groups. The types of scoliosis (King-Moe and Lenke classifications), fusion levels, and curve flexibility were identified and measured using plain radiography.

2. **Surgical Approach in MISS**
   
   In the prone position, planned upper and lower instrumented vertebrae were confirmed using fluoroscope. After drawing a line connecting the center of the upper and lower vertebrae, the line was divided into upper and lower halves. An incision of 4 cm was performed at the midpoint of each site. Following skin incision and thoracolumbar fascial exposure, skin and subcutaneous tissue were retracted using right angle retractor. Paraspinal muscle was dissected until lamina and lat-

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**Fig. 1.** A 21-year-old female with a Lenke type 3 curve. Twenty-six pedicle screws were inserted from T4 to L4. The surgery was performed through 2 skin incisions.
eral side of facet joint was exposed.

3. Pedicle Screw Insertion Technique

In all the enrolled patients, pedicle screws were inserted using the freehand technique which uses the base of the facet joint as a landmark for entry. The entry point for pedicle screws in the thoracic spine is the lateral third of the lower border of the superior articular process, while the entry point in the lumbar spine is just lateral to the base of the facet joint. After confirming the entry point with the eyes, a hole was created at the entry point using a drill. A trajectory was created perpendicular to the surface of the superior articular process using curved-shape probe, and a pedicle screw was inserted through the screw pathway.

Screw lengths of 25–30 mm were inserted into the upper thoracic vertebrae (T1–3), 30–35 mm in the middle thoracic vertebrae (T4–9), 35–40 mm in the lower thoracic vertebrae (T10–12), and 40–45 mm in the lumbar vertebrae. In the case of MISS, a guide pin was inserted through the screw pathway and 5.0–6.0 mm diameter cannulated screws were then inserted along the guide pin. In the case of COSS, a non-cannulated screw with a diameter of 4.0–6.0 mm was inserted.

4. Evaluation of Screw Accuracy and Safety Through CT Scans

The accuracy and safety of the inserted pedicle screws were evaluated using postoperative CT scans. To minimize the effect of metal scattering around the screw, the CT image was adjusted to the bone setting (2,000 HU window width and 500 HU window level). The measurement was made dividing the groups into screws inserted into the thoracic and lumbar regions. Screws inserted into the thoracic vertebrae were divided again into the upper (T1–3), middle (T4–9), and lower (T10–12) thoracic regions.

Violation of the pedicle screw was evaluated in 2 ways. First, the medial and lateral violations of the pedicle screw were defined as invasion of the medial and lateral cortices of the pedicle. Depending on the degree of violation of the screw into the medial and lateral cortical walls of the pedicle, it was classified as grade 0 (if there was no violation of the pedicle), grade 1 (pedicle violation of less than 2 mm), and grade 2 (violation of more than 2 mm). Second, the anterior violation of the pedicle screw was evaluated based on the position of the screw tip and graded as 0, 1, 2 – grade 0 is inside the vertebral body, grade 1 is outside the vertebral body, but no contact with internal organs, and grade 2 is outside the vertebral body with contact with internal organs. All types of grade 2 violations were defined as “critical violations”.

CT evaluations were performed by a spine-trained orthopedic surgeon (YN) and a general orthopedic surgeon (SL) on 2 different occasions (2 weeks apart) to determine inter- and intraobserver reliabilities. Two observers held a consensus meeting prior to each evaluation. After the second evaluation, both observers had a final meeting to decide on the violation grades. If both observers agreed on the grade, this grade was used. If there was a discrepancy between the observers, the higher grade was used. The interobserver reliability between the 2 observers was moderate ($\kappa = 0.534$) at the first evaluation and substantial ($\kappa = 0.744$) at the second evaluation. The intraobserver reliability of the observers was substantial ($\kappa = 0.645, 0.702$).

5. Complication Evaluation

After surgery, complications such as hemothorax, infection, wound dehiscence, and neurological deficit were evaluated. Recovery due to screw malposition was also evaluated.

6. Statistical Analysis

Data analysis was performed using the IBM SPSS Statistics ver. 20.0 (IBM Co., Armonk, NY, USA). Student t-test was used for the analysis of continuous variables, and the chi-square test and Fisher exact test were used for the analysis of categorical variables. Statistical significance was set at $p < 0.05$. Inter- and intraobserver reliability were evaluated using Cohen kappa.

RESULTS

There were no statistically significant differences between the 2 groups in age, height, weight, body mass index, curve type, preoperative Cobb angle, and flexibility of the curve (all $p > 0.05$). There was a difference in sex between the 2 groups ($p = 0.046$). Detailed demographic data are presented in Table 1.

A total of 1,804 pedicle screws were analyzed using CTs. Among them, 630 pedicle screws were inserted in the MISS group and 1,174 pedicle screws in the COSS group. In the MISS group, 14, 320, 168, and 128 screws were inserted in the upper thoracic, middle thoracic, lower thoracic, and lumbar vertebrae, respectively. In the COSS group, 71, 555, 280, and 268 screws were inserted in the upper, middle, lower thoracic, and lumbar vertebrae, respectively. Table 2 provides details on the anatomical regions and the proportion of pedicle screws for each group.

In the MISS group, 106 out of 630 pedicle screws (16.8%)
were identified as critical violations. In the COSS group, 165 of the 1,174 pedicle screws (14.0%) were identified as critical violations. There was no difference in the rate of critical violations between the 2 groups (p = 0.116). When divided by the direction of critical violations, lateral critical violations occurred most frequently as seen in 74 cases (11.7%) in the MISS group and 121 cases (10.3%) in the COSS group (p = 0.348). Medial critical violations were the next most frequent occurrence in the MISS group as seen in 30 cases (4.8%) and in 39 cases in the COSS group (3.3%) (p = 0.128). Anterior critical violations occurred in 8 cases (1.3%) in the MISS group and 19 cases (1.6%) in the COSS group (p = 0.561) (Table 3).

In the thoracic region, medial critical violations occurred more frequently in 28 cases (5.6%) in the MISS group compared to the 27 cases (3.0%) in the COSS group (p = 0.016). There was no difference in the anterior and lateral critical violation rates between the 2 groups (p = 0.334, p = 0.401). In the lumbar region, there was no difference in the critical violation rate in every direction between the 2 groups (Table 4).

In the thoracic regions, there was no difference in the medial critical violation rate between the 2 groups of the upper and lower thoracic regions. In the middle thoracic region, medial critical violations occurred more frequently as seen in 25 cases (7.8%) in the MISS group than the COSS group with 16 cases (2.9%) (p = 0.010) (Table 4). Among the critical violations in the middle thorax, screws on left side exhibited a difference in critical violations (p = 0.003) (Table 4). The medial critical violation rate of the inserted screw at each level is shown in Fig. 2.

There were no postoperative neurologic deficits or revision surgeries due to screw malposition. There was no difference in complications such as hemothorax, wound dehiscence, and in-

Table 1. Demographic data of the patients

<table>
<thead>
<tr>
<th>Variable</th>
<th>MISS group</th>
<th>COSS group</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>17.7 ± 4.7</td>
<td>17.6 ± 5.5</td>
<td>0.921</td>
</tr>
<tr>
<td>Sex, male:female</td>
<td>1:27</td>
<td>1:37</td>
<td>0.046</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>160.6 ± 5.2</td>
<td>161.1 ± 7.7</td>
<td>0.617</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>48.7 ± 6.7</td>
<td>49.9 ± 10.5</td>
<td>0.538</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>18.9 ± 2.5</td>
<td>19.0 ± 3.0</td>
<td>0.823</td>
</tr>
<tr>
<td>Risser stage, 0:1:2:3:4:5</td>
<td>1:1:2:8:15</td>
<td>1:4:3:20:19</td>
<td>0.706</td>
</tr>
<tr>
<td>Flexibility of curve (%)</td>
<td>30.5 ± 16.2</td>
<td>25.9 ± 16.0</td>
<td>0.233</td>
</tr>
<tr>
<td>Preoperative magnitude of main curve (º)</td>
<td>63.9 ± 10.8</td>
<td>65.1 ± 15.1</td>
<td>0.719</td>
</tr>
<tr>
<td>Postoperative magnitude of main curve (º)</td>
<td>21.9 ± 7.6</td>
<td>22.6 ± 11.3</td>
<td>0.724</td>
</tr>
<tr>
<td>Fusion level</td>
<td>10.2 ± 0.9</td>
<td>11.2 ± 1.5</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Values are presented as mean ± standard deviation or number. MISS, minimally invasive scoliosis surgery; COSS, conventional open scoliosis surgery; BMI, body mass index.

Table 2. Number and proportion of inserted pedicle screws by anatomical region

<table>
<thead>
<tr>
<th>Variable</th>
<th>MISS group</th>
<th>COSS group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Right side</td>
<td>Left side</td>
</tr>
<tr>
<td>Total inserted screws</td>
<td>315</td>
<td>315</td>
</tr>
<tr>
<td>Thoracic</td>
<td>251 (79.7%)</td>
<td>251 (79.7%)</td>
</tr>
<tr>
<td>Upper thoracic</td>
<td>7 (2.2%)</td>
<td>7 (2.2%)</td>
</tr>
<tr>
<td>Middle thoracic</td>
<td>160 (50.8%)</td>
<td>160 (50.8%)</td>
</tr>
<tr>
<td>Lower thoracic</td>
<td>84 (26.7%)</td>
<td>84 (26.7%)</td>
</tr>
<tr>
<td>Lumbar</td>
<td>64 (20.3%)</td>
<td>64 (20.3%)</td>
</tr>
</tbody>
</table>

Values are presented as number (%). MISS, minimally invasive scoliosis surgery; COSS, conventional open scoliosis surgery.

Table 3. Number of critical violations and critical violation rate by the direction of the violation

<table>
<thead>
<tr>
<th>Direction</th>
<th>MISS group</th>
<th>COSS group</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior</td>
<td>8 (1.3%)</td>
<td>19 (1.6%)</td>
<td>0.561</td>
</tr>
<tr>
<td>Medial</td>
<td>30 (4.8%)</td>
<td>39 (3.3%)</td>
<td>0.128</td>
</tr>
<tr>
<td>Lateral</td>
<td>74 (11.7%)</td>
<td>121 (10.3%)</td>
<td>0.348</td>
</tr>
<tr>
<td>Overall</td>
<td>106 (16.8%)</td>
<td>165 (14.0%)</td>
<td>0.116</td>
</tr>
</tbody>
</table>

Values are presented as number (%). MISS, minimally invasive scoliosis surgery; COSS, conventional open scoliosis surgery.
The safety and clinical usefulness of MISS surgery has been reported in various studies. However, because of the limited surgical fields of view creating difficulty in identifying and maintaining the pedicle screw trajectory, freehand pedicle screwing in MISS surgery remains technically challenging. In MISS, 2 skin incisions of 4 cm in length are used for pedicle screw insertion and correction maneuvering of the curve. Due to the 4-cm incision, the surgical field consisting of only the 4-cm skin-incised area creates difficulty in identifying the entry point and trajectory due to other areas underneath the skin that are unincised. As a result, the accuracy of the pedicle screw in MISS can be quite different from that of open scoliosis surgery. Therefore, the authors conducted a study related to the accuracy and safety of MISS surgery.

### Table 4. Number of critical violations and critical violation rate by anatomical region

<table>
<thead>
<tr>
<th>Variable</th>
<th>MISS group</th>
<th>COSS group</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thoracic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior</td>
<td>6 (1.2)</td>
<td>17 (1.9)</td>
<td>0.334</td>
</tr>
<tr>
<td>Medial</td>
<td>28 (5.6)</td>
<td>27 (3.0)</td>
<td>0.016</td>
</tr>
<tr>
<td>Lateral</td>
<td>67 (13.3)</td>
<td>107 (11.8)</td>
<td>0.401</td>
</tr>
<tr>
<td>Upper thoracic (T1–3)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior</td>
<td>0 (0)</td>
<td>4 (5.6)</td>
<td>1.000</td>
</tr>
<tr>
<td>Medial</td>
<td>1 (7.1)</td>
<td>4 (5.6)</td>
<td>1.000</td>
</tr>
<tr>
<td>Lateral</td>
<td>1 (7.1)</td>
<td>10 (14.1)</td>
<td>0.682</td>
</tr>
<tr>
<td>Middle thoracic (T4–9)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior</td>
<td>5 (1.6)</td>
<td>11 (2.0)</td>
<td>0.656</td>
</tr>
<tr>
<td>Medial</td>
<td>25 (7.8)</td>
<td>16 (2.9)</td>
<td>0.010</td>
</tr>
<tr>
<td>Right medial</td>
<td>8 (5.0)</td>
<td>6 (2.2)</td>
<td>0.105</td>
</tr>
<tr>
<td>Left medial</td>
<td>17 (10.6)</td>
<td>10 (3.6)</td>
<td>0.003</td>
</tr>
<tr>
<td>Lateral</td>
<td>46 (14.4)</td>
<td>71 (12.8)</td>
<td>0.508</td>
</tr>
<tr>
<td>Lower thoracic (T10–12)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior</td>
<td>1 (0.6)</td>
<td>2 (0.7)</td>
<td>1.000</td>
</tr>
<tr>
<td>Medial</td>
<td>2 (1.2)</td>
<td>7 (2.5)</td>
<td>0.494</td>
</tr>
<tr>
<td>Lateral</td>
<td>20 (11.9)</td>
<td>26 (9.3)</td>
<td>0.377</td>
</tr>
<tr>
<td>Lumbar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior</td>
<td>2 (1.6)</td>
<td>2 (0.7)</td>
<td>0.598</td>
</tr>
<tr>
<td>Medial</td>
<td>2 (1.6)</td>
<td>12 (4.5)</td>
<td>0.242</td>
</tr>
<tr>
<td>Lateral</td>
<td>7 (5.5)</td>
<td>10 (5.2)</td>
<td>0.919</td>
</tr>
</tbody>
</table>

Values are presented as number (%). MISS, minimally invasive scoliosis surgery; COSS, conventional open scoliosis surgery.

### Table 5. Number of complications and complication rate

<table>
<thead>
<tr>
<th>Variable</th>
<th>MISS group</th>
<th>COSS group</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hemothorax</td>
<td>4 (14.3)</td>
<td>16 (33.3)</td>
<td>0.105</td>
</tr>
<tr>
<td>Infection</td>
<td>2 (7.1)</td>
<td>4 (8.3)</td>
<td>1.000</td>
</tr>
<tr>
<td>Wound problem</td>
<td>3 (10.7)</td>
<td>3 (6.3)</td>
<td>0.664</td>
</tr>
<tr>
<td>Neurologic deficit</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>-</td>
</tr>
<tr>
<td>Revision surgery</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>-</td>
</tr>
</tbody>
</table>

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The safety and clinical usefulness of MISS surgery has been reported in various studies. However, because of the limited surgical fields of view creating difficulty in identifying and maintaining the pedicle screw trajectory, freehand pedicle screwing in MISS surgery remains technically challenging. In MISS, 2 skin incisions of 4 cm in length are used for pedicle screw insertion and correction maneuvering of the curve. Due to the 4-cm incision, the surgical field consisting of only the 4-cm skin-incised area creates difficulty in identifying the entry point and trajectory due to other areas underneath the skin that are unincised. As a result, the accuracy of the pedicle screw in MISS can be quite different from that of open scoliosis surgery. Therefore, the authors conducted a study related to the accuracy and safety of MISS surgery.

### DISCUSSION

The safety and clinical usefulness of MISS surgery has been reported in various studies. However, because of the limited surgical fields of view creating difficulty in identifying and maintaining the pedicle screw trajectory, freehand pedicle screwing in MISS surgery remains technically challenging. In MISS, 2 skin incisions of 4 cm in length are used for pedicle screw insertion and correction maneuvering of the curve. Due to the 4-cm incision, the surgical field consisting of only the 4-cm skin-incised area creates difficulty in identifying the entry point and trajectory due to other areas underneath the skin that are unincised. As a result, the accuracy of the pedicle screw in MISS can be quite different from that of open scoliosis surgery. Therefore, the authors conducted a study related to the accuracy and safety of MISS surgery.

### Table 4. Number of critical violations and critical violation rate by anatomical region

<table>
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<th>COSS group</th>
<th>p-value</th>
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</thead>
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<tr>
<td>Thoracic</td>
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<tr>
<td>Anterior</td>
<td>6 (1.2)</td>
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<td>0.334</td>
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<tr>
<td>Medial</td>
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<td>0.016</td>
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<td>Lateral</td>
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<td>Upper thoracic (T1–3)</td>
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<tr>
<td>Anterior</td>
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<td>1.000</td>
</tr>
<tr>
<td>Medial</td>
<td>1 (7.1)</td>
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<td>1.000</td>
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<tr>
<td>Lateral</td>
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<td>0.682</td>
</tr>
<tr>
<td>Middle thoracic (T4–9)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior</td>
<td>5 (1.6)</td>
<td>11 (2.0)</td>
<td>0.656</td>
</tr>
<tr>
<td>Medial</td>
<td>25 (7.8)</td>
<td>16 (2.9)</td>
<td>0.010</td>
</tr>
<tr>
<td>Right medial</td>
<td>8 (5.0)</td>
<td>6 (2.2)</td>
<td>0.105</td>
</tr>
<tr>
<td>Left medial</td>
<td>17 (10.6)</td>
<td>10 (3.6)</td>
<td>0.003</td>
</tr>
<tr>
<td>Lateral</td>
<td>46 (14.4)</td>
<td>71 (12.8)</td>
<td>0.508</td>
</tr>
<tr>
<td>Lower thoracic (T10–12)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Anterior</td>
<td>1 (0.6)</td>
<td>2 (0.7)</td>
<td>1.000</td>
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<td>Medial</td>
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<tr>
<td>Lateral</td>
<td>20 (11.9)</td>
<td>26 (9.3)</td>
<td>0.377</td>
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<tr>
<td>Lumbar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior</td>
<td>2 (1.6)</td>
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<tr>
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<tr>
<td>Lateral</td>
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<td>10 (5.2)</td>
<td>0.919</td>
</tr>
</tbody>
</table>

Values are presented as number (%). MISS, minimally invasive scoliosis surgery; COSS, conventional open scoliosis surgery.
Pedicle Screw Accuracy Safety MISS

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The critical violation rate of inserted pedicle screws in the MISS group was 16.8%, which was slightly higher compared to the COSS group (14.0%) with no statistical significance. The critical violation rate of 16.8% in the MISS group is considered to be similar to the violation rate of 10% to 12% reported in COSS in previous studies.9,11

Eight cases (1.2%) of critical anterior violations occurred in the MISS group. The pedicle screws with anterior critical violations were in contact with the lung in 7 cases and the psoas muscle in 1 case of the MISS group. However, no signs of injury such as hemorrhage were identified in the internal organs. During the follow-up, no complications requiring reoperation or repositioning of screws developed. According to previous studies, screws that are in contact with organs do not always cause complications.9,14,15 However, the thoracic aorta and the esophagus on the left side and the azygous vein and inferior vena cava on the right side of the vertebral column were at the greatest risk for injury in anterior violations.16 There was no statistical difference in anterior critical violations between the MISS and COSS groups (p = 0.561).

In the MISS group, 30 cases (4.8%) of critical medial violations occurred. Medial critical violations occurring in the thoracic spine were identified in 28 cases (11 cases on the right side and 17 cases on the left side). However, none of the 28 patients exhibited neurological symptoms. According to a study by Liljenqvist et al.,17 the safety space for the spinal cord in scoliosis changes according to the concavity with the maximum width of the safety space being approximately 5 mm on the convex side. Due to this wide safety margin on the convex side of scoliosis patients, no neurological injuries developed. In this study, neurological deficits were not observed despite screw violations into the medial wall of the pedicle by more than 2 mm. This could be explained by shifting of the dura mater and spinal cord on the side of the screw.18

Twenty-five cases of critical medial violations occurred in the middle thoracic region. It is interesting that screws only on the left side exhibited differences with statistical significance (p = 0.003). The possible explanation for the common development of critical violations in the left side of the middle thorax are as follows: firstly, the left side of the middle thoracic region is close to the apical vertebra of the concave side where the vertebral column is most severely rotated placing it more vulnerable to medial violations with high convergent screw trajectories. Secondly, the middle thoracic vertebrae are located distal to the skin incision, making approaches difficult with limited visualization of the surgical field (Fig. 3A, B). Narrow surgical fields

Fig. 3. (A) Illustration of the scoliosis curve and location of skin incisions in minimally invasive scoliosis surgery. (B) Visibility is obtained just below the skin incision. However, there is a possible blind spot in the middle thoracic region between the 2 skin incisions.
and soft tissue obstacles interfere with the proper positioning for screw trajectories and probing of the hole with ball tips. For palpation of the continuity of medial wall of the pedicle with ball tip probes, the probes require convergent angles and sufficient soft retraction (Fig. 4A–C). As a result of higher convergent screw trajectories and narrow surgical fields with difficult soft tissue retraction, the safety of the medial wall of the pedicle could not be clearly confirmed and may have resulted in a higher rate of medial wall violations of the left side of the middle thoracic region.

In the MISS group, lateral critical violations occurred in 74 cases (11.7%), but there were no complications after surgery. There was no statistically significant difference, even when compared with the COSS group. When additionally classified by anatomical region, lateral critical violations occurred more frequently in the thoracic region (13.3%) compared to the lumbar region (5.5%). Lateral critical violations in the thoracic region are not “critical” because the lateral pedicle wall at the thoracic region is covered with a rib. Therefore, surgeons tend not to mind lateral violations that occur in the thoracic region.

This study demonstrated the accuracy and safety of pedicle screws using freehand techniques in MISS compared to COSS, but there were limitations. Not all patients who underwent surgeries were included, only patients who underwent both preoperative and postoperative CT scans. The retrospective design and small sample size, especially in the upper thoracic region, limits the statistical power.

**CONCLUSION**

Pedicle screws using the freehand technique in MISS provide similar accuracy and safety when compared with COSS. MISS could be a safe option for the treatment of AIS. Pedicle screws inserted on the left side of the thoracic region, especially the middle thoracic region, exhibited more medial critical violations in the MISS group. Cautious placement of pedicle screws is recommended when inserting pedicle screws into the left side of middle thoracic regions in MISS.

**NOTES**

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The Prediction of Neurological Prognosis for Cervical Spondylotic Myelopathy Using Diffusion Tensor Imaging

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Objective: Although cervical spondylotic myelopathy (CSM) can be easily diagnosed using magnetic resonance imaging (MRI), prediction of surgical effect using preoperative radiological examinations remains difficult. In previous studies, it was reported that diffusion tensor imaging (DTI) may be used for the prediction of surgical effect; however, these studies did not consider the influences of spinal cord compression even though the values of DTI indexes can be distorted by compressive lesions in patients with CSM. Therefore, it is uncertain whether preoperative DTI indexes can actually predict the surgical effect. The aim of this study was to investigate DTI metrics that are hardly affected by spinal cord compression and can accurately predict neurological status after decompressive surgery.

Methods: Twenty-one patients with CSM who underwent surgery and 10 healthy volunteers were enrolled in this study. The subjects underwent cervical MRI, and values of DTI indexes including axial diffusivity (AD), radial diffusivity (RD), apparent diffusion coefficient (ADC), and fractional anisotropy (FA) were recorded at each intervertebral level. Further, the Japanese Orthopaedic Association (JOA) score of each patient with CSM was recorded before and after surgery for neurological status evaluation. Preoperative and postoperative values of DTI indexes were compared, and correlations between preoperative DTI parameters and postoperative neurological recovery were assessed.

Results: After surgery, the lesion-adjacent (LA) ratios of RD and ADC increased (p = 0.04 and p = 0.062, respectively), while the LA ratio of FA decreased (p = 0.075). In contrast, the LA ratio of AD hardly changed. A negative correlation was observed between preoperative LA ratio of AD and JOA recovery rate 6 months after surgery (r = -0.379, p = 0.091). Based on preoperative LA ratio of AD, the patients were divided into a low AD group and a high AD group, and JOA recovery rate 6 months after surgery was found to be higher in the low AD group than in the high AD group (p = 0.024).

Conclusion: In patients with CSM, preoperative LA ratio of AD is seldom affected by spinal cord compression, and it negatively correlates with JOA recovery rate 6 months after surgery.

Keywords: Cervical spondylotic myelopathy, Magnetic resonance imaging, Diffusion tensor imaging
INTRODUCTION

Cervical spondylotic myelopathy (CSM) is a major cause of cervical spinal cord dysfunction, especially in elderly patients. Due to spinal degeneration and consequent cervical spinal cord compression, CSM is often associated with several symptoms. Magnetic resonance imaging (MRI) is the gold standard imaging modality for CSM diagnosis and treatment strategy design. Conventional MRI can reveal compression factors, including the intervertebral disc, ligamentum flavum, vertebral osteophyte, facet joint, and ossification of posterior longitudinal ligament, and T2-weighted hyperintensity in cord parenchyma. In addition, conditions of cervical spinal components including disc degeneration, Modic changes, and facet joint degeneration can be assessed by conventional MRI. However, it is difficult to predict surgical effect using only conventional MRI.

Diffusion tensor imaging (DTI) has been gaining popularity in the assessment of spinal cord microstructure. It can be used to evaluate the magnitude and direction of water molecule diffusion, and it allows for the calculation of various indexes using diffusivities along the 3 principal axes. DTI can be used for spinal cord evaluation given that the spinal cord is an elongated organ and water molecules tend to diffuse in the axial direction. Several studies on CSM evaluation using DTI have been conducted, and some of the studies revealed correlations between preoperative DTI parameters and postoperative neurological function; however, they did not consider the effect of cord compression before surgery. It was reported that values of DTI indexes can be distorted by compressive lesions; this phenomenon is known as aligned fibers effect. Some DTI indexes may be modified under cord compression, making for inaccurate prediction of surgical effect in patients with CSM. The aim of this study was to investigate DTI metrics that are hardly affected by spinal cord compression and can accurately predict postoperative neurological prognosis.

MATERIALS AND METHODS

This study was approved by the Institutional Review Board of Otaru General Hospital (approval number: 30-009), and informed consent was obtained from all study participants.

1. Participants

Twenty-three patients with CSM who underwent surgery at Otaru General Hospital between May 2016 and November 2017 were enrolled in this study. The patients underwent MRI before surgery and a week after surgery, Japanese Orthopaedic Association (JOA) score was used to evaluate the neurological status of the patients, and JOA recovery rate was determined 6 months after surgery. Two of the 23 patients with C6/7 intervertebral level as the most compressed intervertebral level were excluded from the study because of significant errors in DTI indexes due to respiratory artifact. In addition, 10 healthy volunteers were included in this study, and cervical MRI was performed on the healthy volunteers to obtain normal values of DTI indexes.

2. Image Acquisition

Cervical spinal cord MRI was performed using a 3.0-Tesla MRI scanner (Ingenia, Philips, Best, The Netherlands), and zonally oblique multislice (ZOOM) DTI sequences were used as described in a previous study. DTI was performed using a single-shot spin-echo sequence under the following scan parameters: repetition time/echo time = 4,500/63 msec, field of view = 70 x 47 mm$^2$, slice thickness = 5 mm, number of sample averages = 10, and b-value = 600 sec/mm$^2$. The scan range was C2 to C7. From the obtained DTI data, axial diffusivity (AD), radial diffusivity (RD), apparent diffusion coefficient (ADC), and fractional anisotropy (FA) maps were generated. By checking the 3-dimensional region of interest (ROI) square, the maximum possible ROI was manually placed on the cord without including cerebrospinal fluid.

3. Data Assessment

According to a previous study, values of DTI parameters differ across spinal cord levels. Further, absolute values of DTI parameters differ between individuals. Therefore, it is difficult to compare DTI parameters between spinal cord levels or between patients. To circumvent this drawback, the ratio of the value of interest at the level of the lesion to the mean value at the adjacent superior and inferior intervertebral levels, i.e., the lesion-adjacent (LA) ratio, was calculated (Fig. 1).

4. Statistical Analysis

The acquired data are presented as mean ± standard deviation (SD). Statistical analyses were performed using JMP Pro 14 software (SAS Institute Inc., Cary, NC, USA). One-way analysis of variance was used to compare groups, and differences in DTI parameters before and after decompression surgery were evaluated using paired t-test. Student t-test was used to compare 2 independent groups. Pearson correlation analysis was performed to determine correlations between the LA ratio and other variables.
of preoperative DTI parameters and JOA recovery rate. Statistical significance was set at \( p < 0.05 \).

**RESULTS**

1. **Participant Characteristics**

   The demographic data of patients and healthy volunteers are shown in Table 1. There were 21 patients (13 men and 8 women) aged 42–92 years old and 10 healthy volunteers (7 men and 3 women) aged 23–49 years old. The most compressed spinal level was C3/4 in 4 patients, C4/5 in 8 patients, and C5/6 in 9 patients. The mean preoperative JOA score was 10.0 ± 4.3. Of the 21 patients, 12 underwent anterior cervical discectomy/pectomy and fusion, while 9 underwent laminoplasty.

2. **DTI Parameters in Healthy Volunteers**

   Table 2 shows a comparison of the raw data and LA ratio of DTI parameters at the C3/4, C4/5, and C5/6 intervertebral levels of healthy volunteers. Regarding the raw data, statistically significant differences in the mean values of RD, ADC, and FA at the intervertebral levels were observed (\( p = 0.007 \), \( p = 0.013 \), and \( p = 0.02 \), respectively). In contrast, the mean values of LA ratio of DTI indexes (except AD) were generally distributed around 1.00 and did not differ between intervertebral levels. Thus, for comparison between intervertebral levels, LA ratio can be considered more appropriate than absolute value.

3. **Changes of DTI Parameters After Surgery in Patients With CSM**

   The changes between preoperative and postoperative LA ra-

---

**Table 1. Participants’ characteristics**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Patients (n = 21)</th>
<th>Healthy volunteers (n = 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>69.6 ± 12.8</td>
<td>30.2 ± 8.0</td>
</tr>
<tr>
<td>Sex</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>13 (62)</td>
<td>7 (70)</td>
</tr>
<tr>
<td>Male</td>
<td>8 (38)</td>
<td>3 (30)</td>
</tr>
<tr>
<td>Lesion level</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C3/4</td>
<td>4 (19)</td>
<td>-</td>
</tr>
<tr>
<td>C4/5</td>
<td>8 (38)</td>
<td>-</td>
</tr>
<tr>
<td>C5/6</td>
<td>9 (43)</td>
<td>-</td>
</tr>
<tr>
<td>Preoperative JOA score</td>
<td>10.0 ± 4.3</td>
<td>-</td>
</tr>
<tr>
<td>Surgery</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior approach</td>
<td>12 (57)</td>
<td>-</td>
</tr>
<tr>
<td>Posterior approach</td>
<td>9 (43)</td>
<td>-</td>
</tr>
</tbody>
</table>

Values are presented as mean ± standard deviation or number (%). JOA, Japan Orthopaedic Association.

**Table 2. Diffusion tensor imaging parameters in normal healthy participants**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Absolute value</th>
<th>LA ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>p-value</td>
</tr>
<tr>
<td>AD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C3/4</td>
<td>1.98 ± 0.13</td>
<td>0.007</td>
</tr>
<tr>
<td>C4/5</td>
<td>1.91 ± 0.10</td>
<td>0.95 ± 0.07</td>
</tr>
<tr>
<td>C5/6</td>
<td>2.03 ± 0.21</td>
<td>0.94 ± 0.09</td>
</tr>
<tr>
<td>Total</td>
<td>1.97 ± 0.15</td>
<td>0.98 ± 0.09</td>
</tr>
<tr>
<td>RD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C3/4</td>
<td>0.61 ± 0.11</td>
<td>0.013</td>
</tr>
<tr>
<td>C4/5</td>
<td>0.64 ± 0.11</td>
<td>0.92 ± 0.16</td>
</tr>
<tr>
<td>C5/6</td>
<td>0.80 ± 0.16</td>
<td>0.99 ± 0.18</td>
</tr>
<tr>
<td>Total</td>
<td>0.68 ± 0.15</td>
<td>0.99 ± 0.20</td>
</tr>
<tr>
<td>ADC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C3/4</td>
<td>1.06 ± 0.10</td>
<td>0.02</td>
</tr>
<tr>
<td>C4/5</td>
<td>1.06 ± 0.09</td>
<td>0.94 ± 0.10</td>
</tr>
<tr>
<td>C5/6</td>
<td>1.21 ± 0.16</td>
<td>0.96 ± 0.12</td>
</tr>
<tr>
<td>Total</td>
<td>1.11 ± 0.13</td>
<td></td>
</tr>
<tr>
<td>FA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C3/4</td>
<td>0.65 ± 0.07</td>
<td></td>
</tr>
<tr>
<td>C4/5</td>
<td>0.62 ± 0.08</td>
<td>1.03 ± 0.12</td>
</tr>
<tr>
<td>C5/6</td>
<td>0.56 ± 0.07</td>
<td>0.96 ± 0.12</td>
</tr>
<tr>
<td>Total</td>
<td>0.61 ± 0.08</td>
<td>0.99 ± 0.12</td>
</tr>
</tbody>
</table>

Values are presented as mean ± standard deviation. LA, lesion-adjacent; SD, standard deviation; AD, axial diffusivity; RD, radial diffusivity; ADC, apparent diffusion coefficient; FA, fractional anisotropy; NS, not significance.
tios of DTI parameters at the most compressed level are shown in Table 3. After surgery, the LA ratio of RD significantly increased (p = 0.04) and that of ADC showed an increasing trend, while the LA ratio of FA showed a decreasing trend. In contrast, there was almost no difference between preoperative and postoperative LA ratios of AD.

**Table 3.** Pre and postoperative diffusion tensor imaging parameters in patients

<table>
<thead>
<tr>
<th>Variable</th>
<th>Preoperative LA ratio</th>
<th>Postoperative LA ratio</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD</td>
<td>1.03 ± 0.04</td>
<td>1.09 ± 0.06</td>
<td>NS</td>
</tr>
<tr>
<td>RD</td>
<td>1.00 ± 0.05</td>
<td>1.26 ± 0.12</td>
<td>0.04</td>
</tr>
<tr>
<td>ADC</td>
<td>1.02 ± 0.04</td>
<td>1.16 ± 0.09</td>
<td>NS</td>
</tr>
<tr>
<td>FA</td>
<td>1.02 ± 0.03</td>
<td>0.94 ± 0.05</td>
<td>NS</td>
</tr>
</tbody>
</table>

Values are presented as mean ± standard deviation. LA, lesion-adjacent; AD, axial diffusivity; RD, radial diffusivity; ADC, apparent diffusion coefficient; FA, fractional anisotropy; NS, not significance.

4. Correlations Between Preoperative DTI Parameters and the JOA Recovery Rate

A negative correlation was observed between preoperative LA ratio of AD and JOA recovery rate 6 months after surgery (r = -0.379, p = 0.091) (Fig. 2A). In contrast, no correlation was observed between the preoperative LA ratios of the other parameters and JOA recovery rate (Fig. 2B–D).

Based on preoperative LA ratio of AD, patients with CSM were divided into 2 groups: high AD group (or group H) and low AD group (or group L). Group H was defined that the preoperative LA ratio of AD at the most compressed level was greater than mean value+2SD in healthy volunteers, whereas group L was defined that it was less than mean value+2SD. Therefore, cutoff values between group H and L were 1.21 for C3/4 level, 1.09 for C4/5 level, and 1.12 for C5/6 level. Further, JOA recovery rate 6 months after surgery was higher in group L than in group H (Fig. 3) (p = 0.024).

**Fig. 2.** Correlations between preoperative DTI parameters and JOA recovery rate. Preoperative LA ratio of AD (A) negatively correlates with JOA recovery rate 6 months after surgery (r = -0.379, p = 0.091). In contrast, preoperative LA ratios of RD (B), ADC (C), and FA (D) do not correlate with JOA recovery rate. DTI, diffusion tensor imaging; JOA, Japanese Orthopaedic Association; LA, lesion-adjacent; AD, axial diffusivity; RD, radial diffusivity; ADC, apparent diffusion coefficient; FA, fractional anisotropy.

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Prediction of Neurological Prognosis for CSM Using DTI

DISCUSSION

This study revealed that, in patients with CSM, surrounding degenerative structures hardly affect AD but easily affect RD, ADC, and FA. In addition, the results of this study suggest that postoperative neurological recovery negatively correlates with preoperative AD but does not correlate with the other DTI indexes.

There have been multiple studies on DTI in spinal cord disorders such as amyotrophic lateral sclerosis\(^\text{11,12}\) and spinal cord injury.\(^\text{13}\) Such studies demonstrated that FA decreased whereas ADC increased; this is acceptable as these disorders do not usually involve compressive lesions and DTI purely reflects nerve conditions. However, most previous studies on CSM reported decreased FA and increased ADC in patients compared with healthy controls, although DTI values should have been affected by compressive lesions.\(^\text{14-20}\) These results are contrary to the finding in this study of increased FA value and decreased ADC value at the compressed intervertebral level. These differences in findings may be due to differences in image resolution. Since the spinal cord is surrounded by cerebrospinal fluid whose diffusivity in any direction is high, DTI values will be inaccurate if there is ROI protrusion from the spinal cord surface.\(^\text{21}\) Longitudinal neuronal fibers, which are responsible for the high FA value of the spinal cord, are unevenly distributed in the surface layer; therefore, insufficient ROIs result in unreliable DTI values. The results of our other study on muscle FA value support the findings of this study.\(^\text{23}\) In this study, the FA value of muscle fibers was found to be increased by compression similar in nature to spinal cord compression. Unlike earlier studies that used 1.5-Tesla MRI scanners, we used a 3.0-Tesla MRI scanner to obtain high-resolution images. In addition, we used a ZOOM DTI technique to obtain images with fine contrast. We previously reported that, in terms of visibility and with regard to intrater and interrater reliability, ZOOM DTI is superior to conventional DTI; hence, with ZOOM DTI, the spinal cord surface is easily distinguishable.

Unlike FA and ADC, AD and RD have not been extensively focused on in previous studies. AD represents diffusivity parallel to axonal fibers, while RD represents diffusivities perpendicular to axonal fibers.\(^\text{24}\) Consideration of these directions is important in the evaluation of CSM. Zheng et al.\(^\text{25}\) focused on DTI parameters, including AD and RD. They showed that AD is different in behavior than RD, ADC, and FA, and this finding is consistent with the results of this study. Our study results suggest that spinal cord compression affects RD value but hardly affects AD value. This result is in line with the fact that spinal cord compression mainly occurs perpendicular to axonal fibers (Fig. 4).

There is no consensus regarding the correlation between preoperative DTI parameters and postoperative neurological outcome.\(^\text{5}\) Jones et al.\(^\text{26}\) did not report a significant correlation be-
between preoperative FA value and postoperative JOA score. Further, Wang et al.\textsuperscript{27} reported a significant positive correlation between preoperative FA value and JOA recovery rate and a significant negative correlation between preoperative ADC value and JOA recovery rate. In the study by Vedantam et al.\textsuperscript{28} it was reported that preoperative FA value may have a negative correlation with JOA score change. However, all the above-mentioned studies did not consider the compressed intervertebral level and the preoperative modification resulting from cord compression. In this study, we used the LA ratio to minimize the difference due to the affected level and found that postoperative neurological improvement correlates negatively with preoperative AD value but does not correlate with other DTI indexes. This finding is logical given that we found no differences between the preoperative and postoperative values of AD.

This study has some limitations. The evaluated intervertebral levels were limited to C3/4, C4/5, and C5/6 to calculate LA ratio; therefore, our result cannot apply patients with CSM showing compression at other levels. Moreover, most of the patients included in this study were elderly, and they might have other lesions such as lumbar canal stenosis, which could lead to an underestimation of JOA score.

**CONCLUSION**

Although compressive lesions in patients with CSM affect most preoperative DTI indexes, they seldom affect preoperative AD value. Moreover, preoperative AD value may have a negative correlation with JOA recovery rate 6 months after decompressive surgery; therefore, preoperative AD value may be used to predict postoperative neurological improvement in patients with CSM.

**NOTES**

**Conflict of Interest:** The authors have nothing to disclose.

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**Author Contribution:** Conceptualization: ST, MI; Data curation: ST, TY, DO; Formal analysis: ST; Methodology: ST, TY, DO; Visualization: ST; Writing - original draft: ST; Writing - review & editing: MI, YN, MF.

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Risk Factors of Postoperative Cerebrospinal Fluid Leak After Craniovertebral Junction Anomalies Surgery: A Case-Control Study

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Objective: To identify potential risk factors for cerebrospinal fluid (CSF) leakage after craniovertebral junction (CVJ) anomaly surgery and to provide a reference for clinical practice.

Methods: Sixty-six patients who underwent elective CVJ anomaly surgery during a 6-year period (April 2013 to September 2019) were retrospectively included. Research data were collected from the patients’ medical records and imaging systems. Patients were divided into CSF leak and no CSF leak groups. Univariate tests were performed to identify potential risk factors. For statistically significant variables in the univariate tests, a logistic regression test was used to identify independent risk factors for CSF leakage.

Results: The overall prevalence of CSF leakage was 13.64%. Univariate tests showed that a basion-dental interval (BDI) > 10 mm and occipitalized atlas had significant intergroup differences (p < 0.05). Multivariate analysis indicated that a BDI > 10 mm was an independent risk factor for CSF leakage, and patients with CVJ anomalies with a BDI > 10 mm were more likely to have postoperative CSF leaks (odds ratio, 14.67; 95% confidence interval, 1.48–30.88; p = 0.004).

Conclusion: It is necessary to maintain vigilance during CVJ anomaly surgery in patients with a preoperative BDI > 10 mm to avoid postoperative CSF leaks.

Keywords: Craniovertebral junction anomalies, Cerebrospinal fluid leak, Risk factor, Craniovertebral junction instability, Basion-dental interval

INTRODUCTION

Craniovertebral junction (CVJ) anomalies are pathological changes of the anatomical and functional complex surrounding the foramen magnum, including the occipital bone, atlas, axis, related ligaments, and other tissues, which often cause nerve and vascular damage and change cerebrospinal fluid (CSF) dynamics.¹ CVJ anomalies include basilar invagination (BI), Chiari malformation, atlantoaxial dislocation (AAD), occipitalized atlas, atlanto-occipital dislocation (AOD), and platybasia, and may include a single deformity or multiple deformities coexisting.²-⁶ At present, surgical treatment is adopted for patients with obvious neurological symptoms and ataxia.³-⁵ The therapeutic principle is to relieve the compression on the brainstem, spinal cord, and nerve roots, maintain or reconstruct the stability of the CVJ, and restore normal CSF circulation.⁷ Currently, there is no clear definition and diagnostic standard for CVJ instability, and it is difficult to correctly diagnose CVJ instability because of the complex anatomical structure of the CVJ and the diverse clinical manifestations and imaging.³,⁸ However, it is clear that the anatomical structure and stability of the CVJ are destroyed during surgical decompression; therefore, rigid fixation is needed to reconstruct and maintain its stability. The complicated anatomical structure of the CVJ, narrow
operative space, and large individual differences among patients increase the difficulty of the operation and the probability of various postoperative complications. CSF leakage is feared complication after CVJ anomaly surgery. According to our clinical experience, postoperative CSF leak occurs more frequently in patients with preoperative CVJ anomalies than in those with other spinal problems, which often affects the recovery and curative effect and is more difficult to handle. There is limited information about the risk factors for postoperative CSF leak. Therefore, the purpose of this study was to explore the potential risk factors for CSF leak after CVJ anomaly surgery and to provide a reference for clinical practice.

MATERIALS AND METHODS

1. Study Design

This retrospective analysis was conducted after obtaining approval from the Institutional Review Board (IRB) of the First Affiliated Hospital of Kunming Medical University (IRB No. 20211019). Data were collected from the medical records and imaging systems of our hospital. We reviewed the records of 77 patients who underwent an elective CVJ anomaly surgical procedure performed by the third author with the assistance of orthopedic surgery residents and spine fellows from April 2013 to September 2019. Sixty-six patients met the following inclusion criteria: (1) patients with congenital developmental CVJ anomalies who underwent CVJ surgery by anterior transoropharyngeal combined with a posterior approach or simple posterior approach; and (2) patients with complete clinical data. The exclusion criteria were as follows: (1) patients who underwent posterior fossa decompression with duraplasty; (2) CVJ anomalies caused by inflammation, tumor, trauma, tuberculosis, and rheumatoid immune diseases; and (3) revision surgery.

The information recorded for each patient included sex, age, disease course (DC), anterior atlantodental interval (AADI), Chamberlain’s line, basion-dental interval (BDI), basion-posterior axial line interval (BAI), occipitalized atlas, cranial base angle (CBA), clivus-canal angle (CCA), upper cervical stenosis, cerebellar tonsillar herniation (CTHI), syringomyelia, surgical approach, surgical segment, and surgery duration.

2. Recognition of Postoperative CSF Leak

Postoperative CSF leak was recognized by the following: (1) A dural tear or clear fluid extravasation from the dura during surgery; (2) a large amount of clear drainage after surgery, with clear liquid flowing out of the incision, and the presence of tinnitus, blurred vision, orthostatic headache, nausea, and vomiting; (3) some evidence of fluid leakage on postoperative MRI with magnetic resonance myelography.

An artificial dura mater or dural suture was used for patients with an intraoperative dural tear, and drainage was closely monitored after the operation.

3. Measurement Parameters

Important bone markers were mainly obtained by CT image measurement because bony landmarks are easily identifiable and consistently reproducible on CT images, and important nervous system markers were obtained by MRI measurement. The measurement parameters were as follows:

(1) AADI is the horizontal distance between the anterior arch of the atlas and the dens of the axis. Adults with an AADI > 3 mm can be considered to have AAD\(^{13}\) (Fig. 1A).

(2) Chamberlain line is a line joining the back of the hard palate with the opisthion on a lateral view of the CVJ.\(^{14}\) Chamberlain line helps to recognize BI, which is said to be present if the tip of the dens is > 3 mm above the line\(^{15}\) (Fig. 1B).

(3) The BDI is the distance from the most inferior portion of the basion to the closest point of the superior aspect of the dens in the median plane. The BDI was > 10 mm in the median plane, indicating AOD\(^{16,17}\) (Fig. 1C).

(4) The BAI is the distance between the basion and superior extension of the posterior cortical margin of the body of the axis in the median plane. If the basion is in front of the superior extension of the posterior cortical margin of the body of the axis and the BAI is > 12 mm, it indicates AOD. If the basion is located behind the superior extension of the posterior cortical margin of the body of the axis and the BAI is > 4 mm, it indicates AOD\(^{16,17}\) (Fig. 1D).

Almost all patients with a BDI of > 10 mm and BAI of > 12 mm or 4 mm were combined with occipitalized atlas; if they are described as AOD, there may be conceptual contradictions. The original atlanto-occipital joint was replaced by an abnormal atlantoaxial (or occipitoaxial) joint, which belongs to the CVJ. The instability of this abnormal joint should be classified as CVJ instability. Therefore, we regard a BDI of > 10 mm and BAI of > 12 mm or 4 mm as CVJ instabilities (CVJI [BDI] and CVJI [BAI]) in this study.

(5) The CBA is formed by the line joining the nasion with the center of the pituitary fossa and the line joining the anterior border of the foramen magnum with the center of the pituitary fossa; this indicates platybasia if the CBA is > 143°\(^{14}\) (Fig. 1E).

(6) Wackenheim line is formed by drawing a line along the...
clivus and extending it inferiorly to the upper cervical canal\(^6\) (Fig. 1F).

(7) The CCA is formed at the intersection of Wackenheim line with a line constructed along the posterior surface of the axis body and odontoid process, which normally ranges between 150° and 180°. Brain stem and spinal cord compression often occurs when the CCA is ≤ 150º\(^9\) (Fig. 1F).

(8) CTH: If CTH is > 5 mm, the distance of the cerebellar tonsils downward beyond the basion-opisthion line indicates CTH\(^20,21\) (Fig. 1G).

The measurement was performed by third-party radiologists, who were unaware of the patients’ condition and grouping. Each imaging data was measured 3 times and averaged.

### 4. Statistical Analysis

The prevalence of CSF leakage was calculated as the proportion of CSF leakage to the total number of individuals undergoing CVJ anomaly surgery. To identify factors associated with the CSF leaks, we used Student t-tests to determine the relationship between CSF leaks and age, DC, and surgery duration. Chi-square tests were used to determine the relationship between CSF leaks and CVJ instability (BDI), CVJ instability (BAI), AAD, BI, brainstem and spinal cord compression, platybasia, CTH, syringomyelia, surgical approach, and sex. Because the overall number of CSF leaks was small, the Yates correction factor was used to calculate the chi-square statistic if the expected frequency in any one cell was ≥ 1 and < 5. We used Fisher exact test to identify the effect of the occipitalized atlas, upper cervical stenosis, and surgical segment on the risk of CSF leak because the expected frequency in one cell was < 1. We also calculated the odds ratio (OR) and 95% confidence interval (CI) for each risk factor of CSF leakage. The a priori alpha level for all statistical tests was set at 0.05. All statistical analyses were performed using SPSS ver. 17.0 (SPSS Inc., Chicago, IL, USA).

Fig. 1. Measurement parameters. (A) Anterior atlantodental interval (red line). (B) Chamberlain line (white line), the distance between the tip of the dens and Chamberlain line (red line). (C) Basion-dental interval (red line). (D) Basion-posterior axial line interval (red line), the superior extension of the posterior cortical margin of the body of the axis in the median plane (white line). (E) Cranial base angle, the line joining the nasion with the center of the pituitary fossa (left red line), the line joining the anterior border of the foramen magnum with the center of the pituitary fossa (right red line). (F) Wackenheim line (upper red line), the line constructed along the posterior surface of the axis body and odontoid process (lower red line). (G) Cerebellar tonsillar herniation, basion-opisthion line (white line), the distance of the cerebellar tonsils downward beyond the basion-opisthion (red line). CBA, cranial base angle; CCA, clivus-canal angle.
RESULTS

1. Demographic Data

Seventy-seven patients chose surgical treatment, among whom, 66 met the inclusion criteria. Of the 66 patients, 21 were male (31.82%) and 45 were female (68.18%), with an average age of 41.42 ± 12.68 years old. Fourteen patients underwent surgery using the anterior transoropharyngeal combined with a posterior approach, and 52 patients underwent surgery using a simple posterior approach.

CSF leakage occurred in 9 patients, and 3 dural tears were diagnosed intraoperatively by visualizing clear fluid extravasation from the dura. The remaining 6 patients were diagnosed with postoperative CSF leaks due to complications of CSF leak, incision, drainage fluid, and auxiliary examination. The overall prevalence of CSF leaks was 13.64%.

Dural tears occurred during resection of the posterior arch of the atlas and decompression of the foramen magnum (2 patients), and while the posterior atlanto-occipital membrane was incised (1 patient). The other 6 patients with CSF leak had obvious adhesions between the posterior atlanto-occipital membrane (or ligamentum flavum) and dura, which were carefully separated and protected. No visible dural tear occurred during the operation, but clear drainage appeared 2 days after the operation. Of the 19 patients with a BDI > 10 mm, 2 had a dural tear during the resection of the posterior arch of the atlas and decompression of the foramen magnum, and 4 had no visible dural tear but presented with CSF leak postoperatively.

2. Treatment

All dural tears were repaired primarily by tight sutures and the cover of an artificial dura mater (TianXinFu biological membrane 30 × 40 mm, TianXinFu Medical Appliance Co., Ltd., Beijing, China). A submuscular drain was placed for posterior wounds and a drainage bag was placed on the patient’s bed so that it would not hold suction. For patients with CSF leakage, we appropriately extended the drainage time depending on the drainage volume. Submuscular drains were discontinued on postoperative day 4 and 11 (average) in patients without and with CSF leak, respectively. All patients with CSF leak were confined to bed rest with the head elevated at 30° for at least 1 day. We performed debridement, suturing, and pressure bandaging of the incision to close the CSF cutaneous fistula in a patient with clear liquid outflow from the incision in the oper-

Fig. 2. Clinical information of 66 patients. CVJ, craniovertebral junction; CSF, cerebrospinal fluid.
ating room. Antibiotics were also administered in an attempt to avoid central nervous system infections.

3. Outcome

The neurological symptoms of the 66 patients who received surgical treatment were relieved. Three patients with dural tears showed resolution of all signs and symptoms of the leak within 1 day. Of the 9 patients with CSF leak, 3, 2, and 1 patients had resolution of all signs and symptoms within 2, 3, and 6 days, respectively.

Three patients with dural tears still had CSF leaks after dural repair. Of the 3 patients with a dural tear, a lumbar CSF drain was inserted and left in place for 7 days for 1 patient with a persistently draining wound and a large amount of clear drainage. We extended the drainage time for the other 2 patients; however, 1 patient died of a severe central nervous system infection.

With the exception of the patient who died, the other 8 patients with CSF leak healed wounds within 2 to 4 weeks after timely treatment. No patient had wound infection, central nervous system infection, sinus tract formation, or sequelae of CSF leak during the follow-up period of more than 2 years after discharge (Fig. 2).

4. Univariate Analysis

Univariate analysis of potential risk factors showed no significant difference between the CSF leak group and the no CSF leak group in terms of sex (p = 0.294), age (p = 0.119), DC (p = 0.559), AAD (p = 1.000), BI (p = 0.516), CVJ instability

Table 1. Student t-test for potential risk factors for CSF leak

<table>
<thead>
<tr>
<th>Related factor</th>
<th>Group A (n = 57)</th>
<th>Group B (n = 9)</th>
<th>t</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>40.456 ± 13.014</td>
<td>47.556 ± 8.516</td>
<td>-1.578</td>
<td>0.119</td>
</tr>
<tr>
<td>DC</td>
<td>65.684 ± 75.331</td>
<td>83.111 ± 121.155</td>
<td>-0.588</td>
<td>0.559</td>
</tr>
<tr>
<td>AADI</td>
<td>3.365 ± 2.504</td>
<td>4.001 ± 2.830</td>
<td>-0.696</td>
<td>0.489</td>
</tr>
<tr>
<td>BDI</td>
<td>7.280 ± 4.507</td>
<td>11.222 ± 5.539</td>
<td>-2.364</td>
<td>0.021*</td>
</tr>
<tr>
<td>BAI</td>
<td>10.014 ± 9.042</td>
<td>13.818 ± 9.409</td>
<td>-1.167</td>
<td>0.248</td>
</tr>
<tr>
<td>CBA</td>
<td>135.772 ± 9.851</td>
<td>136.556 ± 10.224</td>
<td>-0.221</td>
<td>0.826</td>
</tr>
<tr>
<td>CCA</td>
<td>130.912 ± 17.101</td>
<td>123.444 ± 18.447</td>
<td>1.205</td>
<td>0.233</td>
</tr>
<tr>
<td>SD</td>
<td>267.807 ± 121.417</td>
<td>238.556 ± 103.078</td>
<td>0.684</td>
<td>0.497</td>
</tr>
</tbody>
</table>

Values are presented as mean ± standard deviation. CSF, cerebrospinal fluid; Group A, CSF leak group; Group B, no CSF leak group; DC, disease course; AADI, anterior atlantodental interval; BDI, basion-dental interval; BAI, basion-posterior axial line interval; CBA, cranial base angle; CCA, clivus-canal angle; SD, surgery duration.

*p < 0.05.

Table 2. Univariate analysis for potential risk factors of CSF leak

<table>
<thead>
<tr>
<th>Related factor</th>
<th>Group A (n = 57)</th>
<th>Group B (n = 9)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAI</td>
<td>25 (37.88)</td>
<td>7 (10.61)</td>
<td>0.125</td>
</tr>
<tr>
<td>CVJI</td>
<td>32 (48.48)</td>
<td>2 (3.03)</td>
<td></td>
</tr>
<tr>
<td>Normal</td>
<td>44 (66.67)</td>
<td>3 (4.54)</td>
<td>0.021*</td>
</tr>
<tr>
<td>BDI</td>
<td>13 (19.70)</td>
<td>6 (9.09)</td>
<td></td>
</tr>
<tr>
<td>CVJI</td>
<td>24 (36.36)</td>
<td>4 (6.06)</td>
<td>1.000</td>
</tr>
<tr>
<td>Normal</td>
<td>33 (50.00)</td>
<td>5 (7.58)</td>
<td>0.516</td>
</tr>
<tr>
<td>Chamberlain’s line</td>
<td>49 (74.24)</td>
<td>9 (13.64)</td>
<td></td>
</tr>
<tr>
<td>Normal</td>
<td>8 (12.12)</td>
<td>0 (0)</td>
<td></td>
</tr>
<tr>
<td>CBA</td>
<td>9 (13.64)</td>
<td>2 (3.03)</td>
<td>1.000</td>
</tr>
<tr>
<td>Platỳbasià</td>
<td>48 (72.73)</td>
<td>7 (10.60)</td>
<td></td>
</tr>
<tr>
<td>CTH</td>
<td>28 (42.42)</td>
<td>6 (9.09)</td>
<td>0.604</td>
</tr>
<tr>
<td>Herniation</td>
<td>29 (43.94)</td>
<td>3 (4.55)</td>
<td></td>
</tr>
<tr>
<td>Normal</td>
<td>30 (45.45)</td>
<td>5 (7.58)</td>
<td>1.000</td>
</tr>
<tr>
<td>Syringomyelia</td>
<td>27 (40.91)</td>
<td>4 (6.06)</td>
<td></td>
</tr>
<tr>
<td>Surgical approach</td>
<td>11 (16.67)</td>
<td>3 (4.55)</td>
<td></td>
</tr>
<tr>
<td>Anterior</td>
<td>46 (69.69)</td>
<td>6 (9.09)</td>
<td></td>
</tr>
<tr>
<td>Posterior</td>
<td>20 (30.30)</td>
<td>1 (1.52)</td>
<td></td>
</tr>
<tr>
<td>Sex</td>
<td>37 (56.06)</td>
<td>8 (12.12)</td>
<td>0.294</td>
</tr>
<tr>
<td>Male</td>
<td>33 (50.00)</td>
<td>8 (12.12)</td>
<td>0.376</td>
</tr>
<tr>
<td>Female</td>
<td>24 (36.36)</td>
<td>6 (9.09)</td>
<td></td>
</tr>
<tr>
<td>Surgical segment</td>
<td>5 (7.58)</td>
<td>0 (0)</td>
<td></td>
</tr>
<tr>
<td>C0–2</td>
<td>28 (42.42)</td>
<td>3 (4.55)</td>
<td>0.014*</td>
</tr>
<tr>
<td>C0–3</td>
<td>24 (36.36)</td>
<td>6 (9.09)</td>
<td></td>
</tr>
<tr>
<td>C0–4</td>
<td>5 (7.58)</td>
<td>0 (0)</td>
<td></td>
</tr>
<tr>
<td>Occipitalized atlas</td>
<td>3 (4.55)</td>
<td>1 (1.51)</td>
<td></td>
</tr>
<tr>
<td>Anterior arch/lateral mass fusion</td>
<td>33 (50.00)</td>
<td>8 (12.12)</td>
<td></td>
</tr>
<tr>
<td>Upper stenosis</td>
<td>21 (31.82)</td>
<td>0 (0)</td>
<td>0.585</td>
</tr>
<tr>
<td>Stenosis</td>
<td>6 (9.09)</td>
<td>0 (0)</td>
<td></td>
</tr>
<tr>
<td>Normal</td>
<td>51 (77.27)</td>
<td>9 (13.64)</td>
<td></td>
</tr>
</tbody>
</table>

Values are presented as number (%). CSF, cerebrospinal fluid; Group A, CSF leak group; Group B, no CSF leak group; BAI, basion-posterior axial line interval; BDI, basion-dental interval; CVJI, craniovertebral junction instability; AADI, anterior atlantodental interval; AOD, atlanto-occipital dislocation; BI, basilar invagination; CBA, cranial base angle; CTH, cerebellar tonsillar herniation.

*p < 0.05.
Cerebrospinal Fluid Leak After Craniovertebral Junction Anomalies Surgery

Table 3. Chi-square test for potential risk factors of CSF leak

<table>
<thead>
<tr>
<th>Related factor</th>
<th>$\chi^2$</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CVJI (BAI)</td>
<td>2.351</td>
<td>0.125</td>
</tr>
<tr>
<td>CVJI (BDI)</td>
<td>5.311</td>
<td>0.021*</td>
</tr>
<tr>
<td>AAD</td>
<td>0.000</td>
<td>1.000</td>
</tr>
<tr>
<td>BI</td>
<td>0.422</td>
<td>0.516</td>
</tr>
<tr>
<td>Brain stem and spinal cord compression</td>
<td>0.422</td>
<td>0.516</td>
</tr>
<tr>
<td>Platybasia</td>
<td>0.000</td>
<td>1.000</td>
</tr>
<tr>
<td>CTH</td>
<td>0.384</td>
<td>0.535</td>
</tr>
<tr>
<td>Syringomyelia</td>
<td>0.000</td>
<td>1.000</td>
</tr>
<tr>
<td>Surgical approach</td>
<td>0.269</td>
<td>0.604</td>
</tr>
<tr>
<td>Sex</td>
<td>1.103</td>
<td>0.294</td>
</tr>
</tbody>
</table>

CSF, cerebrospinal fluid; CVJI, craniovertebral junction instability; BAI, basion-posterior axial line interval; BDI, basion-dental interval; AAD, atlantoaxial dislocation; BI, basilar invagination; CTH, cerebellar tonsilar herniation. *p < 0.05.

Table 4. Fisher exact test for potential risk factors of CSF leak

<table>
<thead>
<tr>
<th>Related factor</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occipitalized atlas</td>
<td>0.041*</td>
</tr>
<tr>
<td>Upper cervical stenosis</td>
<td>0.585</td>
</tr>
<tr>
<td>Surgical segment</td>
<td>0.376</td>
</tr>
</tbody>
</table>

CSF, cerebrospinal fluid. *p < 0.05.

Table 5. Logistic regression test for occipitalized atlas

<table>
<thead>
<tr>
<th>B</th>
<th>SE</th>
<th>Wald</th>
<th>Df</th>
<th>p-value</th>
<th>OR</th>
<th>95% CI for OR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occipitalized atlas</td>
<td>1.327</td>
<td>0.797</td>
<td>2.769</td>
<td>1.000</td>
<td>0.096</td>
<td>3.769</td>
</tr>
<tr>
<td>Constant</td>
<td>-4.014</td>
<td>1.534</td>
<td>6.849</td>
<td>1.000</td>
<td>0.009*</td>
<td>0.018</td>
</tr>
</tbody>
</table>

SE, standard error; Df, degrees of freedom; OR, odds ratio; CI, confidence interval. *p < 0.05.

Table 6. Logistic regression test for CVJI (BDI)

<table>
<thead>
<tr>
<th>B</th>
<th>SE</th>
<th>Wald</th>
<th>Df</th>
<th>p-value</th>
<th>OR</th>
<th>95% CI for OR</th>
</tr>
</thead>
<tbody>
<tr>
<td>CVJI (BDI)</td>
<td>1.912</td>
<td>0.774</td>
<td>6.099</td>
<td>1.000</td>
<td>0.014</td>
<td>6.769</td>
</tr>
<tr>
<td>Constant</td>
<td>-2.686</td>
<td>0.597</td>
<td>20.256</td>
<td>1.000</td>
<td>0.000</td>
<td>0.068</td>
</tr>
</tbody>
</table>

CVJI, Craniovertebral junction instability; BDI, basion-dental interval. *p < 0.05.

Fig. 3. Adjusted odds ratio (AOR). Crude OR: logistic regression analysis of the relationship between craniovertebral junction instability (basion-dental interval [BDI] > 10 mm) and cerebrospinal fluid leak without adjustment; AOR (age): OR value corrected for “age” bias based on “Crude OR”; AOR (sex): OR value corrected for “sex” bias based on “Crude OR”; AOR (age & sex): OR value corrected for “age and sex” biases based on “Crude OR.” Calculation of confounding bias: (COR - AOR)/AOR x 100.
5. Multivariate Analysis

Multivariate logistic regression analysis was used to analyze the occipitalized atlas and CVJ instability (BDI). The OR for the development of CSF leak was calculated for nonoverlapping subsets of patients. The OR for the development of a CSF leak for a normal atlas compared to an occipitalized atlas was not statistically significant (p ≥ 0.05) (Table 5). CVJ instability (BDI) was an independent risk factor for CSF leakage (OR, 14.67; 95% CI, 2.418–89.056; p = 0.004) (Table 6).

Without controlling for bias, patients with CVJ anomalies and CVJ instability (BDI > 10 mm) were 6.769 times more likely to develop CSF leaks than those without CVJ instability (BDI > 10 mm). After simultaneously correcting the “age and sex” biases on the basis of the crude OR value, the COR minus the adjusted value (AORage & sex, 14.674; 95% CI, 2.42–89.06; p = 0.004) was negative, indicating that the influence of preoperative CVJ instability (BDI > 10 mm) on the likelihood of postoperative CSF leakage may be underestimated, while age and sex were not considered. The calculation of confounding bias was 53.871%, indicating that the possibility of postoperative CSF leakage was underestimated by 53.871%, regardless of age and sex.

Patients with CVJ instability (BDI > 10 mm) were 14.67 (95% CI, 2.42–89.06) times more likely to have a CSF leak than patients without this condition (31.58% vs. 6.38%, p < 0.05) (Fig. 3).

DISCUSSION

The overall prevalence of CSF leakage after CVJ surgery in our series was 13.64% (9 of 66 patients), which is comparable to the 10% for CVJ surgery and the 13% and 17% for posterior fossa surgery mentioned in other studies. Therefore, the prevalence of CSF leak after CVJ surgery is higher than that of other spine surgeries (generally < 10%). Few studies have examined the correlation analysis of CSF leak and its risk factors after congenital developmental CVJ anomalies surgery, especially simple posterior cranial fossa decompression, CVJ reduction, and fixation without duraplasty. Previous studies on the risk factors of CSF leak after spine surgery have mainly focused on the cervical spine. To the best of our knowledge, few relevant studies have specifically targeted CVJ anomaly surgery. The incidence of postoperative complications, including postoperative CSF leak, has been mentioned in some studies on CVJ surgery; however, the risk factors have not been analyzed. The risk factor of “BDI > 10 mm” identified in this study has not been found in other studies of CSF leak after CVJ anomalies or upper cervical spine surgery. The BDI, as an imaging parameter of the CVJ, can be easily obtained by preoperative imaging examination in the diagnosis and treatment of patients with congenital developmental CVJ anomalies. The BDI has a unique guiding significance for the prevention of CSF leakage after CVJ anomaly surgery.

Among the 66 patients, 45 had occipitalized atlas and 9 had CSF leak, with a prevalence of 20%, which was higher than the overall prevalence. In other words, all patients who developed postoperative CSF leakage had an occipitalized atlas. Although occipitalized atlas is not an independent risk factor for CSF leak after CVJ anomaly surgery, it does increase the difficulty of decompression and has a greater possibility of damaging the dura. This may be because the posterior arch of the atlas in such patients usually protrudes forward into the spinal canal, making surgical decompression difficult. The dura mater is closely adhered to the periosteum in the region of the foramen magnum, and the abnormal bony structure computes the space between the dura mater and the posterior arch of the atlas, which not only increases the difficulty of bone decompression but also makes the posterior atlanto-occipital membrane (ligamentum flavum) more likely to adhere to the dura mater, increasing the possibility of dural and arachnoid injuries when the posterior atlanto-occipital membrane (ligamentum flavum) is released for decompression. Additionally, ligamentous laxity, weakened “holding ligaments,” and weight-bearing and age-related degenerative changes may precipitate joint instabilities. With the stimulation of abnormal joint activities and inflammatory reactions, the soft tissue around the joint is hyperplasia and adhesion, making it more difficult to separate the soft tissue and the dura during the operation.

The presence of a preoperative BDI of > 10 mm was an independent risk factor for the development of CSF leak in our series. Patients with CVJ anomalies who have a preoperative BDI > 10 mm are 14.67 times more likely to have postoperative CSF leak than those who do not (p < 0.05). Of the 66 patients included in our study, 19 had a preoperative BDI > 10 mm and 6 of them developed CSF leak (31.58%), which was significantly higher than the overall prevalence. This may be because weight-bearing over time weakened the “holding ligaments” and increased the obliquity of joints and ligamentous laxity. Moreover, age-related degenerative changes may precipitate progressive telescoping of the cervical spine into the skull base, resulting in an increased distance from the basion to the odontoid tip (BDI) and joint instability. With aging, joint stability worsens, abnormal joint movement increases, minor local damage accu-
Fig. 4. Cause analysis. BDI, basion-dental interval; CVJ, craniovertebral junction; CSF, cerebrospinal fluid.

Fig. 5. Algorithm for the treatment of CVJ anomalies. CVJ, craniovertebral junction; BDI, basion-dental interval; CSF, cerebrospinal fluid.
mulates, and repeated inflammatory reactions lead to tissue hyperplasia. In the long-term, the bone structure and surrounding soft tissue easily adhere to the dura mater, which is difficult to separate during the operation. Additionally, the complex anatomical structure and narrow operation space in the CVJ often necessitates the use of a Kerrison rongeur to resect the posterior arch of the atlas, posterior edge of the foramen magnum, and posterior atlanto-occipital membrane during the operation, which may cause visible or undiscovered dural tear during the operation, eventually leading to postoperative CSF leak (Fig. 4).

For the patients whose occipitalized posterior arch of the atlas or posterior margin of the foramen magnum protrates forward into the spinal canal, it is difficult to contact the deep bone through the Kerrison rongeur and to remove the bone from the posterior arch of the atlas or posterior margin of the foramen magnum. If the Kerrison rongeur is pushed deep, the dura mater can be easily teared when the bony structure is removed. In such patients, the “invagination” of the bony structure can be detected by imaging examination before surgery. Our experience is to combine preoperative computed tomography and magnetic resonance imaging to determine the extent of surgical decompression, and to perform “concentric decompression” from the edge. Ultrasonic osteotome, grinding drill, and Kerrison rongeur can be used to make the operation safer and more effective. For some patients with an occipitalized atlas, the boundary between the ligamentum flavum and the dura mater is unclear, which may be due to the reasons mentioned above. When the ligamentum flavum is cut and separated between the atlas and axis, it can easily cause dural tears or microtears not found during the operation, which eventually leads to postoperative CSF leakage. For such patients, our experience is to progressively remove the fascial tissue by searching for a weak spot between the ligamentum flavum and dura. Rather than blindly pursuing complete resection of the fascia or ligamentum flavum, more attention should be paid to decompression of the bone, release of membranous structures, and reduction of abnormal anatomical relationships. However, excessive reduction should be avoided due to the possibility of causing dural tears or new spinal cord or nerve damage (Fig. 5).

This study has a few limitations. First, as a single-surgeon or single-group case series, it may have to do with the technique used by our group. Second, the small sample size may have resulted in missing true risk factors due to inadequate power. Third, there may be additional risk factors that were not analyzed.

CONCLUSION

In the treatment of patients with CVJ anomalies with a preoperative BDI > 10 mm, it is necessary to maintain vigilance during surgery to avoid postoperative CSF leaks. For such patients, the surgical strategy should be adjusted appropriately, and careful separation of tissue and protection of the dura are warranted during surgery. When necessary, power devices can be combined to improve the efficiency and safety of the operation.

NOTES

Conflict of Interest: The authors have nothing to disclose.
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Author Contribution: Conceptualization: YX, BW; Data curation: YX, LC, ZG; Formal analysis: YX, YC; Funding acquisition: BW; Methodology: BW; Project administration: BW; Visualization: YX; Writing - original draft: YX; Writing - review & editing: BW, ZL

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Predicting Mechanical Complications After Adult Spinal Deformity Operation Using a Machine Learning Based on Modified Global Alignment and Proportion Scoring With Body Mass Index and Bone Mineral Density

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Objective: This study aimed to create an ideal machine learning model to predict mechanical complications in adult spinal deformity (ASD) surgery based on GAPB (modified global alignment and proportion scoring with body mass index and bone mineral density) factors.

Methods: Between January 2009 and December 2018, 238 consecutive patients with ASD, who received at least 4-level fusions and were followed-up for ≥ 2 years, were included in the study. The data were stratified into training (n = 167, 70%) and test (n = 71, 30%) sets and input to machine learning algorithms, including logistic regression, random forest gradient boosting system, and deep neural network.

Results: Body mass index, bone mineral density, the relative pelvic version score, the relative lumbar lordosis score, and the relative sagittal alignment score of the global alignment and proportion score were significantly different in the training and test sets (p < 0.05) between the complication and no complication groups. In the training set, the area under receiver operating characteristics (AUROCs) for logistic regression, gradient boosting, random forest, and deep neural network were 0.871 (0.817–0.925), 0.942 (0.911–0.974), 1.000 (1.000–1.000), and 0.947 (0.915–0.980), respectively, and the accuracies were 0.784 (0.722–0.847), 0.868 (0.817–0.920), 1.000 (1.000–1.000), and 0.856 (0.803–0.909), respectively. In the test set, the AUROCs were 0.785 (0.678–0.893), 0.808 (0.702–0.914), 0.810 (0.710–0.910), and 0.730 (0.610–0.850), respectively, and the accuracies were 0.732 (0.629–0.835), 0.718 (0.614–0.823), 0.732 (0.629–0.835), and 0.620 (0.507–0.733), respectively. The random forest achieved the best predictive performance on the training and test dataset.

Conclusion: This study aimed to create an ideal machine learning model to predict mechanical complications in adult spinal deformity (ASD) surgery based on GAPB (modified global alignment and proportion scoring with body mass index and bone mineral density) factors. The best prediction accuracy was 73.2% for predicting mechanical complications after ASD surgery. This information can be used to prevent mechanical complications during ASD surgery.

Keywords: Machine learning, Adult spinal deformity, Mechanical complication, Body mass index, Bone mineral density, Random forest
INTRODUCTION

Adult spinal deformity (ASD) is a disorder that is globally prevalent.\(^1\) It is characterized by significant low back/leg pain, stooping, and poor health-related quality of life (HRQoL) in patients with ASD compared with the general population. Although spinal surgery for correcting ASD is invasive, it is effective in symptomatic cases where conservative treatment is often unsuccessful.\(^2\) However, the surgical correction of ASD is a difficult procedure that is known to have a high risk of complications during the surgery and postoperative period.\(^3\) The estimated incidence of morbidity and mortality due to surgical correction is 31.3% and 0.5%, respectively.\(^4\) Since there are many complications of ASD surgery, there are some ideal surgical target parameters such as Scoliosis Research Society-Schwab classification and age-adjusted alignment goals.\(^5,6\) There are also formulas, such as the global alignment and proportion (GAP) score, which predict mechanical complications after ASD surgery, and the modified global alignment and proportion scoring with body mass index and bone mineral density (GAPB) system, which combines body mass index (BMI) and bone mineral density (BMD) with the GAP score.\(^6,7\)

Most studies have been performed using simple statistical techniques such as linear regression and logistic regression, and in practice, they provide information on mean values that do not properly reflect the characteristics of the population. However, in the past few years, the medical field has increasingly adopted computational techniques that allow the processing of large amounts of data and the creation of complex mathematical models that describe the relationships between different variables. The idea behind artificial intelligence is to create a system that mimics the natural ability of humans to continuously learn as they access new data and apply it to new situations in the future. Our research team reported that GAPB predicts mechanical complications better than other systems related to ASD\(^3\). This study aimed to create an ideal machine learning model to predict mechanical complications in ASD surgery based on the GAPB system.

MATERIALS AND METHODS

1. Patient Population

This was a retrospective analysis of surgically treated patients with ASD enrolled from 2009 to 2017. This study was approved by the Institutional Review Board (IRB) of the Ajou University Hospital (IRB No. 2022-0546-008). Written informed consent was obtained from all participants. The inclusion criteria were as follows: patients who underwent ASD surgery to correct sagittal imbalance; the presence of one of the following radiological criteria, including coronal Cobb angle > 20°, sagittal vertical axis > 5 cm, pelvic tilt (PT) > 25°, and/or thoracic kyphosis > 60°, and/or pelvic incidence minus lumbar lordosis (PI–LL) > 10°; use of posterior spinal fixation and instruments with ASD surgery at ≥ level 4; and patients with a follow-up period of ≥ 2 years. The exclusion criteria were patients with ASD due to syndrome, autoimmune disease, infection, tumor, or other pathological conditions. Between January 2009 and December 2017, 491 patients with ASD underwent ASD surgery at our hospital. Among them, 253 patients with a follow-up period of < 2 years, patients without corrective surgery for ASD, and those with a surgical level of ≤ 3 were excluded. Between January 2009 and December 2017, 238 consecutive patients with sagittal imbalance who underwent ASD surgery were ultimately included in the study.

2. Data Collection

Demographic data, radiologic parameters, surgical characteristics, HRQoL data were collected for all 238 patients included in the electronic medical records. Demographic data included age, sex, BMI, BMD, and GAP score variables. Yilgor et al.\(^7\) created the GAP score. The overall goal of the GAP score is to achieve patient-specific spine-pelvic alignment guidance, and the GAP score predicts mechanical complications. After that, Noh et al.\(^8,9\) made GAPB including BMI and BMD in GAP. Factors frequently used to predict mechanical complications after ASD were used to create an artificial intelligence model.

The following sagittal alignment parameters were measured: PI, PT, lumbar vertebral lordosis (LL [L1–S1]), PI–LL, and global tilt. Radiographic measures included preoperative, postoperative, and final follow-up alignment parameters. We defined mechanical complications after ASD surgery as the following (proximal junctional kyphosis, proximal junctional failure, distal junctional failure, distal junctional kyphosis, rod fracture, implant-related complications) and investigated their prevalence. Proximal junctional kyphosis was defined as a ≥ 10° increase in kyphosis between upper Instrumented vertebra (UIV) and UIV+2 between the early postoperative and 2-year follow-up radiographs. Proximal junctional failure was defined as a fracture of UIV or UIV+1, withdrawal of the instrument in UIV, and/or sagittal subluxation. Distal junctional kyphosis/failure referred to a ≥ 10° increase in kyphosis angle between lowest instrumented vertebra (LIV) and LIV-1, and/or withdrawal of the apparatus from the LIV. Rod breakage referred to...
Mechanical Complications After Adult Spinal Deformity Operation

Noh SH, et al.

https://doi.org/10.14245/ns.2244854.427

January 2009–December 2017

491 Patients

Adult spinal deformity

253 Patients

Less than 4 level & less than 2-year F/U

238 Patients

Training set

167 Patients (70%)

Test set

71 Patients (30%)

Fig. 1. Flowchart of the patients in our study. F/U, follow-up.

single or double rod breakage. Implant-related complications included other radiographic implant-related complications such as screw loosening, breakage, pullout, or interbody graft, hook, or screw leave. HRQoL was measured using the Oswestry Disability Index, the Scoliosis Research Society-22 Spinal Malformation Questionnaire, and Short Form-36.

3. Prediction Models and Evaluation

The patients were randomly divided into training (n = 167, 70%) and test (n = 71, 30%) datasets (Fig. 1). The training set was used to develop the model, and the test set was used to evaluate the model. Among the models that can be implemented

Table 1. Patient demographics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Training set (n = 167)</th>
<th>p-value</th>
<th>Test set (n = 71)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Complication</td>
<td></td>
<td>Complication</td>
<td></td>
</tr>
<tr>
<td></td>
<td>No (n = 96)</td>
<td></td>
<td>No (n = 42)</td>
<td></td>
</tr>
<tr>
<td>Age (yr)</td>
<td>67.18 ± 7.07</td>
<td>0.215</td>
<td>66.40 ± 6.64</td>
<td>0.438</td>
</tr>
<tr>
<td>Sex</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>12</td>
<td></td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>84</td>
<td>0.973</td>
<td>34</td>
<td>0.847</td>
</tr>
<tr>
<td>Sex</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>12</td>
<td></td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>84</td>
<td>0.973</td>
<td>34</td>
<td>0.847</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>23.54 ± 2.92</td>
<td>0.013*</td>
<td>23.39 ± 2.53</td>
<td>0.013*</td>
</tr>
<tr>
<td>BMD (T-score)</td>
<td>-1.57 ± 0.85</td>
<td>&lt;0.001*</td>
<td>-1.85 ± 0.83</td>
<td>0.007*</td>
</tr>
<tr>
<td>GAP score</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative pelvic version score</td>
<td>0.003*</td>
<td></td>
<td>0.002*</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>41</td>
<td>17</td>
<td>24</td>
<td>5</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
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<td>4</td>
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</tr>
<tr>
<td>2</td>
<td>35</td>
<td>25</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>23</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Relative lumbar lordosis score</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>42</td>
<td>13</td>
<td>19</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>45</td>
<td>21</td>
<td>18</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>37</td>
<td>&lt;0.001*</td>
<td>5</td>
</tr>
<tr>
<td>0</td>
<td>54</td>
<td>33</td>
<td>26</td>
<td>13</td>
</tr>
<tr>
<td>1</td>
<td>9</td>
<td>6</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>16</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>18</td>
<td>16</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>Relative spinopelvic alignment score</td>
<td></td>
<td>0.547</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>0</td>
<td>35</td>
<td>15</td>
<td>19</td>
<td>4</td>
</tr>
<tr>
<td>1</td>
<td>51</td>
<td>31</td>
<td>17</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>25</td>
<td>&lt;0.001*</td>
<td>6</td>
</tr>
</tbody>
</table>

Values are presented as mean ± standard deviation or number.
GAP, global alignment and proportion; BMI, body mass index; BMD, bone mineral density.
*p < 0.05, statistically significant differences.
with R, we compared logistic regression, which is widely used conventionally, gradient boosting, which is a representative boosting method, random forest, which is a representative bagging method, and deep neural network, which has recently become an issue. We performed 4 analyses to classify the occurrence of complications. First, univariable and multivariable logistic regressions were used. Variables with $p < 0.05$ in the univariable analysis were entered in the multivariable analysis. The final multivariable model was determined using a stepwise variable selection method. Second, the gradient boosting model was created with the R package “xgboost,” and variable importance was visualized. For this analysis, a maximum tree depth of 2, learning rate of 0.3, and number of boosting of 20 were considered. Third, random forest classification was performed using the R package “random forest.” For this analysis, the number of trees was set to 500, and the number of variables used in each 3 was set to 5, which had the largest Kappa value. Fourth, a deep neural network was used via the R package “nnet.” For this analysis, a hidden layer of 10 was employed.

Diagnostic performance was evaluated using the area under receiver operating characteristic (AUROC), area under precise recall curve (AUPRC), accuracy, sensitivity, and specificity for each dataset. To calculate the accuracy, sensitivity, and specificity, the optimal cutoff points were computed using Youden index. Comparisons of AUROC, AUPRC, accuracy, sensitivity, and specificity were performed using generalized estimating equations.

### 4. Statistical Analysis

Descriptive statistics are presented as frequencies and percent-
ages for categorical variables and as means and standard deviations for continuous variables. To compare the characteristics of patients in the complication and no complication groups, the chi-square test (or Fisher exact test) was used for categorical variables and an independent 2-sample t-test was used for continuous variables. All statistical analyses were performed using SAS 9.4 (SAS Institute Inc., Cary, NC, USA). Statistical significance was set at p < 0.05.

RESULTS

1. Patient Demographics

Two hundred thirty-eight patients underwent ASD surgery (204 females [86%], 34 males [14%]); their demographic data are shown in Table 1. Of those patients, 167 (70.2%) were assigned to the training set and 71 (29.8%) to the test set. The patients’ average age and follow-up period were 67.1 ± 6.17 years and 28.54 ± 4.25 months, respectively. The mean ages of patients in the training and test sets were 67.80 ± 7.49 years and 66.94 ± 6.98 years, respectively. When comparing the groups with and without complications in the training set, BMI, BMD, the relative pelvic version score, the relative lumbar lordosis score, and the relative sagittal alignment score were statistically significant. When comparing the groups with and without complications in the test set, BMI, BMD, the relative pelvic version score, the relative lumbar lordosis score, and relative sagittal alignment score were statistically significant. When comparing the group with and without complications in the test set, BMI, BMD, the relative pelvic version score, the relative lumbar lordosis score, the lordosis distribution index score, and the relative sagittal alignment score were statistically significant.

2. Logistic Regression Model

The results of the univariate and multivariate logistic regression analyses are presented in Table 2. The following variables were significantly related to mechanical complications of ASD surgery in univariate logistic regression: BMI, BMD, relative pelvic version score, relative lumbar lordosis score, and relative sagittal alignment score. In the multivariate logistic regression, BMD and relative lumbar lordosis score were significantly related to mechanical complications of ASD surgery.

3. Gradient Boosting Model

The results of the gradient boosting analysis are shown in Fig. 2. BMI, BMD, and relative lumbar lordosis score were the most important variables in the gradient boosting model.

4. Random Forest Model

The results of the random forest analyses are shown in Fig. 3. BMI, BMD, and relative lumbar lordosis score were the most important variables in the random forest model. Since random forest has the possibility of overfitting in the training set, it must be interpreted carefully considering the validation result.

Fig. 2. Results of the gradient boosting model. The most important variables in the model were BMI, BMD, and relative lumbar lordosis score. BMD, bone mineral density; BMI, body mass index; Lumbarlordo, relative lumbar lordosis score; Lordoindex, lordosis distribution index score; Sagittal, relative spinopelvic alignment score; Pelvic, relative pelvic version score.
5. Deep Neural Network Model

The results of the deep neural network analyses are shown in Fig. 4. The most important variables in this model were the lordosis distribution index score and relative sagittal alignment score.

6. Diagnostic Performance of the Machine Learning Models

The AUROCs and AUPRCs for the 4 machine learning models are presented in Table 3. In the training set, the AUROCs for logistic regression, gradient boosting, random forest, and deep neural network model were 0.871 (0.817–0.925), 0.942 (0.911–0.974), 1.000 (1.000–1.000), and 0.947 (0.915–0.980), respectively, the AUPRCs for logistic regression, gradient boosting, random forest, and deep neural network model were 0.793 (0.677–0.895), 0.93 (0.878–0.965), 1.000 (1.000–1.000), and 0.942 (0.898–0.972), respectively, and the accuracies were 0.784 (0.722–0.847), 0.868 (0.817–0.920), 1.000 (1.000–1.000), and 0.856 (0.803–0.909),
respectively. In the test set, the AUROCs for the same models were 0.785 (0.678–0.893), 0.808 (0.702–0.914), 0.810 (0.710–0.910), and 0.730 (0.610–0.850), respectively, the AUPRCs for logistic regression, gradient boosting, random forest, and deep neural network model were 0.711 (0.523–0.87), 0.717 (0.529–0.89), 0.748 (0.554–0.882), and 0.667 (0.475–0.818), respectively, and the accuracies were 0.732 (0.629–0.835), 0.718 (0.614–0.823), 0.732 (0.629–0.835), and 0.620 (0.507–0.733), respectively. The random forest achieved the best predictive performance on the training and test dataset. Fig. 5 shows the AUPRCs of each model in the training and test sets.

**DISCUSSION**

The prevalence of mechanical complications, with radiologic

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**Table 3. Diagnostic performance between machine learning model**

<table>
<thead>
<tr>
<th>Model</th>
<th>Cutoff point</th>
<th>AUROC (95% CI)</th>
<th>AUPRC (95% CI)</th>
<th>Accuracy (95% CI)</th>
<th>Sensitivity (95% CI)</th>
<th>Specificity (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Logistic regression</td>
<td>&gt; 0.405</td>
<td>0.871 (0.817–0.929)</td>
<td>0.785 (0.678–0.893)</td>
<td>0.798 (0.697–0.903)</td>
<td>0.868 (0.787–0.958)</td>
<td>0.714 (0.532–0.895)</td>
</tr>
<tr>
<td>Gradient boosting</td>
<td>&gt; 0.483</td>
<td>0.942 (0.881–0.997)</td>
<td>0.808 (0.722–0.894)</td>
<td>0.915 (0.853–0.963)</td>
<td>0.898 (0.837–0.959)</td>
<td>0.786 (0.604–0.967)</td>
</tr>
<tr>
<td>Random forest</td>
<td>&gt; 0.405</td>
<td>0.942 (0.881–0.997)</td>
<td>0.808 (0.722–0.894)</td>
<td>0.915 (0.853–0.963)</td>
<td>0.898 (0.837–0.959)</td>
<td>0.786 (0.604–0.967)</td>
</tr>
<tr>
<td>Deep neural network</td>
<td>&gt; 0.406</td>
<td>0.947 (0.895–0.998)</td>
<td>0.836 (0.780–0.924)</td>
<td>0.924 (0.861–0.988)</td>
<td>0.876 (0.808–0.944)</td>
<td>0.793 (0.659–0.928)</td>
</tr>
</tbody>
</table>

**Fig. 5.** Area under precise recall curve of each model in the training set (A) and test set (B). LR, logistic regression; GB, gradient boosting; RF, random forest; DNN, deep neural network.
and clinical manifestations, after surgery for adult spinal deformities is reported to be 30%, and more than 50% of these patients undergo revision surgery for treatment. Soroceanu et al. reported that radiographic and implant-related complications accounted for 31.7%, and in 52.6% of these complications, reoperation for mechanical correction was required. There are many aspects of ASD surgery with notable variability, including the occurrence of complications and outcomes. GAPB is a system that is used to predict mechanical complications that occur after ASD surgery, including both patient-specific and radiological factors. In this study, we constructed a model to predict mechanical complications after ASD surgery using GAPB factors. The GAPB system, including BMI and BMD, showed improved predictability of predicting mechanical complications compared to the GAP scoring system. In particular, Noh et al. reported that GAPB better predicted mechanical complications in the moderately disproportioned and severely disproportioned groups in GAP. Park et al. reported that osteoporosis and obesity are important risk factors for proximal junctional kyphosis, proximal junctional failure and other mechanical complications. Since most elderly patients in ASD surgery have low muscle mass and severe osteoporosis, BMI and osteoporosis are essential when discussing mechanical complications. Recently, several studies using deep learning algorithms, such as random forest, gradient boosting, and neural networks, have been conducted for the spine. Yagi et al. created a postsurgical complication prediction model for ASD surgery in adults using spinal alignment, demographic data, and surgical invasiveness; 170 participants were enrolled in this study. A decision tree for 2-year postoperative complications was constructed and confirmed by splitting data in a 7:3 ratio for training and testing, with the external validation of 25 ASD patients who underwent surgery at different hospitals. For the test sample, the predictive model was 92% accurate, the AUC was 0.963, and the external validation was 84% accurate. Lafage et al. created a machine learning model to determine the upper vertebra in ASD surgery. The samples were stratified into 3 groups: 70% for training, 15% for validation, and 15% for performance testing. A neural network model was used, and the results showed an accuracy of 81.0%, precision of 87.5%, and recall of 87.5%. Pellisé et al. created a model to predict the incidence of adverse events after ASD surgery using a random forest model. The model was trained using 80% of the data for the training set and 20% for the test set and showed adequate predictive accuracy, with AUCs ranging from 0.67 to 0.92. Durand et al. created a model for predicting blood transfusion following surgery for adult spinal deformities. A total of 1,029 patients were analyzed and divided into datasets for training (n = 824) and validation (n = 205). The random forest model showed an AUC of 0.85 (95% confidence interval, 0.80–0.90) and was reported to show better predictive ability than single-decision tree models. Ames et al. created a model to predict the cost of surgery for ASD. The regression tree and random forest models were used to predict the occurrence of treatment costs exceeding $100,000. The results of the regression tree analysis using CTREE resulted in an adjusted R² value of 56% at 90 days and 35.6% at 2 years of direct cost forecasting. Random C-forest regression analysis showed an adjusted R² value of 57.4% at 90 days and 28.8% at 2 years of direct cost forecasts. Peng et al. created a model to predict proximal junctional kyphosis after surgery in adolescent patients with idiopathic scoliosis. The random forest has great value for predicting the individual risk of developing proximal junctional kyphosis after long instrumentation and fusion surgery in patients with Lenke 5 adolescent idiopathic scoliosis. Jain created a model to predict discharge delay, medical complications, and readmission within 90 days after long-segment posterior lumbar spine fusion surgery using logistic regression, random forest, and elastic net. In our study, we created a model to predict the mechanical complications that occur after ASD surgery. We used logistic regression, gradient boosting, random forest, and deep neural networks. Important factors were BMD, BMI, relative lumbar lordosis score, lordosis distribution index score, and relative sagittal alignment score. The patients were randomly divided into training (70%) and test (30%) datasets. In the training set, the AUROC for random forest was 1.000 and the accuracy was 1.000. In the test set, the AUROC for random forest was 0.81 and the accuracy was 0.732. Random forest achieved the best predictive performance on the training and test dataset.

This study has several limitations. Because our models were built using retrospective data, future efforts to update these models are required. Additionally, the reasons for mechanical complications after ASD correction are multifactorial. Many factors affect the outcome of surgery, including the surgical method, upper level instrumentation, muscle mass, and various underlying conditions. These factors were excluded when the model was created.

However, the GAPB system is helpful in predicting mechanical complications after ASD surgery. Noh et al. reported that the GAPB system was more meaningful in the moderately disproportioned and severely disproportioned GAP groups. We believe that it will be helpful to develop models that predict me-
Mechanical complications through machine learning. And the overfitting problem caused by using small data samples is a limitation of this study. We will study with more data samples later.

CONCLUSION

This study created a comprehensive model to predict mechanical complications after ASD surgery. The best prediction accuracy was 73.2% for predicting mechanical complications after ASD surgery. This information can be used to prevent mechanical complications during ASD surgery.

NOTES

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REFERENCES


Commentary on “Predicting Mechanical Complications After Adult Spinal Deformity Operation Using a Machine Learning Based on Modified Global Alignment and Proportion Scoring With Body Mass Index and Bone Mineral Density”

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Predictive modeling has become a hot topic in many fields of medical research including spine surgery. Several models able to predict the risk of mechanical complications based on patients’ demographic and clinical information have been described,1 with some of them including data derived from radiological imaging. The paper “Predicting mechanical complications after adult spinal deformity operation using a machine learning based on modified global alignment and proportion scoring with body mass index and bone mineral density”2 follows this line of research, introducing the global alignment and proportion score as well as other relevant radiological measurements such as relative pelvic version, relative lumbar lordosis and bone mineral density. On the dataset on which the model was tested, the recorded performances were promising with accuracies in the range of 62%–73%. It is worthy of note that a simple method, such as logistic regression, achieved accuracies very similar to that of the best-performing method, which was in this case a random forest. Even techniques usually considered state-of-the-art in the field like XGBoost and deep neural networks did not perform better than logistic regression in this dataset.

Such surprising results highlight the challenges hidden in the development and validation of predictive models. While the performance of a model may look favourable in absolute terms when examined on a relatively small test set, the model may result inadequate when implemented in the clinical practice or, more simply, to a dataset collected in another center or country. In particular, complex models, such as deep neural networks, are well-known for their high-risk of overfitting when trained on small datasets and not properly validated. In fact, this also emerges in the present paper in which the gap between the training (1.0) and the test accuracy (0.7/0.8) for the random forest might indicate some degree of overfitting. As with Ockham’s razor, simpler is usually better; if a logistic regression or decision tree performs similarly to a deep neural network, there is no reason to prefer the

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Commentary "Predicting Mechanical Complications"

Galbusera F, et al.

more complex solution which inevitably involves the risk of overfitting and lower generalizability. Moreover, simpler models such as logistic regression and random forests are easier to interpret, therefore giving the opportunity to explain the model's decision which is very important in a clinical setting. For the present study, we commend the choice of analyzing in comparative terms the performance of various machine learning techniques, even if we would have rather concluded that advanced machine learning methods did not provide a conspicuous advantage with respect to logistic regression in this dataset.

A key limitation to the present work is the lack of external validation. Prior to contemplating the use of a predictive model in clinical practice to provide guidance in the choice of the most appropriate treatment, its capability to provide accurate predictions for patients different from those used for training the model must be proven. This does not mean that the model would be expected to perform well using different inclusion and exclusion criteria, but rather in patients selected in the same way and treated by different clinicians, possibly in other centers or countries. Cases of predictive models showing excellent performance in the population used for their development but poor generalization in other patient groups are well-known and extensively reported, including in the field of spine surgery. A recent systematic review by Lubelski et al. reported that, of 31 papers describing prognostic models for degenerative spine surgery, only 5 described an external validation; thereby, underscoring the heterogeneity and lack of robustness between studies, the need for more "quality control."

As a matter of fact, most papers about predictive models in the medical field employ the so-called "random split" approach, also used in this study, in which the majority (70%–90%) of the available data (most commonly from a single dataset) is used for training the model, while the remaining 10%–30% for testing its performance. While this approach is meaningful for a first assessment of the model capabilities and to an extent to address internal validation, it is not generally deemed sufficient for the aim of "external" validation. Temporal and geographical splits can be considered acceptable solutions; nevertheless, the golden standard for external validation is a replication of the test by independent researchers using novel data, which eliminates the possibility of adjusting or fine-tuning the model after a first attempt at external validation is conducted.

Journals reporting the performance of novel predictive models should consider implementing a policy about the level of validation, similar to the requirement of declaring the level of evidence that was introduced by several journals for clinical research papers or in the similar spirit as various study checklists, such as the CONSORT (Consolidated Standards of Reporting Trials) checklist in reporting clinical trials. While highly innovative or methodologically-oriented studies may be of interest to the readers even if the validation of the model has not been comprehensively completed yet, for papers describing prognostic models and suggesting their clinical implementation in the near future a proper external validation may be considered imperative and thus be strictly required.

Another issue about machine learning-based prognostic models that is frequently overlooked by the scientific community, even if it is not strictly related to the publications that should describe their development and validation, is the "regulatory aspect." In many countries including the USA and the European Union, prognostic models used as decision-support tools in the management of patients are considered "software as a medical device" (SaMD). Based on the definition of the International Medical Device Regulators Forum, SaMD is "software intended to be used for one or more medical purposes that perform these purposes without being part of a hardware medical device"; therefore, such a position would include tools for predictive outcomes and complications of surgical treatments. While the exact requirements for SaMD depend on the specific local regulations, they generally include risk categorization, a quality management system, and a clinical evaluation to be conducted by means of a clinical trial. Machine learning tools used as SaMD generally have further requirements, such as transparency, explicability, minimization of biased, human oversight, repeatability, reliability, safety, and possibly others. While this should not be considered a criticism of the present paper since regulatory issues are evidently out of its scope, we believe that it is worth noting that any predictive tool should undergo such an assessment before any conceivable clinical implementation.

Taking into account these open challenges in the development of valid prognostic models in spine surgery, it emerges that the major bottleneck is the availability of a large pool of high-quality data from multiple centers worldwide that can be accessed by interested researchers. National and international spine registries such as SweSpine, SIRIS Spine and Spine Tango, naturally lend themselves to this aim, but also offer drawbacks. First, for the sake of keeping their use simple and less time-consuming as possible, the quantity of collected data is minimized; outcome measures are scarcely represented, as well as radiological imaging and parameters. The documentation of all cases in international registries, such as Spine Tango, is not mandatory due to the complexity of the legal framework, leading to the risk of se-
lection bias. Besides, rights of data use and potential commercial exploitations would need to be discussed in advance among the institutes participating in the data collection, which may lead to disagreements and tension within the consortium. The latter issue is especially important because of the high costs associated with the regulatory assessment of SaMD, as mentioned above mandatory before any clinical implementation, which would necessarily involve the participation of industry players. Nevertheless, large data collection projects involving multiple hospitals in different countries, possibly building on existing registries and databases, will undoubtedly play a major role in the future development of large-scale predictive models that can effectively impact the quality of healthcare in spine surgery. That said, quality control, validation and replication, and following regulatory guidelines are no doubt to be a cornerstone if any platform fuelled by artificial intelligence is to be adopted by the community for clinical decision-making and patient care.

**Conflict of Interest:** The authors have nothing to disclose.

**REFERENCES**

The Rehabilitation-Related Effects on the Fear, Pain, and Disability of Patients With Lumbar Fusion Surgery: A Systematic Review and Meta-Analysis

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Objective: The lumbar fusion is an important surgery for the orthopedic diseases. The rehabilitation might improve the outcome of patients with lumbar fusion surgery. The rehabilitation-related effects can be revealed by a systemic review and meta-analysis of randomized clinical trials (RCTs). The purpose of this study is to clarify the rehabilitation effects in the patients with lumbar fusion surgery.

Methods: We performed a systematic search and a meta-analysis for the RCT of rehabilitation treatment on the patients with lumbar fusion surgery. The comparison between rehabilitation treatment (including psychological rehabilitation, exercise, and multimodal rehabilitation) and typical treatment was performed to find if the rehabilitation treatment can improve the outcome after the lumbar fusion surgery. Fifteen studies of lumbar fusion patients under rehabilitation treatment and typical treatment were enrolled in a variety of rehabilitation modalities. The focused outcome was the rehabilitation-related effects on the fear, disability, and pain of patients after the lumbar fusion surgery.

Results: Five hundred twenty-eight rehabilitation subjects and 498 controls were enrolled. The psychological-related rehabilitation showed a significant decrease in pain-related fear when compared to usual treatment. The multimodal rehabilitation can improve the disability outcome to a greater extent when compared to usual treatment. The multimodal rehabilitation seemed to have a more significantly positive effect to decrease disability after lumbar fusion surgery. In addition, the exercise and multimodal rehabilitation can relieve the pain after lumbar fusion surgery. The exercise rehabilitation seemed to have a more significantly positive effect to relieve pain after lumbar fusion surgery.

Conclusion: The rehabilitation might relieve the pain-related fear, disability, and pain after lumbar fusion surgery.

Keywords: Lumbar fusion surgery, Rehabilitation, Fear, Disability, Pain, Meta-analysis

INTRODUCTION

The lumbar fusion surgery is an important treatment for a variety of orthopedic diseases, including degenerative disc disease, traumatic injury, scoliosis, spondylolisthesis, congenital deformity, spinal tumors, tuberculosis deformity, and pseudo-arthrosis, etc.¹ The indications has been broadened in recent years. However, the complications after the lumbar fusion surgery will be the major obstacles for patients to return to normal life and daily function. The complications included the pain-re-
related fear, pain, and disability, which will be related the outcome. Therefore, the management of the complications after lumbar fusion surgery will be a major issue for the treatment of patients after lumbar fusion surgery.

The rehabilitation might be beneficial for decreasing the pain-related fear, pain, and disability. According to the previous meta-analysis, the complex rehabilitation program might reduce the short-term and long-term disability and fear-avoidance behaviors. However, the low quality evidence might bias the results of the meta-analysis. In addition, another previous systematic review showed no evidence to support the positive effects of rehabilitation in relieving the pain after lumbar fusion surgery. The latest meta-analysis of enrolled more randomized clinical trials (RCTs) studies and showed more conclusive effects of rehabilitation on the pain, fear, and disability. Therefore, more enrollment of RCT studies might be helpful for elucidating the relationship between rehabilitation and relieving effects for the complications after lumbar fusion surgery.

In this study, we will include more RCT studies with the more stringent selection criteria for the enrolled studies. In addition, we will include latest RCT studies of rehabilitation on the patients after lumbar fusion surgery in this meta-analysis. We will also focus on the treatment effects of psychological rehabilitation, which mostly belongs to the cognitive behavioral therapy (CBT). The CBT-related rehabilitation has not been emphasized in previous meta-analysis. Therefore, we chose this kind of rehabilitation as our first measure in this meta-analysis. According to the literature mentioned above, we hypothesized that rehabilitation should have the relieving effects on the pain-related fear, pain, and disability. In addition, different kinds of rehabilitation program might demonstrate the different impacts on the complications after lumbar fusion surgery.

MATERIALS AND METHODS

1. Literature Search and Selection Criteria

The systematic review and meta-analysis study was conducted based on the Cochrane Handbook for Systematic Reviews and Interventions. The results were reported according to the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines. We used the following keywords “rehabilitation” or “lumbar fusion” or “surgery” or “exercise” or “fear” or “pain” or “pain-related” or “disability” or “exercise” or “randomized” or “trials” or “multimodal” or “clinical” or “training” or “short-term” or “function” or “outcome” or “comparison” or “versus” or “usual treatment” or “typical treatment,” and “strength” to search and collect the related articles in the PubMed, ScienceDirect, Embase, Web of Science, Scopus databases, CINAHL (Cumulative Index for Nursing and Allied Health Literature) and the CENTRAL (Cochrane Central Register of Controlled Trials). The articles were limited to those published or e-published online before March 2022.

The inclusion criteria of enrolled studies were as follows: (1) The comparisons between rehabilitation and usual care or treatment after lumbar fusion surgery. (2) The studies including the baseline and postrehabilitation outcome profile. (3) The studies with detailed data of outcome in the dimension of pain-related fear, pain, and disability. (4) These studies were published in English style in the journals of science citation index database. (5) Experimental rehabilitation or multimodal rehabilitation. The definition of multimodal rehabilitation was simultaneous or sequential application of different rehabilitations with the applications on different dimensions. (6) RCTs. The exclusion criteria were as follows: (1) Detailed outcome data with some parts were unavailable in the content of the articles (the corresponding authors would be inquired about the data we needed in this meta-analysis.) (2) The authors did not respond or already could not have access to the dataset. (3) The studies without the rehabilitation treatment after lumbar fusion surgery. (4) Review articles. (5) Not RCTs. (6) The studies without the comparison between rehabilitation and usual care or treatment after lumbar fusion surgery.

2. Quality Assessment and Data Extraction

The quality of the included RCTs was independently assessed as ‘low,’ ‘uncertain’ or ‘high’ risk of bias by 2 reviewers (CH and LJ), using the Cochrane Collaboration Revised Risk of Bias tool for RCTs (RoB 2.0, version 22 August 2019). Due to the nature of rehabilitation treatment, blinding of participants was impossible. Therefore, the blinding step was not considered in the overall summary risk of bias judgment. The risk of bias for each study was assessed by bias arising from the randomization process, bias due to deviations from intended interventions, bias due to missing outcome data, bias in measurement of the outcome, and bias in selection of the reported result. We extracted the following data from the eligible articles. First, the baseline rating scale scores of pain-related fear, pain, and disability of subjects before rehabilitation and routine care respectively. Second, the posttreatment rating scale scores of pain-related fear, pain, and disability of subjects after rehabilitation and routine care respectively. Third, the treatment duration of rehabilitation. Fourth, the baseline and posttreatment rating scale scores...
of pain-related fear, pain, and disability of subjects under multimodal rehabilitation. For the above data extraction, the sample mean and standard deviation were calculated from reported confidence interval if the standard deviation was not included in the enrolled articles.

3. Meta-Analysis and Statistical Analysis

We used the Cochrane Collaboration Review Manager Software Package (Rev Man Version 5.4) to perform the meta-analyses. The rehabilitation and usual care or treatment were compared to each other to find if the rehabilitation will be superior in decreasing the pain-related fear, pain, and disability. The overall effect size of the baseline and posttreatment rating scale scores of pain-related fear, pain, and disability of subjects was calculated as the weighted average of the inverse variance for the study-specific estimates. For continuous variables, the weighted mean difference was used to estimate numerical variables. The standardized mean difference was used due to the anticipation of multiple different scales might be used to measure the same outcomes prior to the conduction of current meta-analysis. The method to obtain the standardized mean difference was the Hedges’ (adjusted) g. The χ² distribution test with Cochran Q, Higgins I² index, and Tau square test (specífic for the random effects model) were used to estimate the heterogeneity. The cut-off value of Higgins I² index was as follows: 0% to 40%: might not be important; 30% to 60%: may represent moderate heterogeneity*; 50% to 90%: may represent substantial heterogeneity*; 75% to 100%: considerable heterogeneity. The synthesized results were conducted by pooling the data and using a random effects model meta-analysis. In addition, the forest plot was used to estimate if the meta-analysis would favor rehabilitation in decreasing the pain-related fear, pain, and disability when compared to usual treatment.

RESULTS

1. Description of Studies

The initial literature search through dataset found 4,613 articles and additional records from other sources were 0 article. Then 2,471 duplicate articles were removed and the residual 2,142 articles were screened according to the relevance of abstracts and titles. The 2,045 articles were discarded after this

Fig. 1. The PRISMA (preferred reporting items for systematic reviews and meta-analyses) flow diagram of current meta-analysis. The current meta-analysis followed the PRISMA guideline to identify the potentially relevant literature and screen the identified literature using abstract and title selection. The full text of screened literature was assessed to find the eligible studies and include the suitable ones for the final meta-analysis. RCT, randomized clinical trial.
### Table 1. Summary of enrolled studies for rehabilitation treatment on patients after lumbar fusion surgery

<table>
<thead>
<tr>
<th>Study</th>
<th>Subjects and inclusion period</th>
<th>Orthopedic diseases</th>
<th>Rehabilitation</th>
<th>Outcome assessment of interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abbott 2010 (Denmark)</td>
<td>107 (66 females vs. 41 males) (50.7 ± 10.4 years old), 3 sessions (90 min) between 0–3 months (postoperative)</td>
<td>Degenerative disc disease, spinal stenosis, degenerative/isthmic spondylolisthesis, spondylisis</td>
<td>CBT-related multimodal psychomotor therapy including CBT and graded motor relearning therapy (lumbopelvic stabilization) vs. home-based exercise program (dynamic exercises, stretches, cardiovascular)</td>
<td>3 Months, 6 months, 1 year, 2 years, 3 years: disability (ODI), pain (VAS), pain-related fear, Euro-QOL Quality of Life Scale for quality of life, Short Form for Health Survey (SF-36) for mental health and Socioeconomic status scale, Brunnsviken Brief Quality of life scale, Tampa Scale of Kinesiophobia, work status</td>
</tr>
<tr>
<td>Christensen 2003 (Denmark)</td>
<td>90 (60 females vs. 30 males), median 47 years old, 16 postoperative sessions (90 min) during 8 weeks</td>
<td>Isthmic spondylolisthesis grades I to II, degeneration</td>
<td>Exercise rehabilitation (Exercise training (conditioning training, dynamic muscular endurance training of back/abdominal/leg muscles and stretching) vs. video-recorded demonstration, with 1-time oral instruction, of exercises (dynamic muscular endurance training of back/abdominal/leg muscles)</td>
<td>3, 6, 12, 24 Months; pain low back pain rating scale (leg, back, physical and emotional components), work status</td>
</tr>
<tr>
<td>Elsayyad 2021 (Egypt)</td>
<td>60 (35 females vs. 25 males), 42.05 ± 3.65 years old, visited the hospital 3 times per week for 4 weeks</td>
<td>Degenerative disc disease with or without spinal stenosis</td>
<td>Exercise rehabilitation (neural mobilization and stabilization exercise program; 12 to 15 minutes per session, including 30 seconds hold and 1 minute rest.) vs. stabilization exercise rehabilitation (hand, knee, leg dynamic training with Swiss ball balancing)</td>
<td>1 Month and follow-up; disability (ODI), pain (VAS), right and left rotation, right and left lateral flexion, extension, flexion</td>
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<tr>
<td>Greenwood 2019 (United Kingdom)</td>
<td>52 (35 females vs. 27 males), 54.2 ± 13.5 years old, 10 sessions, starting 3 months (postoperative)</td>
<td>Degenerative disc disease, spinal stenosis, isthmic spondylolisthesis</td>
<td>Multimodal rehabilitation (peer support, education, exercise training (cardiovascular, limb and spine strengthening) vs. referral to external physiotherapy (no lifting heavier than a full kettle until 3 months)</td>
<td>3, 6, 12 Months, disability (ODI)</td>
</tr>
<tr>
<td>He 2021 (China)</td>
<td>78 (40 females vs. 38 males), 51.29 ± 7.48 years old, day of surgery to postoperative 4 days</td>
<td>Lumbar degenerative disease lumbar disc herniation lumbar spinal stenosis, lumbar spondylolisthesis</td>
<td>A nurse-led early postoperative rehabilitation program combined with the importance of early postoperative rehabilitation exercises (breathing, bedside exercise, rehabilitation guidance) vs. routine care model (postoperative assessment of general condition, postoperative guidance of patients’ eating, regular axial turning, absolute rest in a flat position)</td>
<td>3rd day, 1 month disability (ODI), pain (VAS), Barthel index, compliance rate, complication rate</td>
</tr>
<tr>
<td>Ilves 2022 (Finland)</td>
<td>98 (72 females vs. 26 males), 59 ± 12 years old, 6 sessions between 3–15 months postoperative</td>
<td>Degenerative/isthmic spondylolisthesis</td>
<td>Exercise rehabilitation (progressive back specific exercise [control, coordination, strength, and endurance of back, abdominal, gluteal and thigh muscles], aerobic training) vs. single session guidance, independent training with no progression (abdominal, [back and hip muscles], stretching and balance)</td>
<td>3 Months, 12 months pain (VAS), strength, Schober, finger-tip to floor distance, lateral flexion, time-up and go test</td>
</tr>
<tr>
<td>Kernc 2018 (Slovenia)</td>
<td>27 (13 females vs. 14 males), 60.7 ± 7.9 years old, 18 sessions, during 9 weeks starting at 3rd week postoperative</td>
<td>Degenerative/isthmic spondylolisthesis; degenerative disc disease</td>
<td>Exercise rehabilitation (strength training [focus on lumbopelvic stabilization muscles, intra-abdominal pressure utilization]) vs. no exercises prior to 3 months postoperative</td>
<td>3 Weeks, 3 months, 18 months: disability (ODI), pain (VAS), intra-abdominal pressure activation and performance</td>
</tr>
<tr>
<td>Study</td>
<td>Subjects and inclusion period</td>
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<td>Lotzke(^{19}) 2019 (Sweden)</td>
<td>118 (63 females vs. 55 males), 45.7 ± 8.3 years old, 4 pre- (1 hr) and 1 postoperative (30 min) session</td>
<td>Disc herniation, foraminal stenosis, isthmic spondylolisthesis</td>
<td>CBT-related rehabilitation; multimodal (targeting psychological risk factors and promoting physical activity) vs. Referral to local physiotherapist (i.e., one preoperative session with core Exercise program, information and advice to stay active)</td>
<td>1 Week preoperative; 3, 8, 12, 26 weeks postoperative: disability (ODI), pain (VAS), Tampa Scale of Kinesiophobia, Pain Catastrophizing Scale</td>
</tr>
<tr>
<td>Monticone(^{22}) 2014 (Italy)</td>
<td>130 (79 females vs. 51 males), 57.3 ± 13.1 years old, 8 postoperative sessions (1 hr) in 4 weeks</td>
<td>Spinal stenosis, degenerative/isthmic spondylolisthesis</td>
<td>CBT-related rehabilitation (controlling catastrophizing, kinesiophobia and maladaptive behavior) (in addition to control exercise condition) vs. hospital-based, physiotherapist-supervised exercise program, 5 times/wk during 4 weeks with active spinal mobilization and exercise training</td>
<td>1 Month, 1 year posttreatment: pain-related fear, disability (ODI), pain (Numerical Rating Scale), Tampa Scale of Kinesiophobia</td>
</tr>
<tr>
<td>Nielsen(^{20}) 2010 (Denmark)</td>
<td>60 (35 females vs. 25 males), 50.1 years old, 2 preoperative sessions, 2 times/day mobilization postoperative</td>
<td>Degenerative disc disease</td>
<td>Exercise rehabilitation (home-based exercise program [strengthening back and abdomen muscle, cardiovascular] postoperative early mobilization [aim discharge on day 5]) and exercise program vs. postoperative mobilization once/day (aim discharge on day 8)</td>
<td>2-Month preadmission, discharge, 1, 3, 6 months postoperative: disability (ODI), pain (VAS), Roland-Morris Questionnaire</td>
</tr>
<tr>
<td>Oestergaard(^{16}) 2020 (Denmark)</td>
<td>82 (41 females vs. 41 males), 46.8 ± 8.8 years old, 1 pre- and voluntary multiple postoperative sessions</td>
<td>Degenerative disc disease isthmic spondylolisthesis grades I to II</td>
<td>Multimodal rehabilitation (case-manager assisted rehabilitation program [preoperative meeting to determine rehabilitation program, postoperative (phone-) meeting [in addition to control condition]) vs. rehabilitation unit-based, exercise program, 1–2 times/wk during 8–10 weeks, starting at 8th week after surgery</td>
<td>3, 6, 9, 12, 24 Months: disability (ODI), pain (VAS), work status</td>
</tr>
<tr>
<td>Reichert(^{13}) 2011 (Germany)</td>
<td>39 (22 females vs. 17 males), 59.1 years old, 1 pre- and 1 postoperative session (30 min)</td>
<td>Spinal stenosis and instability</td>
<td>CBT-related rehabilitation (short psychological intervention focusing on reducing fear-avoidance and motivational strategies)</td>
<td>1st day, 6 weeks: pain-related fear, VAS, fear-avoidance beliefs questionnaire</td>
</tr>
<tr>
<td>Rolving(^{11}) 2015 (Denmark)</td>
<td>90 (51 females vs. 39 males), 50.1 ± 9.2 years old, 4 pre- and 2 postoperative sessions (3 hr)</td>
<td>Disc degenerative disease spondylolisthesis grades I to II</td>
<td>CBT-related Rehabilitation; multimodal (CBT covering interaction of cognition and pain perception, coping strategies, pacing principles, ergonomic directions, return to work and details about the surgical procedure [in addition to control condition]) vs. postoperative physiotherapist-supervised exercises in group or individual, starting 3 months after surgery</td>
<td>1st week: Numeric Rating Scale 12 and 52nd week: disability (ODI), Low Back Pain Rating Scale, fear-avoidance beliefs questionnaire, work status 12 and 52 weeks</td>
</tr>
<tr>
<td>Salik(^{13}) 2021 (Turkey)</td>
<td>37 (19 females vs. 18 males), 53.9 years old, Daily for 6 weeks, starting 2nd day postoperative, 2 follow-up telephone calls</td>
<td>Spinal stenosis, degenerative/isthmic spondylolisthesis, disc degenerative disease with instability, spondylolisthesis</td>
<td>Exercise rehabilitation; multimodal (home-based exercise program, each time preceded by motor imaginary exercises, facilitated by voice commands) vs. home-based exercise program (education, neutral spine control, maximal voluntary isometric contraction), starting 2nd day postoperative</td>
<td>3 and 6 weeks: disability (ODI), pain (VAS), Tampa Scale of Kinesiophobia</td>
</tr>
<tr>
<td>Strom(^{17}) 2019 (Denmark)</td>
<td>114 (74 females vs. 40 males), 54 years old, all-time access by web-based system</td>
<td>Lumbar multilevel degenerative disease</td>
<td>Multimodal rehabilitation (preoperative access to web-based system [web-based information/animation/diary/peer support, in line with CBT principles] [in addition to control condition]) vs. Physiotherapist-supervised exercise program, starting 3rd month postoperative</td>
<td>2nd day, 3, 6 months: disability (ODI), Low Back Pain Rating Scale, EuroQoL Quality of Life Scale, Hamilton Rating Scale for Depression</td>
</tr>
</tbody>
</table>

CBT, cognitive behavioral therapy; ODI, Oswestry Disability Index; VAS, visual analogue scale.
step. Full text contents were assessed for the eligibility for the 97 articles. Then 82 articles were excluded due to the various reasons (Fig. 1). The qualitative analysis of residual 15 articles was performed and the residual 15 studies were included in this meta-analysis. The flow diagram was presented according to the PRISMA guideline (Fig. 1). The detailed characteristics of the 15 studies22-26 were also summarized in Table 1. The risk of bias assessment of each study was listed as Fig. 2. The study of Monticone et al.22 might be the outlier to be excluded in the pain and disability domain due to the high heterogeneity. However, due to that there was no high risk of bias, no huge variation of trial protocol, or no significant difference in trial population, the study was still included in the meta-analysis.

2. The Meta-Analysis Results for the Pain-Related Fear Under the Comparison Between the Psychological Rehabilitation and Usual Treatment

The psychological rehabilitation (CBT-related) group was presented as the “experimental” group in this meta-analysis. The usual treatment group was presented as the “control” group in this meta-analysis (Fig. 3). For the study of Lotzke et al.,18 we collected the data of “Tampa Scale of Kinesiophobia” in this meta-analysis. The reason was that we wanted to focus on the kineiophobia, which was more related to rehabilitation perspectives and the Tampa Scale of Kinesiophobia can objectively quantify the degree of kinesphobia.27 Total subject number of the psychological rehabilitation (CBT-related) group was 242 and total subject number of the usual treatment group was 208. In the random effect model, the standard mean difference of rating scale scores of pain-related fear between psychological rehabilitation (CBT-related) group and usual treatment group was -0.56 (95% CI, -0.99 to -0.14), which suggested that the rating scale scores of pain-related fear was lower in the psychological rehabilitation (CBT-related) group when compared to usual treatment group. The results were significant (test for overall effect \( Z = 2.58 \)). However, significant heterogeneity was noted (\( I^2 = 79\% \)).
3. The Meta-Analysis Results for the Pain Under the Comparison Between the Exercise Rehabilitation and Usual Treatment

The exercise rehabilitation group was presented as the “exercise” group in this meta-analysis. The usual treatment group was presented as the “control” group in this meta-analysis (Fig. 4). Total subject number of the exercise rehabilitation group was 193 and total subject number of the usual treatment group was 198. In the random effect model, the standard mean difference of rating scale scores of pain between exercise rehabilitation group and usual treatment group was -0.56 (95% CI, -0.83 to -0.28), which suggested that the pain was relatively lower in the exercise rehabilitation group. The results were also significant (test for overall effect $Z = 3.97$). The significant heterogeneity was also noted ($I^2 = 42\%$).

4. The Meta-Analysis Results for the Pain Under the Comparison Between the Multimodal Rehabilitation and Usual Treatment

The multimodal rehabilitation group was presented as the
The usual treatment group was presented as the "control" group in this meta-analysis (Fig. 5). Total subject number of the multimodal rehabilitation group was 256 and total subject number of the usual treatment group was 231. In the random effect model, the standard mean difference of rating scale scores of pain between multimodal rehabilitation group and usual treatment group was -0.26 (95% CI, -0.51 to -0.01), which suggested that the pain was relatively lower in the multimodal rehabilitation group. The results were also significant (test for overall effect $Z = 2.05$). Moderate heterogeneity was also noted ($I^2 = 45\%$).

5. The Meta-Analysis Results for the Disability Under the Comparison Between the Exercise Rehabilitation and Usual Treatment

The exercise rehabilitation group was presented as the "exercise" group in this meta-analysis. The usual treatment group was presented as the "control" group in this meta-analysis (Fig. 6). Total subject number of the exercise rehabilitation group was 167 and total subject number of the usual treatment group was 169. In the random effect model, the standard mean difference of rating scale scores of disability between exercise rehabilitation group and usual treatment group was -0.63 (95% CI, -1.27 to 0.01), which suggested that the disability was not significantly lower in the exercise rehabilitation group. The p = 0.05 (test for overall effect $Z = 1.92$) was statistically significant. However, the 95% CI results still indicated the result was not significant. The significant heterogeneity was also noted ($I^2 = 87\%$).

6. The Meta-Analysis Results for the Disability Under the Comparison Between the Multimodal Rehabilitation and Usual Treatment

The multimodal rehabilitation group was presented as the "multimodal" group in this meta-analysis. The usual treatment group was presented as the "control" group in this meta-analysis (Fig. 7). Total subject number of the multimodal rehabilitation group was 274 and total subject number of the usual treatment group was 253. The standardized mean differences between multimodal rehabilitation group and usual treatment group were -0.30 (95% CI, -0.48 to -0.13), which suggested that the disability was relatively lower in the multimodal rehabilitation group. The results were also significant (test for overall effect $Z = 2.05$). Moderate heterogeneity was also noted ($I^2 = 45\%$).
fect \( Z = 3.35 \). Low heterogeneity was also noted (\( I^2 = 0 \% \)).

7. Assessments of Certainty (or Confidence) in the Body of Evidence

After our evaluation, we reported the moderate confidence in the effect estimate.

DISCUSSION

Our meta-analysis results found that CBT-related rehabilitation might significantly decrease the pain-related fear when compared to usual treatment. For the disability domain, the multimodal rehabilitation seemed to improve the disability outcome to a greater extent when compared to usual treatment. In addition, the multimodal rehabilitation seemed to have a more significantly positive effect to decrease disability after lumbar fusion surgery. However, the exercise rehabilitation seemed not significantly decrease the disability scores in current meta-analysis. For the pain domain, the exercise and multimodal rehabilitation seemed to decrease the pain after lumbar fusion surgery. The exercise rehabilitation seemed to decrease the pain more than the multimodal rehabilitation on the patients after lumbar fusion surgery. The focus on the CBT-related rehabilitation, exercise, and multimodal rehabilitation with statistically significant results on the pain-related fear, pain, and disability domains was the strength point of our meta-analysis. In addition, the more stringent selection and enrollment of RCT studies in the current meta-analysis might be another strength point. At last, the beneficial effects of the specific type of rehabilitation (CBT-related rehabilitation for the pain-related fear, multimodal rehabilitation for the disability, and exercise rehabilitation for the pain) can provide the useful information for the clinicians to determine the rehabilitation programs for the patients after lumbar fusion surgery. Our study was different from the latest meta-analysis in several perspectives. First, our search deadline was March 2022, approximately 1 year more than the search deadline of the latest meta-analysis. Second, our meta-analysis enrolled latest references, especially for the articles published in the 2021 and 2022. It might provide a more comprehensive viewpoint. Third, our meta-analysis results showed more significant effects of rehabilitation on the pain-related fear, pain, and disability domains, especially for the effect of the multimodal rehabilitation on the disability domain. Fourth, our meta-analysis focused more on the short-term effects of rehabilitation on the pain-related fear, pain, and disability. Fifth, our meta-analysis enrolled more studies and subjects for the analysis on the pain-related fear, pain, and disability.

Our findings of the positive effects of rehabilitation on pain were opposite of the findings of the previous meta-analysis. The possible reasons might be that the previous meta-analysis enroll too few studies. In addition, our meta-analysis results of CBT-related rehabilitation on the pain-related fear might provide the additional information for another previous meta-analysis, which showed that CBT-related rehabilitation did not have a positive effect on the pain and physical function of patients after lumbar fusion surgery. The CBT-related rehabilitation might still have a beneficial effect on the pain-related fear, even without a significant treatment effect on the pain and physical function. The beneficial effect on the pain-related fear might be derived from the improvement of pain coping mechanism and reduce the catastrophic fear. The multimodal rehabilitation might be beneficial for decreasing the disability scores, which have been reported in 2 previous meta-analysis studies. Our meta-analysis also replicated this finding. It might be related to shift the conceptualization of pain to a coping skill to protect the body tissue during cognitive or educational rehabilitation and inter-hemispheric interaction to improve the neural plasticity of primary motor cortex during motor rehabilitation. The relief of pain might also be helpful to reduce the disability of patients. The pain-relieving effects of exercise rehabilitation might be due to the enhancement of central descending inhibitory pathway or the modulation of angiotensin or glutamate transmission system. However, the exercise rehabilitation seemed not to significantly reduce the disability. The exercise rehabilitation seemed to decrease the pain more than the multimodal rehabilitation on the patients after lumbar fusion surgery. The potential mechanism might be that multimodal rehabilitation focused more on the educational and cognitive training, which might be more focused on decreasing the disability due to the pain-related fear and neural plasticity can improve the disability outcome. The exercise might be more focused on the hypoalgesic mechanism, which involved the central pain inhibition system. It suggested that the different kinds of rehabilitation programs might demonstrate different treatment effects on the outcome of postoperative duration for the patients after lumbar fusion surgery. In the recent study, the rehabilitation might play a role as an independent predictor for the wound complications after lumbar fusion surgery. Even the current meta-analysis did not survey the wound complications, the improvement of disability and pain might be related to the factor. However, a recent study reported that discharged to rehabilitation and discharged to home showed a statistically similar postdis-
charge morbidity status. The rehabilitation did not predict the postdischarge morbidity.\textsuperscript{37} In addition, another meta-analysis of lumbar fusion due to degenerative diseases showed that the evidence of positive effects of rehabilitation on the outcome of patients still have not been significantly proved.\textsuperscript{38} Therefore, there is still a lot of space to improve the study design of rehabilitation on the outcome of patients after lumbar fusion surgery. More RCT studies with a better study design can clarify the real effects of rehabilitation on the pain-related fear, pain, and disability of patients after lumbar fusion surgery.

The current meta-analysis did not perform the correlation and cause-relationship analysis between these outcomes. However, the potential relationship pain, pain-related fear, and disability in the patients after lumbar fusion surgery might influence each other. For example, the improvement of disability might be related to the improvement in the pain and pain-related fear. This might be an intrigue issue for further research.

There were several limitations in the current meta-analysis. First, the limited sample size for each comparison (mostly around 100–300 subjects in each group) might limit the interpretation of current results. In addition, most meta-analysis dimensions in the current manuscript just had around 200 subjects for each group. The statistical power from the sample size might be limited in the current meta-analytic results. More subjects will be warranted in the future meta-analysis. Second, a relatively high statistical heterogeneity was noted in the different comparison groups (except the comparison of multimodal rehabilitation for disability). Third, the lack of transparency of detailed rehabilitation programs was noted in the enrolled RCT studies. Fourth, the variability of subject age, sex, and orthopedic diseases in each enrolled RCT study might also bias our findings. Fifth, the variability of treatment duration and enrolled time in each RCT study might be another obstacle to reach a more consistent finding for positive effects of the rehabilitation on the patients after lumbar fusion surgery. Sixth, the statistically significant results might not represent the significant results in the clinical perspective. The most enrolled studies were based on 10-point scale (commonly used in clinical practice). For instance, pooled result of difference in pain scores between exercise and usual treatment may not represent clinically importance due to more than half evidence in the meta-analysis showed mean difference < 2 in original reports. Therefore, the statistically significant results should be interpreted with caution in the viewpoint of clinical perspectives. Seventh, the timing evaluating pain, disability and pain-related fear differs between the enrolled studies was different. For instance, Lotzke et al.\textsuperscript{18} initiated the rehabilitation during 8–12 weeks before the surgery but Abbott et al.\textsuperscript{25} started it at the first day after the surgery. The timing issue of rehabilitation protocol would also influence the interpretation of current meta-analysis results. Eighth, the diverse contents of CBT-related rehabilitation might influence the pain-related fear outcome. This limitation should be taken into consideration when we interpreted with the current meta-analysis.

**CONCLUSION**

The rehabilitation might relieve the pain-related fear, disability, and pain after lumbar fusion surgery. The beneficial effects of the specific type of rehabilitation (CBT-related rehabilitation for the pain-related fear, multimodal rehabilitation for the disability, and exercise rehabilitation for the pain) can provide the useful information for the clinicians to determine the rehabilitation programs for the patients after lumbar fusion surgery.

**NOTES**

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Author Contribution: Conceptualization: HC, JL; Data curation: HC, JL; Formal analysis: HC, XH; Funding acquisition: XH; Methodology: HC; Project administration: XH; Visualization: LS; Writing - original draft: HC; Writing - review & editing: XH.

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Weekend Admission Increases Risk of Readmissions Following Elective Cervical Spinal Fusion

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Objective: The “weekend effect” occurs when patients cared for during weekends versus weekdays experience worse outcomes. But reasons for this effect are unclear, especially amongst patients undergoing elective cervical spinal fusion (ECSF). Our aim was to analyze whether index weekend admission affects 30- and 90-day readmission rates post-ECSF.

Methods: All ECSF patients > 18 years were retrospectively identified from the 2016–2018 Healthcare Cost and Utilization Project Nationwide Readmissions Database (NRD), using unique patient linkage codes and International Classification of Diseases, Tenth Revision codes. Patient demographics, comorbidities, and outcomes were analyzed. Univariate logistic regression analyzed primary outcomes of 30- and 90-day readmission rates in weekday or weekend groups. Multivariate regression determined the impact of complications on readmission rates.

Results: Compared to the weekday group (n = 125,590), the weekend group (n = 1,026) held a higher percentage of Medicare/Medicaid insurance, incurred higher costs, had longer length of stay, and fewer routine home discharge (all p < 0.001). There was no difference in comorbidity burden between weekend versus weekday admissions, as measured by the Elixhauser Comorbidity Index (p = 0.527). Weekend admissions had higher 30-day (4.30% vs. 7.60%, p < 0.001) and 90-day (7.80% vs. 16.10%, p < 0.001) readmission rates, even after adjusting for sex, age, insurance status, and comorbidities. All-cause complication rates were higher for weekend admissions (8.62% vs. 12.7%, p < 0.001), specifically deep vein thrombosis, infection, neurological conditions, and pulmonary embolism.

Conclusion: Index weekend admission increases 30- and 90-day readmission rates after ECSF. In patients undergoing ECSF on weekends, postoperative care for patients at risk for specific complications will allow for improved outcomes and health care utilization.

Keywords: Elective cervical spinal fusion, Readmission rates, Weekend admission, Complications, Perioperative characteristics, Postoperative outcomes

INTRODUCTION

Cervical spinal fusions have had increasing incidence, partly owing to the increasing elderly population and an increasing emphasis on quality-based reimbursement metrics and cost-effective solutions for degenerative spine disorders. The estimated rate of anterior cervical discectomy and fusion (ACDF) and posterior cervical fusions is 50.6 per 100,000 population and is predicted to continue to increase. ACDF, the most common surgery for degenerative cervical disease, has experienced increasing readmission rates. As cervical spinal fusion procedures continue to rise, it is imperative that we analyze risk factors for 30- and 90-day readmission to improve patient outcomes.

Readmission rates are an excellent measure of patient outcomes since they serve as a widespread quality and reimbursement metric. Readmission is associated with higher costs making it a current focus of improvement for both the Centers for...
Medicare and Medicaid Services (CMS) as well as institutions. In 2006, an estimated $41 billion were spent as a result of unplanned readmissions, placing significant stress on both patients and the healthcare system. Notably, the CMS and National Quality Forum use readmission rates as a metric to rate hospital performance and to determine quality-based reimbursement.

The “weekend effect” is a clinical phenomenon where there are more negative outcomes in patients cared for during the weekend compared to a weekday, but reasons for this effect are unclear. Studies have found weekend admission to be associated with higher risk of mortality, cost, increased length of stay (LOS), and worse outcomes in patients undergoing spine procedures for idiopathic scoliosis, cervical fusion due to trauma, and thoracolumbar fusion. However, other studies have found no association between index weekend admission and complication or mortality rates in emergent spinal cord injury patients. Although risk factors for readmission in patients undergoing cervical spinal fusions have been identified, the day of surgery was not considered.

To our knowledge, this is the first paper to consider readmission rates in patients who were admitted on the weekend to undergo either anterior or posterior elective cervical spinal fusions (ECSF). A more contemporary analysis of specific complications and readmission rates can help elucidate the causes of different clinical outcomes associated with day of index admission. Findings may inform providers on potential methods to address causes of readmission, in the context of the weekend effect, to minimize the negative impact and costs associated with weekend admission on ECSF.

As such, the objectives of this study are to (1) compare 30- and 90-day readmission rates between weekday and weekend admission for patients undergoing ECSF and (2) identify differences in complications between the weekday vs weekend cohorts to explain differences in readmission rates.

**MATERIALS AND METHODS**

We queried the 2016–2018 versions of the Nationwide Readmissions Database (NRD), which holds data on millions of hospital discharges in the United States (US) every year. Institutional review board exemption was obtained from our institution for this retrospective analysis. The 2016–2018 datasets use the International Classification of Diseases, Tenth Revision (ICD-10) diagnosis and procedural codes to identify specific medical conditions and surgical procedures. The NRD contains data from 28 state inpatient databases. Sampling discharge weights are provided by the Healthcare Cost and Utilization Project to allow for national estimates from the NRD. The NRD discharge data includes patient demographics, hospital characteristics, payer status, total hospital charges to patient, readmission information, and patient diagnoses and procedures.

All adult patients (> 18 years of age) who underwent ECSF were identified using ICD-10, Clinical Modification procedure codes. Procedures include both ACDF and posterior spinal fusion, and nonelective procedures were excluded based on ICD-10 codes. Patients were then separated into 2 subgroups based on whether or not their index admission was on a weekday or weekend. The NRD uses the binary variable “AWEEKEND” to identify whether an admission is on a weekend (= 1) versus weekday (= 0), where weekend admission equates to receiving surgery on Saturday or Sunday. Patient characteristics were obtained from the NRD database including demographic information (sex and age), diagnoses, and payer type. Preoperative comorbidities were identified using ICD-10 codes and the R Comorbidity package. This package allows for the calculation of the Elixhauser Comorbidity Index (ECI) as well as incidence of specific comorbidities among the patient population. Additionally, total LOS and total hospital charges were analyzed for each patient. Total hospital charges for each patient were reported by the NRD in dollar amounts; we then adjusted each charge for inflation using the consumer price index.

The NRD contains data on 14 million US hospitalizations each year, and allows for the longitudinal tracking of patients and their care as they are readmitted throughout a specific year via patient-specific identifiers within the database. However, the data is specific to year and state, so if a patient is readmitted to a different facility in a different state or if their readmission occurs after the calendar year ends, the readmission is not accounted for and could be coded as an initial admission. In order to capture 90-day readmissions, patients admitted during the last quarter of the calendar year were excluded. We were able to quantify the incidence of 30- and 90-day readmissions, the primary diagnoses associated with the 30- and 90-day readmissions, and all procedures performed during the 30- and 90-day readmissions. These analyses were performed for both the weekend-admit and weekday-admit subgroups.

SciPy version 1.6.1 (The SciPy community) was used for all statistical analyses. Univariate regression analyses were performed to assess demographic differences, average total charges, and LOS between the weekend-admit and weekday-admit groups. Multivariate logistic regression was performed to ana-
lyze the association between weekend index admission and both 30- and 90-day readmission, adjusted for demographic and comorbidity factors.

RESULTS

1. General Patient Data

A total of 126,616 patients undergoing ECSF were identified, with 125,590 in the weekday cohort and 1,026 in the weekend cohort. Compared to the weekday group, the weekend group had a higher percentage of elderly patients over the age of 70 (p < 0.001), higher percentage of Medicare/Medicaid payor status (p < 0.001), incurred higher costs by $23,819.79 ($121,780.58 vs. $97,960.79, p < 0.001), and had longer postoperative LOS (5.27 days vs. 2.76 days, p < 0.001) (Table 1).

Patients with weekend index admissions had lower incidences of routine discharge (p < 0.001), defined as discharge to home without further required hospital care. Additionally, the weekend cohort had higher rates of discharge to home health care (HHC) (p < 0.001), skilled nursing facilities (SNFs)

Table 1. General characteristics of weekday versus weekend index admission cohorts

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Weekday (n = 125,590)</th>
<th>Weekend (n = 1,026)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Female sex</td>
<td>63,546 (50.68)</td>
<td>506 (49.32)</td>
<td>0.716</td>
</tr>
<tr>
<td>Age (yr)</td>
<td></td>
<td></td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>18–49</td>
<td>27,352 (21.78)</td>
<td>223 (21.73)</td>
<td></td>
</tr>
<tr>
<td>50–59</td>
<td>38,096 (30.33)</td>
<td>262 (25.54)</td>
<td></td>
</tr>
<tr>
<td>60–69</td>
<td>36,094 (28.74)</td>
<td>278 (27.1)</td>
<td></td>
</tr>
<tr>
<td>70–79</td>
<td>20,339 (16.19)</td>
<td>199 (19.4)</td>
<td></td>
</tr>
<tr>
<td>≥ 80</td>
<td>3,709 (2.95)</td>
<td>64 (6.24)</td>
<td></td>
</tr>
<tr>
<td>Payor status</td>
<td></td>
<td></td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Medicaid</td>
<td>12,453 (9.92)</td>
<td>111 (10.82)</td>
<td></td>
</tr>
<tr>
<td>Medicare</td>
<td>50,141 (39.92)</td>
<td>501 (48.83)</td>
<td></td>
</tr>
<tr>
<td>Other/unknown</td>
<td>11,677 (9.92)</td>
<td>66 (6.43)</td>
<td></td>
</tr>
<tr>
<td>Private insurance</td>
<td>49,969 (39.79)</td>
<td>327 (31.87)</td>
<td></td>
</tr>
<tr>
<td>Self-pay</td>
<td>1,187 (0.95)</td>
<td>19 (1.85)</td>
<td></td>
</tr>
<tr>
<td>Total charges (USD)</td>
<td>97,960.79 ± 87,451.10</td>
<td>121,780.58 ± 132,717.32</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>LOS (day)</td>
<td>2.76 ± 4.51</td>
<td>5.37 ± 9.53</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Elixhauser comorbidity index</td>
<td></td>
<td></td>
<td>0.527</td>
</tr>
<tr>
<td>0</td>
<td>27,180 (21.64)</td>
<td>238 (23.2)</td>
<td>0.279</td>
</tr>
<tr>
<td>1–4</td>
<td>89,253 (71.07)</td>
<td>710 (69.2)</td>
<td>0.187</td>
</tr>
<tr>
<td>≥ 5</td>
<td>9,157 (7.29)</td>
<td>78 (7.6)</td>
<td>0.794</td>
</tr>
<tr>
<td>Discharge status</td>
<td>&lt; 0.001*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Routine</td>
<td>97,021 (77.25)</td>
<td>659 (64.23)</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Short-term hospital</td>
<td>255 (0.2)</td>
<td>†</td>
<td>0.816</td>
</tr>
<tr>
<td>Home health care</td>
<td>18,467 (14.7)</td>
<td>193 (18.81)</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Skilled nursing facility, intermediate care facility, and other facilities</td>
<td>9,464 (7.54)</td>
<td>162 (15.79)</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Against medical advice</td>
<td>181 (0.14)</td>
<td>†</td>
<td>0.910</td>
</tr>
<tr>
<td>Readmissions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30 Days</td>
<td>5,423 (4.30)</td>
<td>78 (7.60)</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>90 Days</td>
<td>9,742 (7.80)</td>
<td>165 (16.10)</td>
<td>&lt; 0.001*</td>
</tr>
</tbody>
</table>

Values are presented as mean ± standard deviation or number (%).
USD, United States dollar; LOS, length of stay.
*p < 0.05, statistically significant differences. †Incidence is less than or equal to 11 and is omitted for data privacy.
(p < 0.001), and intermediate care facilities (p < 0.001) (Table 1).

Weekend admitted patients had higher rates of coagulopathy (1.66% vs. 1.63%, p = 0.001) and peripheral vascular disease (4.48% vs. 2.39%, p < 0.001), but there were no differences in comorbidity burden between the 2 groups as measured by the ECI (p = 0.527) (Table 2). All-cause complication rates were higher for weekend admissions (12.7% vs. 8.62%, p < 0.001), namely deep vein thrombosis (DVT), neurological conditions, postoperative infections, and pulmonary embolism (p < 0.001) (Table 3).

### 2. Readmission Rates

Multiple logistical analysis was conducted to investigate the association between weekend surgery and readmission rates. The 30-day readmission rates were 4.30% on weekdays and 7.60% on weekends (odds ratio [OR], 1.82; 95% confidence interval [CI], 1.44–2.30; p < 0.001). The 90-day readmission rates were 7.80% on weekdays and 16.10% on weekends (OR, 2.28; 95% CI, 1.93–2.70; p < 0.001). After adjusting for sex, age, and payor status, and comorbidities, both 30-day (OR, 1.71; 95% CI, 1.35–2.15; p < 0.001) and 90-day (OR, 2.15; 95% CI, 1.81–2.55; p < 0.001) weekend admission remained an independent risk factor for readmission (Tables 4, 5).

### Table 2. Comorbidities in weekday versus weekday index admission patients

<table>
<thead>
<tr>
<th>Comorbidity</th>
<th>Weekday (n = 104,431)</th>
<th>Weekend (n = 742)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acquired immunodeficiency syndrome</td>
<td>162 (0.13)</td>
<td>†</td>
<td>0.351</td>
</tr>
<tr>
<td>Alcohol abuse</td>
<td>2,097 (1.67)</td>
<td>18 (1.75)</td>
<td>0.945</td>
</tr>
<tr>
<td>Blood loss anemia</td>
<td>272 (0.22)</td>
<td>†</td>
<td>0.985</td>
</tr>
<tr>
<td>Cardiac arrhythmias</td>
<td>8,858 (7.05)</td>
<td>62 (6.04)</td>
<td>0.389</td>
</tr>
<tr>
<td>Congestive heart failure</td>
<td>3,739 (2.98)</td>
<td>36 (3.51)</td>
<td>0.572</td>
</tr>
<tr>
<td>Coagulopathy</td>
<td>2,042 (1.63)</td>
<td>17 (1.66)</td>
<td>0.001*</td>
</tr>
<tr>
<td>Chronic pulmonary disease</td>
<td>23,858 (19.0)</td>
<td>175 (17.06)</td>
<td>0.082</td>
</tr>
<tr>
<td>Deficiency anemias</td>
<td>1,228 (0.98)</td>
<td>16 (1.56)</td>
<td>0.167</td>
</tr>
<tr>
<td>Depression</td>
<td>21,944 (17.47)</td>
<td>173 (16.86)</td>
<td>0.810</td>
</tr>
<tr>
<td>Diabetes (with chronic complications)</td>
<td>9,381 (7.47)</td>
<td>79 (7.7)</td>
<td>0.395</td>
</tr>
<tr>
<td>Diabetes (uncomplicated)</td>
<td>17,578 (14.0)</td>
<td>133 (12.96)</td>
<td>0.460</td>
</tr>
<tr>
<td>Drug abuse</td>
<td>3,285 (2.62)</td>
<td>22 (2.14)</td>
<td>0.608</td>
</tr>
<tr>
<td>Fluid/electrolyte disorder</td>
<td>6,735 (5.36)</td>
<td>53 (5.17)</td>
<td>0.859</td>
</tr>
<tr>
<td>Hypertension (with chronic complications)</td>
<td>7,738 (6.16)</td>
<td>64 (6.24)</td>
<td>0.292</td>
</tr>
<tr>
<td>Hypertension (uncomplicated)</td>
<td>14,698 (11.7)</td>
<td>126 (12.28)</td>
<td>0.603</td>
</tr>
<tr>
<td>Hypothyroidism</td>
<td>59,976 (47.76)</td>
<td>481 (46.88)</td>
<td>0.852</td>
</tr>
<tr>
<td>Liver disease</td>
<td>2,153 (1.71)</td>
<td>19 (1.85)</td>
<td>0.912</td>
</tr>
<tr>
<td>Lymphoma</td>
<td>329 (0.26)</td>
<td>†</td>
<td>0.586</td>
</tr>
<tr>
<td>Metastatic cancer</td>
<td>576 (0.46)</td>
<td>†</td>
<td>0.982</td>
</tr>
<tr>
<td>Obesity</td>
<td>23,862 (19.0)</td>
<td>184 (17.93)</td>
<td>0.655</td>
</tr>
<tr>
<td>Other neurological disorders</td>
<td>4,891 (3.89)</td>
<td>45 (4.39)</td>
<td>0.664</td>
</tr>
<tr>
<td>Paralysis</td>
<td>2,405 (1.91)</td>
<td>26 (2.53)</td>
<td>0.341</td>
</tr>
<tr>
<td>Pulmonary circulation disorders</td>
<td>771 (0.61)</td>
<td>†</td>
<td>0.649</td>
</tr>
<tr>
<td>Psychoses</td>
<td>494 (0.39)</td>
<td>†</td>
<td>0.885</td>
</tr>
<tr>
<td>Peptic ulcer disease</td>
<td>351 (0.28)</td>
<td>†</td>
<td>0.454</td>
</tr>
<tr>
<td>Peripheral vascular disease</td>
<td>3,005 (2.39)</td>
<td>46 (4.48)</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Renal failure</td>
<td>6,168 (4.91)</td>
<td>48 (4.68)</td>
<td>0.850</td>
</tr>
<tr>
<td>Rheumatoid arthritis/collagen vascular disease</td>
<td>5,845 (4.65)</td>
<td>35 (3.41)</td>
<td>0.154</td>
</tr>
<tr>
<td>Solid tumor without metastases</td>
<td>1,016 (0.81)</td>
<td>†</td>
<td>0.955</td>
</tr>
<tr>
<td>Valvular disease</td>
<td>2,732 (2.18)</td>
<td>20 (1.95)</td>
<td>0.846</td>
</tr>
<tr>
<td>Weight loss</td>
<td>1,063 (0.85)</td>
<td>†</td>
<td>0.835</td>
</tr>
</tbody>
</table>

Values are presented as number (%).

*p < 0.05, statistically significant differences. †Incidence is less than or equal to 11 and is omitted for data privacy.

### Table 3. Complications of weekday versus weekday index admission patients

<table>
<thead>
<tr>
<th>Complication</th>
<th>Weekday (n = 125,590)</th>
<th>Weekend (n = 1,026)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>All-cause</td>
<td>10,826 (8.62)</td>
<td>130 (12.7)</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Deep vein thrombosis</td>
<td>300 (0.24)</td>
<td>13 (1.27)</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Dehiscence</td>
<td>153 (0.12)</td>
<td>†</td>
<td>0.300</td>
</tr>
<tr>
<td>Dural tear</td>
<td>16 (0.01)</td>
<td>†</td>
<td>0.936</td>
</tr>
<tr>
<td>Foreign body reaction</td>
<td>142 (0.11)</td>
<td>†</td>
<td>0.239</td>
</tr>
<tr>
<td>Gastrointestinal complications</td>
<td>256 (0.2)</td>
<td>†</td>
<td>0.994</td>
</tr>
<tr>
<td>Genitourinary complications</td>
<td>149 (0.12)</td>
<td>†</td>
<td>0.542</td>
</tr>
<tr>
<td>Hardware related complications</td>
<td>505 (0.4)</td>
<td>†</td>
<td>0.303</td>
</tr>
<tr>
<td>Intraoperative complications</td>
<td>6,990 (5.57)</td>
<td>46 (4.48)</td>
<td>0.286</td>
</tr>
<tr>
<td>Neurologic complications</td>
<td>1,251 (1.0)</td>
<td>25 (2.44)</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Nonunion</td>
<td>370 (0.29)</td>
<td>†</td>
<td>0.994</td>
</tr>
<tr>
<td>Peripheral vascular complications</td>
<td>165 (0.13)</td>
<td>†</td>
<td>0.954</td>
</tr>
<tr>
<td>Post-operative infection</td>
<td>418 (0.33)</td>
<td>27 (2.63)</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Post-operative shock</td>
<td>54 (0.04)</td>
<td>†</td>
<td>0.801</td>
</tr>
<tr>
<td>Pulmonary embolism</td>
<td>198 (0.16)</td>
<td>†</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Respiratory complications</td>
<td>892 (0.71)</td>
<td>13 (1.27)</td>
<td>0.107</td>
</tr>
</tbody>
</table>

Values are presented as number (%).

*p < 0.05, statistically significant differences. †Incidence is less than or equal to 11 and is omitted for data privacy.
Common diagnosis upon 30-day readmission includes infection (7.01% weekday vs. 7.52% weekend) and sepsis (4.54% weekday vs. 6.15% weekday). Similarly, common diagnosis upon 90-day readmission includes infection (4.77% weekday vs. 5.87% weekend), sepsis (3.69% weekday vs. 6.70% weekend), and cervical spinal stenosis (6.09% weekday vs. 1.23% weekend) (Table 6).

**DISCUSSION**

This study is the first to demonstrate that patients with index weekend admission for both anterior and posterior ECSF procedures have increased rates of 30- and 90-day readmission, compared to patients admitted on weekdays. This relationship remains true even after controlling for demographic characteristics and comorbidities.

1. **Resource Utilization and Costs**

We found that weekend admitted patients incurred $23,819.79 more in total costs, but did not achieve better outcomes than weekday admissions, as assessed by higher readmission rates, longer LOS, and all-cause complications. These findings suggest that amongst weekend admission patients, higher postoperative complication rates may have led to longer LOS and therefore increased hospital costs.

Unplanned readmissions following surgery pose a significant impact on the US healthcare system, with an estimated 3.3 million 30-day all-cause readmissions resulting in an expenditure of $41 billion. In elective ACDF patients, the median cost of 30- and 90-day readmissions were $6,727 and $8,507, respectively. In cervical trauma patients, weekend admits incurred $11,301 more in total hospital costs than weekday admits. Factors contributing to higher costs for weekend admitted ECSF patients may be due to higher LOS, as a moderately strong correlation between LOS and hospital cost has been described in joint arthroplasty patients. Furthermore, Adogwa et al. suggests reducing LOS after ACDF can help minimize costs and optimize patient outcomes. Of note, the costs reported in this study reflect the financial burden of index admission, and did not take into account the costs of readmission. Given the financial burden of readmission events, describing the relationship between weekend index admission and possible readmission is critical for informing providers on the importance of improving weekend care to decrease the risks of readmission and the costs associated with readmission.

Comorbidities and weekend admission were found to be associated with higher hospital costs after acoustic neuroma microsurgery and percutaneous coronary interventions. Coagulopathy increased overall hospital costs by $3,787 in patients undergoing joint arthroplasty, and coagulopathy and peripheral vascular disease increased risks of infections and complications in patients undergoing spinal fusion. In our study, the weekend ECSF cohort had significantly higher rates of coagulopathy and peripheral vascular disease comorbidities, and more thromboembolic complications. Thus, optimizing preoperative coagulation profiles and being cognizant of blood transfusion sequelae for patients with coagulopathy and peripheral vascular disease may reduce complication risks and costs – associations that can be explored in future studies under the context of the “weekend effect” in ECSF patients.
Table 6. Diagnosis upon 30-day and 90-day readmissions in weekday versus weekday index admission cohorts

### Reasons for 30-day readmission

<table>
<thead>
<tr>
<th>ICD-10 code</th>
<th>Frequency, weekday (%)</th>
<th>Diagnosis on readmission</th>
<th>ICD-10 code</th>
<th>Frequency, weekend (%)</th>
<th>Diagnosis on readmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>T814XXA</td>
<td>7.01</td>
<td>Infection following a procedure</td>
<td>T814XXA</td>
<td>7.52</td>
<td>Infection following a procedure</td>
</tr>
<tr>
<td>M4802</td>
<td>5.42</td>
<td>Spinal stenosis, cervical region</td>
<td>A419</td>
<td>6.15</td>
<td>Sepsis, unspecified organism</td>
</tr>
<tr>
<td>A419</td>
<td>4.54</td>
<td>Sepsis, unspecified organism</td>
<td>J189</td>
<td>2.78</td>
<td>Pneumonia, unspecified organism</td>
</tr>
<tr>
<td>M4712</td>
<td>3.22</td>
<td>Other spondylosis with myelopathy, cervical region</td>
<td>J690</td>
<td>2.61</td>
<td>Pneumonitis due to inhalation of food and vomit</td>
</tr>
<tr>
<td>I2699</td>
<td>2.03</td>
<td>Other pulmonary embolism without acute cor pulmonale</td>
<td>G8918</td>
<td>2.40</td>
<td>Other acute postprocedural pain</td>
</tr>
<tr>
<td>T8131XA</td>
<td>1.89</td>
<td>Disruption of external operation (surgical) wound, not elsewhere classified, initial encounter</td>
<td>I2699</td>
<td>2.18</td>
<td>Other pulmonary embolism without acute cor pulmonale</td>
</tr>
<tr>
<td>G8918</td>
<td>1.74</td>
<td>Other acute postprocedural pain</td>
<td>R1310</td>
<td>1.96</td>
<td>Dysphagia, unspecified</td>
</tr>
<tr>
<td>J189</td>
<td>1.68</td>
<td>Pneumonia, unspecified organism</td>
<td>T8131XA</td>
<td>1.85</td>
<td>Disruption of external operation (surgical) wound, not elsewhere classified, initial encounter</td>
</tr>
<tr>
<td>J690</td>
<td>1.48</td>
<td>Pneumonitis due to inhalation of food and vomit</td>
<td>N179</td>
<td>1.80</td>
<td>Acute kidney failure, unspecified</td>
</tr>
<tr>
<td>T8132XA</td>
<td>1.28</td>
<td>Disruption of internal operation (surgical) wound, not elsewhere classified, initial encounter</td>
<td>M96842</td>
<td>1.36</td>
<td>Postprocedural seroma of a musculoskeletal structure following a musculoskeletal system procedure</td>
</tr>
<tr>
<td>N179</td>
<td>1.28</td>
<td>Acute kidney failure, unspecified</td>
<td>G9782</td>
<td>1.31</td>
<td>Other postprocedural complications and disorders of nervous system</td>
</tr>
<tr>
<td>M4722</td>
<td>1.08</td>
<td>Other spondylosis with radiculopathy, cervical region</td>
<td>T8132XA</td>
<td>1.20</td>
<td>Disruption of internal operation (surgical) wound, not elsewhere classified, initial encounter</td>
</tr>
<tr>
<td>T84226A</td>
<td>1.08</td>
<td>Displacement of internal fixation device of vertebrae, initial encounter</td>
<td>N390</td>
<td>1.20</td>
<td>Urinary tract infection, site not specified</td>
</tr>
<tr>
<td>G9782</td>
<td>1.07</td>
<td>Other postprocedural complications and disorders of nervous system</td>
<td>L7632</td>
<td>1.03</td>
<td>Postprocedural hematoma of skin and subcutaneous tissue following other procedure</td>
</tr>
<tr>
<td>R1310</td>
<td>0.94</td>
<td>Dysphagia, unspecified</td>
<td>T8189XA</td>
<td>1.20</td>
<td>Other complications of procedures, not elsewhere classified, initial encounter</td>
</tr>
</tbody>
</table>

### Reasons for 90-day readmission

<table>
<thead>
<tr>
<th>ICD-10 code</th>
<th>Frequency, weekday (%)</th>
<th>Diagnosis on readmission</th>
<th>ICD-10 code</th>
<th>Frequency, weekend (%)</th>
<th>Diagnosis on readmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>M4802</td>
<td>6.09</td>
<td>Spinal stenosis, cervical region</td>
<td>A419</td>
<td>6.7</td>
<td>Sepsis, unspecified organism</td>
</tr>
<tr>
<td>T814XXA</td>
<td>4.77</td>
<td>Infection following a procedure</td>
<td>T814XXA</td>
<td>5.87</td>
<td>Infection following a procedure</td>
</tr>
<tr>
<td>A419</td>
<td>3.69</td>
<td>Sepsis, unspecified organism</td>
<td>J189</td>
<td>2.47</td>
<td>Pneumonia, unspecified organism</td>
</tr>
<tr>
<td>M4712</td>
<td>3.39</td>
<td>Other spondylosis with myelopathy, cervical region</td>
<td>J690</td>
<td>1.87</td>
<td>Pneumonitis due to inhalation of food and vomit</td>
</tr>
<tr>
<td>M4806</td>
<td>1.54</td>
<td>Spinal stenosis, lumbar region</td>
<td>N179</td>
<td>1.87</td>
<td>Acute kidney failure, unspecified</td>
</tr>
<tr>
<td>T84226A</td>
<td>1.46</td>
<td>Displacement of internal fixation device of vertebrae, initial encounter</td>
<td>I2699</td>
<td>1.63</td>
<td>Other pulmonary embolism without acute cor pulmonale</td>
</tr>
<tr>
<td>I2699</td>
<td>1.32</td>
<td>Other pulmonary embolism without acute cor pulmonale</td>
<td>T8131XA</td>
<td>1.47</td>
<td>Disruption of external operation (surgical) wound, not elsewhere classified, initial encounter</td>
</tr>
<tr>
<td>T8131XA</td>
<td>1.32</td>
<td>Disruption of external operation (surgical) wound, not elsewhere classified, initial encounter</td>
<td>G8918</td>
<td>1.6</td>
<td>Other acute postprocedural pain</td>
</tr>
</tbody>
</table>

(Continued)
Patients with weekend admission in our study utilized more Medicare/Medicaid insurance and fewer private insurance plans than patients with weekday admission. However, multivariate analysis did not reveal payor status to be associated with higher readmission rates. Our results add evidence to previous findings that payor status were insignificant risk factors in predicting 30-day readmission rates in posterior cervical fusion patients. However, our results also contradict previous findings that Medicaid status is independently associated with increased 30-day readmission after anterior cervical spine and other orthopedic procedures.

Thus, interactions between socioeconomic status and outcomes after spinal surgeries are complex and require analysis in future studies.

### 2. Readmission Rates

Significant differences in the adjusted multivariate analysis of 30- and 90-day readmission following ECSF of weekend and weekday admitted patients suggest that weekend admission is an independent predictor of readmission. To our knowledge, weekend admission has only been described as a risk factor for 30-day readmission in the context of posterior cervical spine surgery and thoracolumbar spine fusion.

A study using 2014 NRD data for ACDF subjects suggest payor status, NRD, co-morbidities, and LOS are significant predictors for readmission, but weekend admission was not found to be a risk factor for readmission rates. Other studies identify payor status and race, and all-cause complications, Medicaid insurance, hospital bed size, and age as predictors for high readmission rates. These papers did not consider day of the week of admission as a variable in their analysis. Though Neifert et al. found NHD and postdischarge complications to be independent predictors of readmission, they did not observe the reason for readmission in these cases. Rosenberg et al. identified DVT, infections, and nonroutine discharge to be risk factors for 30-day readmission in patients with index weekend admission for thoracolumbar fusion surgery. In our ECSF cohort, the most common diagnoses upon readmission are related to postprocedural pain, infections, and surgical site complications. This further highlights the importance of preoperative medical optimization and postoperative management, concerns that should be especially scrutinized for patients admitted and receiving surgery on weekends.

Utilizing a larger and more recent NRD sample size and controlling for baseline characteristics, we found that weekend status is an independent predictor of higher 30- and 90-day readmission rates, as compared to weekday status. Thus, this study clarifies weekend status as an important preoperative variable to decrease risk of readmissions after ECSF. Furthermore, our findings suggest complications, NHD, and longer LOS are also associated with an increased risk of readmission. We therefore pose that the interactions between various factors such as hospital resources, complications, and postoperative care including discharge and LOS, can contribute to increased risk of readmission in weekend index admission patients.

### 3. Complications

Moreover, our study analyzed complication rates to explain differences in readmission rates between weekday and weekend admissions. The weekend admissions group experienced higher all-cause complications than the weekday admissions group.
Weekend Admission on Readmission Risk After Cervical Fusion

Ren R, et al.

The weekend effect, in which patients admitted on the weekend have higher rates of complications and longer hospital stays, is well-documented in the medical literature. This phenomenon is thought to result from a variety of factors, including reduced staffing, decreased diagnostic capacity, and delayed access to medical care. In the case of cervical fusion surgery, the weekend admission cohort had an 8-fold higher incidence of postoperative infection rates compared to weekday admission patients. Previous studies did not necessarily find an association between complication rates such as infections and weekend admission. However, our study used a 2016-2018 national dataset to provide findings from a scoping national-level perspective that contributes to existing literature and highlights the need for further investigation. Future actions to mitigate postoperative wound complications leading to readmission includes rigorous methicillin-resistant Staphylococcus aureus screening, optimizing operating room air quality, and ensuring antibiotic compliance. Thus, definitively correcting such complications in the patient’s initial hospitalization prior to discharge can prevent negative clinical sequelae of those complications that may result in readmission. A study of hospital support services for critical care units found delays in blood culture incubation and processing during weekends, delaying diagnosis of sepsis and antibiotic prescriptions. These findings can potentially be applied to the patients in our study, where emphasis on clinical care factors such as addressing gaps in weekend staffing can help minimize complications and consequently decrease readmission rates in patients undergoing ECSF. Higher complications in weekend admitted patients may also be related to our finding that weekend patients had higher rates of discharge with HHC and SNFs. Malik et al. stated that discharge to inpatient-care facilities that provide higher levels of supervised care, compared to HHC, can ensure improved outcomes following lumbar fusion. Discharge to SNFs have been associated with higher rates of complications following spine surgery. Of note, our weekend admission cohort incurred higher costs, held more Medicare/Medicaid insurance types than weekday admissions, and SNFs have been found to account for approximately $31 billion of Medicare spending in 2012. Thus, decisions to discharge to costly nonhome care facilities should involve careful cost-benefit considerations. Success of home-discharge care and discharge to SNFs rely on careful patient selection, preoperative planning, and regular communication between home attendants and the patient’s physician care team. However, conclusions regarding discharge destination in reducing complications following weekend ECSF should involve further analysis beyond the scope of the present study.

4. LOS and Discharge Status

In our study, LOS is significantly increased in patients who were admitted on the weekend. Previous findings identified trauma and hospital acquired conditions as factors that increase complications and prolong LOS in weekend ECSF patients. However, analysis of the direct impact of weekend admission on LOS following ECSF has been minimally explored, so our findings provide significant insight. Patients admitted on the weekend were found to have increased rates of nonhome discharge (NHD), discharge with HHC, and discharge to a SNF, intermediate care facility (ICF), and other facilities. The correlation between LOS and NHD has been described as a result of lengthy precertification required for acceptance into a care facility and availability of beds. Thus, weekend admitted patients can also consider additional coordination with these facilities prior to surgery to minimize LOS and costs. Elsamadicy et al. found that patients with prolonged LOS following ACDF were more often discharged to locations other than home. However, our study is the first to provide a detailed description of discharge locations and its associations with weekend index admission, thereby raising awareness of the importance of improving NHD services, specifically SNFs, ICFs, and HHC. Previous literature have suggested that risk factors of NHD are largely nonmodifiable factors such as demographics and long term comorbidities. Additionally, NHD can lead to a significantly increased rate of severe adverse events and death following discharge. Therefore, in a population such as weekend admitted patients which is suggested to have increased risk of NHD, minimizing NHD when possible is critical. Because previous literature has suggested comorbidities as a risk factor of NHD, future studies looking into whether weekend admission independently leads to NHD after ECSF can help providers closely consider criteria to suggest NHD for weekday versus weekend admission patients.
5. Limitations and Further Steps

Our findings highlight that weekend surgery is an area of improvement that can decrease readmission rates after ECSF. Currently, solutions such as the redistribution of physical therapy services from weekday to weekend has served as a successful solution in improving these quality metrics and reducing cost per patient.9 However, more research is needed to elucidate methods to improve outcomes for patients undergoing weekend surgery.

Limitations in this study include the data source, because the NRD only longitudinally tracks 49.3% of hospitalizations,25 and incomplete data can bias results. However, inclusion of data from 2016–2018 would result in a sufficient sample size, and in general these findings shed light onto the importance of weekend admission on ECSF outcomes. A meta-analysis of studies regarding readmission rates and day of surgery could address discrepancies in the literature and compare results from studies that utilize different databases. Additionally, granular data such as the number of operating room staff and turnover rate are not tracked by the NRD. However, an institutional study found that the average number of operating room personnel was 10.0 for elective neurological procedures, and staff turnover was found to be significantly correlated with increased risk for surgical site infections and operation duration.39 Thus, future studies can investigate whether the number and turnover of personnel is a significant factor in increasing risks for readmission rates, cost, infections, NHD, and prolonged LOS following weekend ECSF. Surgical approach was not analyzed in this study as a potential factor influencing readmission rates. Posterior cervical spinal fusion patients have a higher 90-day readmission rate and different baseline demographics than patients undergoing an anterior approach.40 Thus, future studies that differentiate patients by surgical approaches can further elucidate the impact of weekend admissions on readmissions. Regardless, our paper is the first to confirm the weekend effect in patients undergoing ECSF, highlighting the significant clinical and financial benefits that can be achieved by improving care for weekend-admitted patients.

CONCLUSION

Understanding the impact of surgical operation day on postoperative outcomes is key to improving cost-effective care delivery and preoperative planning in ECSF. Our study is the first to define the association between the weekend effect and complications such as thromboembolic events and neurological complications. Thus, postoperative infections, neurological conditions, DVT, and pulmonary embolism are important risk factors that should be carefully monitored after surgery to help mitigate the risks of readmission. On the other hand, baseline patient characteristics are not predictive of readmission rates in weekend vs weekday admissions for ECSF. Our study underscores the fact that weekend elective surgery is a potential area of focus for quality improvement.

NOTES

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Pelvic Incidence–Lumbar Lordosis Mismatch Is Predisposed to Adjacent Segment Degeneration After Single-Level Anterior Lumbar Interbody Fusion: A Retrospective Case-Control Study

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Objective: Spinopelvic parameters play important roles in clinical outcomes and disability after short-segment fusion surgery for degenerative spine disease. This study aimed to investigate the relationship between preoperative or postoperative spinopelvic parameters and symptomatic adjacent segment degeneration (ASD) after single-level anterior lumbar interbody fusion (ALIF) surgery at the L4–5 segments.

Methods: All patients who underwent single-level ALIF at the L4–5 level from January 2010 to December 2013 and were followed up for 5 years were analyzed. We collected the degree of degeneration at adjacent segments and preoperative and postoperative spinopelvic parameters. We compared the preoperative and postoperative parameters between patients with and without symptomatic ASD.

Results: Sixty-one patients were included in our study, and 30 patients had symptomatic ASD. Degeneration at adjacent segments and preoperative spinopelvic parameters did not affect the occurrence of symptomatic ASD. Patients with symptomatic ASD had higher postoperative pelvic tilt (PT) and a mismatch between lumbar lordosis (LL) and pelvic incidence (PI) compared to those without. Postoperative PT > 15° and PI–LL mismatch > 10° were significant risk factors for symptomatic ASD.

Conclusion: High PT and PI–LL mismatch were significant risk factors for symptomatic ASD after single-level ALIF surgery. Spine surgeons should consider achieving proper LL to insert the cage at the appropriate angle and prevent a PI–LL mismatch value > 10° after single-level fusion surgery.

Keywords: Spinopelvic parameter, Single-level fusion, Adjacent segment disease

INTRODUCTION

Although the use of segmental motion-preserving spine surgery has increased recently, spinal fusion surgery still remains an important method of standard surgical treatments for degenerative spinal disease.¹ Improvements in the fusion rate and clinical outcome have been increasing because of the development of spinal instruments and bone grafts, such as demineralized bone matrix and bone morphogenetic protein.¹ However, an abnormal spinal biomechanical phenomenon occurs in adjacent segments and vertebral bodies, which accelerates the degeneration of the disc or facet joint at the adjacent segments.²
These changes in biomechanical forces are called adjacent segment disease (ASD). A recent systematic review article by Xia et al. reported that the rate of ASD after spinal interbody fusion ranged from 4.8% to 92.9%. According to previous articles, the risk factors of ASD after lumbar fusion surgery included age, sex, body mass index, preexisting disc degeneration, the degree of facet degeneration, number of fused levels, and lower lordotic curves of fused segments. Recent studies have highlighted the importance of spinopelvic parameters in the occurrence of ASD. Other studies showed that spinopelvic sagittal malalignment may contribute to the occurrence of ASD. However, most of these studies dealt with the relationship between spinopelvic parameters and ASD in posterior approach spinal fusion surgery, such as posterior lumbar interbody fusion (PLIF) and transforaminal lumbar interbody fusion (TLIF), at various vertebral levels.

The present study aimed to reveal the relationship between spinopelvic parameters and ASD after single-level anterior lumbar interbody fusion (ALIF) surgery. Our study only included patients with degenerative spinal disease at the L4–5 level who underwent single-level ALIF surgery to exclude other variables.

**MATERIALS AND METHODS**

1. **Ethics Statements**
   The study design was approved by the Institutional Review Board (IRB) of Busan Wooridul Spine Hospital (IRB No. WRDIRB-2019-07-007) in September 2019, and written informed consent was obtained from all the participants.

2. **Study Design and Population**
   We performed this retrospective case-control study to analyze the relationship between spinopelvic parameters and the occurrence of ASD after single-level ALIF surgery. We reviewed the medical records and radiologic examinations of all patients who underwent elective single-level ALIF performed by HCL from January 2010 to December 2013. The inclusion criteria were as follows: (1) single-level ALIF at the L4–5 level, (2) follow-up over 5 years, (3) fusion for degenerative lumbar disease, and (4) radiologic examination performed 5 years after the operation. Patients were excluded if they had scoliosis (Cobb angle > 20°) or underwent surgery for trauma or infection.

3. **Patient Grouping**
   Patients were divided into an ASD group or a control group.

The ASD group was defined as those who met the following 3 criteria: (1) newly developed lower back pain, claudication, and radiating pain 6 months after the symptoms were relieved after the previous operation, (2) newly developed instability (spondylolisthesis or dynamic instability with slippage more than 4 mm and/or angle change more than 10 degrees on flexion and extension) of adjacent segments, (3) the patients who underwent additional surgery in the adjacent segments.

4. **Radiologic Evaluation**
   Our study analyzed the known risk factors for ASD (age, body mass index, osteoporosis, preoperative facet, and disc degeneration, coronal wedge, vacuum disc, and spondylolisthesis). The preoperative degree of adjacent disc degeneration on magnetic resonance imaging was classified according to the Pfirrmann et al. grading system, and facet joint degeneration on computed tomography (CT) was rated from grade 0 to grade 3 using Weishaupt classification system. A positive coronal wedge was defined as > 5° of tilt between the inferior margin of the upper vertebral body and the superior bone margin at the lower vertebral body. The presence of air in the adjacent segmental disc on the CT scan was defined as a vacuum disc. Spondylolisthesis was defined as > 3 mm anterior or posterior vertebral slip on standing lateral radiographs.

   Simple plain radiography films of the lumbar spine, including the femoral head, were obtained for all patients before and after surgery. We measured the composition of spinopelvic parameters, including the pelvic incidence (PI), sacral slope (SS), pelvic tilt (PT), lumbar lordosis (LL), segmental lordosis, and disc height at the L4–5 level in all patients before and after surgery. We calculated the difference between PI and LL (PILL = PI–LL) and the height at the operative level on the preoperative and postoperative films. To evaluate the lumbar sagittal alignment according to the reciprocal uppermost lumbar vertebral position change in the sagittal plane after single-level fusion of the L4/5 level, we used the L1 axis S1 distance, which is the distance from the L1 plumb line to the posterior corner of the first sacral body, in all patients before and after surgery.

5. **Statistical Analysis**
   The demographic and radiologic factors regarding the risks of ASD were compared between the 2 groups and within the groups using the Student t-test for continuous values and the chi-square test for categorized values. All statistical analyses were performed using SPSS ver. 12.0 (SPSS Inc., Chicago, IL, USA). Statistical significance was set at p < 0.05.
Table 1. Baseline characteristics and preexisting degenerative pathologies

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>ASD (n = 30)</th>
<th>Non-ASD (n = 31)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex</td>
<td></td>
<td></td>
<td>0.934</td>
</tr>
<tr>
<td>Male</td>
<td>9 (30)</td>
<td>9 (29)</td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>21 (70)</td>
<td>22 (71)</td>
<td></td>
</tr>
<tr>
<td>Age (yr)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>59.6 ± 8.5</td>
<td>63.2 ± 8.1</td>
<td>0.091</td>
</tr>
<tr>
<td>Range (IQR)</td>
<td>54.3–66.0</td>
<td>55.0–70.0</td>
<td></td>
</tr>
<tr>
<td>BMI</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>24.0 ± 3.8</td>
<td>23.9 ± 2.3</td>
<td>0.868</td>
</tr>
<tr>
<td>Range (IQR)</td>
<td>22.6–25.6</td>
<td>21.9–25.0</td>
<td></td>
</tr>
<tr>
<td>Follow-up</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>68.5 ± 11.1</td>
<td>71.8 ± 12.0</td>
<td>0.264</td>
</tr>
<tr>
<td>Range (IQR)</td>
<td>59.0–75.3</td>
<td>62.0–81.0</td>
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</tr>
<tr>
<td>Smoking</td>
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<td></td>
<td>&gt; 0.999</td>
</tr>
<tr>
<td>Post decompression</td>
<td>3 (10.0)</td>
<td>4 (12.9)</td>
<td></td>
</tr>
<tr>
<td>Disease (index level)</td>
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<td>0.161</td>
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<tr>
<td>DS</td>
<td>20 (66.7)</td>
<td>24 (77.4)</td>
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</tr>
<tr>
<td>FS</td>
<td>7 (23.3)</td>
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<td>CS</td>
<td>2 (6.7)</td>
<td>4 (12.9)</td>
<td></td>
</tr>
<tr>
<td>DH</td>
<td>1 (3.8)</td>
<td>0 (0)</td>
<td></td>
</tr>
<tr>
<td>Disease (adjacent level)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>L3–4 segment</td>
<td>n = 13</td>
<td>n = 48</td>
<td>0.238</td>
</tr>
<tr>
<td>Disc degeneration*</td>
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</tr>
<tr>
<td>Grade 2</td>
<td>1 (7.7)</td>
<td>2 (4.2)</td>
<td></td>
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<tr>
<td>Grade 3</td>
<td>2 (15.4)</td>
<td>20 (61.7)</td>
<td></td>
</tr>
<tr>
<td>Grade 4</td>
<td>10 (76.9)</td>
<td>25 (52.1)</td>
<td></td>
</tr>
<tr>
<td>Grade 5</td>
<td>0 (0)</td>
<td>1 (2.1)</td>
<td></td>
</tr>
<tr>
<td>Facet degeneration†</td>
<td></td>
<td></td>
<td>0.290</td>
</tr>
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<td>Grade 0</td>
<td>3 (23.1)</td>
<td>22 (45.8)</td>
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</tr>
<tr>
<td>Grade 1</td>
<td>7 (53.8)</td>
<td>21 (43.8)</td>
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<tr>
<td>Grade 2</td>
<td>2 (15.4)</td>
<td>3 (6.3)</td>
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</tr>
<tr>
<td>Grade 3</td>
<td>1 (7.7)</td>
<td>2 (4.2)</td>
<td></td>
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<tr>
<td>Vacuum disc</td>
<td>4 (30.8)</td>
<td>12 (25.0)</td>
<td>0.728</td>
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<tr>
<td>Wedge deformity‡</td>
<td>1 (7.7)</td>
<td>6 (12.5)</td>
<td>0.999</td>
</tr>
<tr>
<td>Spondylolisthesis§</td>
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</tr>
<tr>
<td>Anterior</td>
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<td>1 (2.1)</td>
<td></td>
</tr>
<tr>
<td>Retro</td>
<td>3 (23.1)</td>
<td>8 (16.7)</td>
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<tr>
<td>L5-S1 segment</td>
<td>n = 21</td>
<td>n = 40</td>
<td>0.709</td>
</tr>
<tr>
<td>Disc degeneration*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grade 2</td>
<td>2 (9.5)</td>
<td>9 (7.5)</td>
<td></td>
</tr>
<tr>
<td>Grade 3</td>
<td>4 (19.0)</td>
<td>12 (30.0)</td>
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</tr>
<tr>
<td>Grade 4</td>
<td>14 (66.7)</td>
<td>21 (52.5)</td>
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<tr>
<td>Grade 5</td>
<td>1 (4.8)</td>
<td>4 (10.0)</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Baseline characteristics and preexisting degenerative pathologies (Continued)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>ASD (n = 30)</th>
<th>Non-ASD (n = 31)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disc degeneration*</td>
<td></td>
<td></td>
<td>0.547</td>
</tr>
<tr>
<td>Grade 0</td>
<td>11 (52.4)</td>
<td>21 (52.5)</td>
<td></td>
</tr>
<tr>
<td>Grade 1</td>
<td>9 (42.9)</td>
<td>17 (42.5)</td>
<td></td>
</tr>
<tr>
<td>Grade 2</td>
<td>0 (0)</td>
<td>2 (5.0)</td>
<td></td>
</tr>
<tr>
<td>Grade 3</td>
<td>1 (4.8)</td>
<td>0 (0)</td>
<td></td>
</tr>
<tr>
<td>Vacuum disc</td>
<td>12 (57.1)</td>
<td>14 (35.5)</td>
<td>0.097</td>
</tr>
<tr>
<td>Wedge deformity‡</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>&gt; 0.999</td>
</tr>
<tr>
<td>Spondylolisthesis§</td>
<td></td>
<td></td>
<td>0.533</td>
</tr>
<tr>
<td>Anterior</td>
<td>1 (4.8)</td>
<td>0 (0)</td>
<td></td>
</tr>
<tr>
<td>Retro</td>
<td>1 (4.8)</td>
<td>3 (7.5)</td>
<td></td>
</tr>
</tbody>
</table>

Values are presented as number (%) unless otherwise indicated. ASD, adjacent segment disease; SD, standard deviation; IQR, interquartile range; BMI, body mass index; DS, degenerative spondylolisthesis; FS, foraminal stenosis; CS, central spinal stenosis; DH, lumbar disc herniation.

Chi-square test and Student t-test were used for statistical analysis. *Disc degeneration was graded according to the Pfirrmann grading system. †Facet degeneration was graded according to the Weishaupt classification system. ‡Wedge deformity was defined as > 5° of tilt between the inferior margin of the upper vertebral body and the superior bone margin at the lower vertebral body in the coronal radiograph. §Spondylolisthesis was defined as > 3 mm anterior or posterior vertebral slip on standing lateral radiographs.

RESULTS

Of the 61 patients enrolled in our study, 43 patients had degenerative spondylolisthesis, 11 patients had foraminal stenosis, 6 patients had central spinal stenosis, and 1 patient had lumbar disc herniation. Mean patient ages at the time of operation were 61.42 ± 8.44 years (range, 45–77 years). The mean follow-up period was 70.16 ± 11.59 months (range, 60–101 months). Thirty patients were classified into the ASD group according to our criteria. In the ASD group, 13 patients had ASD at the L3–4 segment, and the remaining patients had ASD below that level. Demographic characteristics did not differ between the groups.

There were no significant differences in the grade of the adjacent facet joint and disc degeneration, frequency of vacuum discs, wedge deformity, spondylolisthesis, and retrolisthesis between the groups (Table 1).

In the ASD group, LL, the segmental angle, and disc height at the fused level and PI–LL mismatch were significantly improved after surgery. In the non-ASD group, LL, the fused segmental angle, disc height, and PI–LL mismatch improved similarly. The PT and L1 sagittal vertical axis decreased while the SS
increased after fusion in the non-ASD group (Table 2).

There were no significant differences in the preoperative parameters between the groups. The segmental angle at the L4–5 disc level was higher in the ASD group than in the non-ASD group (4.06 ± 3.96 and 1.52 ± 5.89, respectively; \( p = 0.060 \)), but the difference was not statistically significant.

Regarding the postoperative radiologic parameters, the PT was higher (21.10 ± 10.80 vs. 14.94 ± 8.76, \( p = 0.017 \)) and the incidence of PT > 15° was higher in the ASD group than in the non-ASD group (22 patients [73.3%] vs. 14 patients [45.2%], \( p = 0.037 \)). The postoperative values of LL and PI were not different between the groups. However, the PI–LL mismatch was higher in the ASD group than in the non-ASD group (10.36 ± 16.12 vs. 3.94 ± 10.37, \( p = 0.006 \)), and the incidence of PI–LL mismatch > 10° was significantly higher in the ASD group than in the non-ASD group (21 patients [70.0%] vs. 9 patients [29.0%], \( p = 0.002 \)) (Table 3).

**DISCUSSION**

We investigated the risk factors for ASD after single-level ALIF surgery. The results of our study revealed 2 factors, one was high postoperative PT and the other was a large mismatch between LL and PI. ASD is the most significant complication

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**Table 2. Preoperative and postoperative spinopelvic parameters in ASD and non-ASD groups**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Preoperative ASD (n = 30)</th>
<th>Preoperative Non-ASD (n = 31)</th>
<th>Postoperative ASD (n = 30)</th>
<th>Postoperative Non-ASD (n = 31)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvic incidence (PI)</td>
<td>55.34 ± 11.85</td>
<td>55.33 ± 11.85</td>
<td>52.56 ± 11.25</td>
<td>52.64 ± 11.26</td>
<td>0.999</td>
</tr>
<tr>
<td>Pelvic tilt</td>
<td>22.16 ± 10.14</td>
<td>21.10 ± 10.80</td>
<td>19.04 ± 8.76</td>
<td>14.94 ± 8.76</td>
<td>0.294</td>
</tr>
<tr>
<td>Sacral slope</td>
<td>33.16 ± 9.38</td>
<td>34.23 ± 7.82</td>
<td>33.51 ± 8.99</td>
<td>37.61 ± 7.68</td>
<td>0.999</td>
</tr>
<tr>
<td>Lumbar lordosis (LL)</td>
<td>40.63 ± 15.30</td>
<td>44.96 ± 12.08</td>
<td>39.67 ± 14.45</td>
<td>48.61 ± 10.20</td>
<td>0.039</td>
</tr>
<tr>
<td>Segmental angle</td>
<td>4.06 ± 3.96</td>
<td>10.78 ± 3.21</td>
<td>1.52 ± 5.89</td>
<td>10.62 ± 3.27</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>L1 SVA (mm)</td>
<td>24.86 ± 21.84</td>
<td>18.30 ± 22.49</td>
<td>27.90 ± 24.57</td>
<td>18.88 ± 17.76</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Disc height (mm)</td>
<td>8.58 ± 2.55</td>
<td>13.98 ± 1.85</td>
<td>7.74 ± 2.57</td>
<td>13.48 ± 1.60</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>

Values are presented as mean ± standard deviation. ASD, adjacent segment disease; SVA, sagittal vertical axis. Student t-test were used for statistical analysis. *\( p < 0.05 \), statistically significant difference.

**Table 3. Differences of spinopelvic parameters between ASD and non-ASD groups**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Preoperative ASD (n = 30)</th>
<th>Preoperative Non-ASD (n = 31)</th>
<th>Postoperative ASD (n = 30)</th>
<th>Postoperative Non-ASD (n = 31)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvic incidence (PI)</td>
<td>55.34 ± 11.85</td>
<td>52.56 ± 11.25</td>
<td>55.33 ± 11.85</td>
<td>52.64 ± 11.26</td>
<td>0.353</td>
</tr>
<tr>
<td>Pelvic tilt</td>
<td>22.16 ± 10.14</td>
<td>19.04 ± 8.76</td>
<td>21.10 ± 10.80</td>
<td>14.94 ± 8.76</td>
<td>0.203</td>
</tr>
<tr>
<td>PT &gt; 15</td>
<td>22 (73.3)</td>
<td>22 (71.0)</td>
<td>22 (73.3)</td>
<td>14 (45.2)</td>
<td>0.999</td>
</tr>
<tr>
<td>Sacral slope</td>
<td>33.16 ± 9.38</td>
<td>33.51 ± 8.99</td>
<td>34.23 ± 7.82</td>
<td>37.61 ± 7.68</td>
<td>0.882</td>
</tr>
<tr>
<td>Lumbar lordosis (LL)</td>
<td>40.63 ± 15.30</td>
<td>39.67 ± 14.45</td>
<td>44.96 ± 12.08</td>
<td>48.61 ± 10.20</td>
<td>0.801</td>
</tr>
<tr>
<td>Segmental angle</td>
<td>4.06 ± 3.96</td>
<td>1.52 ± 5.89</td>
<td>10.78 ± 3.21</td>
<td>10.62 ± 3.27</td>
<td>0.638</td>
</tr>
<tr>
<td>PI–LL &gt; 10</td>
<td>22 (73.3)</td>
<td>22 (74.2)</td>
<td>21 (70.0)</td>
<td>9 (29.0)</td>
<td>0.002</td>
</tr>
<tr>
<td>L1 SVA (mm)</td>
<td>24.86 ± 21.84</td>
<td>27.90 ± 24.57</td>
<td>18.30 ± 22.49</td>
<td>18.88 ± 17.76</td>
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<tr>
<td>Disc height (mm)</td>
<td>8.58 ± 2.55</td>
<td>7.74 ± 2.57</td>
<td>13.98 ± 1.85</td>
<td>13.48 ± 1.60</td>
<td>0.205</td>
</tr>
</tbody>
</table>

Values are presented as mean ± standard deviation or number (%). ASD, adjacent segment disease; SVA, sagittal vertical axis. Chi-square test and Student t-test were used for statistical analysis. *\( p < 0.05 \), statistically significant difference.
affecting the long-term outcome after lumbar fusion. The incidence of ASD after lumbar fusion has been investigated in many studies. Sears et al. reported that the incidence of ASD requiring reoperation after lumbar fusion was 22.2%, and the prevalence per year was 2.5% over 10 years. In Ghiselli et al.'s study, the incidence of ASD after lumbar surgery was 36.1% at 10 years postoperatively, the 27.4% of patients who underwent lumbar surgery required reoperation at adjacent segments. In our study, the incidence of symptomatic ASD was 49.1%, and the rate of reoperation was 21.3%. It is controversial whether the presence of degenerative discs in adjacent segments has an effect on increasing the incidence of ASD. Edwards et al. reported that degeneration of the adjacent segment was a risk factor for the occurrence of ASD in 34 patients who underwent thoracolumbar fusion and were followed up for an average of 5.6 years. However, many other authors reported that the degeneration of adjacent segments did not affect the incidence of ASD. In particular, Ghiselli et al., who included 215 patients who underwent a revision surgery at adjacent segments after lumbar fusion, found no relationship between the occurrence of ASD and adjacent segment degeneration. In our study, degeneration at the adjacent disc level did not affect the incidence of ASD. The effect of preoperative facet degeneration on ASD is also controversial. Two articles reported that the presence of facet arthropathy at the adjacent segment affected the occurrence of ASD. In contrast, Kaito et al. reported that facet degeneration did not affect the occurrence of ASD. Our study showed that facet degeneration had no effect on the occurrence of ASD. Therefore, further studies are needed to identify the effect of facet degeneration at the adjacent level on the occurrence of ASD. Some studies have reported that mismatches in sagittal spinopelvic parameters play important roles in the occurrence of postoperative ASD after lumbar fusion surgery.

Kumar et al. revealed that an abnormal C7 costovertebral angle preoperatively and SS play significant roles in the occurrence of ASD after lumbar fusion. Other articles reported that preoperative PT > 20° and SS < 40° affected the incidence of ASD. Matsumoto et al. reported that a low LL and high PT preoperatively were important risk factors for the high incidence of ASD after single-level PLIF surgery. In contrast, our study showed that preoperative spinopelvic parameters were not associated with the incidence of symptomatic ASD after single-level ALIF surgery. Therefore, we believe that the effects of preoperative abnormal spinopelvic parameters on postoperative ASD need to be investigated in high-quality studies.

Many studies have investigated the relationship between ASD and LL or PI. Djurasovic et al. reported that patients with less LL had more ASD after lumbar fusion. Nakashima et al. revealed that a low PI was a significant risk factor for developing ASD after fusion. However, these studies did not suggest ideal LL and PI because these ideal values are individual, making them difficult to determine. In our study, preoperative or postoperative LL and PI did not affect ASD development after single-level ALIF surgery. Some studies have reported that the balance between PI and LL affects the incidence of ASD. The balance between LL and PI has been used in adult spinal deformity surgeries, and the mismatch between LL and PI was correlated with disability and low patient-reported outcome measures. A study by Senteler et al. used biomechanical models reported that the mismatch between LL and PI had a tendency to increase segmental axial loadings in unfused and fused lumbar spines. The first study about the effect of PI–LL mismatch on ASD was reported by Rothenfluh et al. This study included patients who underwent lumbar fusion surgery from 1 to 3 segments and reported that a higher mismatch between PI and LL had more effects on the occurrence of ASD. Matsumoto et al. included only single-level PLIF surgery and reported that spinopelvic imbalance (PI–LL mismatch ≥ 10°) was the most important risk factor for ASD. Tempel et al. suggested that a high PI–LL mismatch had a meaningful relationship with the development of symptomatic ASD in single-level TLIF surgery. They proposed that the positive cutoff value for the development of symptomatic ASD was PI–LL mismatch > 11°. In our study, the postoperative mismatch between PI and LL was a significant risk factor for symptomatic ASD after single-level ALIF surgery. Our cutoff value of postoperative PI–LL mismatch for symptomatic ASD was > 10°. The association between LL and PI mismatch and ASD occurrence is thought to be influenced by the following. The mismatch between PI and LL after single-level ALIF is caused by the insufficient restoration of LL. In this situation, the L1 SVA increases as the proximal lumbar spine move to the ventral side from the sagittal view of the lumbar spine. As the L1 SVA increases, the loading axis of the lumbar spine leans forward, increasing the ventral bending force throughout the lumbar spine. Due to the increased ventral bending force, the segmental axial loading of the adjacent segment is further increased and the tensile force on the posterior element is increased, which can promote degenerative changes of the disc and facet of the adjacent segment (Fig. 1). As a retrospective study, our study has limitations. We believe that the high incidence of ASD in our study was due to a selection bias. There is a possibility that patients with good

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outcomes after surgery did not visit the hospital anymore, which may cause selection bias. One hundred ten patients underwent ALIF surgery at the L4–5 level from January 2010 to December 2013, but only 61 patients (55.4%) were followed up for more than 5 years. Second, the PI values of patients are widely distributed, and the characteristics of the correlation with LL or PT may differ depending on the range of PI values. But in our study, additional research could not be conducted due to the small number of the patients. If analysis according to this PI distribution is added in the future, more clear results could be derived. Various methods are tried to prevent ASD. When performing long-segment fusion, a hook is used in the most proximal or distal transverse process or lamina, and there is also an attempt to use an additional polyetheretherketone rod in the upper instrumented vertebra. However, not only the use of these additional instruments but also obtaining an appropriate spinopelvic parameter, as shown in the studies mentioned above, is important for postoperative disability and quality of life after spinal fusion surgery. In degenerative spinal disease, the spinal surgeon should consider the patient’s symptoms, neurological examination findings, and correlative radiologic examination results when performing surgery or choosing the method of operation. If the surgeon chooses fusion surgery, the patient’s spinopelvic parameters and sagittal alignment should be considered. In particular, the segmental angle of the cage was the only parameter that affected postoperative LL, and the surgeon at our hospital selected an adequate angle for cage insertion to avoid a mismatch between the PI and LL.

### CONCLUSION

This study investigated the association between symptomatic ASD after single-level ALIF surgery and spinopelvic parameters. Preoperative spinopelvic parameters did not affect the development of symptomatic ASD. Postoperative high PT and PI–LL mismatch were significant risk factors for symptomatic ASD after single-level ALIF surgery. The results of this study suggest that PI–LL mismatch should be avoided by achieving a proper LL even when performing single-level fusion.

### NOTES

**Conflict of Interest:** The authors have nothing to disclose.

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**Author Contribution:** Conceptualization: SML; Data curation: HCL, SML; Formal analysis: SGY; Methodology: SGY; Project administration: SML; Writing - original draft: SGY; Writing - review & editing: HCL.

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### REFERENCES

Comparison of Cortical Bone Trajectory to Pedicle-Based Dynamic Stabilization: An Analysis of 291 Patients

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Objective: Pedicle-based dynamic stabilization (DS) has gained popularity outside of America. Although pedicle screw (PS) loosening has always been a concern, it is reportedly innocuous. Cortical bone trajectory (CBT) screw is an emerging option with less invasiveness and similar effectiveness to PS in short-segment lumbar fusion. This study aimed to verify the use of CBT for DS by comparing the outcomes between pedicle- and CBT-based DS.

Methods: Consecutive patients with lumbar spondylosis or low-grade spondylolisthesis who underwent 1- or 2-level DS between L3–5 with a minimum follow-up of 24 months were reviewed. Screw loosening was determined by computed tomography and the incidences were compared.

Results: A total of 291 patients who underwent Dynesys DS (235 pedicle- and 56 CBT-based, respectively) were compared. The demographics and preoperative conditions were similar. All the clinical outcomes improved at 24-month postoperation, while the CBT-based group had less operation time and blood loss than the pedicle-based group. The rates of screw loosening were lower in the CBT-based (5.4% per screw and 12.5% per patient) than the pedicle-based group (9% per screw and 26.4% per patient). Furthermore, there were no differences in the clinical outcomes and complication profiles.

Conclusion: The CBT-based DS for 1- or 2-level lumbar degeneration demonstrated equivalent clinical improvement as the pedicle-based DS. The adoption of CBT-based screws for DS could be a less invasive approach (shorter operation time and less blood loss), with lower chances of screw loosening than the conventional PS-based DS.

Keywords: Pedicle screw-based, Dynamic stabilization, Screw loosening, Cortical bone trajectory

INTRODUCTION

Although lumbar fusion remains a standard surgical option for instability caused by spondylosis or spondylolisthesis, spinal arthrodesis inevitably would raise the concern of decreased segmental mobility and subsequent risks of adjacent segment disease (ASD). Therefore, there has been the emerging technology of dynamic stabilization (DS) as an alternative management, which has aimed at preservation of the segmental motion and mitigation of the risks of ASD.1–15 In the past decade, reports have demonstrated satisfactory outcomes, including clinical improvements, low complication rates, and potential of motion preservation in the management of lumbar degenerative diseases of short-segments.5,7,9,16,17 However, there are also adverse events reported with DS, including pedicle screw (PS) loosening and unintended facet arthrodesis.18–21
In the nonfusion construct of DS, which theoretically under long-term and repeated mechanical load, the PS reasonably may be subject to loosening or fatigue at the metal-to-bone interface. In the literature regarding DS, the reported incidences of PS loosening varied among the series, ranging from 7% to 20%. Interestingly, the PS loosening of DS is usually associated with little adverse clinical outcomes, and some of the recent series have attributed this to the unintended facet fusion after DS. Furthermore, it is unclear whether the dynamic motility of lumbar segments after instrumentation is maintained for long or they are fused slowly.

The recent innovation of cortical bone trajectory (CBT) screws, first reported in 2009 as an alternative to traditional PS, assume a medial-to-lateral and caudal-to-cephalad direction to engage the dense cortical bone of pars interarticularis, pedicle, and lateral wall of the vertebrae (Fig. 1). The adaption of CBT has demonstrated feasibility and effectiveness in short-segment lumbar fusion surgery. According to biomechanical studies, the CBT had up to a 30% increase of pullout strength compared to the conventional pedicle trajectory. Since CBT potentially improves bone-to-screw osteointegration and reinforces the screw purchase to decrease screw loosening or breakage, it might be a reasonable innovation to adapt CBT for DS in the management of lumbar instability. Moreover, CBT screws require less muscle dissection than the conventional PS, because the medial-to-lateral directions of CBT spare the need for exposure of the transverse-process-facet junction. Less extensive dissection of the soft tissues for CBT may also merit the rationale of motion preservation in DS. The authors have previously reported the safety and feasibility of CBT-based DS.

In this study, an attempt was made to compare the innovative CBT-based DS to standard pedicle-based DS. Clinical and radiological evaluations, including screw loosening, over more than 2 years of follow-up are demonstrated.

**MATERIALS AND METHODS**

1. **Study Design and Patient Inclusion**

   This was a single center, retrospective comparison study that included consecutive patients with degenerative disease between L3 to L5 who underwent DS. The DS was indicated in patients who had degenerative spondylosis included symptomatic lumbar spinal stenosis without instability, recurrent disc herniation with or without previous discectomy, degenerative disc disease with discogenic pain, intractable radicular pain, back pain, or neurologic claudication that were refractory to conservative treatment for more than 4 months. The DS was also indicated in patients who had spondylolisthesis no more than Meyerding grade I (percentage of vertebrae slip between 0% to 25%). Exclusion criteria were patients who did not complete the 24-month follow-up, had involved levels of disease other than at L3-4-5, spondylolisthesis more than Meyerding grade I, lytic spondylolisthesis, or thoracolumbar deformity indicated by screening standing radiographs. All methods were carried out in accordance with STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) guidelines and regulations. The study protocol had been approved by the Institutional Review Board (IRB) of Taipei Veterans General Hospital (IRB No. 2019-12-001AC) and informed consent from each patient was obtained.

   All patients used the same system of instrumentation, Dynesys DS (Zimmer Biomet, Warsaw, IN, USA) featured with screws, polycarbonate urethan spacers, and polyester cords to achieve DS. Since mid-2017, all patients who underwent DS adopted the CBT screws in the authors’ service and were compared to previous patients who used the PS in DS. Thus, patients were grouped into two: the PS-based and the CBT-based groups by the timing of surgery. All the perioperative management and follow-ups were constant in the series.
2. Surgical Technique

1) Decompression

After general anesthesia, patients were put in a prone position on the Wilson frame with neutral lumbar lordosis. A midline incision was made and deepened for subperiosteal muscular dissection. The lamina was removed as well as the thickened ligamentum flavum. The medial part of the facet joints was removed up to the pedicles to decompres the lateral recess. If needed, foraminotomy was performed by removing bone spur and flavum ligament with curette and Kerrison rongeur to enlarge the foramen. Nerve roots were palpated along the exiting path with a Woodson dissector to ensure adequate decompression of the neuroforamen. Typically, the surgery required no discectomy since the lateral recesses were always decompressed thoroughly. However, removal of sequestrated disc fragments was performed on those patients who had ruptured intervertebral discs. Care was taken to avoid violation of the facets more than the medial-third.

2) Pedicle-based DS

From the midline wound, bilateral fascia dissections were then made for entering the intermuscular plane (Wiltse plane) under the guidance of intraoperative fluoroscopy. The Dynesys screws were placed in a transpedicular trajectory via the insertion point at the base of the transverse process without additional facet destruction. The length and diameter of the screws were determined by preoperative computed tomography (CT) scans and confirmed intraoperatively. The diameter of the most commonly used screws in pedicle-based DS was 6.4 mm. The polycarbonate urethan spacers were tailored for only slight distraction of the facet joints. The spacers were then inserted together with the polyester cord, following the standard procedures.3,4,12,20 (Fig. 2. Please see https://sketchfab.com/TaroYen/models for interactive 3-dimensional images and an enhanced version of Fig. 2).

3) CBT-based DS

The entry points of the CBT screws were generally over the cephalad lateral part of the pars interarticularis, slightly caudal to the sulcus of the facet complex. A high-speed drill was used to break through the cortex. The trajectory was confirmed by intraoperative fluoroscopy, which allowed the screw to course through the dense cortical bone with the screw tip barely penetrating the cortex of the vertebral body laterally. According to biomechanical studies, the proper size of CBT screws was 5.0 to 5.5 mm in diameter and 35 to 40 mm in length.32 Therefore, the most commonly used screws were 5.2 mm × 35 mm in CBT-based DS. A 5.2-mm cannulated tap was used to create the screw tract. The Dynesys screws were subsequently placed. The polycarbonate urethan spacer and polyethylene-terephthalate cord were subsequently assembled31 (Fig. 2).

4) Clinical evaluation

The clinical data were prospectively collected and retrospectively reviewed. Clinical outcomes, including visual analogue scale (VAS) for back and leg pain and the Oswestry Disability Index (ODI) scores, were assessed pre-operatively and at 6 weeks and at 3, 6, 12, 18, and 24 months postoperatively.

5) Radiographical evaluation

Every patient underwent preoperative lumbar images, including anteroposterior and lateral radiography, lateral dynamic radiography, magnetic resonance imaging and CT scans. Fol-
low-up images included standard anteroposterior, lateral and flexion-extension radiography immediately postoperative, and at 6 weeks, and at 3, 6, 12, 18, and 24 months after surgery. An initial halo sign (a radiolucent line around the implant > 1 mm wide) followed by a double halo sign on anteroposterior radiographs or CT scans was defined as screw loosening. The measurement was performed using quantitative measurement analysis software (SmartIris, Taiwan Electronic Data Processing Co.) For any ambiguity, the CT scan was reviewed with radiologists for the final determination of a halo sign.

3. Statistics
Medcalc (Ostend, Belgium) was used for statistical analysis. Descriptive statistics were reported as means and standard deviations, and as frequencies and percentages where appropriate. Continuous variables were compared using an unpaired Student t-test, and categorical variables were compared using Pearson chi-square test. Probability values were 2-tailed and an alpha of 0.05 was considered statistically significant.

RESULTS

1. Demographics
A total of 291 consecutive patients were included in this study. The first 235 patients received pedicle-based DS and the later 56 patients underwent CBT-based DS. The mean age was 61.7 ± 10.9 versus 62.5 ± 10.4, p = 0.61. There were 117 male patients (49.7%) in the pedicle-based group compared to 27 (48.2%) in the CBT-based group (p = 0.83). Medical comorbidities were similar between the 2 groups, as the incidence rates of hypertension and diabetes mellitus were similar (42.6% vs. 37.5% and 21.7% vs. 16.1%, p = 0.49 and 0.35, respectively) in both groups. There was no difference in the body mass index (BMI) between the 2 groups (25.8 ± 3.8 kg/m² vs. 25.7 ± 2.4 kg/m², p = 0.92). The pathologies and distribution of levels were also similar in both groups (p = 0.82 and 0.87, respectively). The pedicle-based group had an average longer follow-up than the CBT-based group (61.8 ± 34.9 months vs. 31.2 ± 6.1 months, p < 0.001) (Table 1).

2. Perioperative Parameters and Clinical Improvement
In this study, patients of the CBT-based group used significantly less operation time for both 1-level and 2-level surgery (163.2 ± 26.6 minutes vs. 196.9 ± 62.1 minutes, p = 0.005 and 227.1 ± 43.1 minutes vs. 257.7 ± 75.3 minutes, p = 0.04, respectively) than the pedicle-based group. The CBT-based group also had significantly less blood loss for 1-level and 2-level surgery (173.2 ± 157.2 mL vs. 399.1 ± 303.3 mL, p < 0.001 and 353.7 ± 248.8 mL vs. 816.8 ± 463.7 mL, p < 0.001, respectively) than the pedicle-based group (Table 2).

Both groups demonstrated significant improvement in VAS for back and leg pain, and ODI scores. Moreover, both groups demonstrated similar scores in VAS for back pain (2.3 ± 2.5 vs. 2.2 ± 2.5, p = 0.88), VAS for leg pain (2.1 ± 2.7 vs. 2.5 ± 2.5, p = 0.62), and ODI scores (19.6 ± 17.3 vs. 15.5 ± 10.8%, p = 0.43) at the final follow-up, 24 months after surgery (Fig. 4).

3. Screw Loosening, Fracture, and Other Complications
There was no breach of the screws that caused symptoms or

Table 1. Demographics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Pedicle-based DS</th>
<th>CBT-based DS</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of patients</td>
<td>235</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>Mean age (yr)</td>
<td>61.7 ± 10.9</td>
<td>62.5 ± 10.4</td>
<td>0.61</td>
</tr>
<tr>
<td>Sex, male:female</td>
<td>117:118</td>
<td>27:29</td>
<td>0.83</td>
</tr>
<tr>
<td>Hypertension</td>
<td>100</td>
<td>21</td>
<td>0.49</td>
</tr>
<tr>
<td>Diabetes mellitus</td>
<td>51</td>
<td>9</td>
<td>0.35</td>
</tr>
<tr>
<td>Body mass index (kg/m²)</td>
<td>25.8 ± 3.8</td>
<td>25.7 ± 2.4</td>
<td>0.92</td>
</tr>
<tr>
<td>Level</td>
<td></td>
<td></td>
<td>0.82</td>
</tr>
<tr>
<td>L3/4</td>
<td>14</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>L4/5</td>
<td>93</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>L3/4/5</td>
<td>128</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>Pathology</td>
<td></td>
<td></td>
<td>0.87</td>
</tr>
<tr>
<td>Spondylosis</td>
<td>116</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>Spondylolisthesis</td>
<td>119</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>Follow-up (mo)</td>
<td>61.8 ± 34.9</td>
<td>31.2 ± 6.1</td>
<td>&lt;0.001*</td>
</tr>
</tbody>
</table>

Values are presented as mean ± standard deviation or number. DS, dynamic stabilization; CBT, cortical bone trajectory. *p < 0.05.

Table 2. Comparison of perioperative parameters

<table>
<thead>
<tr>
<th>Variable</th>
<th>Pedicle-based DS</th>
<th>CBT-based DS</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation time (min)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Level</td>
<td>196.9 ± 62.1</td>
<td>163.2 ± 26.6</td>
<td>0.005*</td>
</tr>
<tr>
<td>2 Levels</td>
<td>257.7 ± 75.3</td>
<td>227.1 ± 43.1</td>
<td>0.04*</td>
</tr>
<tr>
<td>EBL (mL)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Level</td>
<td>399.1 ± 303.3</td>
<td>173.2 ± 157.2</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>2 Levels</td>
<td>816.8 ± 463.7</td>
<td>353.7 ± 248.8</td>
<td>&lt;0.001*</td>
</tr>
</tbody>
</table>

Values are presented as mean ± standard deviation. DS, dynamic stabilization; CBT, cortical bone trajectory; EBL, estimated blood loss. *p < 0.05.
required revision surgery in the entire series. In the pedicle-based
group, there were 108 loosened screws (9%) in 62 patients (26.4%),
which was significantly higher than that in the CBT-based group
(15 screws [5.4%] in 7 patients [12.5%], p = 0.045 and 0.028, re-
spectively). Moreover, there were 7 fractured screws (0.6%) in 5
patients (2.1%) in the pedicle-based group, while there were
none in the CBT-based group (Table 3).

Other surgical complications (e.g., incidental durotomy, su-
perficial or deep wound infections) were similarly low in both
groups. There were 3 wound infections and 3 incidental duroto-
mies in the CBT DS group. On the other hand, there were 13 in-
cidental durotomies, 2 wound infections, and 1 epidural hema-
toma in the pedicle-based DS group. There was no newly-onset
foot-drop or other lumbosacral radiculopathy causing weakness
after surgery in both groups. In pedicle-based DS group, there
were 38 patients had ASD. Among them, 6 patients had revision
fusion surgery. Three patients had progressed spondylolisthesis
over the index level. In CBT-based DS group, there were 2 pa-
tients had asymptomatic ASD. One patient had recurrent disc
over the index level that revision fusion surgery was performed.

4. Effects of Screw Loosening

Comparisons were made between the intact and loosened
screws in and between both the CBT-based and pedicle-based
groups. In the CBT-based DS group, most of the demographic
data demonstrated no differences, except that patients with screw
loosening were older than those without. In the pedicle-based
DS group, with or without screw loosening, there were no dif-
fences in patients’ age, BMI, or bone density. However, there
was a male predominance of screw loosening in pedicle-based
DS for uncertain reasons. At 24-month postoperation, there
were no differences between the subgroups of loosened and in-
tact screws, within both the pedicle-based or CBT-based groups.

Table 3. Analysis of screw loosening

<table>
<thead>
<tr>
<th>Variable</th>
<th>Pedicle-based DS</th>
<th>CBT-based DS</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loosen screw</td>
<td>108 (9.0)</td>
<td>15 (5.4)</td>
<td>0.045*</td>
</tr>
<tr>
<td>Nonloosen screw</td>
<td>1,088 (91)</td>
<td>265 (94.6)</td>
<td></td>
</tr>
<tr>
<td>Patients with loosen screw</td>
<td>62 (26.4)</td>
<td>7 (12.5)</td>
<td>0.028*</td>
</tr>
<tr>
<td>Patients without loosen screw</td>
<td>173 (73.4)</td>
<td>49 (87.5)</td>
<td></td>
</tr>
<tr>
<td>Fractured screw</td>
<td>7 (0.6)</td>
<td>0 (0)</td>
<td>0.19</td>
</tr>
<tr>
<td>Patients with fractured screw</td>
<td>5 (2.1)</td>
<td>0 (0)</td>
<td>0.27</td>
</tr>
</tbody>
</table>

Values are presented as number (%). DS, dynamic stabilization; CBT, cortical bone trajectory. *p < 0.05.
The loosened screws had no adverse effects on the patient-reported outcomes (Table 4).

## DISCUSSION

This series demonstrated that CBT is a feasible alternative to pedicle trajectory for DS, with less soft tissue dissection and higher strength of the screws. The novel CBT DS had less incidence of screw loosening in the current series compared to the conventional DS. The CBT was first described by Santoni et al.\textsuperscript{26} in 2009 as a novel method for PS placement in lumbar surgery. Biomechanical studies demonstrated the superiority of the CBT, which could yield a 30% increase in pullout strength and a 71% increase in insertional torque.\textsuperscript{26,32} Using CBT could theoretically enhance bony integration at the bone-screw interface and reduce the incidence of screw loosening. Because CBT uses an entry point at the pars interarticularis and a medial-to-lateral trajectory, it inherently allows avoidance of a wide exposure of the transverse process or muscle detachment at both index and cephalad facet joints. Minimizing muscle detachment from the facet joint could maintain structural integrity of the facet joint and would likely help to reduce future ASD. The features of CBT, less soft tissue violation, coincidentally matches the design rationale of screw-based DS to preserve motility by preservation of muscles. The invention of adapting CBT for DS was first attempted by the authors with a promising preliminary report.\textsuperscript{31} Most of the series of CBT used cortical screws in lumbar fusion, and both the trajectory and design of the screws could have enhanced the purchase. Although the original design of screws of DS was similar to common PSs rather than cortical screws, the novel trajectory reportedly plays a more important role than the screw per se.\textsuperscript{33}

The concept of preservation of motion in surgery for lumbar degeneration has gained popularity outside North America. Most of the reported series of DS came out of Europe and the Asia-Pacific region. Several reports demonstrated satisfactory and noninferior outcomes of DS compared to that of lumbar fusion surgery.\textsuperscript{16,34} The historic concern that the DS screws were subject to loosening after repeated load challenge has been addressed with little clinically significant consequences.\textsuperscript{21,35,36} Stoll et al.\textsuperscript{10} reported 10 loose screws (3.6%) in 7 of 83 patients (8.4%) at a mean follow-up of 38.1 months. Grob et al.\textsuperscript{32} reported on screw loosening in 4 of 31 patients (13%) at a 2-year follow-up, and all these patients underwent reoperation. Bothmann et al.\textsuperscript{1} documented screw loosening in 7 of 40 patients (17.5%). Furthermore, they reported a case with screw breakage at 21 months.

### Table 4. Comparison of loosened screw and intact group

<table>
<thead>
<tr>
<th>Variable</th>
<th>Pedicle-based DS Screw loosening</th>
<th>CBT-based DS Screw loosening</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yes (n = 62)</td>
<td>No (n = 173)</td>
<td></td>
</tr>
<tr>
<td>Age (yr)</td>
<td>62.4 ± 11.3</td>
<td>61.5 ± 10.9</td>
<td>0.57</td>
</tr>
<tr>
<td>Sex</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>38</td>
<td>79</td>
<td>0.03*</td>
</tr>
<tr>
<td>Female</td>
<td>24</td>
<td>94</td>
<td></td>
</tr>
<tr>
<td>Sex</td>
<td></td>
<td></td>
<td>0.61</td>
</tr>
<tr>
<td>BMI (kg/m(^2))</td>
<td>26.1 ± 4.1</td>
<td>25.7 ± 3.7</td>
<td>0.63</td>
</tr>
<tr>
<td>Diabetes mellitus</td>
<td>13</td>
<td>38</td>
<td>0.87</td>
</tr>
<tr>
<td>DEXA T score</td>
<td>-0.36 ± 1.6</td>
<td>-0.56 ± 1.5</td>
<td>0.52</td>
</tr>
<tr>
<td>Preoperation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VAS back</td>
<td>5.7 ± 3.1</td>
<td>5.6 ± 3.2</td>
<td>0.81</td>
</tr>
<tr>
<td>VAS leg</td>
<td>6.8 ± 2.4</td>
<td>6.3 ± 3.1</td>
<td>0.35</td>
</tr>
<tr>
<td>ODI</td>
<td>52.7 ± 16.1</td>
<td>48.7 ± 19.5</td>
<td>0.19</td>
</tr>
<tr>
<td>24-Month postoperation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VAS back</td>
<td>2.1 ± 2.6</td>
<td>2.2 ± 2.4</td>
<td>0.83</td>
</tr>
<tr>
<td>VAS leg</td>
<td>1.7 ± 2.4</td>
<td>2.2 ± 2.7</td>
<td>0.4</td>
</tr>
<tr>
<td>ODI</td>
<td>17.6 ± 16.1</td>
<td>20.3 ± 17.7</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Values are presented as mean ± standard deviation or number. DS, dynamic stabilization; CBT, cortical bone trajectory; BMI, body mass index; DEXA, dual-energy x-ray absorptiometry; VAS, visual analogue scale; ODI, Oswestry Disability Index. *p < 0.05.
after surgery. Schaeren et al.\(^8\) reported 3 of 19 patients (15.7%) with screw loosening at a 4-year follow-up. Additionally, 1 of 19 patients (5.2%) experienced screw breakage. They also pointed out neither screw breakage nor screw loosening was related to the patients’ satisfaction or back pain. Wu et al.\(^12\) documented 31 cases (4.7%) of screw loosening in 25 of 126 patients (19.8%), with a mean follow-up of 37 months. Most of the rates reported for screw loosening range from 10% to 20% of the patients and seldom require revision surgery. This feature of DS is distinct from the arthrodesis series, in which screw loosening often causes pseudarthrosis warranting reoperation. The biggest difference between fusion surgery and DS is that the facet should be preserved as much as possible in DS to prevent iatrogenic instability. Once the screw loosening occurred in DS, the preserved facet joint could still provide enough support to prevent the progression of instability. This might be the reason why the revision surgery was seldom required in DS patients with screw loosening. Nonetheless, minimization of screw loosening and enhancement of osteointegration are certainly important for DS. In the present study, CBT-based DS demonstrated superior screw integrity, with lower rates of screw loosening than the pedicle trajectory (12.5% vs. 26.4%, \(p = 0.028\)). The subgroup analysis also demonstrated that the screw loosening rates were lower in the CBT-based group than the pedicle-based group in any of the subgroup analyses. Moreover, there was no screw breakage in the CBT-based group, compared with 7 screws (0.6%) broken in 5 patients (2.1%) in the pedicle-based group. In our experience, the utilization of the new trajectory yielded a lower screw loosening rate and breakage in DS. Furthermore, at 24-month postoperation, all the clinical outcomes, including the VAS for back and leg pain, and the ODI scores, demonstrated equally significant improvement in all subgroups, which were also compatible with the published series.

There were limitations to the study. This was a single institute, retrospective, nonrandomized, comparison study. The 2 cohorts were enrolled with the same indication but at different time points. There was study bias in that the pedicle-based cohort had a significantly longer follow-up which may have influenced the occurrence of screw loosening. However, all the complication profiles were analyzed with equal scrutiny, and the time point of screw loosening always occurred within 24 months after surgery. Since all patients in this study had a minimum of 2 years of follow-up, the influence of unequal follow-up on the occurrence of screw loosening would be minimal and omissible. Furthermore, the DS screws used in the 2 subgroups were slightly different. Not only the diameters but also the lengths of the screws for the CBT and PSs were different by design. The CBT-based group used shorter and smaller screws. However, this was compatible with all the published series of CBT screws that were used for fusion. Whether the differences of screw size and shape matter in DS as in fusion constructs remain elusive. Investigations with a longer follow-up and larger sample sizes are warranted to understand the long-term outcome of the novel strategy.

**CONCLUSION**

The CBT-based DS for 1- or 2-level lumbar degenerative disease demonstrated equivalent clinical improvements as the pedicle-based DS. The adoption of CBT-based screws for DS could be a less invasive approach (shorter operation time and less blood loss), with lower chances of screw loosening than the conventional PS-based DS.

**NOTES**

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**REFERENCES**


Carbon Fiber-Reinforced Polyetheretherketone Spinal Implants for Treatment of Spinal Tumors: Perceived Advantages and Limitations

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Purpose: Carbon-fiber reinforced polyetheretherketone (CFRP)-based spinal implants are an alternative to titanium, offering less image artifact as their metallic counterparts while maintaining similar biomechanical and biocompatibility properties. Its use in the management of spinal tumors has been reported, however the perceived advantages related to improved imaging quality, radiation treatment planning, and detection of tumor recurrence have not been fully assessed.

Methods: We performed a retrospective review of medical records amongst oncologic patients treated at MD Anderson Cancer Center with CFRP implants. Histology, tumor location, construct features, time of follow-up, adjuvant radiation, recurrences, overall survival, and hardware-related complications were recorded.

Results: Sixty-nine consecutive patients were assessed (22 primary tumors, 47 metastases) and the median time for follow-up was 5.4 months. Amongst the cohort, a total of 491 CFRP pedicle screws were implanted. Hardware complications were observed in 5 cases (7.04%). Adjuvant radiation was completed in 8 patients with primary tumors and 29 patients with spinal metastases. A total of 28 patients (40.5%) from the combined primary and metastatic cohorts experienced systemic disease progression, with 12 patients (17.3%) demonstrating local recurrences. Amongst primary and metastatic tumors, overall survival (p = 0.363) and rate of local recurrence (p = 0.112) were similar.

Conclusion: This largest series of CFRP implants demonstrates safe and effective spinal stabilization for patients with both primary and metastatic tumors. Enhanced postoperative imaging led to minimal imaging artifacts which facilitated postoperative radiation planning and the ability to detect local recurrence.

Keywords: Spinal oncology, Carbon fiber, Radiation

INTRODUCTION

The structural integrity of the spine can be compromised by a variety of pathological processes, with cancer being a relatively common occurrence. Due to a variety of factors including improved systemic therapies and enhanced imaging modalities, the reported incidence of spinal metastases has increased in recent years.1 It is estimated that metastatic involvement of the spine occurs in up to 40% of oncological patients with approximately 10% of these cases becoming symptomatic. Although the incidence of primary tumors is less common, they are typically symptomatic at initial presentation.2,3 With the advances in chemotherapies, surgical techniques, and radiosurgery, the treatment algorithm for these patients continues to evolve and requires multidisciplinary management.4-7 The role of surgery within spinal oncology is multi-faceted, including histological
diagnosis, cytoreduction, decompression of neural elements, control of pain, and treatment of spinal instability.6,8,9

Titanium implants are commonly used for spinal stabilization; however, they can produce significant artifact on magnetic resonance imaging (MRI) and computed tomography (CT), which can impair proper delineation of tumor and neural structures during radiation planning and delay the detection of local disease progression on postoperative surveillance imaging.2,9 Radiation therapy, especially when heavy particles are used, is affected by the presence of metallic implants that leads to an uneven dose distribution that has the potential of reducing therapeutic efficacy and increasing the risk to nearby tissue.3,8 To overcome these limitations, carbon fiber-reinforced polyetheretherketone (CFRP) implants have been recently introduced as an alternative to titanium in the manufacturing of spinal implants. This material has been shown to have biocompatibility and biomechanical properties equivalent titanium constructs.10-12 Due to its radiolucency, CFRP spinal implants have the potential to improve long-term outcomes for patients with spinal malignancies when compared to titanium implants due to minimal interference with surveillance imaging and improved radiation therapy planning and delivery. However, due to the novelty of CFRP implants in spinal oncology practices, there are limited reports studying their long-term results, surgical nuances, and technical challenges that should be considered when incorporating them into surgical decision-making.

We present our experience with the utilization of CFRP spinal implants in a tertiary cancer center, outlining our perceived advantages and limitations of the material, discussing surgical technical nuances, providing examples of improved postoperative follow-up imaging, and insights for future directions of the use of CFRP materials.

**MATERIALS AND METHODS**

**1. Data Collections**

A retrospective review of the medical records of consecutive patients harboring primary and metastatic spinal tumors treated with CFRP spinal implants (icotec ag, Altstätten, Switzerland) at The University of Texas MD Anderson Cancer Center from September 2019 to August 2021 was performed. This study complied with an Institutional Review Board of MD Anderson Cancer Center approved protocol (2021-0372). Included patients had either primary or metastatic spinal tumors requiring surgical stabilization with CFRP thoracolumbar pedicle screws with CFRP or titanium rods. Patients with cement augmentation were not excluded. Given our aim to present our institutional experience, all patients with CFRP thoracolumbar pedicle screw were included in this retrospective study. Their clinical data were retrospectively collected, including age, sex, tumor pathology, surgical procedure, length of construct, presence of intraoperative or postoperative surgical complications, length of clinical and radiographic follow-up, type of radiation treatment, local control and patient survival.

**2. Surgical and Radiotherapy**

CFRP implants were implanted using either an open or minimally invasive technique using intraoperative CT. Intraoperative image intensifier and/or intraoperative navigation was used to aid screw placement and to assess the screws’ position following implantation. The carbon fiber pedicle screws are a combination of continuous, high-strength carbon fibers in a polyetheretherketone (PEEK) polymer matrix and a composite flow molding process resulting in an interwoven 3-dimensional fiber architecture. The screws are cannulated, fenestrated, and titanium coated in the area of the pedicle for improved osseointegration. A tantalum marker is incorporated into the tip of the screw to enable visualization of the implant position.11 The decision to use CFRP or titanium rods was dictated by the available contour and length of CFRP rods. Following surgery, patients underwent consultation with the treating radiation oncologist and the decision was made regarding the need for CT myelogram or MRI for treatment planning. A treatment plan consisting of either stereotactic spinal radiosurgery (SSRS), intensity-modulated radiotherapy (IMRT), or conventional external beam radiotherapy (cEBRT) was made in coordination with a multidisciplinary spine tumor board decision.

**3. Follow-up Analysis**

Clinical and radiographic follow-up was performed every 3 months postoperatively to assess hardware stability, local recurrence, disease progression, and overall survival. Pre- and postoperative images, including CT scan and MRI, were retrospectively reviewed. Postoperative CT scans were used to identify screw position, fusion, and hardware integrity. Screw loosening was considered when a hypodense halo appeared around the screw on the CT scan. Local recurrences were identified using follow-up MRI images. Disease progression was monitored with CT scan of the chest, abdomen, and pelvis as coordinated by the treating medical oncologist. Kaplan-Meier curves with log-rank testing were used to compare and demonstrate overall survival and local recurrence data in the primary and metastatic
tumor groups.

4. Statistical Analysis

A descriptive analysis was made and shown in the form of text or table. The cohort was primarily divided into the groups “primary” and “metastatic,” depending on the histopathological diagnosis, for comparative analyses. For mean comparisons between groups we used the Welch T-test with bootstrapping. Continuous variables were correlated using Pearson and Spearman correlations, depending on the normality of the distribution. Statistical analyses were performed using the IBM SPSS Statistics ver. 29.0 (IBM Co., Armonk, NY, USA). A p-value of less than 0.05 (2-sided) was regarded as significant.

RESULTS

1. Patient Demographics

A total of 69 patients were included in the cohort, with 47 male patients (68%), 22 female patients (32%), and a mean age of 56.1 ± 14.6 years. Metastatic tumors corresponded to 47 of the cases (68%) while primary bone tumors represented the remaining 22 cases (32%). Within both the metastatic and primary tumor cohort, the thoracic spine was primarily affected (78.7% and 81.8%, respectively) followed by the lumbar spine (21.3% and 18.2%, respectively). Amongst metastatic tumors, the most common histologies included renal cell carcinoma (12 cases), lung (6 cases), thyroid (4 cases), colon (3 cases), and prostate (3 cases). Chondrosarcoma and non-specified sarcoma represented the most common primary tumor histologies (5 and 3 cases, respectively). Patient demographics are shown in Table 1.

2. Treatment Outcome of Surgery and Radiotherapy

A total of 491 CFRP pedicle screws were implanted in 69 patients. CFRP rods were used in 56 cases while titanium rods were used in 13 procedures in order to match the rod to the patient’s spinal curvature. The average construct length was similar between metastatic (4.7 levels; range, 3–7) and primary bone tumors (4.9 levels; range, 3–9). While all screw placement for primary bone tumors was performed with an open, posterior approach, metastatic tumors included both open (43 cases) and percutaneous (4 cases) posterior stabilizations. Cement augmentation of the pedicle screws was performed in 10 metastatic cases due to concern for osteopenia which assessed for on preoperative CT imaging. Surgical data is summarized in Table 2. Out of the 491 pedicle screws implanted, 3 screws had the head stripped during insertion, requiring removal and a larger screw.

Table 1. Patient demographics and clinical characteristics of primary bone/soft tissue neoplasm and metastatic groups

<table>
<thead>
<tr>
<th>Variable</th>
<th>Primary neoplasm (n = 22)</th>
<th>Metastasis (n = 47)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>15</td>
<td>32</td>
</tr>
<tr>
<td>Female</td>
<td>7</td>
<td>15</td>
</tr>
<tr>
<td>Mean age (yr)</td>
<td>52.55</td>
<td>57.73</td>
</tr>
<tr>
<td>Tumor location, n (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cervical</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Thoracic</td>
<td>18 (81.8)</td>
<td>37 (78.7)</td>
</tr>
<tr>
<td>Lumbar</td>
<td>4 (18.2)</td>
<td>10 (21.3)</td>
</tr>
<tr>
<td>Sacral</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Histology, n (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chondrosarcoma</td>
<td>5 (22.7)</td>
<td></td>
</tr>
<tr>
<td>Sarcoma</td>
<td>3 (13.6)</td>
<td></td>
</tr>
<tr>
<td>Chordoma</td>
<td>1 (4.5)</td>
<td></td>
</tr>
<tr>
<td>Epitheloid fibrosarcoma</td>
<td>1 (4.5)</td>
<td></td>
</tr>
<tr>
<td>Ewing sarcoma</td>
<td>1 (4.5)</td>
<td></td>
</tr>
<tr>
<td>Giant cell</td>
<td>1 (4.5)</td>
<td></td>
</tr>
<tr>
<td>Leiomyosarcoma</td>
<td>1 (4.5)</td>
<td></td>
</tr>
<tr>
<td>Myxoid liposarcoma</td>
<td>1 (4.5)</td>
<td></td>
</tr>
<tr>
<td>Osteoblastoma</td>
<td>1 (4.5)</td>
<td></td>
</tr>
<tr>
<td>Osteochondroma</td>
<td>1 (4.5)</td>
<td></td>
</tr>
<tr>
<td>Recurrent solitary fibrous tumor</td>
<td>1 (4.5)</td>
<td></td>
</tr>
<tr>
<td>Sarcomatoid tumor</td>
<td>1 (4.5)</td>
<td></td>
</tr>
<tr>
<td>Schwannoma</td>
<td>1 (4.5)</td>
<td></td>
</tr>
<tr>
<td>Aneurysmal bone cyst</td>
<td>1 (4.5)</td>
<td></td>
</tr>
<tr>
<td>Myeloma</td>
<td>1 (4.5)</td>
<td></td>
</tr>
<tr>
<td>Undifferentiated pleomorphic sarcoma</td>
<td>1 (4.5)</td>
<td></td>
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<tr>
<td>Renal cell carcinoma</td>
<td>12 (25.5)</td>
<td></td>
</tr>
<tr>
<td>Lung</td>
<td>6 (12.8)</td>
<td></td>
</tr>
<tr>
<td>Thyroid</td>
<td>4 (8.5)</td>
<td></td>
</tr>
<tr>
<td>Colon</td>
<td>3 (6.4)</td>
<td></td>
</tr>
<tr>
<td>Prostate</td>
<td>3 (6.4)</td>
<td></td>
</tr>
<tr>
<td>Esophageal carcinoma</td>
<td>2 (4.3)</td>
<td></td>
</tr>
<tr>
<td>Melanoma</td>
<td>2 (4.3)</td>
<td></td>
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<tr>
<td>Paraganglioma</td>
<td>2 (4.3)</td>
<td></td>
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<tr>
<td>Breast cancer</td>
<td>2 (4.3)</td>
<td></td>
</tr>
<tr>
<td>Metastatic carcinoma, primary unknown</td>
<td>2 (4.3)</td>
<td></td>
</tr>
<tr>
<td>Adrenal carcinoma</td>
<td>2 (4.3)</td>
<td></td>
</tr>
<tr>
<td>Anal carcinoma</td>
<td>1 (2.1)</td>
<td></td>
</tr>
<tr>
<td>Cholangiocarcinoma</td>
<td>1 (2.1)</td>
<td></td>
</tr>
<tr>
<td>Hepatic carcinoma</td>
<td>1 (2.1)</td>
<td></td>
</tr>
<tr>
<td>Malignant thymoma</td>
<td>1 (2.1)</td>
<td></td>
</tr>
<tr>
<td>Pheochromocytoma</td>
<td>1 (2.1)</td>
<td></td>
</tr>
<tr>
<td>Squamous cell carcinoma of the tongue</td>
<td>1 (2.1)</td>
<td></td>
</tr>
<tr>
<td>Teratoma</td>
<td>1 (2.1)</td>
<td></td>
</tr>
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</table>
inserted as salvage. Hardware-related complications occurred in a total of 5 patients (7.2%) and included: haloing around the screw in 4 patients and one intraoperative screw breakage where the screw fragment partially inserted into sclerotic bone and could not be retrieved. Hardware revision was not required in these cases. Additionally, perioperative complications included infection (3 metastatic patients), pseudomeningocele (2 metastatic patients), hematoma (1 metastatic patients), and durotomy (1 metastatic patient).

Radiation was used as adjuvant therapy for 8 patients with primary tumors and for 29 patients with metastatic tumors. One of the patients with metastatic disease had 2 segments of the spine treated. Stereotactic radiosurgery was the most common modality in both cohorts. The median dose of SSRS was 2,458 cGy divided into 1.6 fractions, on average. A CT myelogram was used for simulation purposes in 24 of these cases. MRI simulation was used for the remaining patients treated with SSRS, reflecting changing institutional radiation planning for patients with CFRP implants. Comparison of the postoperative MRI and the corresponding CT myelogram is provided (Fig. 1). For patients undergoing IMRT, the median dose was 4,998 cGy in 10 fractions while cEBRT was 3,000 cGy in 10 fractions. Median time from surgery to radiation for all patients in the study was 30 days (interquartile range [IQR], 25.5–42.0 days). One patient with metastatic anal carcinoma was radiated 108 days

Table 2. Surgical data – descriptive analyses of implants, hardware, and technique used

<table>
<thead>
<tr>
<th>Variable</th>
<th>Primary neo-plasm (n = 22)</th>
<th>Metastasis (n = 47)</th>
</tr>
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<tbody>
<tr>
<td>Total screws</td>
<td>156</td>
<td>335</td>
</tr>
<tr>
<td>Total titanium rods</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>Total carbon/PEEK rods</td>
<td>18</td>
<td>38</td>
</tr>
<tr>
<td>Average length of construct/levels</td>
<td>4.9</td>
<td>4.7</td>
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<tr>
<td>Screw placement technique</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open</td>
<td>22</td>
<td>43</td>
</tr>
<tr>
<td>MIS</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>No. of screws utilized per case, median (range)</td>
<td>8 (2–13)</td>
<td>8 (2–12)</td>
</tr>
<tr>
<td>Vertebral body reconstruction</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Cement vertebroplasty</td>
<td>0</td>
<td>10</td>
</tr>
</tbody>
</table>

PEEK, polyetheretherketone; MIS, minimally invasive surgery.

Fig. 1. Comparison of postoperative magnetic resonance imaging (MRI) and computed tomography (CT) myelogram following carbon fiber-reinforced polyetheretherketone (CFRP) utilization. (A) Postoperative sagittal T2-weighted MRI demonstrating postoperative changes related to a laminectomy of T2–3 and partial corpectomy at T3 with placement of CFRP screws from T1 to T5 for metastatic renal cell carcinoma. Note the absence of metallic artifact on the image. (B) Corresponding sagittal image of a CT myelogram used for planning of postoperative stereotactic spinal radiosurgery treatment. Note unobscured identification of the spinal cord. Axial T2-weighted MRI (C) and corresponding axial CT myelogram (D) image demonstrating clear identification of the spinal cord without metallic artifact. The arrow points to embolization material used to decrease blood supply to the tumor prior to surgical resection.
following surgery due to wound healing complications unrelated to spinal hardware. The type of the rod ($t(33) = -0.323, p = 0.772$), use of cement augmentation ($t(7.75) = 0.034, p = 0.981$), vertebral body reconstruction ($t(33) = 0.211, p = 0.712$), number of screws ($p = 0.041, p = 0.816$), and the length of construct ($p = 0.039, p = 0.825$) were not significantly associated with the time to radiation. No radiation associated complications were observed. Radiation treatment data is shown in Table 3.

3. Follow-up Outcomes

Amongst the cohort of 69 patients, the median length of follow-up was 5.37 months (IQR, 2.4–11.9 months) with overall survival of 70% (72.7% for primary bone tumors, 68.0% for metastatic tumors). A total of 28 patients (40.5%) from the combined primary and metastatic cohorts experienced systemic disease progression, with 12 patients (17.3%) demonstrating local recurrences. Outcomes data are shown in Table 4. Kaplan-Meier curves for overall survival and local recurrence are also reported (Fig. 2). There was no statistically significant difference in overall survival between primary and metastatic tumors ($p = 0.363$) (Fig. 2A). Additionally, the mean time for recurrence between metastatic and primary tumors was 4.5 months.

### Table 3. Radiation data – descriptive analyses of the techniques, use of CT myelogram, and timing

<table>
<thead>
<tr>
<th>Variable</th>
<th>Primary neoplasm (n = 8)</th>
<th>Metastasis (n = 29)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation treatment modality</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SSRS/SBRT</td>
<td>7</td>
<td>24</td>
</tr>
<tr>
<td>IMRT</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>cEBRT</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>CT myelogram</td>
<td>5</td>
<td>19</td>
</tr>
<tr>
<td>Time from OP to RT (day), median (range)</td>
<td>35 (14–48)</td>
<td>30 (3–108)</td>
</tr>
</tbody>
</table>

CT, computed tomography; SSRS, stereotactic spinal radiosurgery; SBRT, stereotactic body radiotherapy; IMRT, intensity-modulated radiotherapy; cEBRT, conventional external beam radiotherapy; OP, operation; RT, radiotherapy.

*All loosened screws. †Two cases of loosened screws and 1 case of intraoperative screw breakage. ‡Two cases of wound infection and 1 case of surgical site infection.

### Table 4. Outcomes data – descriptive analyses of survival, recurrence, and complications

<table>
<thead>
<tr>
<th>Variable</th>
<th>Primary neoplasm (n = 22)</th>
<th>Metastasis (n = 47)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient status</td>
<td></td>
<td></td>
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<tr>
<td>Alive</td>
<td>16</td>
<td>32</td>
</tr>
<tr>
<td>Deceased</td>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>Overall disease progression</td>
<td>8</td>
<td>20</td>
</tr>
<tr>
<td>Local recurrence</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Hardware complications</td>
<td>2*</td>
<td>3†</td>
</tr>
<tr>
<td>Infectious complications</td>
<td>0</td>
<td>3†</td>
</tr>
<tr>
<td>Reoperation</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Length of follow-up (day), median (range)</td>
<td>205 (5–636)</td>
<td>141 (26–546)</td>
</tr>
</tbody>
</table>

CT, computed tomography; SSRS, stereotactic spinal radiosurgery; SBRT, stereotactic body radiotherapy; IMRT, intensity-modulated radiotherapy; cEBRT, conventional external beam radiotherapy; OP, operation; RT, radiotherapy.

Fig. 2. Overall survival and local recurrence rates between primary and metastatic tumors treated with carbon fiber-reinforced polyetheretherketone implants. Kaplan-Meier estimates of overall survival (A) and local recurrence (B) were plotted and stratified by primary and metastatic spinal tumor. Log-rank testing demonstrated a nonsignificant difference between overall survival ($p = 0.363$) (A) or local recurrence ($p = 0.112$) (B) between primary or metastatic tumors.
(standard deviation [SD], ± 3.9) and 5.0 months (SD, ± 2.6), respectively, without significant difference between groups (p = 0.112) (Fig. 2B). One patient had a reoperation due to tumor recurrence and progression to adjacent levels requiring extension of the original construct to achieve adequate spinal stabilization. Radiographic evidence of arthrodesis was not observed.

**DISCUSSION**

CFRP is a thermoplastic composite material that has increasingly been used as an implant due to its excellent biocompatibility, wear resistance, fracture toughness, and chemical/thermal resistance. Biomechanical studies demonstrate that CFRP spinal constructs have similar mean bending and cycling capacity as titanium counterparts when applied in spine cadaveric models, resulting in comparable screw anchorage, stiffness and resistance to motion when compared to titanium constructs. CFRP implants are delivered sterile and have an elastic modulus closer to cortical bone which could result in less bone absorption due to better distribution of mechanical stress. Kang et al. investigated the biomechanics and effects of titanium, PEEK, and CFRP lumbar rods on adjacent segment disease. They observed that carbon fiber-reinforced implants reduced the risk of pedicle screw fracture when compared to titanium implants.

Conventional titanium implants are associated with metallic artifact on CT and MRI, which can interfere with postoperative surveillance imaging. CFRP implants reduced 90% of artifacts when compared to titanium in phantom models. This radiolucency has multiple potential advantages including evaluation of the arthrodesis status and early detection of local tumor recurrence which has the potential of improving clinical management and patient outcomes. Krätzig et al. compared the impact of CFRP and titanium implants on the density values of CT scans in different areas of interest adjacent to the construct including the spinal cord, neuroforamen, and vertebral body. CFRP improved visualization in most regions of interest, except for the neuroforamen. Another study conducted by Fleege et al. suggest that CFRP pedicle screws exhibit fewer artifact areas on vertebral body surfaces and surrounding tissues when compared to titanium in patients undergoing posterior spondylodesis.

In our series, we showed an example of early tumor detection at the pedicle and adjacent foramen, which was readily identified due to reduced imaging artifacts related to the CFRP implant (Fig. 3). The titanium tulip allows easy manipulation and evaluation of the arthrodesis status and early detection of local tumor recurrence which has the potential of improving clinical management and patient outcomes. Krätzig et al. compared the impact of CFRP and titanium implants on the density values of CT scans in different areas of interest adjacent to the construct including the spinal cord, neuroforamen, and vertebral body. CFRP improved visualization in most regions of interest, except for the neuroforamen. Another study conducted by Fleege et al. suggest that CFRP pedicle screws exhibit fewer artifact areas on vertebral body surfaces and surrounding tissues when compared to titanium in patients undergoing posterior spondylodesis.

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greatly facilitates rod placement, and the metallic artifact of tulip is mostly located at the level of the posterior paraspinal muscles far from the laminectomy site. Moreover, visualization of the spinal canal at the level of the pedicle and the foramen is clear of distortion and is particularly useful to identify early recurrences or epidural spread to adjacent levels in the postoperative MRI scans.

Radiation therapy is frequently used to treat spinal metastases and primary tumors either alone or combined with surgery.\(^{2,8,18,19}\) Dose calculation can be impaired if the planning images are excessively distorted due to metallic artifacts.\(^*\) As a result, CT myelogram following implantation of titanium hardware is typically performed for identification of the spinal cord and cauda equina for SSRS contouring. As noted in our study, the majority of patients with CFRP implants also received CT myelogram for radiation planning, reflecting institutional radiation oncology preferences. However, we have examples where MRI simulation has been used for postoperative SSRS planning rather than CT myelogram, the benefits of which will require further study. Notably, CT myelogram is associated with risks due to its invasive nature. Additionally, benign postoperative fluid collections can create compressive effects over the thecal sac leading to myelography blockage precluding the identification of the spinal cord. In such situations, the collection needs to be drained and the imaging repeated, resulting in delays and invasive procedures to the patient. In our experience, the quality of postoperative MRI associated with CFRP implants was sufficient to allow adequate contouring and SSRS planning in cases where fluid collections resulted in suboptimal myelographic imaging.

The impact of using CFRP for the surgical management of primary radioresistant tumors like chordomas and chondrosarcomas requires further study. In our series, we treated 22 patients with primary tumors, of which 8 were treated with adjuvant radiation therapy. It is our surgical practice that an en bloc resection, when associated with negative margins, is not followed by radiotherapy. However, when the surgical margin is compromised, we typically treat the tumor bed or recurrent lesions with photon or proton directed radiotherapy. Due to the atomic composition of titanium, these implants can have an attenuation effect resulting in the reduction of delivered dose of radiation. These interactions occur with any type of radiation, however heavy particles such as protons are the most affected.\(^{3,8}\) In contrast, CFRP implants may facilitate planning and delivery of radiation as it promotes significantly less image disturbance and has small interaction with radiation particles, even when coated with a thin layer of titanium.\(^{2,18}\) For this reason, we prefer and routinely use CFRP implants in patients undergoing SSRS. Future studies will be needed to systematically compare the influence of titanium and CFRP hardware on proton and photon radiation planning, administration, and local recurrence in the setting of both primary and metastatic tumors.

Our series includes patients with primary tumors, which were treated with en bloc resections and patients with metastatic disease who were treated with decompressive surgery followed by postoperative radiation. We did not observe differences in hardware-related complication rates among these 2 groups of tumors. Cofano et al.\(^{20}\) studied the differences in postoperative complications amongst patients with metastatic tumors treated with either CFRP or titanium implants. They did not observe a significant difference between the 2 groups in either postoperative clinical complications or hardware-related complications. However, Boriani et al.\(^{21}\) reported a series of 34 patients with primary or metastatic spine tumors with an intraoperative screw fracture occurring in one case. Additionally, 2 patients had screw loosening due to disease progression, requiring revision surgery. Another series with 28 patients reported by Neal et al.\(^{4}\) reported 1 case of screw loosening which was managed expectantly and 2 patients who required a reoperation due to complications unrelated to carbon fiber hardware. Overall, our results are consistent with these reports.

Our experience with 69 cases and 491 implanted pedicle screws represents the largest series reported in the literature. The decision to utilize CFRP implants in spinal oncology is multifactorial. However, our institutional practice is to incorporate CFRP implants for spinal stabilization in the thoracic or lumbar spine, particularly in situations where radioresistant histologies will require postoperative SSRS. Additionally, CFRP implants are utilized when there is significant concern for the ability to detect local recurrence, particularly amongst patients where long-term follow-up is anticipated due to a favorable oncologic status (e.g., single site of disease, treatment naïve, etc.). The greatest advantage of CFRP implants is the significant reduction in imaging artifact with follow-up MRI when compared to titanium pedicle screws.\(^{2,16,17}\) This is particularly important for patients being treated with SSRS.\(^{9}\) Future studies comparing the accuracy of spinal cord contouring on MRI and CT myelogram using CFRP implants could lead to a change in practice, avoiding the need for an invasive CT myelogram and expediting the delivery of treatment. In addition, subsequent image studies benefit from less distortions, allowing easier identification of tumor recurrences.
1. Pitfalls and Pearls

Carbon fiber screw placement is associated with reduced haptic feedback during screw insertion. In order to reduce the risk of a false trajectory, we recommend the use of a k-wire after the pedicle is cannulated to guide the placement of the screw into the vertebral body. A k-wire approach is used rather than 3-dimensional intraoperative image guidance due to current limitations in navigated carbon fiber instruments. However, with further technical advancements, the use of intraoperative navigation would obviate the risks inherent with k-wires such as cortical bone breakthrough and injury to vascular structures and organs.

We experienced 3 cases where the screwdriver was not coaxial with the screw head and the insertional torque stripped the screw head and prevented further advancement of the screw. Additionally, we encountered a case of intraoperative screw fracture in blastic metastasis and recommend tapping the pedicle trajectory prior to screw insertion, particularly in sclerotic bone. Amongst our cohort, we did not observe evidence of arthrodesis, which is similar to our experience with titanium screws in the oncologic setting. For this reason, it is our practice to perform cement augmentation of both CFRP and titanium pedicle screws in cases of severe osteopenia or tumor involvement in order to enhance screw anchorage. An additional technical consideration during screw insertion is achieving adequate visualization of the implants with intraoperative fluoroscopy. Tantalum tips facilitates screw localization. However, we find this particularly difficult to visualize with intraoperative fluoroscopy in the upper thoracic spine. We recommend to obtain an intraoperative CT scan following screw placement in order to confirm adequate placement and before cement administration.

Up to this date, the thinnest CFRP screw available has a 5.5-mm diameter, which limits its use in small pedicles. While CFRP rods are radiolucent and come in different prebent shapes, there are situations where appropriately shaped, preexisting CFRP rods do not exist. We found that proper alignment of the pedicle screws is crucial to allow the use of CFRP rods. With the inability to bend the CFRP rods, screw height must also be adjusted to allow a smooth fit of the rod inside the tulip without excessive tension. We do not recommend use of a persuader tool to reduce the rod into the screw tulip, as applying excessive force to reduce the rod can compromise the screw purchase and decreasing the screw pull-out strength. We had 13 cases where we were not able to accommodate the prebent carbon fiber rods and the alternative titanium rod was utilized. In such cases, the metallic artifact on MRI was more pronounced, but still did not affect the adequate visualization of the spinal canal and foramen (Fig. 4). Also, the maximum length of CFRP rods is 160 mm, which limits its use in long constructs. Availability of additional rod contours and lengths in the future will reduce the need for titanium rods.

Fig. 4. Comparison of imaging artifact between carbon fiber and titanium rods. (A) Postoperative axial T2-weighted magnetic resonance imaging (MRI) at the T4 level with both carbon fiber-reinforced polyetheretherketone (CFRP) pedicle screws and CFRP rod. (B) Postoperative axial T2-weighted MRI at the T4 level with CFRP pedicle screws and titanium rod. Increased imaging artifact is observed with the titanium rod but does not obscure imaging of the spinal canal.
2. Study Limitation

To date, this is the largest institutional experience of carbon fiber screw placement with associated follow-up. This study has significant limitations due to its retrospective, single arm nature. The follow-up time is short, and our sample size includes both primary and metastatic tumors with relatively small numbers. Future studies are warranted to expand the cohort size, evaluate the differential impact of CFRP constructs on proton and photon-based radiotherapy, increase clinical follow-up in order to facilitate the likelihood of detecting local recurrence, follow construct durability, and monitor overall survival. Additionally, matched comparisons with titanium constructs are warranted.

CONCLUSION

We reported largest series outcomes of oncologic patients treated with CFRP spinal implants. Consistent with other studies in the literature, we demonstrate that the use of CFRP is safe and feasible. Although its favorable radiographic properties are associated with reduced imaging artifacts compared to titanium implants, further prospective multicenter is needed.

NOTES

Conflict of Interest: Dr. Tatsui has an educational grant from Icotec. Dr Rhines discloses educational commitments with Stryker. The other authors have nothing to disclose.

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Author Contribution: Conceptualization: CAB, LR, CT; Data curation: CAB, RDA, AH, MM, JB, RN; Formal analysis: CAB, AH, CT; Methodology: CAB, J Bird, R North, LR, CT; Project administration: CAB, CT; Visualization: AH; Writing - original draft: CAB, RDA; Writing - review & editing: CAB, RDA, J Bird, R North, LR, CT

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Spinal reconstruction with instrumentation has become an important part in the treatment plan for spinal oncology patients, especially since 2005 where surgery was shown to confer benefit over radiation alone in patients with epidural malignant cord compression.1 (Lancet, 2005). Maximizing decompression while reconstructing spinal stability allows for patients to preserve neurologic and functional status during the treatment course for cancer. Titanium alloy implants are routinely employed in achieving spinal reconstruction however imaging artifact from metallic implants are not ideal for follow-up and can interfere with targeted radiation plans. Nonmetallic options exist but are uncommon with very limited experiences reported.

This is a single center retrospective study of 69 consecutive patients treated with carbon fiber-reinforced peak (CFRP) spinal implants for a total of 491 implant screws.2 Patient with metastatic tumors comprised 60% of the group, while 32% of patients had primary spinal tumors. Average follow-up was 54 months.

Hardware complications were overall low at 7%, or 5 cases. They included difficulty with implantation of the screws due to stripping and/or fracturing. Additionally, hybrid constructs were required in 13 patients where titanium rods were used due to contouring limits of the carbon fiber-reinforced rods.

The authors are commended for taking a bold step forward using a unique material for use on complicated patients, but with progress should come caution. First, the lack of ability to contour peek implants may make it difficult for widespread use and likely has a steep learning curve with regards to placing screws appropriately to fit precontoured rods. Improper alignment and excessive stress on the implants may result in higher rates of implant or construct failure. Using a hybrid construct with titanium may be a good solution to this issue however this contradicts some of the benefit of using such nonmetallic materials to begin with. Second, the true benefit of enhanced imaging characteristics to detect early recurrence and make a clinical impact for such patients is still to be determined. Though visualization around the spinal construct is certainly better with nonmetallic implants, much higher numbers and longer follow-up are needed to show this potential effect. In the end, the effect may be so small or the difference inconsequential to make a meaningful impact...
for patients. Currently, not placing pedicle screws at the primary/index site of surgery/disease, where it is most likely to recur, allows for acceptable visualization with current magnetic resonance imaging (MRI) hardware suppression protocols to visualize adjacent areas in most patients. Additionally, the future of treatment for patients with metastatic cancer will be progress in immunotherapy and targeted single transduction therapies that are now becoming more prevalent for specific cancers. Even if recurrence is detected, does it change what options the patient has? Many patients have already maximized radiation dose and are not fit for further surgery. Finally, the authors did not touch on the cost of such implants. Costs can certainly vary based on market and contracting agreements, but in general nonmetallic spinal implants come at a high markup over regular metallic implants. The cost-benefit ratio which needs to be carefully considered especially given the ongoing strained environment of the healthcare economy.

A subset of spinal oncology patients, however, may have the most to benefit from CFRPs and similar implants. Patients with malignant primary spinal tumors have limited systemic treatment options and therefore depend more readily on surgical excision and monitoring for progression free survival. The utility of such implants may be higher in these cases where there is lack of effective targeted therapies and surveillance is paramount. In this setting, the cost-benefit ratio may be in favor of CFRPs in early detection of residual or recurrence and in obviating the need for further invasive imaging tests such as computed tomography myelograms or repeated MRI’s. Overall, the authors have indeed demonstrated overall safety with using such implants in this paper, and I will be interested to see how overall clinical outcomes can be impacted by such innovations in the future.

- **Conflict of Interest:** The author has nothing to disclose.

**REFERENCES**

Robotics in Cervical Spine Surgery: Feasibility and Safety of Posterior Screw Placement

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Objective: Robot-assisted (RA) techniques have been widely investigated in thoracolumbar spine surgery. However, the application of RA methods on cervical spine surgery is rare due to the complex morphology of cervical vertebrae and catastrophic complications. Thus, the feasibility and safety of RA cervical screw placement remain controversial. This study aims to evaluate the feasibility and safety of RA screw placement on cervical spine surgery.

Methods: A comprehensive search on PubMed, Cochrane Library, Embase Database, Web of Science, Chinese National Knowledge Databases, and Wanfang Database was performed to select potential eligible studies. Randomized controlled trials (RCTs), comparative cohort studies, and case series reporting the accuracy of cervical screw placement were included. The Cochrane risk of bias criteria and Newcastle-Ottawa Scale criteria were utilized to rate the risk of bias of the included literatures. The primary outcome was the rate of cervical screw placement accuracy under robotic guidance; subgroup analyses based on the screw type and insertion segments were also performed.

Results: One RCT, 3 comparative cohort studies, and 3 case series consisting of 160 patients and 719 cervical screws were included in this meta-analysis. The combined outcomes indicated that the rates of optimal and clinically acceptable cervical screw placement accuracy under robotic guidance were 88.0% (95% confidence interval [CI], 84.1%–91.4%; p = 0.073; I² = 47.941%) and 98.4% (95% CI, 96.8%–99.5%; p = 0.167; I² = 35.954%). The subgroup analyses showed that the rate of optimal pedicle screw placement accuracy was 88.2% (95% CI, 83.1%–92.6%; p = 0.057; I² = 53.305%); the rates of optimal screw placement accuracy on C1, C2, and subaxial segments were 96.2% (95% CI, 80.5%–100.0%; p = 0.167; I² = 44.134X%), 89.7% (95% CI, 80.6%–96.6%; p = 0.370; I² = 0.000X%), and 82.6% (95% CI, 70.9%–91.9%; p = 0.057; I² = 65.127X%), respectively.

Conclusion: RA techniques were associated with high rates of optimal and clinically acceptable screw positions. RA cervical screw placement is accurate, safe, and feasible in cervical spine surgery with promising clinical potential.

Keywords: Robot, Cervical vertebrae, Accuracy, Spinal surgery, Meta-analysis

INTRODUCTION

Cervical screw instrumentation has been widely utilized in the treatment of cervical spinal diseases for the promising great properties in the biomechanical stabilization, pullout strength, and protection of spinal cord and nerve roots.1,2 However, the cervical region, an anatomically complex area, is adjacent to several vital structures, which are vulnerable to catastrophic

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complications from the malposition of cervical screws, including the neurological damage and vertebral artery injury. Moreover, the anatomical morphology of cervical vertebrae is complicated by alterations due to the cervical fractures and congenital malformation, increasing the difficulty of cervical screw insertions. Correspondingly, surgeons require years to gain sufficient experience to safely complete cervical screw instrumentation. Therefore, the demands for safety and accuracy of cervical screw placement drive advance in robot-assisted (RA) techniques on cervical spine surgery.

RA techniques have been widely and deeply investigated in thoracolumbar spine surgery, indicating promising clinical and radiographic outcomes. However, studies on the application of RA methods in cervical spine surgery are still limited. In 2016, Tian initially assessed the feasibility of TINAVI robot (TINA VI Medical Technologies, Beijing, China) for the posterior C1–2 transarticular screw placement in a case report, and concluded that the robotic guidance had a remarkable clinical potential in cervical spine surgery. Asuzu et al. performed a percutaneous screw fixation of a hangman’s fracture under the guidance of the Mazor X robot (Mazor Robotics Ltd., Caesarea, Israel), and achieved accurate screw insertions with satisfactory fracture reductions. In another case report conducted by Farah et al., 1 patient underwent C1–2 posterior percutaneous fixation using Cirq robot (Brainlab AG, Munich, Germany). Finally, all 4 screws were safely placed and rated as acceptable. In the 2020, Fan et al. conducted the first randomized controlled trial (RCT) comparing TINAVI RA techniques with conventional freehand (FH) methods in terms of the accuracy of cervical screw placement. They found that the RA techniques showed superiority to FH methods in accuracy and clinical outcomes in cervical spine surgery. This finding is consistent with the conclusions obtained from the comparative studies performed by Su et al., Lyu et al., and Zhan et al. However, the rates of cervical screw placement accuracy with RA methods varied widely ranging from 66.7% to 91.4% in the published literatures of comparative studies and case series. In addition, the application of RA system on cervical spine surgery is still in its early developmental stage, and whether the RA techniques are safe and accurate in cervical screw placement remains controversial.

Thus, this single-arm meta-analysis aims to demonstrate the safety and accuracy of cervical screw placement using the RA methods, which might provide references for surgeons in the selection of insertion methods and revolutionization of spinal surgeries, following improvement of RA techniques.

MATERIALS AND METHODS

1. Search Strategy

This research was performed in line with PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). The eligible studies were systematically searched from PubMed, Cochrane Library, Embase Database, Web of Science, Chinese National Knowledge Databases, and Wanfang Database without language restriction up to October 23, 2022. The following terms were searched in PubMed, Cochrane Library, Embase Database, and Web of Science: (“Cervical Vertebrae” [MeSH] or “Cervical Vertebra” or “Cervical Spines” or “Cervical Spine”) and (“Robotics” [MeSH] or robot or robotic). The keywords including “ji qi ren” and “jing zhui” were used in Chinese National Knowledge Databases, and Wanfang Database. The search strategy is shown in Supplementary Table 1. The inclusion of studies was determined by 2 reviewers, who independently screened the titles, abstracts, and full-text articles. Meanwhile, the reference lists and other relative studies were manually reviewed to identify additional worthy literature. Any disagreement was resolved by a third investigator.

2. Eligibility Criteria

The potentially relevant literatures were identified in accordance with the PICOS (Population, Intervention, Comparison, Outcomes, and Study) principle. The criterion of comparison was excluded due to the single-arm of this meta-analysis. (1) Population: The study population consisted of patients diagnosed with surgical indications in cervical spine. Studies involving cadavers or animals were excluded. (2) Intervention: RA techniques for cervical screw placement were performed in the single-arm or multi-arm studies. (3) Outcomes: Studies reporting the primary outcome, that is, the rate of cervical screw placement accuracy with robotic guidance, were eligible. Meanwhile, the subgroup analyses based on the screw type and insertion segments were performed. The assessment of screw position included the Gertzbein-Robbins, Rampersaud, and Ravi criteria. The screw completely within the trajectory, without cortex breach, was regarded as an optimal position; the screw breaching the cortex by < 2 mm was considered clinically acceptable; the screw breaching the cortex by ≥ 2 mm indicated malposition. (4) Study design: RCTs, comparative cohort studies, and case series were included, whereas case reports, reviews, and conference reports were excluded in this study.
3. Data Extraction
The data were extracted by 2 pairs of independent reviewers from the qualified researches, and the controversies were settled by a third reviewer. The parameters, including the accuracy of screw insertion, the first author, the year of publication, study design, area, age, sex, body mass index (BMI), robot type, sample size, and number of screws were obtained to study the characteristics.

4. Qualitative Analyses
The methodological quality of included RCT was evaluated using the Cochrane risk of bias criteria. In addition, the Newcastle-Ottawa Scale (NOS) criterion was used to rate the risk of bias in the selected comparative cohort studies and case series. For the comparative cohort studies, quality assessment was performed in respect to patient selection, comparability, and outcomes with the total score of 9, and the scores more than 6 represent high quality. For the case series, the comparability questions from NOS criteria were removed, and the scores range from 0 to 7; the final scores more than 4 represent high quality. The qualitative analyses were independently conducted by 2 reviewers, and disagreements were resolved through discussion to reach consensus.

5. Statistical Analyses
The statistical analyses were performed using STATA 15.1 (StataCorp LLC, College Station, TX, USA). The pooled rate and its 95% confidence interval (CI) of summarized cervical screw placement accuracy was estimated by performing a meta-analysis of proportions using the cases with RA techniques in each study. Simultaneously, the pooled results of estimated blood loss during surgery and operation time were also calculated. The F at a significance level of p < 0.05 was utilized to evaluate the statistical heterogeneity, and the sensitivity and subgroup analyses were conducted to determine the source of heterogeneity. A p-value of < 0.05 was regarded statistically significant.

RESULTS
1. Literature Search
The process of literature selection for inclusion in this research is shown in Fig. 1. In the preliminary search from all databases, 740 studies were inspected. Moreover, 12 additional articles were identified through the reference lists and other relative studies. After duplicate elimination, 527 articles underwent title and abstract assessment, maintaining 16 studies for full-text screen-
ing. Finally, 1 RCT, 13 3 comparative cohort studies, 14–16 and 3 case series 17–19 were included in our meta-analysis.

2. Characteristics of the Selected Studies

The baseline characteristics of the included studies are presented in Table 1. All 7 articles including 160 patients and 719 screws were newly published from 2020 to 2022. Among the included studies, 1 study was performed in Texas (the United States), 18 Marseille, (France), 17 Beijing (China), 13 Nanjing (China), 19 and Guangdong (China). 16 The 2 remaining studies were conducted in Shanghai (China). 14,15 The Mazor X Stealth/Medtronic 18 and Cirq/Brainlab 17 were used in one study, and the Ti-Robot/TINAVI 13–16,19 was reported in 5 studies.

3. Results of Qualitative Analyses

The quality of the RCT evaluated by Cochrane risk of bias criteria was moderate due to the high risk of blinding of participants and the personal and outcome assessment. Moreover, the 6 remaining studies were regarded as high quality, with 3 comparative cohort studies scored higher than 7, and 3 case series scored higher than 4, according to NOS criteria. The results of risk of bias for the selected studies are shown in Supplementary Tables 2, 3.

4. Outcomes of the Meta-Analysis

1) Accuracy of screw placement on cervical spine

A total of 719 cervical screws were placed in the 160 patients undergoing cervical spinal intervention with RA techniques. All the 7 studies 13–19 provided data on the optimal screw position that cervical screw was completely within the pedicle. The combined outcomes indicated that the rate of accuracy of cervical screw placement in RA methods was 88.0% (95% CI, 84.1%–91.4%; p < 0.001; I² = 47.941%) (Fig. 2).

Seven studies 13–19 provided data on the clinically acceptable screw position that pedicle cortical breach was less than 2 mm. The combined results presented that the rate of clinically acceptable screw position with RA techniques was 97.8% (95% CI, 95.2%–99.5%; p < 0.001; I² = 63.713%) (Supplementary Fig. 1). Considering the significant heterogeneity (I² = 63.713%, p = 0.011), sensitivity analysis was performed. After the sequential removal of the included researches, the result indicated that the study of Farah et al. 17 led to the heterogeneity. After the exclusion of the study, the combined outcomes based on the remaining 6 studies 13,16,18,19 showed that the rate of clinically acceptable screw position was 98.4% (95% CI, 96.8%–99.5%; p < 0.001; I² = 35.954%) (Fig. 3).

Table 1. Characteristics of included studies

<table>
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<tr>
<th>Study</th>
<th>Study design</th>
<th>Area</th>
<th>Period</th>
<th>No. of Screws</th>
<th>No. of patients</th>
<th>Age (yr)</th>
<th>Sex, male: female</th>
<th>BMI (kg/m²)</th>
<th>Robot type</th>
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<td>Farah et al. 2021</td>
<td>CS</td>
<td>Marseille, France</td>
<td>February 2020–December 2020</td>
<td>7</td>
<td>4/3</td>
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<td>21.8 (17–38.05)</td>
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<td>33</td>
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<td>14.8 ± 3.96</td>
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<td>60.40 ± 4.99</td>
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<td>23.3 ± 3.52</td>
<td>TiRobot/TINAVI</td>
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<td></td>
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BMI, body mass index; RCT, randomized controlled trial; Retro, retrospective comparative trial; CS, case series; Pro, prospective comparative trial; NR, not reported.
Fig. 2. Forest plot showing that the rate of optimal accuracy of cervical screw placement in robot-assisted methods was 88.0% (95% CI, 84.1%–91.4%; \( I^2 = 47.941\% \); \( p = 0.073 \)). ES, effect size; CI, confidence interval.

Fig. 3. Forest plot showing that the rate of clinically acceptable accuracy of cervical screw placement in robot-assisted methods was 98.4% (95% CI, 96.8%–99.5%; \( I^2 = 35.954\% \); \( p = 0.167 \)). ES, effect size; CI, confidence interval.

2) Subgroup analyses of pedicle screw placement on cervical spine

A total of 597 cervical pedicle screws were used in patients with RA techniques. The study of Fan et al.\textsuperscript{13} with 86 pedicle screws was excluded due to the absence of illustration on the number of patients undergoing pedicle screws. Therefore, the combined outcomes based on the 6 studies\textsuperscript{14–19} with 99 patients and 511 screws showed that with RA techniques, the rate of optimal pedicle screw position was 88.2% (95% CI, 83.1%–92.6%; \( p < 0.001 \); \( I^2 = 53.305\% \)) (Fig. 4).

For the clinically acceptable pedicle screw position, the com-
combined outcomes based on the 6 studies\textsuperscript{14-19} showed that the rate of clinically acceptable screw position was 97.4% (95% CI, 93.6%–99.7%; \( p < 0.001; I^2 = 66.955\%\)) (Supplementary Fig. 2). The heterogeneity was significantly high (\(I^2 = 66.955\%, p = 0.010\)), which resulted from the study of Farah et al.\textsuperscript{17} detected using sensitivity analysis. Finally, the combined outcomes based on the remaining 5 studies\textsuperscript{14-16,18,19} with 92 patients and 490 screws indicated that the rate of clinically acceptable pedicle screw position was 98.4% (95% CI, 96.1%–99.8%; \( p < 0.001; I^2 = 42.156\%\)) (Supplementary Fig. 3).

3) Subgroup analyses of accuracy of screw placement on C1 segment

Three studies\textsuperscript{16,17,19} provided data on the screw position on C1 segment. The combined outcomes indicated that the rate of optimal screw position on C1 segment was 96.2% (95% CI, 80.5%–100.0%; \( p < 0.001; I^2 = 44.134\%\)) (Supplementary Fig. 4), and the rate of clinically acceptable screw position with RA techniques was 100.0% (95% CI, 98.0%–100.0%; \( p < 0.001; I^2 = 0.000\%\)) (Supplementary Fig. 5).

4) Subgroup analyses of accuracy of screw placement on C2 segment

Three studies\textsuperscript{16,18,19} provided data on the screw position on C2 segment. The combined results showed that the rate of optimal screw position on C2 segment was 89.7% (95% CI, 80.6%–96.6%; \( p < 0.001; I^2 = 0.000\%\)) (Supplementary Fig. 6), and the rate of clinically acceptable screw position with RA techniques was 97.1% (95% CI, 90.4%–100.0%; \( p < 0.001; I^2 = 0.000\%\)) (Supplementary Fig. 7).

5) Subgroup analyses of accuracy of screw placement on subaxial cervical segments

Three studies\textsuperscript{17,18} provided data on the screw position on subaxial cervical segments. The combined results showed that the rate of optimal screw position on subaxial cervical segments was 82.6% (95% CI, 70.9%–91.9%; \( p < 0.001; I^2 = 65.127\%\)) (Supplementary Fig. 8), and the rate of clinically acceptable screw position with RA techniques was 96.4% (95% CI, 84.5%–100.0%; \( p < 0.001; I^2 = 83.735\%\)) (Supplementary Fig. 9).

DISCUSSION

The application of RA techniques in the cervical spine surgery remains relatively nascent compared with that in thoracolumbar regions, because the surgery on cervical spine, especially the upper cervical spine, is almost the most complex and risky spinal surgery with steep learning curve.\textsuperscript{10} Recently, RA techniques have been increasingly utilized in cervical spine surgery, showing promising accuracy of screw insertion. In the RCT per-
formed by Fan et al., 13 87.6% of the 186 cervical screws in RA groups were graded as optimal position, whereas this proportion in FH group was only 60.8% in 204 cervical screws. Su et al., 14 prospectively enrolled 58 patients and 374 cervical pedicle screws in RA and FH cohorts, respectively, and demonstrated that the rate of optimal accuracy of screw insertion was remarkably higher in the RA group (90.6%) than that in the FH group (71.1%). In the 2 retrospective cohort studies, the accuracies of cervical screw placement were 84.1%–91.8% and 49.2%–73.2% in RA and FH groups, respectively. 15,16 Our meta-analysis demonstrated that the rates of optimal and clinically acceptable screw positions in RA techniques were 88.0% and 98.4%, respectively. Moreover, cervical pedicle screw placement has been widely used due to the biomechanically satisfactory fixation and pull-out strength. Thus, the subgroup analysis based on the cervical pedicle screws were also performed. We found that for pedicle screws, the rates of optimal and clinically acceptable screw positions with RA methods were 88.2% and 97.4%, respectively, showing promising insertion accuracy. The combined outcomes indicate that the RA techniques are feasible and safe in cervical screw placement, as explained in the follow statements. First, robotic system can identify the ideal entry point and trajectory for accurate screw insertion based on the 3-dimensional (3D) computed tomography (CT) reconstructions. 26 In the trajectory view, the RA techniques were reported to deviate screws from preoperative planning by 1.32 ± 1.17 mm in the axial plane and by 1.27 ± 1.00 mm in the sagittal plane with low rate of cortical breaches. 18 However, for the conventional FH methods, the entry point and trajectory are assessed through x-ray fluoroscopy, and the accuracy of screw insertion depends heavily on the surgical experience and skills of surgeons. Moreover, cervical fractures and congenital malformation in patients increase the operative difficulty in FH methods. Thus, the RA technique can reduce human error and the rate of malposition. In addition, the robotic system is associated with high stability on the accurate insertion. Surgeons might experience fatigue due to the long surgical time and complex operation in traditional FH procedures, thereby increasing the likelihood of malposition. By contrast, RA methods have reliable reproducibility and fatigue resistance, further improving the safety and accuracy in cervical spine surgery.

Computer-assisted navigation (CAN) techniques have also been applied as an alternative selection to improve the insertion accuracy. Chachan et al. 27 prospectively included 241 cervical screws under the O-arm based CAN, and found that 92.95% of the screws caused no pedicle breach. Moreover, none of the screws resulted in neurovascular injury, showing promising clinical outcomes. Meanwhile, Gan et al. 28 and Zhang et al. 29 drew similar outcomes that 22.9% and 29.7% of the cervical screws with CAN breached the pedicles but without intraoperative or postoperative complication caused by malposition. However, in the study of Farber et al., 30 CAN cohort did not present remarkably improved rate (64.0%) of accuracy in transpedicular screw placement compared with the direct visualization group (88.0%) in the subaxial cervical pedicle screw insertion. Our meta-analysis showed that the accurate rate of cervical screw placement with RA techniques was 88.0%, which was higher than the results of insertion accuracy with CAN reached by Gan et al. 28 (77.1%), Zhang et al. 29 (70.3%), and Farber et al. 30 (64.0%). With CAN techniques, the position of screw during insertion procedures can be tracked real time. However, the entry point and trajectory are ultimately determined by surgeons, requiring rich surgical experience and professional judgment based on the 3D imaging. 27 In addition, the attention of surgeon is easily distracted from screw insertion when focusing on the navigation screen. Thus, remarkable hand-eye coordination is required with CAN methods. 31 Meanwhile, the surgeons should maintain stable arm as much as possible during the operation because the cervical segments are not rigidly connected to the navigation recognition frame; thus, they are prone to errors due to relative motion. 18 By contrast, the entry point and trajectory were automatically identified in RA methods, which required short learning curves for surgeons. 32 Moreover, the arm of the robotic system can operate in a real-time dynamic compensation mode, thereby reducing error-prone movements and improving insertion accuracy.

The anatomical morphologies of atlas, axis, and subaxial cervical vertebrae varied largely, probably resulting in outcome bias on the accurate rate of cervical screw placement. Therefore, the subgroup analyses on cervical segments of C1, C2, and subaxial cervical vertebrae were conducted to determine the influence of cervical levels on the accuracy of screw insertion. The current study has demonstrated that the rates of optimal screw positions on C1, C2, and subaxial cervical segments with RA techniques were 96.2%, 89.7%, and 82.6%, respectively, which were broadly consistent with previous studies. In the study of Li et al., 13 the rates of optimal pedicle position on C1 and C2 with RA techniques were 97.06% and 91.67%, respectively, whereas the rate of subaxial levels was 88.3%, and the lowest rate of accuracy was 71.4% on C4. Mao et al. 33 performed RA cervical screw placements on C2–C7 segments in 4 cadaver specimens. They found that the rate of breach on C2 was 16.6%, whereas
the breach distributions on C3–C7 were 71.4%, 66.6%, 50.0%, 33.3%, and 25.0%. Moreover, they further analyzed the anatomical metrics, demonstrating that the mean pedicle height was largest in C2, and the pedicle width of C2 was larger than those of C3 and C4. Thus, the accuracy of screw placement on C2 was higher than that on subaxial segments. Furthermore, the mean width of C1 lateral mass was 13.7 mm, as reported by Lin et al.\(^4\); it was larger than that of C2 lateral mass (9.9 mm), which was measured by Ji et al.\(^3\) presenting larger safe zones for screw insertion in the atlas. Moreover, the limitation of pedicle screw utilization on C2 was the pedicle width with the average lengths of 5.50 and 3.97 mm at the middle and lower parts; whereas the limitation of pedicle screw utilization on C1 was the posterior vertebral groove height with the average length of 4.9 mm.\(^3\)\(^\text{36}\)\(^\text{34}\)

Furthermore, a study by Huang et al.\(^3\)\(^7\) further revealed that a 3.5- or 4.0-mm-diameter screw can be safely inserted into the C1 pedicle with the posterior vertebral groove height less than 4.0 mm, when the C1 pedicle has a medullary canal. Therefore, the rate of cervical screw placement on C1 level might be higher than that on C2 segment.

Robotic systems in cervical spine surgery also showed promising clinical outcomes compared with FH methods, including less blood loss during surgery and shorter length of hospital stay after surgery.\(^1\)\(^3\)\(^\text{16}\) Menger et al.\(^3\)\(^8\) reported that the application of RA methods on spine surgery was cost-effective with less revision surgery and low infection rate. In the current study, we have found that the combined blood loss during surgery was 197.67 mL, and the combined operation time was 268.88 minutes with RA methods. In addition, RA methods were associated with remarkably less radiation time and radiation dose to patients and surgeons than conventional FH methods.\(^1\)\(^4\)\(^\text{16}\) In the conventional FH cervical surgery to guarantee insertion accuracy, the fluoroscopies were repeatedly performed to adjust the screw deviation. RA methods mainly required preoperative planning with 3D CT scans and postoperative verification with a fluoroscopy in a fast speed. Lieberman et al.\(^3\)\(^9\) reported that the RA methods might reduce 40% to 70% intraoperative radiation exposure for patients, surgeons, and operating-room personnel compared with the FH methods. Regarding the clinical outcomes under robotic guidance, further studies are required to assess the utility in the future work.

There are potential risks of RA cervical instrumentation. The drift and deviation are very important risk in all cervical posterior instrumentation surgery. The drift and deviation of cervical screws from preplanned entry point and trajectory due to pressure of soft tissues and irregular bony surfaces might cause insertion errors, which increase the risk of neurological and vascular complications.\(^\text{32}\) Meanwhile, the cervical spine easily bends, and 3 levels away from the reference tracker were the risk factors for malposition in not only RA pedicle screw placement but also CAN method. Moreover, the imaging software in the robotic systems should be updated and enhanced for better image registration and reduction of the draft from tidal volume during mechanical ventilation.\(^3\)\(^8\) The slight deviation causing no complications in thoracolumbar insertion might contribute to fatal consequences in cervical instrumentation, the avoidance of which demands elevated technical innovation. Besides, according to a study by Zhang et al.\(^4\)\(^1\) among 163 patients and 780 screws, severe obesity (BMI ≥ 30 kg/m\(^2\)), osteoporosis, and segments 3 levels away from the tracker were the risk factors for malposition in RA pedicle screw placement. Furthermore, the penetration level of robotic systems is still relatively low due to the expensive robotic equipment for hospitals and high medical expenses for patients. In addition, serious complications such as neurovascular injury and cerebrospinal fluid leakage due to the screw fixations might result in catastrophic consequences. In the current research, 6 of the included 7 studies reported the complications due to RA screw malposition, but no serious complications were observed in the 6 literatures.\(^1\)\(^4\)\(^\text{19}\) Thus, the meta-analysis on the complications was not performed.

The challenges, including the technical difficulties, fiscal investment, learning curves, and minor improvements in clinical outcomes, would inevitably arise in the penetration and popularity of a new technology.\(^4\) With modification and revolution of skills and techniques, the RA techniques not only expand the approaches to cervical surgery, but also redefine the concept of cervical surgery.\(^4\)\(^1\) For instance, RA methods conform to the minimal invasion and rapid rehabilitation surgery concept. Patients suffering from the displaced atlas fractures could receive the minimally invasive percutaneous lag screw insertion with RA methods for rapid rehabilitation, instead of the traditional medical interventions of external reduction with skull traction and immobilization with a Halo-vest. Furthermore, the real-time remote surgery can be implemented based on fifth generation wireless system (5G) and RA techniques. Tian et al.\(^4\)\(^1\) assessed the efficacy and feasibility of 5G telerobotic spinal surgery on 12 patients with spinal disorders, concluding that 5G remote RA surgery is accurate and reliable with safety. In the assistance with 5G remote RA application, patients requiring cervical surgery in emergency can nearby receive remote intervention from surgeons with excellent skills and rich experience, and patients in remote rural areas can receive spinal surgery conducted by
experts worldwide. At present, the robotic systems only work as assistive tools for accurate insertion, but the spinal robots might transform as a major or an independent surgical operator with the development of robotic technology in the future.

Several potential weaknesses of this meta-analysis exist. First, the current single-arm meta-analysis has only demonstrated the safety and accuracy of RA cervical screw placement without the conventional FH methods as control group. Only a few studies compared RA and FH methods in terms of the clinical and radiographic outcomes because the robotic guidance on cervical spine is still a new clinical and applied technique. Thus, the meta-analysis comparing the 2 methods cannot be performed. Nevertheless, this research presented the safety and feasibility of RA cervical screw and provided references for surgeons and technologists. Second, 5 studies were conducted in China. However, the 5 studies were performed in 4 different areas with large geographical distances, which might not bias the combined outcomes of this study in terms of the publication areas. Third, the clinical outcomes, including the blood loss during surgery and operation time, might be biased due to surgical segments, the number of inserted screws, and the number of surgical levels. Thus, the meta-analyses on these clinical results were not performed. Fourth, only 7 studies with 160 patients and 719 cervical screws were included. More RCTs and prospective cohort studies with large samples were urgently required for high levels of evidence to support this recommendation.

**CONCLUSION**

RA techniques were associated with high rates of optimal and clinically acceptable screw positions. RA cervical screw placement is accurate, safe, and feasible in cervical spine surgery with promising clinical potential.

**NOTES**

**Supplementary Materials:** Supplementary Tables 1-3 and Figs. 1-9 can be found via https://doi.org/10.14245/ns.2244952.476.

**Conflict of Interest:** The authors have nothing to disclose.

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**Author Contribution:** Conceptualization: LPZ, ZGZ, RJZ, CLS; Data curation: LPZ, ZGZ, DL, RS, RJZ; Formal analysis: ZGZ, D Li, SF; Funding acquisition: CLS; Methodology: LPZ, D Li, RJZ, CLS; Project administration: CLS; Visualization: LPZ, ZGZ, SF, CLS; Writing - original draft: LPZ; Writing - review & editing: ZGZ, DL, SF, RS, RJZ, CLS.

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32. Pennington Z, Judy BF, Zakaria HM, et al. Learning curves in robot-assisted spine surgery: a systematic review and pro-
posal of application to residency curricula. Neurosurg Focus 2022;52:E3.


### Supplementary Table 1. Search strategy for each database

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| Chinese National Knowledge Databases | #1 "ji qi ren" [TS]  
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**Supplementary Table 2.** Risk of bias assessment of the randomized controlled trial study

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### Supplementary Table 3. Risk of bias assessment of the included nonrandomized controlled trials

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Supplementary Fig. 1. Forest plot showing that the rate of clinically acceptable accuracy of cervical screw placement before sensitivity analysis in robot-assisted methods was 97.8% (95% CI, 95.2%–99.5%; $I^2 = 63.713\%$). ES, effect size; CI, confidence interval.
Supplementary Fig. 2. Forest plot showing that the rate of clinically acceptable accuracy of cervical pedicle screw placement before sensitivity analysis in robot-assisted methods was 97.4% (95% CI, 93.6%–99.7%; $I^2 = 66.955\%$). ES, effect size; CI, confidence interval.
Supplementary Fig. 3. Forest plot showing that the rate of clinically acceptable accuracy of cervical pedicle screw placement in robot-assisted methods was 98.4% (95% CI, 96.1%–99.8%; $I^2 = 42.156\%$). ES, effect size; CI, confidence interval.
**Supplementary Fig. 4.** Forest plot showing that the rate of optimal accuracy of cervical screw placement on C1 segment in robot-assisted methods was 96.2% (95% CI, 80.5%–100.0%; $I^2 = 44.134\%$). ES, effect size; CI, confidence interval.
Supplementary Fig. 5. Forest plot showing that the rate of clinically acceptable accuracy of cervical screw placement on C1 segment in robot-assisted methods was 100.0% (95% CI, 98.0%–100.0%; I² = 0.000%). ES, effect size; CI, confidence interval.
Supplementary Fig. 6. Forest plot showing that the rate of optimal accuracy of cervical screw placement on C2 segment in robot-assisted methods was 89.7% (95% CI, 80.6%–96.6%; $I^2 = 0.000\%$). ES, effect size; CI, confidence interval.
Supplementary Fig. 7. Forest plot showing that the rate of clinically acceptable accuracy of cervical screw placement on C2 segment in robot-assisted methods was 97.1% (95% CI, 90.4%–100.0%; $I^2 = 0.000$%). ES, effect size; CI, confidence interval.
Supplementary Fig. 8. Forest plot showing that the rate of optimal accuracy of cervical screw placement on subaxial cervical segments in robot-assisted methods was 82.6% (95% CI, 70.9%–91.9%; $I^2 = 65.127\%$). ES, effect size; CI, confidence interval.
Supplementary Fig. 9. Forest plot showing that the rate of clinically acceptable accuracy of cervical screw placement on subaxial cervical segments in robot-assisted methods was 96.4% (95% CI, 84.5%–100.0%; $I^2 = 83.735\%$).
Commentary on “Robotics in Cervical Spine Surgery: Feasibility and Safety of Posterior Screw Placement”

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Over the last few decades, emerging technologies and high-end equipment have rendered minimally invasive spine surgery (MISS) the standard of care for several different spinal procedures. Compared to traditional open surgery, MISS has demonstrated to significantly reduce blood loss, hospital stay, surgical site infection, and postoperative narcotic requirements.1 In this regard, the use of spinal navigation technologies for percutaneous pedicle screw and interbody cage placement has allowed a more efficient workflow and improved safety in MISS procedures.2,3 Moreover, robotic-assisted (RA) systems have been introduced as competitive or complementary tools to the use of spinal navigation.4,5 To date, safety and efficacy of navigated thoracolumbar instrumentation has been extensively demonstrated. Indeed, increased accuracy with navigated screw placement has been associated with promising clinical and radiographic outcomes. Therefore, the advantages and feasibility of spinal navigation in thoracolumbar spine surgery are well established.4

However, the application of RA techniques in cervical spine surgery has been delayed due to the unique anatomical and biomechanical characteristics of the cervical spine. During surgery, the cervical segment is substantially more mobile compared to the thoracolumbar spine, especially when applying pressure on bony structures. Unwanted movements can lead to screw misplacement due to deviation from preplanned entry point and trajectory of RA instruments, with possibly devastating neurovascular complications. In addition, the cervical spine is characterized by a considerable anatomic variability, especially in case of severe trauma, advanced degeneration, and developmental abnormalities.6 These aspects must be carefully taken into account by the surgeon experienced in thoracic and lumbar RA MISS techniques when operating on the cervical spine.

In this paper,7 the authors have performed a single-arm meta-analysis to evaluate feasibility, safety and accuracy of cervical screw placement using RA tools. More specifically, the authors have systematically reviewed all available studies in which cervical spine instrumentation was performed with RA methods and screw accuracy was reported as the primary outcome. Secondary outcomes included mean blood loss and average operation time. Unsurprisingly, the quality of extracted evidence was limited by the moderate risk of bias of the only randomized controlled trial included, while remaining manuscripts were composed of small cohort studies or noncontrolled case series. Moreover, most included papers reported the use of TiRobot (Tinavi Medical Technologies, Beijing, China), which is not li-
enced for use outside China, thus further limiting the generalizability of results. Overall, the authors reported that 97.8% of the screws were clinically acceptable, namely fully intrapedicular without breach of the pedicle cortex or with a cortical breach < 2 mm, corresponding to Gertzbein and Robbins grades A and B, respectively. Interestingly, the rate of Gertzbein and Robbins grade A screws reached 96.2% in instrumented C1 vertebrae, while dropping to 89.7% in C2 and 82.6% in subaxial vertebrae. This can be imputed by the considerable variability of pedicle width in the subaxial cervical spine, which may have hampered optimal screw placement.3 However, the percentage of clinically acceptable screws was still higher than 95% in all subgroups.

Furthermore, the authors have reported that RA cervical spine instrumentation resulted in a mean blood loss of 197.67 mL and an average operative time of 268.88 minutes. While reduced blood loss is advantageously correlated with decreased surgical invasiveness and lesser anatomical exposure, longer operation time is a significant drawback of contemporary computer-assisted navigation (CAN) and RA tools in spine surgery. This may result from a combination of several factors, including increased setup time, steep learning curve, need for intraoperative recalibration and readjustment, additional staff requirements, and technical issues. Nonetheless, the use of spinal navigation and RA technologies has been associated with reduced intraoperative radiation exposure, lower surgical site infection rates, and diminished hospital stay.10 Although promising, the data presented in this study should be cautiously interpreted. Due to the paucity of controlled trials, the lack of a comparative meta-analysis does not allow to draw scientifically sound conclusions on safety and efficacy of RA screw placement in cervical spine surgery. Indeed, additional studies directly comparing RA techniques with conventional free-hand or CAN approaches are required to confirm feasibility and superiority of the former. This also poses relevant ethical issues, as allocating patients to a less advanced technology, although established for decades as the standard of care, might not be acceptable in all clinical contexts. Furthermore, as adverse events occurring in included studies have not been analyzed and discussed, attention must be paid to the definition of surgical safety.

While still in its infancy, RA cervical spine surgery appears a promising field which may potentially revolutionize the surgical treatment of increasingly common conditions. Though technological advancements offer new tools at a relentless pace, there is an urgent need in the spine community to gather high-quality data that may corroborate safety, efficacy, and cost-effectiveness of MISS approaches. Indeed, most clinical studies investigating the applicability of novel technologies in spine surgery are usually poorly designed, noncontrolled and without enough statistical power to detect clinically meaningful differences. As a result, despite intriguing innovations, most quantitative analyses and evidence summaries conclude that there is no recommendation in favor or against the majority of discussed points.11 We are optimistic that high-quality research in the next future will definitely shed a bright light on the immense potential of RA technology in spine surgery.

- **Conflict of Interest:** The authors have nothing to disclose.

**REFERENCES**


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Pediatric Spinal Hemangioblastomas: Clinical Features and Surgical Outcomes of 39 Cases

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²National Cancer Center/National Clinical Research Center for Cancer/Hebei Cancer Hospital, Chinese Academy of Medical Sciences, Langfang, China
³National Cancer Center/National Clinical Research Center for Cancer/Cancer Hospital, Chinese Academy of Medical Sciences and Peking Union Medical College, Beijing, China

Objective: Spinal hemangioblastomas (HBs) are a rare pathology, especially in the pediatric population. The natural history and long-term outcomes of pediatric patients with spinal HBs remain unclear due to their scarcity.

Methods: A retrospective review of the clinical data and treatment outcomes of children with spinal HBs in our institution from 2012 to 2021 was conducted.

Results: Thirty-nine pediatric patients were included, with an average age of 15.9 ± 2.9 years (range, 8–18 years), and 51.3% were female. Children were more likely to have von Hippel-Lindau (VHL) disease (p < 0.001), a family history of VHL (p < 0.001), multiple symptoms (p = 0.006), a shorter duration of symptoms (p < 0.001), and a larger lesion size (p = 0.004) and volume (p = 0.008) than their adult counterparts. The VHL-associated group of patients was more likely to present with multiple symptoms (p = 0.026), have a family history of VHL (p < 0.001), have multiple HBs (p < 0.001) and have synchronous intracranial lesions (p < 0.001) than the sporadic group. After surgery, 15 patients (38.5%) showed improved clinical outcomes, 17 patients (43.6%) remained unchanged, 4 patients (10.2%) worsened, and 3 patients (7.7%) died of tumor progression. During follow-up, there was a high rate of recurrence and repeated surgery, especially for children in the VHL-associated group.

Conclusion: Pediatric patients with spinal HBs appear to have a higher relapse risk than their adult counterparts. Therefore, life-long follow-up of these patients is necessary, especially for VHL-associated cases. Surgery can benefit children with HBs and should be considered early to avoid irreversible neurological deterioration.

Keywords: Hemangioblastoma, Pediatrics, von Hippel-Lindau disease, Spinal cord, Natural history

INTRODUCTION

Spinal hemangioblastomas (HBs) are benign, hypervascular entities that may either present sporadically or be associated with von Hippel-Lindau (VHL) disease.¹⁻⁴ HBs, together with an accompanying cyst/syrinx, may trigger symptoms as they expand and mechanically compress the spinal cord or the nerve root. HBs account for 2%–6% of all spinal cord neoplasms and usually affect adults in their 3rd–4th decades.⁵⁻⁶ Patients may experience disease progression in the form of local recurrence, distant tumor progression or formation of new HBs after surgery.⁷⁻⁸

Pediatric patients with spinal HBs are rarely encountered, and these cases are usually reported conjointly with adult or intracranial HBs.⁹⁻¹² Moreover, despite being biologically identical, children with HBs may be different from their adult counterparts.¹¹⁻¹² The optimal management strategy, prognostic factors, and surgical outcome are still controversial, and the proper sur-
gical timing and follow-up strategy are unclear. Since the optimal management decision-making and follow-up strategy is mainly based on realizing the natural history of the disease, this study was undertaken to identify the clinical features and prognosis of pediatric patients with spinal HBs.

MATERIALS AND METHODS

Pediatric patients (≤ 18 years) treated with spinal HBs from January 2012 to January 2021 in our institution were identified and enrolled in this study. Clinical characteristics, magnetic resonance imaging (MRI) features, treatment strategies, and follow-up data were collected and analyzed. Patient charts were collected after obtaining permission from the Institutional Review Board of Beijing Tiantan Hospital, Capital Medical University (KY 2022-112-02-2). All human studies were approved by the appropriate ethics committee and therefore performed in accordance with the ethical standards defined in the 1964 Declaration of Helsinki.

VHL was determined through genetic analyses with the presence of established clinical diagnostic criteria (≥ 1 VHL-associated HBs with a family history of VHL, or ≥ 2 VHL-associated HBs regardless of family history). The Modified McCormick Scale (MMCS) was used to evaluate neurological function (Table 1). The tumor size was defined as the largest diameter of solid part, not including the extratumoral cysts or edema. The extent of resection (EOR) was defined as total, subtotal, or partial. Disease progression was divided into local recurrence or formation of new HBs on MRI during the follow-up period.

After discharge, all patients were routinely followed at clinics at 3, 6, and 12 months, and subsequently assessed on a yearly basis either by telephone or outpatient visits. MRI was routinely performed in the first 2 years after discharge, then according to patients’ compliance or for new onset of symptoms to assess for tumor recurrence. Neurological changes and imaging features were evaluated at each visit and compared with previous data. The last follow-up was performed in May 2022.

Baseline characteristics were summarized using descriptive statistics. χ² test (parametric) or Fisher exact test (nonparametric) were used to compare categorical variables, and Student t-test (parametric) or the Wilcoxon rank-sum test (nonparametric) were used to compare continuous variables between the 2 groups by using IBM SPSS Statistics ver. 22.0 (IBM Co., Armonk, NY, USA). Kaplan-Meier and cox proportional hazards methods were used for time to event analysis for recurrence on follow-up. Probability values < 0.05 were considered statistically significant. All p-values were reported as 2 sided.

RESULTS

1. Baseline Characteristics

Thirty-nine eligible pediatric patients treated with HBs were included; 157 adults with HBs were also included for the comparison of clinical characteristics. Five children (12.8%) underwent 3-dimensional computed tomography angiography preoperatively, and 7 patients (17.9%) underwent cerebral HB resection before admission. The mean age of the children was 15.9 ± 2.9 years (range, 8–18 years) (Fig. 1); female predominance (51.3%) was found among the pediatric patients, which was different from the male predominance (54.8%) in the adult group. Pediatric patients had a higher prevalence of VHL (p < 0.001), family history of VHL (p < 0.001), and multiple HBs (p =

<table>
<thead>
<tr>
<th>Grade</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Neurologically intact, ambulates normally, may have minimal dysesthesia</td>
</tr>
<tr>
<td>2</td>
<td>Mild motor or sensory deficit, maintains functional independence</td>
</tr>
<tr>
<td>3</td>
<td>Moderate deficit, limitation of function, independent with external aid</td>
</tr>
<tr>
<td>4</td>
<td>Severe motor or sensory deficit, dependent with external aid</td>
</tr>
<tr>
<td>5</td>
<td>Paraplegia or quadriplegia</td>
</tr>
</tbody>
</table>

Fig. 1. Age distribution of 39 children with spinal hemangioblastomas.
Symptoms in children on admission were mainly sensory disturbance (n = 26, 66.7%), limb weakness (n = 23, 58.9%), and pain (n = 25, 64.1%), followed by urinary/bowel disturbance (n = 8, 20.5%), and spinal spondylosis or scoliosis (n = 5, 12.8%), and these symptoms were consistent with those in the adult patient population. Pediatric patients had a much shorter duration of symptoms (7.1 months vs. 33.3 months, p < 0.001) and more symptoms (p = 0.007) than adults. On admission, neurological disability was mostly MMCS grade 1 and grade 2 in both pediatric and adult patients.

The lesion location was mostly in the thoracic (n = 24, 54.6%) segment in the pediatric group, followed by the cervical (n = 14, 31.8%) segment, which was different from an obvious cervical predominance (n = 106, 58.2%) in the adult group. Pediatric patients had a larger lesion size (p = 0.004) and volume (p = 0.008) as well as a higher proportion with lesion size ≥ 2 cm (p = 0.003) and volume ≥ 2 cm³ (p = 0.001) than adults. No statistically significant differences were found between the 2 groups in terms of sex, lesion site, or associated cerebral lesion signals on presentation (Table 2). A typical MRI features of HBs can be seen in Fig. 2.

2. Sporadic and VHL Associated Spinal HBs

Children in the VHL-associated group were more likely to present with multiple symptoms (p = 0.026), have a family history of VHL (p < 0.001), have concurrent cerebral HBs (p < 0.001), and have multiple spinal HBs (p < 0.001). The mean maximum size and volume of the lesion were larger in the VHL associated group than in the sporadic group (p = 0.035 and 0.010, respectively), and there was a higher proportion of lesions ≥ 2 cm (p = 0.012) and ≥ 2 cm³ (p = 0.001) in the VHL associated group. No difference in age, sex distribution, symptom duration, function status, lesion level or site between the sporadic and VHL associated groups was observed (Table 3). Additionally, children in the VHL-associated group had a higher recurrence rate than children in the sporadic group (p = 0.008).

3. Surgical Details and Intraoperative Findings

The operation was performed via a conventional posterior midline approach, and somatosensory-evoked and motor-evoked potentials were routinely used to monitor neurological function. Removal of the solid HBs abided by the principles of arteriovenous malformation dissection. After laminectomy/myelotomy, the feeding arteries and dark-red or purplish-red HBs can usually be found. The HBs were circumferentially microdissected along the tumor-pial margin, and the feeding arteries were coagulated to reduce blood flow. The HBs were removed en bloc, rather than piecemeal, to avoid extensive bleeding. For cystic HBs, the nodule of HBs was excised microsurgically, but the peritumoral cyst walls and the associated syringes were left unmanipulated.

Fig. 2. Magnetic resonance imaging (MRI) features of a 15 years old boy with spinal hemangioblastomas (HBs). Preoperative MRI shows a solid HBs at C3–4 level with iso-hyperintensity on T2-weighted images (A), and significant heterogeneous enhancement on sagittal (B) and coronal (C) view. The HB is associated with complex syrinx and perilesional edema. Computed tomography angiography can reveal the feeding arteries that comes from branches of left vertebral artery and the anterior spinal artery.

https://doi.org/10.14245/ns.2244970.485
Table 2. Comparison of characteristics between pediatric and adult patients with spinal hemangioblastomas

<table>
<thead>
<tr>
<th>Variable</th>
<th>Total (n = 196)</th>
<th>Pediatric (n = 39)</th>
<th>Adult (n = 157)</th>
<th>p-value</th>
</tr>
</thead>
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<tr>
<td><strong>Clinical characteristics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age (yr)</td>
<td>35.9 ± 14.9 (8–68)</td>
<td>15.9 ± 2.9 (8–18)</td>
<td>41.4 ± 12.5 (19–68)</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Sex</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>105 (53.6)</td>
<td>19 (48.7)</td>
<td>86 (54.8)</td>
<td>0.497</td>
</tr>
<tr>
<td>Female</td>
<td>91 (46.4)</td>
<td>20 (51.3)</td>
<td>71 (45.2)</td>
<td></td>
</tr>
<tr>
<td>Symptoms</td>
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<td></td>
<td></td>
<td>0.332</td>
</tr>
<tr>
<td>Sensory</td>
<td>155 (79.1)</td>
<td>26 (66.7)</td>
<td>129 (82.2)</td>
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</tr>
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<td>Motor</td>
<td>103 (52.6)</td>
<td>23 (58.9)</td>
<td>80 (51.0)</td>
<td>0.369</td>
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<tr>
<td>Pain</td>
<td>112 (57.1)</td>
<td>25 (64.1)</td>
<td>87 (55.4)</td>
<td>0.326</td>
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<td>Sphincter disorders</td>
<td>32 (16.3)</td>
<td>8 (20.5)</td>
<td>24 (15.3)</td>
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<td>Others</td>
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<td>5 (12.8)</td>
<td>8 (5.1)</td>
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</tr>
<tr>
<td>No. of symptoms</td>
<td>2.2 ± 0.9 (1–4)</td>
<td>2.6 ± 1.0 (1–4)</td>
<td>2.1 ± 0.9 (1–4)</td>
<td>0.007*</td>
</tr>
<tr>
<td>Symptoms ≥ 2</td>
<td>141 (71.9)</td>
<td>35 (89.7)</td>
<td>106 (67.5)</td>
<td>0.006*</td>
</tr>
<tr>
<td>Duration of symptoms (mo)</td>
<td>28.7 ± 42.5 (11 days–240)</td>
<td>7.1 ± 10.1 (1–60)</td>
<td>33.3 ± 44.9 (11 days–240)</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Preoperative MMCS ≤ 2</td>
<td>160 (81.6)</td>
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<td>128 (81.5)</td>
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<td>Preoperative MMCS</td>
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<td></td>
<td>0.115</td>
</tr>
<tr>
<td>1</td>
<td>88 (44.9)</td>
<td>12 (30.8)</td>
<td>76 (48.4)</td>
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<tr>
<td>2</td>
<td>72 (36.7)</td>
<td>20 (51.3)</td>
<td>52 (33.1)</td>
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</tr>
<tr>
<td>3</td>
<td>33 (16.9)</td>
<td>6 (15.4)</td>
<td>27 (17.2)</td>
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</tr>
<tr>
<td>4</td>
<td>2 (1.0)</td>
<td>1 (2.5)</td>
<td>1 (0.65)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1 (0.5)</td>
<td>0 (0)</td>
<td>1 (0.65)</td>
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</tr>
<tr>
<td>VHL</td>
<td>43 (21.9)</td>
<td>17 (43.6)</td>
<td>26 (16.6)</td>
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</tr>
<tr>
<td>Family history</td>
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<td>11 (28.2)</td>
<td>8 (5.1)</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Presence of cyst/syrinx</td>
<td>177 (90.3)</td>
<td>35 (89.7)</td>
<td>142 (90.4)</td>
<td>1.000</td>
</tr>
<tr>
<td>Associated cerebral lesions</td>
<td>47 (24.0)</td>
<td>11 (28.2)</td>
<td>36 (22.9)</td>
<td>0.490</td>
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<tr>
<td>Multilesions</td>
<td>60 (30.6)</td>
<td>17 (43.6)</td>
<td>43 (27.4)</td>
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<td>MRI features</td>
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<td></td>
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<tr>
<td>No. of resect lesions</td>
<td>226</td>
<td>44</td>
<td>182</td>
<td></td>
</tr>
<tr>
<td>Level of lesion</td>
<td></td>
<td></td>
<td></td>
<td>0.012*</td>
</tr>
<tr>
<td>C</td>
<td>120 (53.1)</td>
<td>14 (31.8)</td>
<td>106 (58.2)</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>78 (34.5)</td>
<td>24 (54.6)</td>
<td>54 (29.7)</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>11 (4.9)</td>
<td>3 (6.8)</td>
<td>8 (4.4)</td>
<td></td>
</tr>
<tr>
<td>CT</td>
<td>5 (2.2)</td>
<td>1 (2.3)</td>
<td>4 (2.2)</td>
<td></td>
</tr>
<tr>
<td>Conus medullaris</td>
<td>12 (5.3)</td>
<td>2 (4.5)</td>
<td>10 (5.5)</td>
<td></td>
</tr>
<tr>
<td>Maximum size (cm)</td>
<td>2.0 ± 1.3 (0.2–11)</td>
<td>2.4 ± 1.5 (0.3–7)</td>
<td>1.8 ± 1.2 (0.2–11)</td>
<td>0.004*</td>
</tr>
<tr>
<td>Maximum volume (cm³)</td>
<td>3.6 ± 7.2 (0.008–72)</td>
<td>5.3 ± 9.4 (0.018–63)</td>
<td>3.1 ± 6.5 (0.008–72)</td>
<td>0.008*</td>
</tr>
<tr>
<td>Maximum size ≥ 2 (cm)</td>
<td>114 (50.4)</td>
<td>31 (70.5)</td>
<td>83 (45.6)</td>
<td>0.003*</td>
</tr>
<tr>
<td>Maximum volume ≥ 2 (cm³)</td>
<td>121 (53.5)</td>
<td>33 (75.0)</td>
<td>88 (48.4)</td>
<td>0.001*</td>
</tr>
<tr>
<td>Site</td>
<td></td>
<td></td>
<td></td>
<td>0.793</td>
</tr>
<tr>
<td>Intramedullary</td>
<td>108 (47.8)</td>
<td>19 (43.2)</td>
<td>89 (48.9)</td>
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</tr>
<tr>
<td>Intramedullary-extramedullary</td>
<td>71 (31.4)</td>
<td>15 (34.1)</td>
<td>56 (30.8)</td>
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</tr>
<tr>
<td>Extramedullary</td>
<td>47 (20.8)</td>
<td>10 (22.7)</td>
<td>37 (20.3)</td>
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</tr>
<tr>
<td>Resection</td>
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<td>0.014*</td>
</tr>
<tr>
<td>GTR</td>
<td>220 (97.3)</td>
<td>40 (90.9)</td>
<td>180 (98.9)</td>
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</tr>
<tr>
<td>STR</td>
<td>6 (2.7)</td>
<td>4 (9.1)</td>
<td>2 (1.1)</td>
<td></td>
</tr>
</tbody>
</table>

Values are presented as mean ± standard deviation (range) or number (%). MMCS, modified McCormick scale; VHL, von Hippel-Lindau; MRI, magnetic resonance imaging; GTR, gross total resection; STR, subtotal resection.

*p < 0.05, statistically significant differences.
Table 3. Comparison of characteristics of sporadic and VHL associated spinal hemangioblastomas

<table>
<thead>
<tr>
<th>Variable</th>
<th>Total (n = 39)</th>
<th>Sporadic (n = 22)</th>
<th>VHL associated (n = 17)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Clinical characteristics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age (yr)</td>
<td>15.9 ± 2.9 (8–18)</td>
<td>15.5 ± 3.1 (8–18)</td>
<td>16.7 ± 2.4 (10–18)</td>
<td>0.085</td>
</tr>
<tr>
<td>Sex</td>
<td></td>
<td></td>
<td></td>
<td>0.855</td>
</tr>
<tr>
<td>Male</td>
<td>19 (48.7)</td>
<td>11 (50.0)</td>
<td>8 (47.1)</td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>20 (51.3)</td>
<td>11 (50.0)</td>
<td>9 (52.9)</td>
<td></td>
</tr>
<tr>
<td><strong>Symptoms</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensory</td>
<td>26 (66.7)</td>
<td>12 (54.5)</td>
<td>14 (82.4)</td>
<td>0.068</td>
</tr>
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<td>Motor</td>
<td>23 (58.9)</td>
<td>13 (59.1)</td>
<td>10 (58.8)</td>
<td>0.987</td>
</tr>
<tr>
<td>Pain</td>
<td>25 (64.1)</td>
<td>12 (54.5)</td>
<td>13 (76.5)</td>
<td>0.157</td>
</tr>
<tr>
<td>Sphincter disorders</td>
<td>8 (20.5)</td>
<td>3 (13.6)</td>
<td>5 (29.4)</td>
<td>0.261</td>
</tr>
<tr>
<td>Others</td>
<td>5 (12.8)</td>
<td>3 (13.6)</td>
<td>2 (11.8)</td>
<td>1.000</td>
</tr>
<tr>
<td><strong>No. of symptoms</strong></td>
<td>3 ± 1 (1–4)</td>
<td>2 ± 1 (1–4)</td>
<td>3 ± 1 (1–4)</td>
<td>0.094</td>
</tr>
<tr>
<td>Symptoms ≥ 2</td>
<td>35 (89.7)</td>
<td>18 (81.8)</td>
<td>17 (100)</td>
<td>0.026*</td>
</tr>
<tr>
<td>Duration of symptoms (mo)</td>
<td>7.1 ± 10.1 (1–60)</td>
<td>8.7 ± 12.6 (1–60)</td>
<td>4.5 ± 3.5 (1–12)</td>
<td>0.294</td>
</tr>
<tr>
<td>Preoperative MMCS ≤ 2</td>
<td>32 (82.1)</td>
<td>18 (81.8)</td>
<td>14 (82.4)</td>
<td>1.000</td>
</tr>
<tr>
<td><strong>Symptoms ≥ 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VHL</td>
<td>35 (89.7)</td>
<td>19 (86.4)</td>
<td>16 (94.1)</td>
<td>0.618</td>
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<td>Family history</td>
<td>11 (28.2)</td>
<td>1 (4.5)</td>
<td>10 (58.8)</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Presence of cyst/syrinx</td>
<td>17 (43.6)</td>
<td>2 (9.1)</td>
<td>15 (88.2)</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Associated cerebral lesions</td>
<td>12 (30.8)</td>
<td>3 (13.6)</td>
<td>9 (42.9)</td>
<td>0.008*</td>
</tr>
<tr>
<td><strong>Multileions</strong></td>
<td>84.6 ± 43.5 (12–124)</td>
<td>85.8 ± 44.7 (16–124)</td>
<td>82.9 ± 43.2 (12–124)</td>
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<tr>
<td>No. of resect lesions</td>
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<td>23</td>
<td>21</td>
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<td><strong>Level of lesion</strong></td>
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<td>0.786</td>
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<td>8 (38.1)</td>
<td></td>
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<td>T</td>
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<td>14 (60.9)</td>
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<td>CT</td>
<td>1 (2.3)</td>
<td>0 (0.0)</td>
<td>1 (4.76)</td>
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</tr>
<tr>
<td>Conus medullaris</td>
<td>2 (4.5)</td>
<td>1 (4.3)</td>
<td>1 (4.76)</td>
<td></td>
</tr>
<tr>
<td>Maximum size (cm)</td>
<td>2.4 ± 1.5 (0.3–7)</td>
<td>2.9 ± 1.5 (0.6–7)</td>
<td>2.0 ± 1.3 (0.3–4.6)</td>
<td>0.035*</td>
</tr>
<tr>
<td>Maximum volume (cm³)</td>
<td>5.3 ± 9.4 (0.018–63)</td>
<td>7.4 ± 12.3 (0.12–63)</td>
<td>3.1 ± 3.2 (0.72–10.64)</td>
<td>0.010*</td>
</tr>
<tr>
<td>Maximum size ≥ 2 (cm)</td>
<td>31 (70.5)</td>
<td>20 (87.0)</td>
<td>11 (52.4)</td>
<td>0.012*</td>
</tr>
<tr>
<td>Maximum volume ≥ 2 (cm³)</td>
<td>33 (75.0)</td>
<td>22 (95.7)</td>
<td>11 (52.4)</td>
<td>0.001*</td>
</tr>
<tr>
<td><strong>Site</strong></td>
<td></td>
<td></td>
<td></td>
<td>0.506</td>
</tr>
<tr>
<td>Intramedullary</td>
<td>19 (43.2)</td>
<td>9 (39.1)</td>
<td>10 (47.6)</td>
<td></td>
</tr>
<tr>
<td>Intramedullary-extramedullary</td>
<td>15 (34.1)</td>
<td>10 (43.5)</td>
<td>5 (23.8)</td>
<td></td>
</tr>
<tr>
<td>Extramedullary</td>
<td>10 (22.7)</td>
<td>4 (17.4)</td>
<td>6 (28.6)</td>
<td></td>
</tr>
<tr>
<td><strong>Resection</strong></td>
<td></td>
<td></td>
<td></td>
<td>0.924</td>
</tr>
<tr>
<td>GTR</td>
<td>40 (90.9)</td>
<td>21 (91.3)</td>
<td>19 (90.5)</td>
<td></td>
</tr>
<tr>
<td>STR</td>
<td>4 (9.1)</td>
<td>2 (8.7)</td>
<td>2 (9.5)</td>
<td></td>
</tr>
</tbody>
</table>

Values are presented as mean ± standard deviation (range) or number (%).
VHL, von Hippel-Lindau; MMCS, modified McCormick scale; MRI, magnetic resonance imaging; GTR, gross total resection; STR, subtotal resection.
*p < 0.05, statistically significant differences.
Indocyanine green videoangiography was used intraoperatively in 6 patients to show the feeding arteries, abnormal venous drainage, and the border of lesions. For patients with multiple spinal HBs, the principal goal was to remove the larger lesion that was assumed to be responsible for patients’ present symptoms, and adjacent HBs were also removed in one procedure if possible. Subtotal resection was achieved in 4 lesions (9.1%), and these resection processes were technically challenging. One lesion was a large cystic lesion, and total resection was deemed unsafe. One lesion with the feeding artery located ventrally and 2 lesions with obvious and tortuous feeding arteries were adhered tightly to the spinal cord without an obvious gliotic plane, and total resection was unachievable. Gross total resection confirmed by postoperative MRI was achieved for the remaining 40 HBs (90.9%).

4. Clinical Outcomes

Five patients (12.8%) experienced neurological deterioration immediately after surgery, and 3 of them returned to their preoperative status before discharge. Five patients (12.8%) had meningitis and were cured by antibiotics, and no patients experienced cerebrospinal fluid leakage or wound infection.

During a mean follow-up period of 99.4 ± 37.4 months (range, 16–124 months), 12 patients (30.8%) experienced spinal HBs recurrence. Most patients (n = 9, 75%) who experienced recurrence were in the VHL group, and 5 of these patients underwent repeated surgery. Four children did not undergo surgery due to their poor health conditions, and 3 of them died of lesion recurrence for multifocal spinal cord or cerebellar HBs after an average of 77.6 months (24–121 months) after the first surgery. Three patients in the sporadic group experienced recurrences at the site of the original tumor and received a second surgery after lesion relapse. Children in the VHL group under-

![Fig. 3. Kaplan-Meier analyses of recurrence-free survival in pediatric and adult patients with spinal hemangioblastomas.](image)

![Fig. 4. Kaplan-Meier curve for recurrence-free survival (A) and overall survival (B) of sporadic and von Hippel-Lindau (VHL) hemangioblastomas in pediatric patients.](image)

Table 4. Distribution of VHL-associated tumors in 17 patients

<table>
<thead>
<tr>
<th>Tumor</th>
<th>Case No.</th>
<th>Examination</th>
<th>Age at diagnosis (yr)</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spinal HBs</td>
<td>17</td>
<td>MRI</td>
<td>Mean 15.9</td>
<td>Surgery</td>
</tr>
<tr>
<td>Cerebral HBs</td>
<td>14</td>
<td>MRI</td>
<td>Mean 17.5</td>
<td>Surgery</td>
</tr>
<tr>
<td>Pancreatic neuroendocrine tumor</td>
<td>5</td>
<td>Ultrasound and MRI</td>
<td>Mean 17</td>
<td>Medicine</td>
</tr>
<tr>
<td>Renal cell carcinoma</td>
<td>2</td>
<td>MRI</td>
<td>Mean 16</td>
<td>Surgery</td>
</tr>
<tr>
<td>Endolymphatic sac tumor</td>
<td>1</td>
<td>MRI and Audiogram</td>
<td>17</td>
<td>Surgery</td>
</tr>
</tbody>
</table>

VHL, von Hippel-Lindau; MRI, magnetic resonance imaging; HBs, hemangioblastomas.
went more repeated surgeries for progressive spinal HBs as well as cerebellar HBs or other VHL-associated tumors beyond the central nervous system (CNS). The mean recurrent free-survival time was 84.6 ± 43.5 months (12–124 months), which was longer in the sporadic groups than VHL-associated groups (Table 3; Figs. 3, 4). The distribution of VHL-associated tumors is summarized in Table 4.

Pain completely resolved in all but 1 patient (4%), and other symptoms, such as weakness, sphincter disturbance, and sensory disorders, improved in 73.3%, 50.0%, and 37.5% patients, respectively, at the last follow-up. One patient (2.8%) that underwent orthopedic surgery experienced postoperative worsening of scoliosis, but an MRI confirmed no regrowth of the residual lesion 2 years after surgery. Disability calculated by the MMCS was grade 1 in 24 patients (66.7%), grade 2 in 9 patients (25.0%), and grade 3 in 3 patients (8.3%) at the last follow-up.

Compared with children whose functional status was stable at the last follow-up, children who experienced worsened postoperative functional status or death tended to be older (p = 0.004), had a poorer preoperative functional status (p = 0.015), had a higher likelihood of having a baseline spinal deformity (p = 0.002), had a higher rate of recurrence (p = 0.002), were more likely to be worsened after surgery (p = 0.004), and were more likely to undergo repeated surgeries (p = 0.001) (Table 5).

**DISCUSSION**

This study was one of the largest series focusing on the clinical presentation, natural history, management strategies and outcomes of pediatric patients with HBs. A comparison with adult patients was made, and we found that pediatric patients usually had VHL disease, with a family history of VHL, multi-

### Table 5. Comparison of functional status between patients who did and did not worsen at follow-up

<table>
<thead>
<tr>
<th>Variable</th>
<th>Total (n = 39)</th>
<th>Worsened or death (n = 7)</th>
<th>Notworsened (n = 32)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)*</td>
<td>15.9 ± 2.9 (8–18)</td>
<td>17.6 ± 0.8 (17–18)</td>
<td>15.7 ± 3.0 (8–18)</td>
<td>0.004*</td>
</tr>
<tr>
<td>Sex</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>19 (48.7)</td>
<td>4 (57.1)</td>
<td>15 (46.9)</td>
<td>0.695</td>
</tr>
<tr>
<td>Female</td>
<td>20 (51.3)</td>
<td>3 (42.9)</td>
<td>17 (53.1)</td>
<td></td>
</tr>
<tr>
<td>Preoperative symptoms</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensory</td>
<td>26 (66.7)</td>
<td>4 (57.1)</td>
<td>22 (68.8)</td>
<td>0.666</td>
</tr>
<tr>
<td>Motor</td>
<td>23 (58.9)</td>
<td>5 (71.4)</td>
<td>18 (56.3)</td>
<td>0.678</td>
</tr>
<tr>
<td>Pain</td>
<td>25 (64.1)</td>
<td>4 (57.1)</td>
<td>21 (65.6)</td>
<td>0.686</td>
</tr>
<tr>
<td>Sphincter disorders</td>
<td>8 (20.5)</td>
<td>3 (42.9)</td>
<td>5 (15.6)</td>
<td>0.272</td>
</tr>
<tr>
<td>Spinal deformity</td>
<td>5 (12.8)</td>
<td>4 (57.1)</td>
<td>1 (3.1)</td>
<td>0.002*</td>
</tr>
<tr>
<td>No. of symptoms ≥ 2</td>
<td>35 (89.7)</td>
<td>7 (57.1)</td>
<td>28 (87.5)</td>
<td>1.000</td>
</tr>
<tr>
<td>Duration of symptoms (mo)</td>
<td>7.1 ± 10.1 (1–60)</td>
<td>6.8 ± 3.4 (2–12)</td>
<td>7.4 ± 11.8 (1–60)</td>
<td>0.913</td>
</tr>
<tr>
<td>Duration of symptoms ≤ 2 (mo)</td>
<td>9 (23.1)</td>
<td>1 (14.3)</td>
<td>8 (25.0)</td>
<td>0.909</td>
</tr>
<tr>
<td>Preoperative MMCS ≤ 2</td>
<td>32 (82.1)</td>
<td>3 (42.9)</td>
<td>29 (90.6)</td>
<td>0.015*</td>
</tr>
<tr>
<td>VHL</td>
<td>17 (43.6)</td>
<td>4 (57.1)</td>
<td>13 (40.6)</td>
<td>0.677</td>
</tr>
<tr>
<td>Family history</td>
<td>11 (28.2)</td>
<td>3 (42.9)</td>
<td>8 (25)</td>
<td>0.626</td>
</tr>
<tr>
<td>Synchronous intracranial lesions</td>
<td>11 (28.2)</td>
<td>3 (42.9)</td>
<td>8 (25)</td>
<td>0.626</td>
</tr>
<tr>
<td>Multilesions</td>
<td>17 (43.6)</td>
<td>5 (71.4)</td>
<td>12 (37.5)</td>
<td>0.205</td>
</tr>
<tr>
<td>Size ≥ 2 (cm)</td>
<td>31 (79.5)</td>
<td>7 (100)</td>
<td>24 (75.0)</td>
<td>0.308</td>
</tr>
<tr>
<td>Volume ≥2 (cm³)</td>
<td>33 (84.6)</td>
<td>7 (100)</td>
<td>26 (81.3)</td>
<td>0.568</td>
</tr>
<tr>
<td>Recurrence</td>
<td>12 (30.8)</td>
<td>6 (85.7)</td>
<td>6 (18.8)</td>
<td>0.002*</td>
</tr>
<tr>
<td>Worsened after surgery</td>
<td>3 (7.7)</td>
<td>3 (42.9)</td>
<td>0 (0)</td>
<td>0.004*</td>
</tr>
<tr>
<td>Follow-up (mo)</td>
<td>112.8 ± 39.9 (16–168)</td>
<td>123.1 ± 34.7 (48–152)</td>
<td>110.5 ± 50.2 (16–168)</td>
<td>0.532</td>
</tr>
</tbody>
</table>

Values are presented as mean ± standard deviation (range) or number (%).
MMCS, modified McCormick scale; VHL, von Hippel-Lindau.
*p < 0.05, statistically significant differences.
ple symptoms, a shorter duration of symptoms, a larger lesion size, an increased incidence of multifocal tumors, and a higher rate of recurrence. Children in the VHL-associated group tend to have more symptoms at presentation and experienced a higher rate of repeated surgery than children in the sporadic group.

1. Demographics

HBs are rarely encountered in children, and the true incidence of pediatric HBs in a population-based cohort remains unclear. The mean age to receive spinal HBs surgery was 15.9 years in our cohorts, and most patients were aged between 10 and 18 years old, which was similar to previous reports on pediatric patients with brain HBs. The youngest onset age was 8 years in our patients and 6 years in previous reports, which indicated that the occurrence of spinal HBs increased with age and rarely occurred before 10 years.

The sex distribution and lesion location of pediatric HBs are debatable. A slight female predominance was observed in our case series (51.3%), which was different from the male predominance for the adult patients (54.8%). The thoracic predominance in the children (54.6%) in our cohort was different from the significant cervical predominance (58.2%) in the adult patients with HBs. Additionally, we found that the average size and volume of HBs in pediatric patients were larger than those in adults.

2. VHL-Associated HBs

A germline mutation of the VHL gene located on chromosome 3p25-26 that encodes the VHL protein of 213 amino acids is a feature of VHL disease, and 60%–80% of VHL patients will develop CNS HBs, as previously reported. In this study, we found that a higher proportion of pediatric patients had VHL than adult patients, and the most common early manifestations were associated with CNS HBs, followed by renal tumors, pancreatic tumors, and endolymphatic sac tumors. These results were inconsistent with previous reports and indicated that CNS HBs may be highly suggestive of VHL disease in childhood; therefore, germline mutations of the VHL gene should be screened. Furthermore, radiological evaluations of the brain and entire spine, abdomen, and urological as well as an ophthalmological examination should be conducted to rule out VHL-associated lesions.

Adult patients with VHL-associated spinal HBs are thought to have early onset and multiple symptoms. We found that pediatric patients in the VHL-group had multiple symptoms and a much shorter duration of symptoms than pediatric patients in the sporadic-group. This may indicate that tumor and/or tumor-associated pseudocysts may produce more symptoms and progress more rapidly in VHL-associated children since symptoms are caused by these space-occupying components. The mean size and volume of HBs were larger in children, which highlighted the growth patterns of HBs in different age groups, and HBs in children may grow more rapidly than those in adults.

3. Management Strategies and Outcomes

Complete resection is currently the best modality for management of adult HBs since surgery can result in improvement in more than half of adult patients. However, the experience of managing pediatric ISCM is inadequate and has mostly been derived from experience with managing adult patients. However, given that pediatric patients have a higher proportion of VHL and the unpredictable growth pattern of HBs, the indications and best approach for surgical timing in this subset of patients should be clarified.

Our results demonstrated that surgery led to good outcomes in children in the sporadic group before significant neurological deficits occurred; all 22 children improved or were stable after surgery. However, the optimal surgical timing in patients with multiple VHL-associated tumors remains debatable. Resection of HBs that were responsible for the symptoms seems reasonable, and adjacent HBs can be removed in one procedure. However, multiple laminotomies in one surgery may cause spinal instability, thereby worsening neurological function. Staged procedures can be considered for initial asymptomatic lesions since no sudden deterioration is encountered in our patients and neurosurgical intervention can be postponed when radiological progression occurs. In our series, 4 patients underwent resection for multiple HBs at once and experienced no deterioration after surgery. Two patients had initially nonresected spinal HBs that did not grow significantly in size during a relatively long-term follow-up, and these patients underwent repeated surgery 36 months (12–58 months) after the first surgery. However, 4 patients with multispinal HBs did not undergo resection of all lesions, and long-term observation was needed because the growing pattern of these nonoperative HBs was unpredictable.

In general, the functional outcome after microsurgery for pediatric HBs was good, and 82.1% of children were stable. Preoperative neurological status was an important factor associated with long-term outcomes. Worsened functional status immediately following surgery was a predictor of poor outcomes. The
high recurrence rate in children was problematic, especially for children in the VHL-associated group, and these recurrences did not seem to correlate with the EOR. Patients who experienced recurrence can still benefit from surgery. However, an increase in neurological deficits was associated with lesion relapse and multiple surgeries due to the cumulative damage to the spinal cord as the lesion progressed. Additionally, patients exhibited a poorer functional status before a second surgery.

4. Limitations
There were several limitations in this study. First, this study involved a small case series due to the rarity of this disease, and future multicenter large-scale studies are needed to further elucidate the natural history of this disease. Second, genetic screening was not routinely performed in all family members of the children, and extensive radiological, ophthalmological, and urological screening was performed for children according to their compliance and relevance of symptoms. Therefore, the true incidence of familial and VHL-associated tumors of other systems in these pediatric patients may be underestimated. Third, the natural history of children with spinal HBs is unclear; further studies must have long enough follow-up periods to assess the lifelong risk of tumor development in these patients.

CONCLUSION
Pediatric patients with spinal HBs are different from their adult counterparts in terms of clinical features, tumor features, and recurrence rates. Pediatric patients with HBs appear to have a higher relapse risk than their adult counterparts, thus indicating a necessity for life-long follow-up, especially for VHL-associated patients. Surgery can achieve better satisfactory outcomes, even in patients with recurrent lesions, and should be considered early to avoid irreversible neurological deterioration.

NOTES
Conflict of Interest: The authors have nothing to disclose.
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REFERENCES


Effectiveness of the Endplate Reduction Technique Combined With Bone Grafting for the Treatment of Thoracolumbar Fractures by Using Posterior Short-Segment Fixation

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Objective: This study aimed to examine the effect of the endplate reduction (EPR) technique combined with bone grafting for treating thoracolumbar burst fractures using posterior short-segmental fixation.

Methods: Patients with thoracolumbar fractures admitted between January 2018 and October 2021 were retrospectively analyzed, and those meeting the criteria were assigned to the EPR group and the intermediate screws (IS) group. The vertebral wedge angle (VWA), Cobb angle (CA), anterior vertebral body height (AVBH), middle vertebral body height (MVBH), upper endplate line (UEPL), upper intervertebral angle (UIVA), and upper intervertebral disc height (UIDH) indices were examined and compared preoperatively, first day postoperatively, as well as at 12 months postoperatively.

Results: The result indicated that the EPR group achieved better MVBH reduction (p < 0.001), UEPL reduction (p < 0.001), vertebral body fracture healing (p = 0.006), as well as implant breakage (p = 0.04) than the IS group; VWA (p < 0.001), CA (p = 0.005), AVBH (p < 0.001), MVBH (p < 0.001), UEPL (p < 0.001), and UIDH (p < 0.001) were lost after reduction less than those in the IS group. There was no significant difference in operative time (p = 0.315) and intraoperative bleeding (p = 0.274) between the 2 groups.

Conclusion: The EPR group achieved better results in repositioning and maintaining MVBH and endplate morphology, with less correction loss after the reduction of the VWA, CA, AVBH, and endplate morphology. The EPR group exhibited a better healing pattern after vertebral fracture and disc degeneration was better relieved.

Keywords: Direct reduction, Endplate reduction, Bone graft, Disc degeneration

INTRODUCTION

Fractures of the thoracolumbar are more common in spinal trauma for their structural characteristics.¹ Treatment options for unstable thoracolumbar fractures without neurological damage have been controversial.² Some scholars have suggested that conservative treatment can be cost-effective and provide effective long-term results, whereas it can leave a legacy of deformity. As research has been leaping forward, increasing scholars have suggested that surgery is capable of correcting the deformity and achieving a better long-term outcome, thus revealing that unstable thoracolumbar fractures should be treated surgically.

There have been many surgical approaches to the thoracolumbar, with options for anterior fixation, posterior fixation, or combined anterior and posterior fixation.³,⁵ Anterior fixation is...
relatively more damaging and bleeds more, with a loss of some mobility.\textsuperscript{6} Posterior fixation, on the other hand, is less invasive, and simple, and is widely used in clinical practice. Posterior fixation is divided into single-segment fixation, short-segment fixation, and long-segment fixation.\textsuperscript{7} Short-segment fixation is simple, less invasive, and more reliable.\textsuperscript{8,10} However, since the anterior column of the thoracolumbar instability fracture is severely damaged, the use of short-segment fixation causes concentrated stress, thus easily resulting in failure of reduction and implant breakage, resulting in surgical failure. Furthermore, the posterior or short-segment fixation technique refers to an indirect repositioning technique that does not effectively restore the height of the anterior column of the vertebral body due to poor repositioning of the central endplate collapse. To reduce the failure rate of surgery and effectively restore the collapse of the central endplate,\textsuperscript{11} the methods currently applied comprise the placement of pedicle screws in the injured vertebral body or posterior vertebral body kyphoplasty in the injured vertebral body to reduce the stress concentration and restore the injured vertebral body, thus reducing the failure rate of surgery.\textsuperscript{12,14}

This study suggests that good reduction, effective support, and early healing of vertebral fractures are the keys to the successful treatment of short-segment thoracolumbar fractures. By repositioning the endplate and disc as a whole, the endplate can effectively restore the normal space of the disc and reduce further disc degeneration, while effectively repositioning the vertebral body to facilitate the maintenance of fracture repositioning and correction of the kyphosis deformity and reduce the occurrence of recurrent kyphosis deformity. Based on the above concept, direct prying of the repositioned endplate was proposed to restore normal disc and vertebral body height, followed by implantation of allograft bone via the pedicle to fill the repositioned cavity to maintain the repositioning and promote fracture healing.

MATERIALS AND METHODS

1. Patient Population

We conducted a retrospective analysis of patients admitted with thoracolumbar fractures between January 2018 and October 2021. This study was approved by the ethics committee of Hebei Medical University (2018206314). Informed consent was obtained from all individual participants included in the study. Inclusion criteria were as follows: (1) type A3,4 and B1 single-segment thoracolumbar (T11-L2) burst fracture according to AO classification, with fracture involving only the upper endplate or involving the lower endplate without displacement; (2) aged 18–60 years; (3) no symptoms of neurological injury; (4) posterior short-segment fixation using endplate prying and repositioning combined with bone grafting techniques or fixation using intermediate screws (IS) in the injured vertebra; (5) follow-up of not less than 1 year. Exclusion criteria: (1) patients with osteoporosis; (2) multiple vertebral fractures; (3) pathological fractures; (4) history of lumbar spine surgery; (5) removal of internal fixation within 1 year. The collected patients were divided into an endplate reduction (EPR) group and an IS group according to the numerical randomization method.

Patients were assigned to types A and B in accordance with AO fracture classification,\textsuperscript{15} as well as to type I, type II, and type III based on endplate injury classification.\textsuperscript{16} Patients are classified as type I, II, III, and IV, which type I and II are considered well healed, and type III and IV were considered poorly healed.\textsuperscript{17} A load-sharing classification (LSC) score was performed following the extent of vertebral injury, displacement of fracture fragments, and correction of kyphosis as observed on computed tomography (CT).\textsuperscript{18} Implant breakage was recorded.

2. Surgical Technique

General anesthesia was routinely used. The patient was placed prone on the operating table with the chest and pelvis elevated. The paravertebral muscles were dissected on both sides of the spinous process to expose the fractured vertebral body and the small articular joints adjacent to the superior and inferior vertebral bodies. The Universal Spine System from synhes was adopted to fix the fracture, and 4 Schanz screws were placed in the adjacent superior and inferior vertebral bodies at the fractured segment. The above steps were the same for both groups.

1) EPR group

The emphasis was placed on endplate repositioning and the fractured vertebral endplate is repositioned directly by prying, restoring vertebral height and disc space, and implanting allograft bone to maintain repositioning and facilitating fracture healing. After the same steps were completed, the connecting rod was fitted, the ipsilateral screw was held open using a spreader and the Schanz screw was adjusted in position to indirectly reposition the fractured vertebral body by ligamentous distraction. After satisfactory repositioning, the connecting rod and screw were locked, and the screw was cut to fit. The small articular joints of the fractured vertebra were exposed on both sides of the fractured vertebra, and a fluoroscopically guided pedicle opener (4 mm) was placed at the lowest point of endplate col-
lapse on the vertebral body to pry and reposition the collapsed endplate, followed by screwing in the Schanz screw (6.2 mm) via the pedicle to further pry and reposition. Alternating prying was performed on both sides till the collapsed endplate was satisfactorily repositioned, and the Schanz screw was removed. In the process of prying and repositioning the end plate, attention should be paid to gentle movements, avoiding violent prying and repositioning, and the reduction process should be completed under the supervision of the x-ray fluoroscopy. The prying tool should be no less than 5 mm away from the lowest point of the prying and repositioning to reduce further damage to the end plate. A bone graft funnel was placed through the screw channel, and allograft bone was inserted to fill in the bone defect formed after prying. The anterior aspect of the implant funnel is placed at the posterior edge of the middle third of the vertebral body to reduce the risk of intrusion of the implant material into the spinal canal (Figs. 1, 2).

2) IS group
Endplate repositioning was completed through screws placed in the fractured vertebral body, without bone grafting. After completing the same surgical procedure, 2 screws 5 mm shorter than the adjacent fractured vertebral screw were inserted through the pedicle into the fractured vertebral body. After the fitting of the connecting rod, distraction repositioning was performed between the adjacent screws on the ipsilateral side. When the repositioning was satisfactory, the connecting rod and screws were locked, and then the screws were cut to fit.12

3. Postoperative Management
Antibiotics were administered according to the principles, the wound drain was removed 48 hours after surgery, the wound

Fig. 1. Endplate repositioning and bone grafting procedure. (A) Model of L2 vertebral fracture. (B) Poor recovery of middle vertebral height after ligamentous retraction, poor morphology of the upper endplate. (C) Prying and repositioning of the endplate under fluoroscopy with an opener via the pedicle. (D) Further prying and repositioning of the endplate with Schanz screws. (E) Placement of a bone graft funnel. (F) Placement of allograft bone.

Fig. 2. Female, 49 years old, fall from height, L1 vertebral fracture, treated with the method of endplate reduction group. Preoperatively (A, B), postoperatively (C, D), and at 12 months follow-up (E, F) on anteroposterior and lateral x-ray of the lumbar spine.
was changed every 3 days, the stitches were removed 14 days after surgery and a thoracolumbar brace was required for 2 months after surgery.

4. Radiological Evaluation

Preoperative and first postoperative day lumbar anteroposterior and lateral views, lumbar CT, and lumbar magnetic resonance imaging were taken in all patients. Monthly outpatient follow-ups were performed for 3 months after surgery, with the respective lumbar anteroposterior and lateral radiographs being taken. After 3 months postoperatively, the lumbar spine was reviewed every 3 months, with anteroposterior and lateral lumbar spine views taken as required. At the 12-month postoperative review, anteroposterior and lateral spine views and CT of the lumbar spine were taken in preparation to remove the internal fixation. The vertebral wedge angle (VWA), Cobb angle (CA), anterior vertebral body height (AVBH), middle vertebral body height (MVBH), upper endplate line (UEPL) of the fractured vertebra, upper intervertebral angle (UIVA), upper intervertebral disc height (UIDH), and loss of postoperative correction were examined preoperatively, on the first postoperative day, and at 12 months postoperatively, respectively. The VWA refers to the angle formed by the line of the upper and lower endplates of the fractured vertebral body. The CA measurement is based on the line between the upper endplate of the upper vertebral body of the fractured vertebra and the lower endplate of the lower vertebral body of the fractured vertebra. The AVBH refers to the percentage of the anterior height of the fractured vertebral body to the average of the anterior heights of the upper and lower vertebral bodies of the fractured vertebral body. The MVBH refers to the percentage of the middle height of the fractured vertebral body to the average of the middle height of the upper and lower vertebral bodies of the fractured vertebral body. The UEPL represents is the length of the UEPL of the fractured vertebra as a percentage of the mean length of the UEPLs of the upper and lower vertebral bodies of the fractured vertebra, thus indicating the morphology of the endplate. The UIVA was the angle between the upper endplate of the fractured vertebra and the lower endplate of the vertebra above the fractured vertebra, and the UIDH is the average of the anterior and posterior disc heights above the injured vertebra. Changes in the UIVA and disc height reflected changes in the intervertebral disc space (Fig. 3). Postoperative loss of correction, the difference between the index examined at 12 months postoperatively and the postoperative index, reflected the maintenance of postoperative repositioning. All the above indicators were examined on lateral lumbar radiographs, by a senior radiologist independent of the study, and each set of data was averaged and recorded after 3 measurements.

Fig. 3. Measurement of radiographic parameters on lateral x-ray of the lumbar spine. (A) Vertebral wedge angle, the angle formed by the lines c and d; Cobb angle, the angle formed by lines a and e; upper intervertebral angle, the angle formed by the lines b and c. (B) Anterior vertebral body height = 2 b/(a+c) \times 100\%; middle vertebral body height = 2 b’/(a’+c’) \times 100\%; upper endplate line = 2 g/(f+f’) \times 100\%; upper intervertebral disc height = (d+e)/2.

5. Statistical Analysis

Data processing was performed using IBM SPSS Statistics ver. 23.0 (IBM Co., Armonk, NY, USA). Data were expressed as mean ± standard deviation using the 2 independent samples t-test for normally distributed continuous variables and the Mann-Whitney U-test for those that did not conform to a normal distribution. The Pearson chi-square test and Fisher exact test were used for categorical data. Probability values less than 0.05 indicate statistically significant differences.

RESULTS

1. General Information

A total of 63 patients were collected in the EPR group, including 45 males, and 18 females, with a mean age of 45.0 ± 11.5 years, mean body mass index (BMI) of 23.3 ± 3.0 kg/m²; mechanism of injury: 45 high fall injuries, 12 traffic accidents, 6 other injuries; fracture sites: 5 cases of T12 vertebral fractures, 33 cases of L1 vertebral fractures, as well as 25 cases of L2 vertebral fractures. The mean LSC score was 7.8 ± 0.9; 45 fractures healed well (type
I, 23; type II, 22) (71.4%) (Fig. 4) and 18 fractures healed poorly (18.6%) (type III, 16; type IV, 2); no implant breakage occurred. A total of 65 patients were collected in the IS group, 46 males, and 19 females, with a mean age of 45.0 ± 9.8 years, mean BMI of 23.4 ± 4.1 kg/m²; mechanism of injury: 52 high fall injuries, 8 traffic accidents, 5 other injuries; fracture sites: 6 cases of T 12 vertebral fractures, 35 cases of L1 vertebral fractures, 24 cases of L2 vertebral fractures. The mean LSC score was 7.5 ± 1.0; 31 (type I, 8; type II, 23) fractures healed well (47.7%) and 34 fractures (52.3%) healed poorly (type III, 30; type IV, 4) (Figs. 5, 6); 6 cases had implant breakage. No differences with statistical significance were identified between the EPR group and the IS group in gender, age, BMI, mechanism of injury, fracture site, AO classification, endplate injury classification, as well as LSC score. The rate of good fracture healing reached 71.4% in the EPR group compared with 48.7% in the IS group, thus marking a statistically significant difference between the 2 groups (p = 0.006). The risk of implant breakage achieved statistical significance in the EPR group compared with the IS group (p = 0.04), and the risk of implant breakage was lower in the EPR group (0) compared with the IS group (9.2%) (Table 1).

2. Intraoperative Indicators
The mean operative time was 134.7 ± 31.8 minutes and the mean intraoperative bleeding was 361.7 ± 143.9 mL in the EPR group; the mean operative time was 140.0 ± 27.0 minutes and

Fig. 4. Male, 57 years old, fall from height, L2 vertebral fracture treated with the method of endplate reduction group. Preoperative fracture on computed tomography (CT) scan (A-C), postoperative repositioning and allograft bone filling on CT scan (D-F), fracture healing at 12 months follow-up on CT scan (G-I). The red arrows mark good healing of the vertebra after bone grafting.
the mean intraoperative bleeding was 325.8 ± 100.9 mL in the IS group. The differences in operative time (p = 0.315) and intraoperative bleeding (p = 0.274) between the 2 groups were not statistically significant (Table 2).

3. Radiographic Outcomes
The preoperative VWA reached 16.3° ± 6.0° in the EPR group and 17.3° ± 4.1° in the IS group, while no differences with statistical significance were identified between the 2 groups (p = 0.139). The postoperative VWA was corrected to 5.0° ± 3.3° in the EPR group and 4.5° ± 8.7° in the IS group. At 12 months postoperatively, the VWA was lower in the EPR group at 6.8° ± 3.2° as compared with that in the IS group at 7.8° ± 10.6°, whereas the above data were no differences with statistical significance. At 12 months postoperatively, the loss of correction in the EPR group was 1.9° ± 1.6° compared with 3.3° ± 1.9° in the IS group, which were differences with statistical significance (p < 0.001).

The preoperative CA was 18.0° ± 9.4° in the EPR compared with 15.1° ± 6.2° in the IS group, but there were no differences with statistical significance between the 2 groups (p = 0.123). The CA was corrected to 4.9° ± 5.1° in the EPR and 4.8° ± 4.3° in the IS group, with no differences with statistical significance between the 2 groups (p = 0.664). At 12-month postoperative follow-up, the CA was maintained at 7.5° ± 5.0° in the EPR compared with 8.2° ± 5.1° in the IS group, whereas there were no differences with statistical significance (p = 0.31).

The AVBH in the EPR was corrected from 63.4% ± 12.3% preoperatively to 96.2% ± 2.5% postoperatively, and it was maintained at 94.2% ± 2.6% at 12-month postoperative follow-up. The AVBH in the IS group was corrected from 61.0% ± 10.1% preoperatively to 95.8% ± 5.1% postoperatively, and it was maintained at 92.1% ± 5.7% at 12-month postoperative follow-up. The differences in preoperative (p = 0.222) and postoperative AVBH (p = 0.173) did not achieve statistical significance compared with the 2 groups. The AVBH in the EPR at 12-month
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Postoperative follow-up was 94.2% ± 2.6% greater than that in the IS group at 92.1% ± 5.7%, and differences with statistical significance existed between the 2 groups (p < 0.001). The loss of correction in the EPR was 2.0% ± 1.2% less than that in the IS group at 3.7% ± 2.5%, thus marking differences with statistical significance between the 2 groups (p < 0.001).

The preoperative MVBH was 69.4% ± 10.8% in the EPR and 67.2% ± 13.5% in the IS group, with no differences with statistical significance between the 2 groups (p = 0.495). In the EPR group, the postoperative MVBH was corrected to 95.2% ± 3.9%.

| Table 1. Comparison of general information between the EPR and IS groups |
|------------------|------------------|------------------|------------------|
| Variable         | EPR group (n = 63) | IS group (n = 65) | p-value          |
| Sex             |                  |                  | 0.934†          |
| Male            | 45               | 46               |                 |
| Female          | 18               | 19               |                 |
| Age (yr)        | 45.0 ± 11.5      | 45.0 ± 9.8       | 0.8†            |
| Body mass index (kg/m²) | 23.3 ± 3.0    | 23.4 ± 4.1       | 0.175†          |
| Injury mechanisms |                |                  | 0.505†          |
| Fall from height| 45               | 52               |                 |
| Traffic accidents| 12              | 8                |                 |
| Others          | 6                | 5                |                 |
| Fracture site   |                  |                  | 0.933†          |
| T12             | 5                | 6                |                 |
| L1              | 33               | 35               |                 |
| L2              | 25               | 24               |                 |
| AO classification|                |                  | 0.086†          |
| A3              | 30               | 43               |                 |
| A4              | 28               | 20               |                 |
| B1              | 5                | 2                |                 |
| Endplate injury classification |          |                  | 0.257†          |
| I               | 22               | 32               |                 |
| II              | 19               | 16               |                 |
| III             | 22               | 17               |                 |
| Load-sharing classification |          |                  | 7.8 ± 0.9       |
| Fracture healing type |            |                  | 7.5 ± 1.0       |
| Good healing morphology (type I, type II) | 45/63 (71.4) | 31/65 (47.7) | 0.176†          |
| Poor healing morphology (type III, type IV) | 18/63 (28.6) | 34/65 (52.3) | 0.006**†       |
| Implant breakage | 0/63 (0)         | 6/65 (9.2)       | 0.04†          |

Values are presented as mean ± standard deviation or number (%). EPR, endplate reduction; IS, intermediate screws. *p < 0.05 is considered statistically significant. †Chi-square test was used. ‡The Wilcoxon test was used.

postoperative follow-up was 94.2% ± 2.6% greater than that in the IS group at 92.1% ± 5.7%, and differences with statistical significance existed between the 2 groups (p < 0.001). The loss of correction in the EPR was 2.0% ± 1.2% less than that in the IS group at 3.7% ± 2.5%, thus marking differences with statistical significance between the 2 groups (p < 0.001).

The preoperative MVBH was 69.4% ± 10.8% in the EPR and 67.2% ± 13.5% in the IS group, with no differences with statistical significance between the 2 groups (p = 0.495). In the EPR group, the postoperative MVBH was corrected to 95.2% ± 3.9%.

| Table 2. Comparison of perioperative parameters between the EPR and IS groups |
|------------------|------------------|------------------|------------------|
| Variable         | EPR group (n = 63) | IS group (n = 65) | p-value |
| Operating time (min) | 134.7 ± 31.8      | 140.0 ± 27.0     | 0.315† |
| Intraoperative bleeding (mL) | 361.7 ± 143.9    | 325.8 ± 100.9    | 0.274† |

Values are presented as mean ± standard deviation. EPR, endplate reduction; IS, intermediate screws.

†The independent samples t-test was used. †The Wilcoxon t-test was used.

| Table 3. Comparison of radiographic parameters between the EPR and IS groups |
|------------------|------------------|------------------|------------------|
| Variable         | EPR group (n = 63) | IS group (n = 65) | p-value |
| VWA (°)          |                  |                  |              |
| Preoperative     | 16.3 ± 6.0       | 17.3 ± 4.1       | 0.139†   |
| Postoperative    | 5.0 ± 3.3        | 4.5 ± 8.7        | 0.612†   |
| 12-Month follow-up | 6.8 ± 3.2        | 7.8 ± 10.6       | 0.05†    |
| Correction loss  | 1.9 ± 1.6        | 3.3 ± 1.9        | < 0.001** |
| CA (°)           |                  |                  |              |
| Preoperative     | 18.0 ± 9.4       | 15.1 ± 6.2       | 0.123†   |
| Postoperative    | 4.9 ± 5.1        | 4.8 ± 4.3        | 0.664†   |
| 12-Month follow-up | 7.5 ± 5.0        | 8.2 ± 5.1        | 0.391†   |
| Correction loss  | 2.6 ± 1.4        | 3.4 ± 1.8        | 0.005** |
| AVBH (%)         |                  |                  |              |
| Preoperative     | 63.4 ± 12.3      | 61.0 ± 10.1      | 0.222†   |
| Postoperative    | 96.2 ± 2.5       | 95.8 ± 5.1       | 0.173†   |
| 12-Month follow-up | 94.2 ± 2.6       | 92.1 ± 5.7       | < 0.001** |
| Correction loss  | 2.0 ± 1.2        | 3.7 ± 2.5        | < 0.001** |
| MVBH (%)         |                  |                  |              |
| Preoperative     | 69.4 ± 10.8      | 67.2 ± 13.5      | 0.495†   |
| Postoperative    | 95.2 ± 3.9       | 92.9 ± 4.6       | < 0.001** |
| 12-Month follow-up | 93.4 ± 2.9       | 89.4 ± 4.4       | < 0.001** |
| Correction loss  | 1.8 ± 2.6        | 3.5 ± 2.7        | < 0.001** |

Values are presented as mean ± standard deviation. EPR, endplate reduction; IS, intermediate screws; VWA, vertebral wedge angle; CA, Cobb angle; ABH, anterior vertebral body height; MBH, middle vertebral body height; UEPL, upper endplate line. *p < 0.05 is considered statistically significant. †The Wilcoxon test was used.

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2.9 ± 2.0

In our study, the ERP group was used to directly pry and maintained at 93.4% ± 2.9% at 12-month postoperative follow-up, with a correction loss of 1.8% ± 2.6% all better than the postoperative corrected height of 92.9% ± 4.6% in the IS group, with a follow-up height of 89.4% ± 4.4% and a correction loss of 3.5% ± 2.7%, with differences with statistical significance between the 2 groups (p < 0.001).

The preoperative UEPL was 114.4% ± 7.0% in the EPR group and 114.8% ± 6.3% in the IS group, with no differences with statistical significance between the 2 groups (p = 0.905). The EPR group corrected the UEPL to 103.1% ± 2.6% postoperatively and maintained it at 104.3% ± 3.5% at 12-month postoperative follow-up, with a correction loss of 1.2% ± 2.6%, which was better than the postoperative correction of 105.2% ± 3.3% in the IS group, and 108.1% ± 4.4% at follow-up, with a correction loss of 2.9% ± 2.5%, with differences with statistical significance between the 2 groups (p < 0.001) (Table 3).

The EPR group had a preoperative UIVA of 4.3° ± 2.8°, corrected to 3.3° ± 1.7° postoperatively and maintained at 3.6° ± 1.9° at 12-month follow-up, with a corrected loss of 0.27° ± 1.30° versus 4.2° ± 2.5° preoperatively, 2.9° ± 2.0° postoperatively and 3.0° ± 1.4° at follow-up in the IS group, with a corrected loss of 0.12° ± 2.19°. The differences between the 2 groups were not statistically significant. In the EPR group, the UIDH was 6.4 ± 0.2 mm preoperatively, 7.6 ± 0.2 mm postoperatively, and 7.0 ± 0.1 mm at the 12-month postoperative follow-up; in the IS group, it was 6.7 ± 1.4 mm preoperatively, 8.2 ± 1.6 mm postoperatively and 6.6 ± 2.0 mm at the follow-up, with no differences with statistical significance between the 2 groups. However, the loss of disc height in the EPR group was 0.6 ± 1.6 mm less than the loss of 1.5 ± 1.6 mm in the IS group, and the difference between the 2 groups was statistically significant (p < 0.001) (Table 4).

**DISCUSSION**

The technique in EPR group is suitable for thoracolumbar fractures without symptoms of neurological injury, with symptoms of neurological injury, often requiring spinal canal decompression, and poor stability with 4-screw fixation alone. This technique is particularly useful for patients with thoracolumbar fractures with severe central endplate injuries. The LSC score was previously often used to determine whether to perform anterior surgery, and the risk of failure with posterior fixation was higher than an LSC score > 7. The LSC score is used as a reference and is no longer strictly standard for posterior fixation alone.\(^\text{18,24}\) In our study, the ERP group was used to directly pry and reposition the endplate and implant allograft bone to fill the bone defect, maintaining endplate repositioning and achieving reconstruction of the anterior and middle columns of the vertebral body. Some studies demonstrated that the strength of the 4-screw fixation using a short posterior approach across the injured vertebral body was adequate compared to the 6-screw fixation method of IS group by repositioning the endplate and effectively filling the bone defect, consistent with the results of this study.\(^\text{25-27}\)

The EPR group and the IS group were compared in this study, focusing on the assessment of radiological indices. The result indicated that the EPR group had no significant advantage over the IS group in resetting the VWA, CA, and AVBH, whereas it maintained the resetting better with less postoperative correction loss. The EPR group provided better repositioning of the MVBH and UEPL than the IS group, with better postoperative maintenance and less postoperative loss.

Good EPR is capable of allowing for the repositioning of the vertebral body and intervertebral disc, thus leading to better maintenance of the repositioning effect, reducing the risk of internal fixation fracture, and reducing the incidence of recurrent kyphosis.\(^\text{27,28}\)

In recent years, the importance of EPR has begun to attract the attention of orthopedic surgeons.\(^\text{12,25,29}\) EPR is important, but indirect repositioning methods that rely solely on ligamentous torsion are not effective in restoring the collapse of the central endplate injury,\(^\text{22,25,26}\) which directly affects the change in the vertebral space and increases the risk of recurrent kyphosis.

<table>
<thead>
<tr>
<th>Variable</th>
<th>EPR group (n = 63)</th>
<th>IS group (n = 65)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>UIVA (°)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preoperative</td>
<td>4.3 ± 2.8</td>
<td>4.2 ± 2.5</td>
<td>0.901*</td>
</tr>
<tr>
<td>Postoperative</td>
<td>3.3 ± 1.7</td>
<td>2.9 ± 2.0</td>
<td>0.098*</td>
</tr>
<tr>
<td>Follow-up at 12 months</td>
<td>3.6 ± 1.9</td>
<td>3.0 ± 1.4</td>
<td>0.099*</td>
</tr>
<tr>
<td>Correction loss</td>
<td>0.3 ± 1.3</td>
<td>0.1 ± 2.2</td>
<td>0.664*</td>
</tr>
<tr>
<td>UIDH (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preoperative</td>
<td>6.4 ± 0.2</td>
<td>6.7 ± 1.4</td>
<td>0.248*</td>
</tr>
<tr>
<td>Postoperative</td>
<td>7.6 ± 0.2</td>
<td>8.2 ± 1.6</td>
<td>0.114*</td>
</tr>
<tr>
<td>Follow-up at 12 months</td>
<td>7.0 ± 0.1</td>
<td>6.6 ± 2.0</td>
<td>0.083*</td>
</tr>
<tr>
<td>Correction loss</td>
<td>0.6 ± 1.6</td>
<td>1.5 ± 1.6</td>
<td>&lt; 0.001*</td>
</tr>
</tbody>
</table>

Values are presented as mean ± standard deviation. EPR, endplate reduction; IS, intermediate screws; UIVA, upper intervertebral angle; UIDH, upper intervertebral disc height. *p < 0.05 is considered statistically significant. The Wilcoxon test was used.
Endplate prying was employed in the EPR group, prying the endplate and disc as a whole to directly pry and reposition the endplate injury, by prying from a thinner pedicle opener (4 mm), thus increasing the flexibility of the prying and facilitating adjustment of the prying direction and positioning. Subsequently, the Schanz screw (6.2 mm) was adopted to increase the range and reliability of the pry repositioning, allowing satisfactory endplate repositioning to be achieved. Balloon-assisted reduction (percutaneous kyphoplasty) combined with posterior short-segment internal fixation refers to a common method of EPR. The above method comprises the placement of a balloon in the fractured vertebral body, controlled expansion of the balloon to reset a central endplate injury, and then the removal of the balloon followed by cement filling to maintain the reduction. This method is effective in repositioning central endplate collapse, whereas it faces difficulty in positioning the balloon at the base of the collapsed endplate, which is not sufficiently fine. Besides, there exists inevitably some loss of repositioning of the endplate when the balloon is removed for cement filling. Another disadvantage of the balloon-assisted system is that it is complex and costly to perform. Currently, IS have been more commonly used, where 2 pedicle screws are placed through the fractured vertebral body to assist in resetting the central endplate injury. To be specific, 2 slightly shorter pedicle screws are placed underneath the collapsed central endplate, and pressure is applied to the pedicle screw and connecting rod to reposition the collapsed endplate. The above method is capable of facilitating repositioning of the central endplate, whereas the placement of the pedicle screw in the fractured vertebral body can cause further compression of the injured vertebral body, thus resulting in redisplacement of the fracture and risk of injury to the spinal cord. Effective repositioning of the central endplate collapse is achieved by inserting the pedicle screw at the base of the endplate collapse and then using the appropriate movement of the screw to achieve precise repositioning of the endplate. The IS method is capable of only achieving rough repositioning of the central endplate injury by adjusting the length and orientation of the pedicle screws, while precise repositioning is difficult to achieve. Percutaneous screw fixation of thoracolumbar fractures is also widely used in clinical practice. This technique is less traumatic to the soft tissues and results in a faster recovery, shorter hospital stays, and a lower risk of infection. Both four-screw and 6-screw fixation methods have been used in the application of this technique and have achieved good clinical results. However, this technique relies on an indirect approach to repositioning vertebral fractures. The screws placed in the injured vertebral body are polyaxial screws, which do not adequately reposition the endplate of the injured vertebral body, and the soft tissue obstruction also has an impact on the operation of indirect repositioning. The percutaneous screw technique is more suitable for patients with peripheral endplate injuries, where effective repositioning can be achieved by indirect repositioning, but satisfactory repositioning cannot be achieved for vertebrae with central endplate injuries.

The approach of the EPR group is effective in slowing disc degeneration and reducing loss of disc height (0.6 ± 1.6 mm vs. 1.5 ± 1.6 mm, p < 0.001). Effective endplate repositioning restores normal disc space and helps to slow disc degeneration, maintain normal disc space, and reduce recurrent kyphosis and chronic low back pain.

The EPR group resulted in better vertebral healing (71.4% vs. 47.7%, p = 0.006), the varying degree of a cavity remaining in the vertebral body after endplate repositioning can result in loss of fracture reduction and affect vertebral fracture healing, with considerable vertebral fractures still finding cavities when the internal fixation is removed, resulting in loss of vertebral reduction and recurrent kyphosis. To better maintain the reduction and promote fracture healing, we use the allograft bone implant technique, which effectively promotes fracture healing and good postoperative resorption. It is less traumatic, has fewer complications, and is more comfortable than the use of autogenous bone grafting. In contrast, the use of bone cement implants to fill the cavity, has the potential for leakage of the bone cement into the intervertebral disc, muscle block, and venous system, with adverse consequences, though beneficial for filling the residual cavity after reduction and for maintenance of EPR. Bone cement is also difficult to absorb within the vertebral body and prolonged retention within the vertebral body can have a detrimental effect on adjacent vertebrae and discs.

The risk of implant breakage was lower in the EPR group than in the IS group (0% vs. 9.2%, p = 0.04). In the analysis of this study, this was partly because the fracture was better repositioned and maintained in the EPR group and the fracture healed better, which effectively relieved the stresses on the implant; and partly because the 6-screw fixation in the IS group was more robust but had a greater concentration of stresses, whereas the 4-screw fixation in the EPR group retained some mobility above and below the fractured vertebral body, which stress concentrations are reduced.

However, there are still some limitations to the above approach. First, the sample size was relatively small, which may affect the
authenticity of the results. Second, direct prying and repositioning of the endplate only apply to patients with upper endplate injuries, and prying and repositioning of the endplate were difficult to achieve with lower endplate injuries. Third, the degree of prying and repositioning and the amount of implantation of allogeneic bone are difficult to control precisely, which require monitoring and manipulation under an x-ray fluoroscope.

CONCLUSION

Both the EPR group and the IS group achieved good repositioning results based on the treatment of single vertebral burst fractures of the thoracolumbar, whereas the EPR group was more effective in repositioning and maintaining MVBH, as well as endplate morphology, which achieved good maintenance of VWA, CA, AVBH, and endplate morphology after repositioning and less correction loss. The EPR group exhibited a better healing pattern after vertebral fracture, provided better relief from disc degeneration, and achieved a lower risk of implant breakage.

NOTES

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Author Contribution: Conceptualization: PW; Data curation: JH, YC; Formal analysis: JH; Methodology: SY; Project administration: DR, HW, PW; Visualization: LG; Writing - original draft: JH; Writing - review & editing: JH

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REFERENCES


Facet Articular Irregularity Is the Most Relevant Risk Factor for Rapidly Progressive Degenerative Cervical Myelopathy

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Objective: Facet articular irregularity is associated with rapidly progressive degenerative cervical myelopathy (DCM). However, its significance compared with other known risk factors remains unknown. Therefore, this retrospective study aimed to clarify the potential impact of facet articular irregularity as a risk factor for rapid DCM progression.

Methods: This study included 141 consecutive patients with DCM who underwent surgical treatment at our institution. Clinical variables and radiological findings related to DCM progression were collected. Imaging findings were analyzed at the segmental level of myelopathy in each case. The patients were divided into 2 groups based on the presence or absence of rapid DCM progression, and independent risk factors were determined using logistic regression analyses.

Results: Overall, 131 patients with a mean age of 63.9 ± 12.6 years were analyzed; 27 patients (20.6%) were classified into the rapid DCM progression group. The mean age was significantly higher in the rapid progression group than in the slow progression group (72.4 ± 9.6 vs. 61.7 ± 12.4, p < 0.001). According to univariate analysis, facet articular irregularity, dynamic segmental translation (≥ 1.6 mm), upper cervical spine involvement above C4–5, history of cerebrovascular events, preceding minor trauma, local lordotic angle (≥ 4.5°), diabetes, hypertension, ligamentum flavum hypertrophy, and age were independent risk factors. Additionally, multivariate analysis showed that facet articular irregularity was the highest risk factor for rapid DCM progression (p = 0.001).

Conclusion: Facet articular irregularity is the most clinically significant finding among the known risk factors in patients with rapid DCM progression.

Keywords: Articular, Cervical myelopathy, Degenerative, Facet joint, Logistic regression, Risk factor

INTRODUCTION

Degenerative cervical myelopathy (DCM) is a common spinal disorder caused by osteoarthritic changes to the spine, including spondylosis, disc herniation, and facet arthropathy, ligamentous hypertrophy, calcification, or ossification.¹ Degeneration of the cervical spine is initially asymptomatic; however, it may gradually present with and may cause not only arthropathy but also myelopathy or radiculopathy. DCM, which is represented by cervical spondylotic myelopathy (CSM), is an age-related disease that reduces quality of life due to impairment of motor functions.² Additionally, DCM is a slowly progressive disorder that corresponds to the underlying degenerative changes.³ However, it is known that some patients experience rapidly progressive neurological deterioration despite the absence of trauma.⁴

The preoperative severity of myelopathy correlates with poor postoperative outcomes in patients with DCM, similar to those
with CSM. Therefore, in patients with rapid DCM progression, surgical intervention as early as possible is strongly recommended to prevent poor postoperative outcomes. To avoid neurological deterioration in such patients, it is important to identify risk factors that may predict rapid disease progression. However, few reports have described rapid neurological progression in DCM.

We recently reported, for the first time, that the degenerative pathology of the facet joint is potentially important, and that facet articular irregularity is a specific finding in cases of rapidly progressive DCM. However, the impact of facet joint pathology in DCM is still controversial. Thus, the importance of specific findings regarding facet degeneration remain unclear when compared to known factors involved in the progression of myelopathy. Therefore, this study was conducted to determine the predictive factors of rapid DCM progression and their order of relevance with factors involved in myelopathy progression, including facet articular irregularity: a newly known risk factor.

**MATERIALS AND METHODS**

All experiments were conducted in accordance with the Declaration of Helsinki. All research protocols were approved by the Institutional Review Board of Nara Medical University (approval number: 2241). The requirement for informed consent was waived since it was a retrospective study.

**1. Patient Selection**

We retrospectively analyzed consecutive patients with DCM who underwent surgical treatment at Nara Medical University between January 2013 and December 2020. The study population was the same as in the previous study. Inclusion criteria included cervical myelopathy responsible for the subaxial level between C2–3 and C6–7. The diagnosis of cervical myelopathy was based on symptoms and magnetic resonance imaging (MRI) findings. The responsible segmental level was defined as the level of the lesion causing myelopathy and was identified in each case based on neurologic examinations and MRI findings, if necessary. Patients who had undergone revision surgery within 12 months or those with missing data were excluded.

Clinical data and radiological findings were gathered retrospectively from medical records, preoperative and postoperative neurological examinations, and radiographic images.

**2. Clinical Data Collection**

Clinical variables, such as age, sex, comorbidities (hypertension, diabetes mellitus, cigarette smoking, habitual alcohol use), background disorders, responsible spinal segmental level, pre- and postoperative Japanese Orthopaedic Association (JOA) scores for the evaluation of cervical compression myelopathy, and preoperative Nurick grade were collected from the patients’ records. Recovery rate (%) of the JOA score was also calculated using the following formula: ("postoperative score"-"preoperative score")/(17-"preoperative score") × 100. Other clinical variables that are potentially involved in the rapid progression of cervical myopathy in DCM, such as history of cerebrovascular events (CVEs) and preceding minor trauma, were also gathered.

We also assessed the characteristic clinical course and rapid progression of cervical myelopathy in each case. Rapid progression of cervical myelopathy was defined in this study as previously reported. In brief, patients with rapid DCM progression had difficulty maintaining a standing posture or walking without support, which corresponded to Nurick grade 4 or 5, within 4 weeks of symptom onset, due to rapidly progressive neurological deterioration.

**3. Radiological Evaluations**

Radiological variables potentially involved in the progression of cervical myopathy in DCM were gathered from preoperative computed tomography (CT) and MRI and radiograms of the cervical spine in each patient. From the MRI review, intramedullary hyperintense changes on sagittal T2-weighted images at the responsible segmental level (Fig. 1A), hypertrophy of the ligamentum flavum at the responsible segmental level (Fig. 1B), and the number of levels with spinal canal stenosis in each patient were assessed. From the CT review, we carefully evaluated the cervical disc and facet joints at the responsible segmental level and assessed the presence of calcified discs (Fig. 1C) and facet articular irregularity (Fig. 1D), which was defined as equivalent to grade 4 or 5B in the CT classification reported previously at either or both facet joints.

From the review of lateral radiograms, the local lordotic angle (Fig. 2A) and anteroposterior diameter of the space available for the spinal cord (Fig. 2B) in the neutral position were evaluated at the segmental level in addition to the C2–7 lordotic angle (Fig. 2C). Local dynamic instability at the responsible segmental level was also evaluated by the difference in the distances of anteroposterior translation of the upper vertebral body relative to the lower vertebral body in the flexed and extended positions (Fig. 2D).
Risk Factors for Rapid DCM Progression

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4. Data Analysis

The study population was divided into 2 cohorts, namely a rapid progression group and a slow progression group, depending on whether they met the definition of rapid progression. To identify and compare risk factors for rapid progression of DCM, the above-mentioned clinical and radiological variables were compared between the 2 groups; those that showed statistically significant differences were included in the logistic analysis to determine the independent risk factors for preoperative rapid progression of myelopathy and its order of relevance.

5. Statistical Analysis

All statistical analyses were performed using IBM SPSS Statistics ver. 26.0 (IBM Co., Armonk, NY, USA). Continuous variables among the clinical characteristics and radiological variables at each spinal level were compared using an unpaired t-test. Binary and nominal variables among the clinical characteristics and radiological variables were compared using Pearson chi-square test.

Logistic regression analysis was performed according to the following procedures. Independent risk factors and odds ratios (ORs) were obtained by univariate logistic regression analysis. Multivariate logistic regression analysis was performed by adding age, which was the greatest confounding factor, to the variables with large ORs to identify the variables that contributed the most to rapid DCM progression.

Fig. 1. Radiological assessments in the cervical spine on magnetic resonance image (A, B) and computed tomography image (C, D) at the responsible segmental level. (A) Intramedullary hyperintense change on sagittal T2-weighted images (T2WI). (B) Hypertrophy of the ligamentum flavum. (C) Calcified discs. (D) Facet articular irregularity, defined as equivalent to grade 4 or 5B in the computed tomography classification.12

Fig. 2. Radiological assessments of degenerative changes in the cervical spine on lateral radiograms. (A) Local lordotic angle between the upper and lower vertebral body surfaces at the responsible spinal segmental level in the neutral position. (B) Anteroposterior diameter of the space available for the spinal cord in the cervical spinal canal in the neutral position. (C) C2–7 lordotic angle in neutral position. (D) Dynamic segmental translation, evaluated in the flexed and extended positions: |d–d’|. a: local angle; b: space available for cord; c: C2–7 angle; d and d’: distance of anteroposterior translation of the upper vertebral body relative to the lower vertebral body in flexed (d) and extended (d’) positions.
Data are presented as mean ± standard deviation. Statistical significance was defined as \( p < 0.05 \).

**RESULTS**

Although 141 patients were enrolled, only 131 were included in the analyses. One patient was excluded because he had undergone revision surgery within the previous 12 months, and 9 patients were excluded because of insufficient radiological data. Meanwhile, 27 (20.6%) and 104 patients (79.4%) were categorized into the rapid and slow progression groups, respectively (Fig. 3).

There were 86 men and 45 women aged 38–93 years (63.9 ± 12.6 years). Most patients had spondylosis (60.3%) followed by ossification of the posterior longitudinal ligament (22.1%) and cervical disc herniation (17.6%). The most common responsible segmental levels were C5–6 (36.6%) followed by C4–5 (35.1%); C2–3 were the least common (2.3%). Patients with Parkinson disease or the other movement disorders were not included.

1. Clinical Characteristics

The detailed clinical characteristics of the patients in each group are presented in Table 1. There was a significant difference between the 2 groups in terms of age \( (p < 0.001) \), hypertension \( (p = 0.015) \), diabetes \( (p = 0.006) \), history of CVE \( (p = 0.004) \), and preceding minor trauma \( (p = 0.008) \), and responsible segmental level above C4–5 \( (p = 0.001) \). The rapid progression group tended to be older and had a significantly higher incidence of these variables.

The mean preoperative and mean postoperative JOA scores of the rapid and slow progression groups were 8.7 ± 2.3 and 12.7 ± 2.4, and 12.5 ± 2.2 and 14.8 ± 2.0, respectively, which were significantly different \( (all \ p < 0.001) \). Meanwhile, the improvement rates in the JOA scores of the rapid and slow progression groups were 44.8% ± 19.5% and 54.4% ± 30.0%, respectively, which were not statistically significant.

2. Radiological Characteristics

The detailed radiological characteristics of the patients in each group are presented in Table 2. On MRI, the incidence of ligamentum flavum hypertrophy was significantly higher in the rapid progression group than in the slow progression group \( (p = 0.041) \). Meanwhile, there was no statistically significant differences in intramedullary signal changes at the responsible level or number of levels with spinal canal stenosis between the 2 groups. On CT, the incidence of facet articular irregularity was significantly higher in the rapid progression group than in the slow progression group \( (p < 0.001) \), but there was no significant difference in the presence of calcified discs between the 2 groups. Radiographic findings showed that the local lordotic angle \( (p = 0.037) \) and dynamic segmental translation \( (p < 0.001) \) were significantly higher in the rapid progression group than in the slow progression group. However, there was no significant difference in the space available for the spinal cord and C2–7 lordotic angle between the 2 groups.
### Table 1. Clinical characteristics of the 2 groups (n = 131)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Rapid progression group (n = 27)</th>
<th>Slow progression group (n = 104)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>72.4 ± 9.6</td>
<td>61.7 ± 12.4</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Male sex</td>
<td>19 (70.4)</td>
<td>67 (62.5)</td>
<td>0.562</td>
</tr>
<tr>
<td>Risk factor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hypertension</td>
<td>16 (59.3)</td>
<td>35 (33.7)</td>
<td>0.015*</td>
</tr>
<tr>
<td>Diabetes</td>
<td>11 (40.7)</td>
<td>17 (16.2)</td>
<td>0.006*</td>
</tr>
<tr>
<td>Rheumatoid arthritis</td>
<td>1 (3.7)</td>
<td>3 (2.9)</td>
<td>0.826</td>
</tr>
<tr>
<td>Undergoing hemodialysis</td>
<td>1 (3.7)</td>
<td>1 (1.0)</td>
<td>0.300</td>
</tr>
<tr>
<td>Current smoker</td>
<td>6 (22.2)</td>
<td>40 (38.5)</td>
<td>0.115</td>
</tr>
<tr>
<td>Habitual alcohol use</td>
<td>7 (25.9)</td>
<td>37 (35.6)</td>
<td>0.344</td>
</tr>
<tr>
<td>Background disorder</td>
<td></td>
<td></td>
<td>0.214</td>
</tr>
<tr>
<td>Spondylolisthesis</td>
<td>20 (74.1)</td>
<td>59 (56.7)</td>
<td></td>
</tr>
<tr>
<td>Disc herniation</td>
<td>4 (14.8)</td>
<td>19 (18.3)</td>
<td></td>
</tr>
<tr>
<td>OPLL</td>
<td>3 (11.1)</td>
<td>26 (25.0)</td>
<td></td>
</tr>
<tr>
<td>Clinical factors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>History of cerebrovascular event</td>
<td>7 (25.9)</td>
<td>7 (6.7)</td>
<td>0.004*</td>
</tr>
<tr>
<td>Preceding minor trauma</td>
<td>7 (25.9)</td>
<td>8 (7.7)</td>
<td>0.008*</td>
</tr>
<tr>
<td>Responsible segmental level above C4/5</td>
<td>23 (85.2)</td>
<td>53 (51.0)</td>
<td>0.001*</td>
</tr>
<tr>
<td>Surgical outcomes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preoperative JOA score</td>
<td>8.7 ± 2.3</td>
<td>12.7 ± 2.4</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Preoperative JOA score</td>
<td>12.5 ± 2.2</td>
<td>14.8 ± 2.0</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Improvement rate of JOA score (%)</td>
<td>44.8 ± 19.5</td>
<td>54.4 ± 30.0</td>
<td>0.122</td>
</tr>
</tbody>
</table>

Values are presented as mean ± standard deviation or number (%).

OPLL, Ossification of posterior longitudinal ligament; JOA, Japanese Orthopaedic Association.

*p < 0.05, statistically significant differences.

### Table 2. Radiological characteristics of the 2 groups (n = 131)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Rapid progression group (n = 27)</th>
<th>Slow progression group (n = 104)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRI findings</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intramedullary signal change</td>
<td>22 (81.5)</td>
<td>66 (63.5)</td>
<td>0.076</td>
</tr>
<tr>
<td>Ligamentum flavum hypertrophy</td>
<td>16 (59.3)</td>
<td>39 (37.5)</td>
<td>0.041*</td>
</tr>
<tr>
<td>Number of levels involved</td>
<td>2.3 ± 1.1</td>
<td>2.3 ± 1.1</td>
<td>0.799</td>
</tr>
<tr>
<td>CT findings</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Presence of calcified discs</td>
<td>4 (14.8)</td>
<td>19 (18.3)</td>
<td>0.674</td>
</tr>
<tr>
<td>Facet articular irregularity</td>
<td>16 (59.3)</td>
<td>12 (11.5)</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Radiogram findings</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Local lordotic angle (°)</td>
<td>4.9 ± 6.5</td>
<td>2.0 ± 6.3</td>
<td>0.037*</td>
</tr>
<tr>
<td>Space available for cord (mm)</td>
<td>11.3 ± 1.5</td>
<td>10.7 ± 1.8</td>
<td>0.105</td>
</tr>
<tr>
<td>C2–7 angle (°)</td>
<td>12.4 ± 15.4</td>
<td>7.9 ± 11.1</td>
<td>0.097</td>
</tr>
<tr>
<td>Dynamic segmental translation, mm</td>
<td>2.4 ± 1.2</td>
<td>1.4 ± 0.9</td>
<td>&lt;0.001*</td>
</tr>
</tbody>
</table>

Values are presented as number (%) or mean ± standard deviation.

MRI, magnetic resonance imaging; CT, computed tomography.

*p < 0.05, statistically significant differences.

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Table 3. Logistic regression analysis for factors related to preoperative rapid neurological progression

<table>
<thead>
<tr>
<th>Variable</th>
<th>Univariate</th>
<th>Multivariate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OR (95% CI)</td>
<td>p-value</td>
</tr>
<tr>
<td>Age</td>
<td>1.087 (1.039–1.138)</td>
<td>0.001*</td>
</tr>
<tr>
<td>Male sex</td>
<td>1.312 (0.524–3.286)</td>
<td>0.563</td>
</tr>
<tr>
<td>Hypertension</td>
<td>2.868 (1.203–6.836)</td>
<td>0.017*</td>
</tr>
<tr>
<td>Diabetes</td>
<td>3.518 (1.392–8.891)</td>
<td>0.008*</td>
</tr>
<tr>
<td>History of cerebrovascular event</td>
<td>4.850 (1.531–15.36)</td>
<td>0.007*</td>
</tr>
<tr>
<td>Preceding minor trauma</td>
<td>4.200 (1.366–12.91)</td>
<td>0.012*</td>
</tr>
<tr>
<td>Responsible segmental level above C4/5</td>
<td>5.533 (1.789–17.12)</td>
<td>0.003*</td>
</tr>
<tr>
<td>Ligamentum flavum hypertrophy</td>
<td>2.424 (1.022–5.753)</td>
<td>0.045*</td>
</tr>
<tr>
<td>Facet articular irregularity</td>
<td>11.15 (4.205–29.57)</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Local lordotic angle (≥ 4.5°)</td>
<td>3.519 (1.464–8.557)</td>
<td>0.005*</td>
</tr>
<tr>
<td>Dynamic segmental translation (≥ 1.6 mm)</td>
<td>5.744 (2.132–15.47)</td>
<td>0.001*</td>
</tr>
</tbody>
</table>

OR, odds ratio; CI, confidence interval.
*p < 0.05, statistically significant differences.

3. Comparison of Risk Factors for Rapid Progression of DCM

Of the variables that showed statistically significant differences between the 2 groups, the 2 continuous variables, local lordotic angle and dynamic segmental translation, were converted to binary variables to homogenize the conditions of each variable and to compare them by OR; these were applied to the receiver operating characteristic analysis. The cutoff values for each variable that maximized sensitivity and specificity were then determined to be 4.5° and 1.55 mm, respectively. The 2 continuous variables were then converted into binary variables based on these cutoff values. Independent risk factors for preoperative rapid progression of myelopathy and their order of relevance were determined using logistic regression analysis (Table 3).

Univariate logistic regression analysis determined facet articular irregularity (OR, 11.15; p < 0.001), dynamic segmental translation (≥ 1.6 mm) (OR, 5.744; p = 0.001), responsible segmental level above C4–5 (OR, 5.533; p = 0.003), history of CVE (OR, 4.850; p = 0.007), preceding minor trauma (OR, 4.200; p = 0.012), local lordotic angle (≥ 4.5°) (OR, 3.519; p = 0.005), diabetes (OR, 3.518; p = 0.008), hypertension (OR, 2.868; p = 0.017), ligamentum flavum hypertrophy (OR, 2.424; p = 0.045), and age (OR, 1.087; p = 0.001) as independent risk factors. As age was a confounding factor for many of the variables, multivariate analysis was performed by adding age to the top 3 variables based on the OR. The results revealed that facet articular irregularity was the most significant risk factor for rapid progression of DCM (OR, 6.169; p = 0.001).

DISCUSSION

This study evaluated the potential risk factors for rapid preoperative progression of DCM and their order of relevance in patients who were candidates for surgery. While many risk factors were found to be statistically significant, facet articular irregularity was the most significant risk factor.

Facet articular irregularity was reportedly observed at the responsible spinal segmental level especially in patients with rapid DCM progression. The results of the current study suggest that rapid DCM progression is multifactorial, and that the finding of facet articular irregularity is potentially quite significant.

1. Rapid Progression of DCM and Associated Risk Factors

Although some studies identified the natural history or clinical predictors of slow progression in patients with CSM who were asymptomatic or treated conservatively, there have been only 3 studies that investigated rapid CSM progression. Morishita et al. demonstrated that preceding minor trauma and C3–4 spinal level impairment were observed in 50% (4 of 8) and 75% (6 of 8) of cases, respectively. In contrast, comorbid sagittal instability, defined as > 3.5 mm of dynamic translation or ≥ 11° of angulation compared to the adjacent segment, was observed in only 12.5% (1 of 8) of cases. In their retrospective case–series study, Takaasawa et al. also demonstrated 2 risk factors based on logistic regression analysis: past history of CVE and high intramedullary signal on T2-weighted MRI. However, these studies had a major disadvantage: the responsible segmental level was not assessed by detailed neurological examination...
but only by assessment of intramedullary hyperintensity on T2-weighted MRI.\(^6,6^9\)

It is known that patients with asymptomatic spinal canal stenosis may exhibit intramedullary T2 hyperintensity of the cervical spine. In a study of 1,211 asymptomatic Japanese volunteers aged 20–79 years, Nakashima et al.\(^6^6\) reported that significant spinal cord compression, intramedullary T2 hyperintensity, and flattening of the spinal cord were observed in 5.3%, 2.3%, and 3.1% of the subjects, respectively. Meanwhile, approximately one-third of patients with CSM have intramedullary hyperintensity on T2-weighted MRI,\(^6^7,6^8\) but no significant correlation has been reported between the signal intensity change and the severity of clinical symptoms,\(^6^9\) progression of myelopathy,\(^6^6\) or exacerbation of CSM in patients managed conservatively.\(^2^0\) Therefore, MRI signal changes are likely to demonstrate poor reliability as predictive risk factors. Furthermore, in listing and comparing risk factors with each other, we should properly evaluate the radiological characteristics at the responsible segment level. From this perspective, the current study had the advantage of using and evaluating radiological findings of the responsible segmental level based on detailed neurological examination.

2. CT Assessment of Facet Joint Degeneration of the Cervical Spine

Although MRI is commonly used to evaluate the spinal cord in DCM, assessment of skeletal factors is also important. The discs and facet joints are crucial structures for biomechanical shifts of stress on the cervical spine as well as for mobility.\(^2^1\) Rytman et al.\(^2^2\) identified intervertebral disc and facet joint abnormalities as degenerative changes in their study of a CT-based grading system for CSM. In that study, disc height loss, anterior osteophytes of vertebral bodies, and endplate sclerosis were adopted as signs of disc degeneration, while joint space narrowing and the presence of irregular articular surfaces were considered to be characteristics of facet joint pathology. However, these findings generally reflect not only destabilizing factors but also stabilizing ones.

In our previous study, we attempted to subdivide cervical facet joint degeneration by considering the stage of the disease based on CT evaluation.\(^2^3\) In particular, whereas previous reports had 4 categories including normal findings,\(^2^4\) new criteria of “articular subchondral cysts,” “articular irregularity,” “ankylosing change of the joint,” and “facet joint opening” were added, resulting in 6 classifications. With this approach, it was revealed that not only was facet articular irregularity at the responsible segmental level a remarkable finding in rapid DCM progression but that the novel CT classification is also highly reproducible, with a kappa coefficient of 0.822 for interrater concordance.\(^2^5\) Therefore, the assessment of facet joint degeneration based on the novel CT grading proposes the findings of facet articular irregularity with high reproducibility.

3. Implication of Facet Articular Irregularity in Rapid DCM Progression

Because DCM is caused by age-related changes in various parts of the spine, its pathogenesis is multifactorial.\(^1\) While the cervical facet joints play key roles not only in the stability and distribution of the axial load but also in guiding cervical motion, they are included as one of the sites that undergo age-related changes. If the changes occurring in the facet joints disrupt joint function, the facet joint pathology may cause augmentation of dynamic factors and induce DCM progression. In contrast, facet joint degeneration does not always occur synchronously with other age-related changes in the cervical spine. Lee et al.\(^2^6\) showed that facet joint degeneration depends on unco-vertebral joint degeneration and Modic change on MRI but not on disc or endplate degeneration, spinal stenosis, or ossification of the posterior longitudinal ligament. Therefore, facet joint degeneration should not be ignored even if other risk factors for DCM progression have been identified.

The current study found that rapid DCM progression is multifactorial, and facet articular irregularity is the most significant risk factor. There are 2 possible pathogeneses for rapid DCM progression due to facet articular irregularity. First, the multifactorial nature of rapid DCM progression suggests that microinstability of the facet joints in the presence of a pathological background, such as spinal canal stenosis, may exacerbate dynamic compression of the spinal cord.

The other hypothesis is that facet articular irregularity is a symbolic change owing to the effects of excessive motion stress. As cervical degeneration does not occur uniformly, stress from cervical spine motion is not evenly distributed and can sometimes become concentrated at 1 level. Typically, adjacent segment diseases occur after fusion surgery; however, we believe that a similar situation can occur after natural vertebral fusion or intervertebral stabilization due to advanced age. The results of this study, which showed that rapid DCM progression is more common in the elderly and at higher levels above C4–5, suggest that stabilization in the preceding middle and lower cervical spine due to age-related changes may have resulted in greater dynamic stress on the upper intervertebral joints.

We would also like to consider the significance of the differ-
ence in the frequency of facet articular irregularities between the 2 groups. Surprisingly, the rapid DCM progression group had a higher incidence of facet articular irregularity (59.3%), which was 5 times higher than that in the slow progression group. To prevent poor postoperative outcomes in patients with rapid DCM progression, surgical intervention should be performed as early as possible. Therefore, if there is a symbolic change in facet articular irregularity at the intervertebral level accompanied by spinal canal stenosis due to other factors, it may be necessary to identify the responsible spinal segmental level and consider early surgical treatment.

4. Limitations
This study had several limitations. First, it had a retrospective design with a small number of patients. Second, it is uncertain whether the responsible spinal segmental level was accurately estimated in all the cases. Third, there is a pair of facet joints at each intervertebral level that do not always have the same degree of degeneration. In the present study, we were unable to examine the differences in the clinical impact on rapid DCM progression between cases with unilateral and bilateral facet articular irregularities; further studies on this issue are warranted. Fourth, the effect of global sagittal alignment on facet joint degeneration was not evaluated in this study. Fifth, the design of this study was to statistically compare the known risk factors with additional facet articular irregularity and not to examine potential physiological mechanisms. Further studies are warranted to clarify this point.

Despite these limitations, this study demonstrated the importance and clinical usefulness of evaluating risk factors for the rapid progression of myelopathy in patients with DCM. In order to elucidate the significance of facet articular irregularities, a future study of their frequency in normal individuals and asymptomatic cases will be warranted.

CONCLUSION
This study focuses on the potential importance of facet joint pathology in patients with DCM and, for the first time, compares it with known risk factors related to rapidly progressive DCM. Facet articular irregularity is potentially the highest risk factor for rapid progression of DCM and may indicate dynamic pathophysiology in the progressive phase of myelopathy. Early surgical intervention and additional confirmation of the presence of facet articular irregularities and whether its level is consistent with the responsible spinal segmental level may also help improve surgical outcomes.

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A 30-Year Worldwide Research Productivity of Scientific Publication in Full-Endoscopic Decompression Spine Surgery: Quantitative and Qualitative Analysis

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8Department of Orthopedics, The First Affiliated Hospital of Xiamen University, School of Medicine, Xiamen University, Fujian, China
9Department of Orthopaedics, Naresuan University Hospital, Phitsanulok, Thailand
10Department of Neurosurgery, Prince Sultan Military Medical City, Riyadh, Saudi Arabia
11Department of Orthopaedics, Dr D Y Patil Medical College and Vidyapeeth, Pimpri Pune, India
12Yashwantrao Hospital, Satara Basappa Peth, Karanj Surti Sarata, Satara, Maharashtra, India
13Department of Orthopedics, Taipei Medical University Hospital, Taipei, Taiwan
14Department of Orthopedics, Caritas Medical Centre, Sham Shui Po, Hong Kong
15Department of Orthopaedics and Traumatology, United Christian Hospital, Kwun Tong, Hong Kong
16Private Orthopaedic Centre, Mong Kok, Kowloon, Hong Kong
17PSRI hospital and Research Centre, Sheikh Sarai, New Delhi, India
18Department of Orthopaedics, Park Clinic, Elgin, Kolkata, West Bengal, India
19Department of Orthopaedics, Burapha University Hospital, Chonburi, Thailand
20Department of Neurosurgery, Chang Gung Memorial Hospital, Chiayi, Taiwan
21Department of Orthopedics, Aster RV Hospital, Bengaluru, Karnataka, India
22Department of Orthopaedics, KEM Hospital, Pune, India
23Department of Orthopaedics, Hong Kong Baptist Hospital, Kowloon, Hong Kong
24Department of Orthopedics, Al-Kindy Teaching Hospital, Baghdad, Iraq

Objective: The ever-growing number of articles related to full-endoscopic spine surgery published in the last few decades presents a challenge which is perplexing and time-consuming in identifying the current research status. The study aims to identify and analyze the most cited works related to full-endoscopic decompression spine surgery, compare the articles published by different publishers and area, and show the current publication status of full-endoscopic research.
INTRODUCTION

The ongoing coronavirus pandemic pneumonia (severe acute respiratory syndrome coronavirus-2, SARS-CoV-2) has spread rapidly worldwide all over the world for more than 2 years since its nomenclature by World Health Organization. Due to its spread around the world, the low cost of postoperative care is a critical need and the clinical care models have gradually changed to accommodate the new healthcare environment. For this reason, so minimally invasive spine surgery as one of the solutions for clinical practice has been attracted by medical decision-makers due to its shorter perioperative period with less approach-related morbidity than traditional spine surgery. In recent decades, the interest in microscopic and endoscopic surgery has been growing in both developing and developed countries, especially rising fast in the area of full-endoscopic procedure. The ever-growing number of articles related to full-endoscopic technique published recently and present a challenge that is perplexing and time-consuming to recognize the high-impact papers.

The rapid development of modern information technologies significantly influences medical treatment and public health, and knowledge management in clinical medicine has provided new approaches and possibilities. The discipline of “Bibliometry” can be traced back to the beginning of the last century. It is a statistical method branch of information science that combines linguistics, information, and statistics. This bibliometric method can measure the information distribution models via quantitative and qualitative analysis of a particular research area from published journals. In general, the cited times were considered as a determined measurement of the impact of an author, article, or journal. After that, by conducting scientific mathematical methods for data integration and processing, the evolution of the selected research direction could be revealed and help to predict valuable future research directions. The present study aims to demonstrate the bibliometric analysis of the full-endoscopic spine decompression surgery publications and illustrate the research trends with visible scientific mapping. We also investigate the cost and resource allocation of each author’s country’s National Health System and discuss the impact of their likely willingness to submit to journals.

MATERIALS AND METHODS

1. Search Strategy

In our cross-sectional bibliometric analysis research, a thirty-year timespan of literature was searched on the Web of Science Core Collection database based on the modified evidence-based Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Our team performed the search with the “Topic” search function to search the title, abstract, author keywords, and KeyWords Plus on the Web of Science (WOS). The search formula was referenced and designed based on the AOSpine Consensus Paper on Nomenclature for Working-Channel Endoscopic Spinal Procedures of Full-endoscopic Decompression as follows: (endoscopy* or arthroscopy*) and (“Discectomy” or “foraminotomy” or “diskectomy” or “laminotomy” or “disc surgery” or “disc herniation” or “disk herniation” or “foraminoplasty” or “nucleotomy” or “facetectomy” or “flavectomy” or “decompression” or “transforaminal” or “interlaminar”) and (spine or spinal or lumbar or cervical or thoracic).

Methods: Using Bibliometrix, CiteSpace, and VOSviewer, we analyzed the bibliometric data selected from the Web of Science database between 1992 and 2022. Spine has the highest H-index with the most cited journal in the field of full-endoscopic decompression spine surgery. China ranked as the most productive country, whereas the most cited with high H-index papers came from South Korea. For the author analysis, Yeung AT, Ruetten S, Hoogland T, Ahn Y, Choi G, and Mayer HM were the most impactful authors in the global and local citations. The most productive organization is Wooridul Spine Hospital.

Conclusion: The bibliometric study showed a growing trend of research on full-endoscopic decompression spine surgery over the past 30 years. It has demonstrated that there is a significant increase in the number of authors, institutions, and internationally collaborated countries. However, the quality of studies is still low, and the lack of high-quality clinical evidence and the trend of general journal submissions has somewhat affected the quality of endoscopy journals in recent years.

Keywords: bibliometric analysis, citation analysis, spine, spine surgery, VOSviewer, CiteSpace
health information. Therefore, Institutional Review Board approval was not sought from our university. The study search strategy referenced the PRISMA guideline, and the reports followed the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) reporting guideline for cross-sectional studies.\(^7\)

2. Eligibility Criteria

We included English-language articles published in all indexed journals from January 1992 to October 2022. Two reviewers (YT and FV) screened the records independently for eligibility. The screening process had 2 stages. First, we screened the titles and abstracts obtained in the database search results to find relevant studies based on the criteria. Articles not accordant with the following inclusion criteria were excluded: Our search criteria included full-endoscopic clinical prospective/retrospective, randomized/nonrandomized, cohort-controlled studies; case series; case reports; technique reports; full-endoscopic relative basic studies such as finite biomechanical analysis. Other endoscopic techniques, such as biportal-endoscopy, epiduroscopy, joint surgery, microendoscopy, neuroendoscopy, laryngoscopy, thoracoscopy, or non-original articles, such as reviews, proceeding papers, editorial materials, early access, letters, corrections, and conferences, were excluded from this study. The selected publications were thoroughly investigated, and relevant details were recorded. Second, we did cross-checking, testing, and processing of the raw data on the 3 bibliometric software to ensure the various raw formats (.txt; BibTeX Database) and these were fully recognized and analyzed. Any disagreements were resolved through discussion involving a senior author (JS) to make a final consensus.

3. Bibliometrics Analysis

In our study, 3 professional bibliometric software (Bibliometrix 4.0.0,\(^8\) Citaspace 6.1.R3,\(^9\) and VOSviewer 1.6.18\(^10\)) were used for data processing. No software is superior to the others in every aspect. Therefore, the various most valuable elements of the 3 software were discussed and then used separately in our research for different analyses. Bibliometrix (University of the University of Naples Federico II, Naples, Italy) was an R-studio package from the bibliographic database for performance bibliometric analysis. VOSviewer 1.6.18 (Centre for Science and Technology Studies, Leiden University, Leiden, The Netherlands) is a free software tool for drawing graphical representations of bibliometric maps to construct and visualize the bibliometric networks which used to create a keyword co-occurrence network, overlay, and density visualization map in this study. It is based on the bibliographic data unit of the author keywords or KeyWords Plus. The correlation relationship between different units was measured by total link strength (TLS). CiteSpace is a Java application for analyzing and visualizing the scientific literature’s bibliometric character for analyzing an institution’s contribution, decomposing a network into clusters, and creating dual-map thematic overlays on global maps of science.\(^9\)\(^11\)

Figures used for knowledge visualization consist of nodes and links. Each node in the diagram represented one element, such as the institution or cocited reference. The size of each node indicated the occurrence frequency, the lines between the nodes suggested a co-occurrence or cocitation link, and the varying colors of the circles from the inner to the exterior of the node represented the progression of time. Furthermore, we believe that the economic strength of the country and the percentage of investment in the health system may one of the potential crucial factors influencing the implementation of full-endoscopy development and publication. Therefore, we surveyed the selected country’s population, gross domestic product, current estimates of health expenditures, and distribution of medical personnel from the World Bank Open Data which compiles country-level statistical data using information from the statistical systems of member countries and free access.

4. Data Processing

In our research, the number of published articles was considered an index of the quantity of research productivity. The number of citations was considered a quality indicator. Compared to the previous bibliometric publications, we do not rank the results with numbers, only presenting the most influential items of authors, countries, and institutions on tables. Before putting together, the keyword trends and clusters in Bibliometrix, CiteSpace, or VOSviewer, we manually standardized the keywords by merging similar keywords that were similar and replacing keywords that had nothing to do with the research. This improved the validity and quality of the research. Moreover, an independent Java engineer (DX) built Java programs and used secondary filtering and other processing on the raw data to make it fit the expected design of the method. For example, regarding the author analysis, extracting and analyzing only the first author and corresponding author is not available through 3 bibliometric software or the WOS directly. Because of this, it is crucial to get the needed information from the raw document correctly.

The core journals of full-endoscopic decompression spine
surgery (FEDS) are evaluated using Bradford’s law of scattering in descending order of the number of articles carried on the subject. The first zone is the nucleus of journals devoted to the given subjects, publishing about a third of the journals in the entire collection. We gathered data from the citing journal and the cited journal to construct a visual dural map for assessing, comparing, and contrasting publishing portfolio features. Moreover, our team designed a topic dendrogram to depict the object’s hierarchical relationship in FEDS research. It is generally obtained because of hierarchical clustering and is usually used to figure out the best way to allocate objects to clusters.

To find and describe the most-cited FEDS articles, as well as to compare the most-cited articles from the specialty journal and publisher (whether they are comprehensive or commercial publishers), the Scientific Information Web of Science’s Science Citation Index Expanded was used. We compared the top 3 most published established comprehensive publishers’ and open access (OA) or non-OA articles on the same metrics. The analysis was performed on the metrics with H-index, average per item (API), average citations per year (APY) and total number of citations (TC). In addition, we also divided the publishers into comprehensive and specific publishers according to the way they were established. For comprehensive publishers, such as Hindawi Publishing Group, MDPI, and Frontier Media Sà, these journals are peer-reviewed for multidisciplinary scientific publications. Conversely, specialized journals are often established by societies, specific or other medical special issues. The American Society of Interventional Pain Physicians, Thieme Medical Publishers, and the American Association of Neurological Surgeons are a few examples.

5. Statistical Analysis

The Stata 16.0 (Stata Corp., College Station, TX, USA) was used for all statistical analyses, and Microsoft Excel 2016 (Microsoft Corporation, Redmond, WA, USA) was used to analyze and present the data. For statistical analysis, 2-sample Wilcoxon rank-sum (Mann-Whitney) tests and Kruskal-Wallis H-tests were used to compare the TC and the average number of citations per year between OA and non-OA, the most published publisher and comprehensive with specific publishers. Shapiro-Wilk test and normal quantile plot for determining the normal-

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**Fig. 1.** Flowchart diagram illustrating the included articles included in the bibliometric analysis.
ity of data distribution. After applying Levene's test for variance, Mann-Whitney U was used. The Pearson correlation coefficient test (r) determined the statistical significance of correlations. Statistical significance was defined as a p-value of 0.05.

**RESULTS**

1. Descriptive Statistics of Bibliometric Analysis

   The WOS database search returned a total of 2,291 records. After manually reviewing the titles and abstracts of records on the marked list, 314 articles that did not meet the inclusion criteria were excluded. In conclusion, 990 FEDS-related studies that met the search criteria were included in the present bibliometric analysis (Fig. 1). The number of authors is 2,306, with 9.39% international coauthorships from 43 countries contributing to the growth of the FEDS research field. The average number of authors per paper with multiple authors is 5.57. Each article comes from one of 147 journals or books. The number of citations per article is 14.84, and there are a total of 10,469 references. The number of articles published between 2016 and 2021 increased by 128.1 per year. The number of articles published recently years has increased by more than eightfold from 2010 to 2015. The annual growth rate was calculated using the compound annual growth rate, and the average annual growth rate of FEDS research's scientific output will be 17.22% until the beginning of 2022 (Table 1).

2. Bibliometric Analysis of Country and Institute Contribution

   The world map of worldwide research productivity is illustrated in Fig. 2. The color's intensity and the red line's density indicate the number of articles published and the frequency of international collaborations, respectively. There are 10 major producing countries, with at least 10 papers published in each

<table>
<thead>
<tr>
<th>Description</th>
<th>Results</th>
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<tbody>
<tr>
<td>Software and analyzes</td>
<td></td>
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<tr>
<td>Bibliometrics: Biblioshiny &amp; Web of Science: Citation report</td>
<td>Basic analysis: total number of publications, annual growth rate, 3 fields plot, etc.</td>
</tr>
<tr>
<td></td>
<td>Impact of the author (first and corresponding author), countries, institutions, journal</td>
</tr>
<tr>
<td></td>
<td>Annual scientific production</td>
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<td></td>
<td>Keywords (plus), citation analysis (reference spectroscopy)</td>
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<td></td>
<td>General versus specific publisher analysis</td>
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<tr>
<td>CiteSpace</td>
<td>Document cocitation institute and clusters visualization</td>
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<td></td>
<td>Dural map overlay of journals</td>
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<td></td>
<td>Time map of clusters</td>
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<tr>
<td>VOSviewer</td>
<td>Keyword co-occurrence network map</td>
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<tr>
<td>World Development Indicators</td>
<td>Country development data</td>
</tr>
<tr>
<td>Main information about data</td>
<td></td>
</tr>
<tr>
<td>Timespan</td>
<td>1992-2022</td>
</tr>
<tr>
<td>Sources (journals, books, etc.)</td>
<td>147</td>
</tr>
<tr>
<td>Documents</td>
<td>990</td>
</tr>
<tr>
<td>Authors</td>
<td>2,306</td>
</tr>
<tr>
<td>Annual growth rate</td>
<td>17.22%</td>
</tr>
<tr>
<td>Country</td>
<td>43</td>
</tr>
<tr>
<td>Document average age</td>
<td>4.39</td>
</tr>
<tr>
<td>Coauthors per doc</td>
<td>5.57</td>
</tr>
<tr>
<td>Average citations per doc</td>
<td>14.84</td>
</tr>
<tr>
<td>International coauthorships %</td>
<td>9.39</td>
</tr>
<tr>
<td>References</td>
<td>10,469</td>
</tr>
</tbody>
</table>

The coauthors per articles index is calculated as the average number of coauthors per article; the collaboration index is a coauthors per article index calculated only using the multiauthored article set which calculated as total authors of multiauthored articles/total multiauthored articles.
of them. China, South Korea, and the United States were the most productive regions (Table 2). Among the 43 countries with publications, South Korea (t = 4,970), China (t = 3,896), Germany (t = 2,295), and the United States (t = 2,237) achieved the most-cited counts. Moreover, the relatively higher API and H-index in Germany, Korea, and the United States represent the

Fig. 2. World map showing the distributions of publications. The color intensity is proportional to the number of publications, and the red line is the relationship of country collaboration.

Table 2. Country’s impact of FEDS publications and country’s medical resources distribution

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</thead>
<tbody>
<tr>
<td>China</td>
<td>516 (52.4)</td>
<td>7.0</td>
<td>26</td>
<td>516</td>
<td>22</td>
<td>0.04</td>
<td>17.7 (1,412.6)</td>
<td>0.96 (5.4)</td>
<td>2.0/2.7</td>
<td>Upper middle income</td>
</tr>
<tr>
<td>Korea</td>
<td>212 (21.4)</td>
<td>24.0</td>
<td>40</td>
<td>174</td>
<td>32</td>
<td>0.16</td>
<td>1.8 (51.7)</td>
<td>0.15 (8.2)</td>
<td>2.4/7.5</td>
<td>High income</td>
</tr>
<tr>
<td>United States</td>
<td>109 (11.0)</td>
<td>24.6</td>
<td>26</td>
<td>64</td>
<td>18</td>
<td>0.22</td>
<td>23.0 (331.9)</td>
<td>3.86 (16.8)</td>
<td>2.6/15.7</td>
<td>High income</td>
</tr>
<tr>
<td>Germany</td>
<td>51 (5.6)</td>
<td>47.6</td>
<td>20</td>
<td>33</td>
<td>4</td>
<td>0.11</td>
<td>4.2 (83.1)</td>
<td>0.49 (11.7)</td>
<td>4.3/13.5</td>
<td>High income</td>
</tr>
<tr>
<td>Japan</td>
<td>41 (4.1)</td>
<td>7.3</td>
<td>9</td>
<td>35</td>
<td>1</td>
<td>0.03</td>
<td>4.9 (125.7)</td>
<td>0.52 (10.7)</td>
<td>2.5/12.7</td>
<td>High income</td>
</tr>
<tr>
<td>Turkey</td>
<td>21 (2.1)</td>
<td>10.8</td>
<td>7</td>
<td>19</td>
<td>2</td>
<td>0.10</td>
<td>0.8 (85.0)</td>
<td>0.03 (4.3)</td>
<td>1.8/3.0</td>
<td>Upper middle income</td>
</tr>
<tr>
<td>Netherlands</td>
<td>17 (1.7)</td>
<td>15.9</td>
<td>9</td>
<td>5</td>
<td>4</td>
<td>0.44</td>
<td>1.0 (17.5)</td>
<td>0.10 (10.1)</td>
<td>3.7/11.5</td>
<td>High income</td>
</tr>
<tr>
<td>India</td>
<td>14 (1.4)</td>
<td>7.4</td>
<td>5</td>
<td>9</td>
<td>0</td>
<td>0.03</td>
<td>3.1 (1,393.4)</td>
<td>0.09 (3.0)</td>
<td>0.9/2.4</td>
<td>Lower middle income</td>
</tr>
<tr>
<td>Brazil</td>
<td>11 (1.1)</td>
<td>3.0</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>0.20</td>
<td>1.6 (214.0)</td>
<td>0.15 (9.6)</td>
<td>2.3/7.4</td>
<td>Upper middle income</td>
</tr>
<tr>
<td>Italy</td>
<td>10 (1.00)</td>
<td>5.8</td>
<td>5</td>
<td>8</td>
<td>0</td>
<td>0.03</td>
<td>2.1 (59.1)</td>
<td>0.18 (8.7)</td>
<td>8.0/5.9</td>
<td>High income</td>
</tr>
</tbody>
</table>

FEDS, full-endoscopic decompression spine surgery; API, average per item; SCP, single country publications; MCP, multiple country publications; GDP, gross domestic product; POP, population.

* Average for each item represents the overall results set’s average number of cited articles. It is calculated by dividing the total number of results in the set by the times cited count.
average publication of high-quality articles. The highest citation average per article was from Germany (t = 47.6), followed by the United States (t = 24.6) and South Korea (t = 24.0), respectively. The lower multiple country publications ratio, which indicates the lower rates of multinational cooperation research, is likely to be found in China, Japan, and India. As shown in the Fig. 3A, a total of 831 institutions published articles on FEDS with closer cooperation between each other. Among these, the Wooridul Spine Hospital (n = 50, 5.05%) is leading in terms of output, followed by Tongji University (n = 41, 4.14%), Brown University (n = 29, 2.92%), Seoul St. Mary’s Hospital (n = 34, 3.43%), and Lifespan Rhode Island Hospital (n = 48). Moreover, high-income countries’ publications of FEDS articles and health system expenditure costs were higher compared to the upper and lower middle-income countries. We also found that the percentage of clinical caregivers showed very high correlations with health expenditure (r = 0.915, p ≤ 0.001).

3. Bibliometric Analysis of Journal Contribution

The influential impact journals are illustrated in Fig. 2. In our research, the Spine has the highest H-index (n = 22) and is the most-cited (t = 2,864) journal with the earliest publication year (1994) and consider as the most influential impact journal. World Neurosurgery published the most significant number of FEDS research articles (n = 162), followed by the Pain Physician (n = 55) and Spine (n = 34) on the FEDS. Among of them, World Neurosurgery, Pain Physician, Spine Medicine, and European Spine Journal have been identified as the most essential and fundamental journals. In addition, the number of Spine articles among the top 10 most-cited articles is as highest as 7. From the dual-map overlay visualization of journal-to-journal citation, we revealed that the FEDS authors most frequently cite the journal in the areas of medicine, clinical, neurology, and sports; and usually cited by the scope of nursing, rehabilitation, psychology, education, social, economic, political research, respectively (Fig. 3C).

4. Bibliometric Analysis of Author Contribution

According to the citation analysis (including the first and corresponding author), Kim HS is the most prolific author.
Fig. 4. The timeline of the most productive authors was calculated by the author's consecutive production over time. The bubble size is the proportional to the number of articles, and the color intensity of bubble is the proportional to the total citation per year. TC, total citation; PY, publication year.

Fig. 5. (A) The word cloud visualizes various words with different font sizes based on the KeyWords Plus, more crucial words will appear at the central of the cloud with larger size. (B) Network visualization: the higher the weight of an item, the larger the label and the circle of the item. The distance between 2 units in the visualization approximately indicates the relatedness of the unit in terms of cocitation links. The closer 2 unit are located to each other, the stronger their relatedness.
Y has the greatest H-index and G-index of all the authors, and his FEDS paper in FEDS received the most citations with highest fractionalized score (Fig. 4). According to our data, Lee SH and Ahn Y were the authors with the longest period of continuous publication, from 2003 to 2022. Telfian AE and Kim HS authored a large number of articles with high citations in 2016 and 2018, respectively. Moreover, Yeung AT, Ruetten S, Hoogland T, Ahn Y, Choi G, and Mayer HM’s papers are the most impactful according to the global and local bibliometrics analysis (Supplementary Material 1). These articles are highly influential in spinal endoscopy and are also widely referenced in other subdisciplines or disciplines, indicating that other researchers serve them as spine endoscopic flagship for their research. In addition, the 3 field plots highlight the most productive authors’ intellectual origins and research orientation.

5. Bibliometric Analysis of Keywords and Reference Assemblies

A total of 150 keywords were considered in the network analysis (Figs. 5, 6). The 3 frequently co-occurrence keywords are “discectomy” (TLS = 1,663; occurrences = 346), “disc herniation” (TLS = 1,456; occurrences = 281), and minimally invasive spine surgery (TLS = 978; occurrences = 198). In cluster analysis, we obtained 10 different clusters from the analysis. Cluster 1 (color
Cluster 1 (color red) enrolled 28 units related to the general terminology of full-endoscopic approach, technique, and indication, such as transforaminal approach, laminotomy, and stenosis. Cluster 2 (color green) enrolled 22 units related to the full-endoscopic application terms at the cervical level, such as transcorporeal approach, foraminotomy, and instrumentation. Cluster 3 (color blue) enrolled 19 units related to the comparison to microscopic surgery, such as microdiscectomy, recurrence, and cohort trial. Cluster 4 (color yellow) enrolled 17 units related to the focus terms of early technology, such as arthroscopic microdiscectomy, chemonucleolysis, and multifidus muscle. The other clusters from 5 to 10 describe other aspects of endoscopic techniques that are classified separately, such as anesthetic modalities, adjunctive techniques, anatomy, etiology, or complications.

From the overlay visualization, we obtained the recent 10 years of mainstream research areas of anesthetic methods, cost-effective analysis, and cervical or thoracic applications. The density visualization shows the greatest weight of research directions with transforaminal, interlaminar, complications, and spinal stenosis surrounding the lumbar discectomy. Moreover, based on the line chart of annual publications and average citations per year, the jump in 2015 was the turning point of production (Fig. 7). In addition, the most influential articles in the field of FEDS are shown in Table 3.

6. Bibliometric Analysis of Various Classifications by Type of Journal or Publisher

Non-OA, Lippincott, and specific publisher shows the highest H-index, API, TC, and APY. The proportion rate of OA was highest in the comprehensive journal (as high as 87.6%). China is the most productive country that contributes to specific and comprehensive publishers. Conversely, South Korea, and the United States shows a higher proportion of publication in a specific publisher. Wooridul Spine Hospital is the highest contribution to the specific journal, whereas Tongji comprehensively shows the highest contribution to the comprehensive journal.

The publication number of these journals was differentiated according to the different OA or professional attributes (Fig. 8). The differences in TC and APY between the OA and non-OA are statistically significant between each other (Z = -6.964, p < 0.05; Z = -5.760, p < 0.05), as shown in Table 4. The number of TC and APY citations for OA and non-OA is also considered different. There is no statistical difference in APY times between the 3 most productive publishers ($\chi^2 = 5.654$, degrees of freedom \(df = 2\), \(p > 0.05\)); however, it can be assumed that the APY counts of the 3 different journals are not all the same ($\chi^2 = 15.252$, \(df = 2\), \(p < 0.001\)). Based on the statistical test results, the difference between Elsevier and Springer Nature is not statistically significant (rank means: 12.62, \(p = 0.198\)). However, the difference between the TC of Lippincot Williams & Wilkin’s and Elsevier (rank means: 57.15, \(p < 0.05\)); and between Lippincot Williams & Wilkin’s and Springer Nature (rank means: 69.77, \(p < 0.05\)); are statistically significant. The differences in TC and APY between the comprehensive and specific journals were statistically significant (Z = 6.944, \(p < 0.001\); Z = 5.765, \(p < 0.001\)). It can
Table 3. The most influence articles in the field of full-endoscopic decompression spine surgery

<table>
<thead>
<tr>
<th>No.</th>
<th>Title</th>
<th>Authors</th>
<th>Source</th>
<th>Year</th>
<th>Citations</th>
<th>APY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Posterolateral endoscopic excision for lumbar disc herniation -</td>
<td>Yeung AT, Tsou PM</td>
<td>Spine</td>
<td>2002</td>
<td>430</td>
<td>20.48</td>
</tr>
<tr>
<td></td>
<td>Surgical technique, outcome, and complications in 307</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>consecutive cases</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Full-endoscopic interlaminar and transformal lumbar discectomy</td>
<td>Ruetten S, Komp M, Merk H,</td>
<td>Spine</td>
<td>2008</td>
<td>418</td>
<td>27.87</td>
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<td>Percutaneous endoscopic discectomy: surgical technique and</td>
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<td>1993</td>
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<td>2006</td>
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<td>without the combination of a low-dose chymopapain: A prospective</td>
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<td>randomized study in 280 consecutive cases</td>
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<td>Ruetten S, Komp M, Merk H,</td>
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<td>2008</td>
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<td>of lateral disc herniations using 5.9-mm endoscopes - A prospective</td>
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<td>7</td>
<td>Use of newly developed instruments and endoscopes: full-endoscopic</td>
<td>Ruetten S, Komp M, Merk H,</td>
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<td>2007</td>
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<td>resection of lumbar disc herniations via the interlaminar and</td>
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<td>Spine</td>
<td>2004</td>
<td>184</td>
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<td>An extreme lateral access for the surgery of lumbar disc herniations</td>
<td>Ruetten S, Komp M, Godolias G</td>
<td>Spine</td>
<td>2005</td>
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<td>inside the spinal canal using the full-endoscopic uniportal</td>
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<td>463 patients</td>
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APY, average citations per year.

Fig. 8. Stacked area graph of different classification by journal type. OA, open access.
### Table 4. Statistical analysis of various classification by type of journal or publisher

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<td>No.</td>
<td>441</td>
<td>549</td>
<td>249</td>
<td>158</td>
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<td>H-index</td>
<td>30</td>
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<td>API (time)</td>
<td>8.83</td>
<td>19.81</td>
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<td>OA (%)</td>
<td>N/A</td>
<td>N/A</td>
<td>5.6</td>
<td>58.2</td>
<td>45.4</td>
<td>43.0</td>
<td>87.6</td>
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<td>TC (P₂₅–P₇₅, time)</td>
<td>3</td>
<td>7</td>
<td>0.05</td>
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<td>APY (P₂₅–P₇₅, time/yr)</td>
<td>0.86</td>
<td>1.5</td>
<td>0.05</td>
<td>0.05</td>
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<td>Country (%)</td>
<td>China (37.28)</td>
<td>South Korea (29.83)</td>
<td>USA (16.27)</td>
<td>China (83.94)</td>
<td>South Korea (11.68)</td>
<td>USA (3.65)</td>
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<td>Affiliation (%)</td>
<td>Wooridul Spine Hospital (7.90)</td>
<td>Tokushima Univ. (5.26)</td>
<td>Seoul St. Mary’s Hospital (4.825)</td>
<td>Tongji Univ. (5.84)</td>
<td>Capital Medical Univ. (5.11)</td>
<td>Chongqing Medical Univ. (5.11)</td>
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<td>OA, open access; API, average per item (times cited); APY, average citations per year. Publishers at least 5 publications are selected from general (comprehensive) journal or specific journals.</td>
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still be considered that the number of citations of TC and APY for specific publishers and comprehensive publishers is significantly different.

**DISCUSSION**

In this research, we have manually screened and double-checked all results to find any calculation biases inherent in the software used to perform the analyses. We discovered that when the software identifies the name of authors, it aggregates and analyzes the data of all the individual authors of that abbreviation from a bibliometric file, resulting in analytical inaccuracies. The software cannot determine the difference between authors’ names with abbreviations. The WOS or bibliometric software automatically recognizes the abbreviation name, which causes a statistical error when doing the analysis. In our study, we filtered the data, and only the first and corresponding authors were included in our analysis. Meanwhile, we observed that an analysis based just on the number of coauthors would be biased concerning the contribution of authors to the actual research field. Therefore, we believe that the first and corresponding authors tend to contribute the most to clinical endoscopic studies. To the best of our knowledge, similar inaccuracies may have occurred in the published statistics of the past. As a result, the quality of analysis for identical bibliometric findings can vary when using different software. Thus, we selected the high-quality elements from each software for data analysis.

According to our knowledge, the preliminary form of the Full-endoscopic technique was earlier applied at 1993. Then, it has been developing rapidly and published high cited flagship articles which reported with high-safety surgical access and technical improvements. Recently, the areas of interest primarily explore technique indications or collect high-quality clinical evidence. Among of them, before 2015, the Germany, South Korea, the United States contributions as pioneers of FEDS research in spine surgery, followed by the entry of China led to a substantial increase in literature publication. Moreover, from our analysis results of references spectroscopy, the history of publication illustrates that the first 3 peaks from Mayer, Yeung, Rutten, Choi from the 1993 to 2007. They are the pioneer of the Full-endoscopic research which provide solid evidence for the crucial clinical considerations and practice of spinal endoscopic surgery; however, then there is no peak continues to appear after them. We found that even though the number of endoscopic studies published now is more significant than in the past, the citation rate of endoscopy-related papers continues to decline. This, of course, cannot be separated from the precipitous decline in average citations in the literature in the last 2 years impacted by the severe acute respiratory syndrome coronavirus-2. But the more important question is that although various endoscopic novel assisted techniques described recently, such as O-arm navigation system, robots-assisted technique, the high cost blocks the step of other clinicians to replicate despite the popularity.

It is essential to identify demographic risk factors for degenerative spinal conditions to understand the risk, prevention, treatment, and outcome of spinal injuries and distinguish between acute injuries and degenerative disorders. In our study, the topic dendrogram revealed the hierarchical relationship between objects in FEDS research. It shows that the surgical treatment method of myelopathy is related to the nearby bony ossification or ligamentum flavum hypertrophy. Furthermore, disc herniation also indicates a solid connection to radiculopathy. As we understand, reherniation is the most common reason for surgical revision in patients after endoscopic surgery. Thus, it is crucial to consider preoperative risk factors for the patient’s prognosis, such as the characteristics of the pain generator; herniation size and location; patient’s comorbidity; or the access problems due to the patient’s excessive obesity or adjacent anatomical tissue obscuring the access itself (e.g., patients with higher iliac wings than usual). Furthermore, we found that the FEDS research focuses on the impact of biomechanical instability, which is closely linked to the fusion study. In addition, microscopic surgery is strongly associated with endoscopic surgery, primarily since microscopy is frequently used as a revision surgical approach to endoscopic surgery. Likewise, endoscopic surgery through the transforaminal approach can also be used as a solution for revision surgery after microsurgery. Full-endoscopic technique avoids tissue scar adhesions caused by the same approach. At the same time, the magnified view of full-endoscopy improves the surgical view and the safety of nerve tissue stripping during revision surgery. Lastly, due to the steep learning curve in endoscopic surgery, early endoscopic clinicians are frequently advised to select the transforaminal approach as the primary case for adaptation to endoscopic techniques.

We have discovered that many OA articles exist in the included studies. Therefore, the statistical analysis on the various classification of journal type and publisher was conducted and found that the non-OA articles usually have a higher impact than OA articles on the H-index, API, TC, and APY. We discovered that Elsevier published the most articles among the 3 most productive publishers, followed by Springer Nature and Lippincott, re-
spective. However, Springer Nature is related to relatively lower quality of papers, as shown in the evaluated metrics. Although Lippincott has published the lowest number of articles, their papers have a relatively high quality. Furthermore, comparing the comprehensive and specific journals, the latter shows far exceeds the quality of prior journals. Among them, China has the highest number of publications in both types of journals but with a higher number of publications in the comprehensive journal. Comparatively, researchers in South Korea and the United States prefer more than specific journals for their publication. This may also contribute to more government spending on the healthcare sector, as usually seen in high-income nations, as well as the comparatively high number of specialists and nursing staff, which enables physicians to focus more on high-quality clinical research.

Here comes another interesting question. Initially, the original purpose of OA was to make it easier for academics to undertake more collaborative research publicly and to permit more researchers to study and cite more publications without being restricted by a paywall, hence to increase the speed of overall clinical research. However, we found that the general assessment indicators of quality from the OA articles are lower than non-OA articles in the area of FEDS. The reasons could be the following. As is well known, comprehensive publishers frequently use the article processing charge publication model. Nonetheless, this pricey strategy can still not deter endoscopic researchers from submitting their findings. Although many of these comprehensive publishers are indexed in the WOS and have high-impact factors, a high-frequency rate of fast turnaround times and a high acceptance rate make the quality of its review doubtful. Our research results confirm this skepticism. Even though many papers are published among the high-impact factors, the quality of the publication from comprehensive journals is worrisome. Unsurprisingly, innumerable early-career academics choose these publishers over the more reputable ones to speed up their publication in the journal with the highest impact factor possible. These researchers could be poisoned and captivated by incentives from institutions or countries, as they could boost their citation rank among the professionals in a short time as opposed to the quality of their work. Therefore, using impact metrics alone to evaluate the quality of an article related to FEDS seems inappropriate.

We have some limitations in our research. Firstly, our bibliometric analysis was only the extracted data from the WOS core collection database, which may cause source bias. Secondly, since the dissemination of the article and the efficacy of the technique require practice to demonstrate, we regret that we were unable to uncover very recent articles of high quality and potential through our research. These could also reflect the significant influences despite the short-term development of FEDS. However, technologically advanced research typically generates most discussions after 2 years; recent papers published in 2020 and prior have yet to create much-heated discussions. It is also possible that the lack of the appearance of papers related to clinical decision-making with available clinical options or a wide publication base to bury the data of high-quality papers. Finally, since our search strategy was designed and implemented in the middle of the year, it is impossible to generate a descriptive statistic for the articles published later that year. In this instance, we have modified some of the statistical analyses in our research, such as calculating the growth rate solely through the beginning of 2022.

CONCLUSION

The bibliometric study showed a growing trend of research on FEDS over the past 30 years. The number of authors, institutions, and internationally collaborated countries have been significantly increased, but high-quality studies are still lacking. However, a paradigm shift is emerging in a recent series of publications as the higher-quality studies including meta-analysis or attempts to develop standard guidelines have been increasingly published. This indicated that full-endoscopic spine surgery is gradually reaching its maturity.

NOTES

Supplementary Material: Supplementary Material 1 can be found via https://doi.org/10.14245/ns.2245042.521.

Conflict of Interest: The corresponding author, Jin-Sung Kim, is a consultant of Richard Wolf, GmbH, and Elliquence, LLC. The other authors have no conflicts of interest to declare.

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Author Contribution: Conceptualization: YL, VK, JQO, KJ,
Bibliometric Analysis of Full-Endoscopic Spine Surgery

Liu Y, et al.

REFERENCES

Commentary on “A 30-year Worldwide Research Productivity of Scientific Publication in Full-endoscopic Decompression Spine Surgery: Quantitative and Qualitative Analysis”

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4TMU Biodesign Center, Taipei Medical University, Taipei, Taiwan

Full-endoscopic decompression spine surgery (FEDS) has evolved significantly in recent years, revolutionizing the field of minimally invasive spine surgery. FEDS offers advantages over open spine surgery, including faster recovery, reduced hospital stays, and decreased complication incidence.1 During coronavirus disease 2019, it reduces infection risk and hospital burden by minimizing stays and freeing up resources. Since FEDS is an innovative, evolving and attractive minimally invasive technique for spinal surgery, the number of articles published on FEDS has increased in recent decades, making it difficult to identify high-impact papers, which may be a perplexing and time-consuming task.

Based on these perspectives, the authors reported a bibliometric study2 that analyzed research publications related to FEDS between 1992 and 2022 using Bibliometrix, CiteSpace, and VOSviewer. The study found that Spine was the most cited journal in the field of FEDS and had the highest H-index.2 China was the most productive country, and South Korea had the most cited papers with high H-index. The most impactful authors in global and local citations were Yeung AT, Ruetten S, Hoogland T, Ahn Y, Choi G, and Mayer HM, and the most productive organization was Wooridul Spine Hospital. Despite the growing trend of research on FEDS, the quality of studies in this field is still low. This is due to a lack of high-quality clinical evidence and a trend of general journal submissions, which have had a negative impact on the quality of endoscopy journals in recent years.

FEDS has a relatively short history compared to traditional open spinal surgeries. The first documented attempt at endoscopic spinal surgery was in the 1970s by a German neurosurgeon, Dr. Parviz Kambin. He is credited with developing the percutaneous posterolateral approach for accessing the disc space and removing disc material through a minimally invasive technique using a cannula.3 This technique was a significant advance in spinal surgery and paved the way for the development of endoscopic spine surgery, including the en-
doscopic transforaminal approach. Dr. May HM first demonstrated percutaneous endoscopic lumbar discectomy in Germany in 1987 for the removal of a contained lumbar disc herniation via a percutaneous posterolateral approach. The 1990s saw the development of several other endoscopic spinal surgery techniques, including the transforaminal approach, which involves accessing the spinal canal through a small opening in the side of the spine. The Yeung endoscopic spine system (YESS) was described by Dr. Yeung AT in a 1999 publication. In the YESS technique, the working cannula is inserted into the intervertebral disc through the Kambin triangle. Then, the surgeon performs discectomy and decompression by working inside the intervertebral disc towards the spinal canal. Different from the primary surgical scope limited to the intervertebral disc, Dr. Ahn Y and Dr. Choi G demonstrated an evolved epidurally oriented transforaminal endoscopic approach to directly remove herniated disc fragments. Dr. Hoogland T developed a “outside-in” transforaminal endoscopic approach and a foramino-plasty technique, using a trephine to resect part of the superior articular process to provide adequate space for removal of herniated disc. Dr Ruetten S developed the interlaminar technique to overcome lumbar disc herniation at the L5/S1 level of the high iliac crest. The full-endoscopic interlaminar technique is now widely used for the treatment of spinal stenosis, herniated discs, and other spinal conditions. They continuously develop new surgical techniques and instruments, have published numerous research papers and several books on endoscopic spinal surgery, and hold seminars and training courses in many countries around the world. Collectively, the contributions of Yeung AT, Ruetten S, Hoogland T, Ahn Y, Choi G, and Mayer HM to endoscopic spine surgery have to advance the field and have a significant impact on spinal surgery around the world. Their work has led to the development of new techniques and instruments that improve patient outcomes, and increase awareness and adoption of this minimally invasive surgical approach.

South Korea has made significant contributions to the field of endoscopic spine surgery is accurate and well-supported. In recent years, researchers from South Korea have produced a large number of high-quality studies on endoscopic spine surgery that have been published in top-tier medical journals and have received high citation counts and H-indices. This success in endoscopic spine surgery research can be attributed to a variety of factors, including the country’s advanced healthcare system and medical infrastructure, its strong research culture, and the availability of skilled and experienced medical professionals. In South Korea, Wooridul Spine Hospital has played a significant role in the field of endoscopic spine surgery. It is considered as one of the leading institutions in the world for endoscopic spine surgery. The hospital has a dedicated research department that focuses on developing new techniques and technologies in endoscopic spine surgery. It has produced a significant number of high-quality research papers on endoscopic spine surgery, contributing to the knowledge and advancement of the field. These papers have received high citation counts and H-indices, indicating their impact and influence on the field. Therefore, the combination of South Korea’s strong research culture, advanced healthcare system, and institutions like Wooridul Spine Hospital has made a significant contribution to the field of endoscopic spine surgery. The country’s focus on innovation and commitment to patient care has helped to improve patient outcomes and establish South Korea as a leading contributor to the field of minimally invasive spine surgery.

The study also found that the number of endoscopic spine surgery articles published in China increased dramatically over the course of the decade, reflecting the country’s growing investment in research and development in this field. Other countries, such as the United States, South Korea, and Germany, also made significant contributions to the field during this period, but China was the clear leader in terms of article output. The success of China in endoscopic spine surgery research can be attributed to its large population, advanced healthcare system, and significant investment in medical research and development. Chinese researchers have been actively developing and refining innovative endoscopic techniques and technologies, contributing to the advancement of the field. It is worth noting, however, that the number of articles published does not necessarily reflect the quality or impact of the research being conducted. Furthermore, it is important to consider factors such as funding, collaboration, and access to resources when evaluating a country’s overall contribution to a particular field. Nevertheless, China’s emergence as a major contributor to the field of endoscopic spine surgery is a noteworthy development and highlights the increasing global interest in this minimally invasive technique.

In this study, the authors conducted a bibliometric analysis of FEDS to assess research productivity, identify key researchers and institutions, and track research trends. While the number of endoscopic spine surgery studies published has increased over time, the quality of these studies is still an area of concern. Conducting high-quality studies such as meta-analyses, prospective comparable studies, or randomized controlled trials is essential to establish the safety and efficacy of endoscopic spine surgery techniques and to develop standard healthcare guidelines. The
availability of high-quality clinical evidence can guide clinical decision-making and improve patient outcomes. As the field of endoscopic spine surgery continues to evolve, it is essential to prioritize the conduct of rigorous research studies to establish best practices and treatment guidelines. As more high-quality clinical evidence becomes available, full-endoscopic spine surgery will likely continue to mature and improve, making it a more viable option for patients with spinal conditions.

• Conflict of Interest: The authors have nothing to disclose.

REFERENCES


Technique of Distraction, Compression, Extension, Reduction to Reduce and Realign Old Displaced Odontoid Fracture From Posterior Approach: A Novel Technique

Objective: Chronic ‘displaced’ displaced type II fractures, though uncommon, are difficult to manage. They usually require a transoral procedure followed by a posterior instrumented fusion. We describe here, a new method to reduce the fractured displaced odontoid using a posterior cervical approach only.

Methods: Prospective and observational, n = 14 had a ‘displaced and irreducible’ old fracture dens causing cord compression (type I, 1; type II, 13). They underwent a novel technique to reduce the fracture. The C1 arch was first drilled and removed. The C1 lateral masses on both sides were then drilled completely and a spacer was placed between the occiput and C2 facet. Following this, an intraoperative reducing maneuver was performed, utilizing the spacer as a fulcrum, and then achieving complete reduction and realignment.

Results: All patients improved clinically (mean Nurick preoperative score: 4.07 ± 0.8; the postoperative score was 1.3 ± 0.4). The mean correction in effective canal diameter was 74.3% ± 9.5% and the mean correction in actual canal diameter was 77% ± 8.7%. Solid bone fusion was demonstrated in 12 patients with at least 1-year follow-up (follow-up range, 12–35 months; mean, 21.8 ± 9.8 months).

Conclusion: The new described modification of distraction, compression extension, and reduction seems to be effective for ‘displaced’ chronic fracture dens with cord compression. It avoids additional transoral surgery in these patients.

Keywords: Fracture, Odontoid, Irreducible, Atlantoaxial dislocation, Type II dens fracture, Reduction

INTRODUCTION

Cervical spine injuries, especially at the C2 level, may be associated with severe morbidity and mortality, especially in the presence of instability and cord compression. It is essential to understand the diversity of C2 fractures before considering their management: lateral mass fractures, extension teardrop fractures, traumatic spondylolisthesis (hangman fractures), and odontoid fractures.1 Odontoid fractures constitute 10%–20% of all cervical spine injuries and many may be underreported.

The treatment algorithm for odontoid fractures primarily depends on the fracture type and clinical status. The most widely used classification system was that described by Anderson and D’Alonzo in which fractures were classified into 3 main types, and each has been further subcategorized as displaced or non-displaced. Of the 3 types of fractures, type II is commonest and is also characterized by the highest rate of nonunion. In addition, the treatment paradigm is further influenced by the chro-
nicity of the fracture. Acute fractures may be usually treated by first reducing them with traction, followed by applying an odontoid screw. However, chronic nonunited fractures present a challenge for management. Therefore, treatment may include options like conservative management (with immobilization), especially in elderly; posterior transarticular/C1–2 screw-rod fixation, curverting the margins of the fractured segments followed by placement of an odontoid screw and sometimes a transoral excision of the odontoid process followed by posterior instrumented fixation. The latter has been suggested in long-standing displaced nonunited ‘irreducible’ fractures.

The authors describe a new innovative technique based on their earlier described method of distraction, compression extension, and reduction (DCER). First, after C1 laminectomy, total excision of bilateral C1 lateral masses was performed. Following this, a spacer was placed between the occipital condyle and the C2 facet joint creating an artificial articulation. Following this, a reduction maneuver was performed based on the technique of DCER. This technique has been successfully applied to reduce chronic nonunited, irreducible displaced type II fractures causing cord compression. This is the first that this technique has been used for this pathology.

MATERIALS AND METHODS

1. Patient Population

This study is prospective observational study. The study was conducted per the guidelines of the national council of medical research, and permission was taken from the Institute Review Board of All India Institute of Medical Sciences (AIIMS), New Delhi.

Three hundred fifteen patients with basilar invaginations (BI) and atlantoaxial (May 2010–March 2020) underwent DCER (or combined with its modifications) utilizing a single staged posterior approach (PSC). Fourteen patients had chronic displaced ‘displaced’ type II dens fractures.

2. Exclusion Criteria

The following patients were not included in this study: (1) acute type II fractures of dens; (2) undisplaced fractures or those reducing on traction; (3) polytrauma involving fractures in other areas of the cervical spine; (4) cases with ventral C1–2 or fracture bone fusion, where a reduction was not possible. However, bone fusion at the level of articular facets was not a contraindication, as they could be easily separated with drills; (5) anomalous vertebral artery placed directly over the joints. Hence, a computed tomography (CT) angiogram was performed in all cases to exclude anomalous vertebral artery positions; (6) severe osteoporosis, that may not withstand the correction.

3. Preoperative Assessment

Grading pre- and postoperatively was assessed per Nurick grading system.

4. Radiologic Studies

Dynamic plain x-rays, thin-slice CT scans (0.625 mm) with reconstructed views, and magnetic resonance imaging (MRI) was obtained in all patients preoperatively. All patients had displaced fractures, as confirmed on active dynamic x-rays. All patients underwent plain x-rays and thin-slice CT scans with reconstruction views to define the position of the screws and the extent of reduction within 1 week after the surgery. MRI was performed 3 months later to assess the extent of decompression.

During follow-up, dynamic x-rays and CT scans with reconstruction views were performed from 3 to 6 months and again at one year (in those patients with this period of follow-up available) after surgery to check the position of the implants and bone fusion.

5. Surgical Procedure

All patients underwent awake endoscopic intubation without neck manipulation following the placement of skeletal traction (Gardner Wells). Following general anesthesia, the patient was placed in the prone position on a U-shaped headrest with the neck in a neutral or extended position. This was preferred over Mayfield skeletal pin fixation to allow intraoperative maneuvers. Adequate care was taken to provide padding for the eyes. The procedure has already been described in detail earlier and is also shown in Supplementary video clip 1. Briefly, following occiput, C1 and C2, bilateral C1/C2 joints were exposed (Fig. 1A, B). A C1 laminectomy was first performed along with decompression of the posterior rim of the foramen magnum (if necessary) to decompress the cord and prevent any cord injury while performing the reduction maneuver (Fig. 1C).

Following this, the joints were gently distracted using an instrument like a periosteal elevator, and then a distractor was placed between the C1 and C2 posterior lateral arches. In 10 of 14 cases, it was found that the C1 was tightly ‘wedged’ into C2, and it was quite difficult to separate both of them. Once the joint was ‘loosened,’ the articulating cartilage and the entire C1 lateral masses were drilled using a fine diamond drill (Fig. 1D). The
whole lateral masses of C1 vertebrae are drilled medial transverse process. Again, it may be mentioned that drilling the entire C1 lateral mass is unnecessary. It should be drilled enough to provide space to introduce a spacer to articulate between the occiput and C2 articular surface. The lateral portion of the C1 lateral mass may be left behind to protect the vertebral artery. Again, it is prudent to mention that the vertebral artery's exact position must be ascertained using a CT angiogram and 3-dimensional reconstruction. The idea is to provide a pivot between the occiput and C2 articular surface (see below) to provide an axis for the reduction of the deformity. The C2 ganglion and root need to be sacrificed, but C1 may be preserved. This creates enough space to introduce a spacer. The entire drilling must be done with a diamond head drill. Care must be taken not to get into the venous plexus situated laterally, where the vertebral artery will be lodged. If there is some bleeding from the venous plexus, it may be controlled using a wet gel foam with mild tamponade. Next, the cartilage of the joint surfaces of the occiput and C2 were denuded using a fine diamond drill. Bilateral spacers (polyetheretherketone) or special biconvex hollow titanium
cages filled with bone grafts were inserted, the size approximately corresponding to the height from the base of the dens to the fracture level (Fig. 1E). This step resulted in the distraction of the margins of both the fractured segments to allow reduction. The height of the spacers required ranged from 8 mm to 14 mm. Next, a screw (to be removed later) was placed on the occiput, followed by C2 translaminar screws. An offset was next applied on the occipital screw.

A compressor was next applied with its calipers respectively over the offset of the occipital screw and under the C2 spinous process. Compression (converging arrows, Fig. 1F) was performed so that the occiput and C2 were approximated to each other. This maneuver was conducted under fluoroscopic guidance. Careful monitoring of intraoperative motor evoked potentials and D wave was also performed. Slow and progressive compression resulted in the C2 body 'slipping' forward (arrowhead, Fig. 1F) and under the fractured dens (Fig. 1G). Final fixation was now provided by connecting a rod between the occiput and C2 translaminar screw. In 1 case (case 3, Table 1), both laminar and pars screws were provided on C2. It should be noted that this technique is only advised for patients with chronic displaced odontoid fracture, which causes severe cord compression by becoming wedged between the C1 arch and the body of the C2. S, spinal cord; O, occiput; D, dens; C1, C1 anterior arch; PC1, posterior arch of C1. (Continued)
Distraction, Compression, Extension, Reduction for Displaced Fractured Dens

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Fig. 2. A 34-year-old male had a fall from a tree 4 months ago (case 6, Table 1), following which he developed complete quadriplegia. He was provided treatment at a local hospital with traction and other medical treatment (possibly also methylprednisolone, but details were not available). He improved over the next month but was severely hindered (Nurick score was 4) and severely restricted neck movements. On referral to us, magnetic resonance imaging (A) showed a type II dens fracture with a large ventrally displaced fragment wedged between the C1 arch and the C2 body (computed tomography scan; B) with evidence of severe cord compression. (C, D) Following a modified distraction, compression extension, and reduction as described in the text, there was a satisfactory fracture reduction. The effective canal diameter improved by 83% and the actual canal diameter by 63% (see Table 1).

Fig. 3. A 45-year-old female sustained a type II fracture following a road traffic accident 6 months ago (case 10, Table 1). He was initially treated for a head injury and was on ventilator support for almost 2 weeks (diffuse axonal injury). He improved gradually and was then referred to us. Magnetic resonance imaging (A) showed severe cord compression and a sizeable fractured fragment (computed tomography scan, B) wedged between the C1 arch and the C2 body. There was also evidence of 2 small comminuted fractured fragments. Following modified distraction, compression extension, and reduction (C), the fracture reduced satisfactorily (the effective canal diameter improved by 86.4%, and the actual canal diameter improved by 68%).

The length of (3.5 mm, diameter) C2 translaminar screws varied from 24 to 32 mm. While the assistant maintained the compression, the occipital-cervical rod was placed on one side and fixed. Following this, the compressor was removed, and a similar fixation was performed on the other side. Following surgery, the occipital and C2 spinous bone exposed areas were decorticated using a fine diamond drill. Bone chips harvested from the iliac crest mixed with hydroxyl-apatite were placed between the occiput and C2 spinous process. The wound was closed in layers. A drain was placed if felt necessary.

All patients were electively ventilated overnight and slowly weaned off the ventilator, and extubated the next day. Patients were advised to use Philadelphia rigid cervical collar for 6–9 months until bone fusion was demonstrated.

As noted in Fig. 1F, an occipital screw coupled with a translaminar screw provided a greater distance from the fulcrum, which is now located in the center of the spacer lodged between
the occipital condyle and the C2 articulating surface (class III lever). Thus, the forces required to perform the reduction were also significantly more, allowing an optimal removal of the deformity. However, there is a word of caution that such an extent of intraoperative maneuvering requires the presence of good integrity of the bone and a good purchase of a screw. Hence, it is essential to exclude osteoporosis. In addition, the reduction should be performed slowly in small increments taking about 15–20 minutes, rather than doing it rapidly, which will have a greater chance of fracture or loosening of the screws. Finally, keeping an escape option in place is essential in case this strategy fails.

**RESULTS**

1. Patient Population

   The patient population comprised 9 males (and 5 females) ranging from 9 to 48 years (mean age, 24.7 ± 9.3 years).

   The clinical presentations included progressive myelopathy in 12, restriction of neck movements with or without nuchal pain (11), paraesthesias (10), sensory loss (8), incontinence (3), and respiratory compromise (2). The interval between the time of trauma till surgical intervention varied from 3–36 months (mean, 6.6 ± 8.2 weeks). The nature of trauma included falls (10), road traffic accidents (5), and assault with a blunt weapon (1). Initial treatment was provided in 7 in the form of skeletal traction at a local hospital. The other 6 were advised a rigid cervical collar and then referred to a tertiary hospital, and 2 refused any immediate surgery. One patient underwent unsatisfactory surgery (posterior wiring) and was referred to us. All had a type II dens fracture except one (case 4, Table 1).

2. Surgery

   Occipital-C2 DCER, along with total bilateral excision, was performed in all 14 patients (Figs. 2–6). There was no need to complete a transoral procedure on any patients. C2 laminae were suitable in all cases, and the thickness varied from 4.2–5.8 mm. The length of C2 laminar screws went from 24–32 mm. One patient required translaminar and pars-pedicle screws for the C2 vertebra (Fig. 5). The duration of the surgery ranged from 70 to 160 minutes (mean, 105 ± 22 minutes), and blood loss ranged from 90 to 400 mL (mean, 210 ± 125 mL, see also Figs. 2–6).

3. Clinical Outcome

   All patients improved clinically compared to the preoperative Nurick scores (Nurick grade I: 9 patients, and grade II:5 patients; follow-up: 12–35 months, mean: 21.8 ± 9.8 months). The mean preoperative Nurick score was 4.07 ± 0.8, and the mean postoperative score was 1.3 ± 0.4. All patients with nuchal pain improved postoperatively. One patient with respiratory compromise required postoperative ventilation and subsequent tracheostomy that was weaned off and removed after 6 weeks. The other 2 patients with respiratory compromise improved. One patient developed a wound gaping at the upper part as he was chronically bedridden. This healed in 6–8 weeks with appropriate antibiotics and daily sterile dressings.

4. Radiologic Outcome

   X-ray and CT scans were performed 1 week, 3 months, and 6 months to 1 year after surgery. They were performed until bone fusion was confirmed. Solid bone fusion was demonstrated in
all patients with at least 1-year follow-up. The following method was used to calculate the degree of spinal canal restoration. The formula, which was applied, included calculating the actual canal diameter (ACD; distance between the posterior border of the dens and posterior margins of the foramen magnum), preoperative effective canal diameter (pre-ECD; distance between the posterior margin of the upper edge of the C2 body at the level of the fracture and anterior border of the C1 arch) and postoperative ECD (post-ECD; the distance between the posterior wall of fractured dens and occiput). Two parameters were used to calculate the degree of improvement of canal diameter. One is the degree of improvement of ECD (cECD), calculated using the formula 
\[ cECD = \frac{\text{pre-ECD}}{\text{post-ECD}} \times 100. \]

The other parameter was the degree of improvement in ACD (cACD); this was calculated using the formula 
\[ cACD = \frac{\text{post-ECD}}{\text{ACD}} \times 100. \]

The mean cECD was 74.3% ± 9.5% and the mean cACD was 77% ± 8.7%.

**DISCUSSION**

Acute odontoid fractures are a surgical emergency that should be treated immediately. Type II fractures are the commonest...
Fig. 6. A 9-year-old-boy tripped over the ground running while playing cricket 4 months ago (case 4, Table 1). He developed a type I dens fracture (fracture of os odontoideum; A). Magnetic resonance imaging (B) showed severe compression of the cord between the body of C2 and the C1 arch. A modified distraction, compression extension, and reduction (DCER) was necessary as the fractured fragment was in front of the C2 body. Following a modified DCER, there was a satisfactory reduction of the fracture (C). Panel D shows the polyetheretherketone cage placed between the occiput and C2 facet.

Table 1. Table showing the summary of age, sex, time after presentation of trauma, preoperative (preop) and postoperative (postop) Nurick score, % of reduction, follow-up, and bone fusion

<table>
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<th>No.</th>
<th>Age (yr)</th>
<th>Sex</th>
<th>Time for presentation after trauma (mo)</th>
<th>Preop Nurick score</th>
<th>Postop Nurick score</th>
<th>cECD (%)</th>
<th>cACD (%)</th>
<th>Follow-up (mo)</th>
<th>Bone fusion</th>
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<td>Mean</td>
<td>24.7 ± 9.3</td>
<td>-</td>
<td>6.4 ± 8.2</td>
<td>4.07 ± 0.8</td>
<td>1.3 ± 0.4</td>
<td>74.3 ± 9.5</td>
<td>77.0 ± 8.7</td>
<td>21.8 ± 9.8</td>
<td>-</td>
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</table>

Nurick grading: grade 0: signs or symptoms of root involvement but without evidence of spinal cord disease; grade 1: signs of spinal cord disease but no difficulty in walking; grade 2: slight difficulty in walking which does not prevent full-time employment; grade 3: difficulty in walking which prevented full-time employment or the ability to do all housework, but which was not so severe as to require someone else's help to walk; grade 4: able to walk only with someone else's help or with the aid of a frame; grade 5: chair bound or bedridden.

cECD, the degree of improvement in effective canal diameter; cACD, the degree of improvement in actual canal diameter; NA, not applicable.

*Case mentioned in figure and also shown in Supplementary video clip 1. †Cases mentioned in Figures. ‡Patient underwent an unsatisfactory surgery (posterior wiring) at a local hospital and was then referred to us.

and are associated with the highest rates of nonunion.17,18 Type I and type III fractures are uncommon and rarely require surgical intervention and usually may be managed by rigid immobilization only.17,18 Most acute fractures may be reduced with traction followed by an odontoid screw placement, a posterior tran-
is not just to relieve the compression but also to provide optimal stability and correction of deformity.

Chronic displaced ‘irreducible’ nonunited type II fractures are uncommon. They are more commonly found in elderly patients but may also be seen in settings where immediate treatment is unavailable at the site of injury and due to lack of optimal referral systems, due to which they may be left untreated.

Accurate diagnosis of an odontoid fracture depends heavily on good quality x-rays and thin-slice plain CT scan films with reconstruction. CT imaging is much more sensitive to determining the fracture’s extent, looking for minor fractures and bone fragments, planning surgical trajectory, and making out the soft tissues. A type I fracture is considered an avulsion of the attached alar ligament. Though the least common, the diagnosis may be often missed, mainly if a CT scan is not performed. It is usually considered a stable fracture with a high chance of fusion. A type III odontoid fracture involves the cancellous portion of the C2 body. Most of these may be treated with external bracing only and are usually associated with reasonable fusion rates. Rarely, they may become unstable and may require surgery.

Type II odontoid fracture involves the junction of the odontoid process and vertebral body of C2. These are the commonest, are highly unstable, and are associated with high rates of nonunion.

The treatment strategy for type II odontoid fractures aims to protect neural elements, establish spinal stability, and improve clinical symptoms. The optimal treatment strategy, based on evidence, is not well established because of the significant rate of nonunion. This is primarily because dens has very few trabeculae, which form the site of reparative callus formation. This, coupled with other factors like decreased vascularization at the odontoid base, the low bone strength quality at the junction of the dens and C2 body, and decreased trabecular mass with aging, make treatment of this pathology challenging, especially in the elderly. Both rigid (halo-vest immobilization) and nonrigid immobilization, considered viable alternate options especially for elderly patients, are not without significant morbidity (sometimes up to 42%). There are no validated guidelines to suggest which surgical option would provide the best choice for optimal treatment. The proposed surgical intervention indications are based on retrospective analysis. They include displacement of fracture fragment > 5 mm, displacement of 20% of the fracture surface area, age > 50 years, and disruption of transverse ligament.

Analysis of various surgical techniques shows a significant evolution over the past 2 decades. There has been a steady evolution in the development of strategies, which provide more stability. Thus, the surgical techniques initially started with posterior spinous wiring, progressed to interspinous wiring, then to sublaminar wiring. This gave way to screw placement techniques, which included transarticular screws (Magerl), C1 lateral mass, and C2 pedicle/isthmus screw-rod constructs (Goel’s/Harms) and odontoid screw.

Transarticular and C1/C2 rod/screw constructs are biomechanically more stable than wire and hooks. Odontoid screw placement (osteosynthesis) was first described by Bohler in 1982 and is currently one of the most standard techniques for type II fractures. The main indications include fractures < 3 weeks old, intact transverse ligament, horizontal or posterior oblique fractures, and optimal bone quality. The main advantages include improvement of postoperative neck movement, absence of the need for halo-vest immobilization, and reported healing rates ranging from 83% to 100%.

Chronic displaced ‘irreducible’ type II fractures with cord compression are uncommon. They commonly occur in elderly persons or patients who did not receive treatment immediately. They may be more commonly found in situations where treatment may not be available in the immediate vicinity and there is a delay due to referral to a tertiary center due to a treatment gap, which could be because of a knowledge gap or social or financial reasons. Such fractures usually require transoral excision of an odontoid fractured fragment followed by a posterior instrumented fixation (C1/C2 or a trans articular screw fixation). The authors have described a single staged posterior approach technique, which provides all 3 treatment objectives, i.e., cord decompression, stabilization, and correction of the deformity. The author has named the surgical procedure DCER as it utilizes all 3 components of motion, i.e., distraction, followed by compression and extension, leading to the removal of the deformity. This technique has effectively been utilized in over 200 congenital craniovertebral junction anomalies with moderate to severe BI and atlantoaxial dislocation. The principle of the method is based on using the spacers as a pivot, which converts the C1/C2 joints into a type II pivot (in the present study, occipital-C2 joint after drilling the lateral mass of C1 thoroughly). Thus, compression applied posteriorly translates into a movement of extension, resulting in the dens’ forward movement, effectively reducing the atlantoaxial dislocation. This is the first time in the literature that such a technique has been used to reduce certain severe chronic displaced odontoid fractures. The authors have used this technique to correct over 200 BIs cases and atlantoaxial dislocation (AAD).

Following its practical application in BI and AAD, the authors

https://doi.org/10.14245/ns.2244460.230
applied the same technique with minor modifications on patients with chronic displaced 'irreducible' type II fractures. The main modification included performing a C1 laminectomy, posterior decompression of the rim of the foramen magnum, complete drilling of the C1 lateral masses, and denuding the occipital and C2 joint surfaces by a spacer placement between the occiput and C2 joints. This is followed by compression between the occiput and C2 spinous process (Fig. 1). This movement results in the 'slipping back' of the C2 body under the fractured dens (with the spacer now acting as a fulcrum), thus reducing the fracture. Here occipital-C2 fusion was performed instead of C1/C2 fixation. The initial distraction brought the margins of the fractured segment of the dens to the same level. The subsequent compression and extension allowed the C2 body with the base of dens to 'slip forward' under the fractured odontoid segment.

We used 3 measurements to assess the degree of spinal canal widening. These included: ACD: measured between the posterior margin of the dens to the posterior margin of the foramen magnum; pre-EDC: measured between the posterior margin of the C2 body at the level of the fracture and anterior border of posterior C1 arch before surgery; post-EDC: measured between the posterior margin of the C2 body at the level of the fracture and the posterior margin of the occiput after surgery (as the C1 posterior arch is drilled away after surgery). Using these measurements, we used 2 parameters to assess the degree of spinal canal widening. These included: cECD = degree of improvement of ECD, calculated as pre-EDC/post-EDC × 100; cACD: degree of improvement of ACD, calculated as post-EDC/ACD × 100. The mean improvement of ECD was 74.3% ± 9.5% (compared to the pre-ECD) and the mean improvement of ACD was 77% ± 8.7% (compared to the preoperative ACD). The technique provides movement in 2 axes, i.e., in vertical and horizontal directions, and utilizes the spacer as a fulcrum between the occiput and C2 joint to effectively correct the displaced fragments. However, there is a word of caution for patients with osteoporosis, as the bone may not be strong enough to withstand the corrective forces. We also agree that the current series is not very large. However, publishing the current series aims to provide proof of concept. We aim to publish a more extensive series at a later date.

**NOTES**

Supplementary Material: Supplementary video clip 1 can be found via https://doi.org/10.14245/ns.2244406.203.

The supplementary video clip 1 shows the surgical technique of modified DCER (case 3, Fig. 5, Table 1).

Conflict of Interest: The authors have nothing to disclose.

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Acknowledgments: The technique described here has been registered for a global patent vide Patent cooperation treaty (PCT), International application number PCT/IN2014/000385.

Author Contribution: Conceptualization: PSC; Data curation: PSC; Formal analysis: PSC; Funding acquisition: PSC; Methodology: PSC; Project administration: PSC; Visualization: PSC; Writing - original draft: PSC, RS, RD, SV, PS; Writing - review & editing: PSC, R RS, RD, SV, MC, PS.

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Commentary on “Classification(s) of Cervical Deformity”

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To the editor,

I read with interest the abovementioned article that focuses on analysing the various classifications of cervical deformity described in the literature.¹ As discussed by the authors, the classification of cervical deformity is essentially based on underlying aetiology, focus of the curve apex, regional and global spinal alignment. The authors have discussed their own classification scheme that focuses on assisting decisions regarding surgical management. The various classifications schemes, including the one described by Kaidi and Kim¹ are designed on radiological observations of subaxial cervical spinal configuration and include cervicothoracic curvatures, alignments and deformities.

It is surprising that discussion regarding status of craniovertebral junction stability has been entirely ignored in these classifications.² Our observation is that the existing classification schemes have focussed their analysis on physical deformations and radiological observations and not so much the issue of instability in the atlantoaxial and subaxial cervical spine.

The authors could have included our classification of cervical deformities in their reference list.² Our contention is that atlantoaxial and/or subaxial spinal instability is a nodal point of pathogenesis of several spinal deformities. Apart from range of torticollis and short neck that are directly related to atlantoaxial instability, deformities in the cervical spine encountered in a number of pathological conditions that include degenerative spinal disease have their origin in spinal instability that more frequently includes atlantoaxial instability.²,³ Understanding of the underlying unstable spinal segments and their stabilization forms the cornerstone of surgical treatment.

We have recently described a novel clinical entity of central or axial atlantoaxial instability (CAAD).⁴–⁷ In CAAD, the atlantoaxial instability cannot be identified on the basis of conventional validated radiological parameters that include abnormal alteration of atlantoaxial interval or any evidence of neural or dural compression by the odontoid process. In CAAD, instability is diagnosed on the basis of alignment of facets in the lateral profile imaging, tell-tale radiological evidences and is confirmed by direct manipulation of bones of the region during surgery. Chiari formation, basilar invagination, syringomyelia, Klippel-Feil abnormality, platybasia, bifid arches of atlas, os-odontoideum and a range of so-called ‘pathological anomalies’ have their origin in CAAD and constitutes its tell-tale evidences.⁸–¹⁰ Our articles on the subject have observed that all these abnormalities when present discretely or in cohort are secondary to atlantoaxial instability, are naturally protective or adaptive in their role and are potentially reversible following atlantoaxial stabilization. Considering this un-
derstanding, we prefer to call Chiari ‘malformation’ as Chiari ‘formation’ and craniovertebral ‘anomalies’ as craniovertebral ‘alterations’.11,12

For the first time in the literature, we discussed the issue of ‘vertical’ spinal instability as a nodal point of pathogenesis of spinal spondylosis.13 Vertical spinal instability is essentially telescoping of the spinal segments related to weakness of the muscles involved primarily in the standing human posture.14 Such listhesis or instability is difficult if not impossible to identify on conventional radiological imaging. It was speculated that is not disc space reduction or disc degeneration but listhesis of the subaxial facets where the muscles of the nape of neck and back of spine are focussed that is the initial manifestation of spinal degeneration that initiates a cascade of secondary events that culminate into pathology of spinal degeneration. The so-called pathological entities in degenerative spinal disease that include reduction in the intervertebral disc space, bulging of the disc into the spinal canal, osteophyte formation, bulging of the intervertebral ligaments that ultimately result in reduction in the spinal and neural canal are secondary manifestation or tell-tale evidences of vertical spinal instability.12 Cervical deformities that include kyphotic and scoliotic deformities are also secondary manifestation of vertical spinal instability. Our articles discuss that all the secondary alterations observed in spinal degeneration that include spinal deformity are protective or adaptive in their role and are potentially reversible following stabilization of the affected spinal segments.15

On the basis of presence of vertical spinal instability with or without atlantoaxial instability, we classified cervical deformities into 3 groups.2 Type 1 cervical kyphosis was when kyphosis was associated with atlantoaxial instability that was diagnosed on the basis of increased atlantodental interval. Kyphotic deformity was considered to be secondary to atlantoaxial instability and atlantoaxial stabilization was identified to be the treatment. Type 2 cervical kyphosis was when there was subaxial vertical cervical spinal instability. The vertebrae involved in the entire curvature of kyphosis were considered to be unstable and all these segments needed stabilization. Type 3 cervical kyphosis was when both CAAD and vertical spinal instability were identified to be the cause of deformity. Atlantoaxial and subaxial cervical spinal stabilization of the affected spinal segments was the treatment.

Postlaminectomy cervical spinal deformity and alteration in spinal curvature in cases related to neurofibromatosis and other tumors are also related to spinal instability.16,17 Spinal stabilization is the treatment.

Our classification system of cervical spinal deformities is on the basis of identifying the unstable spinal segments. Essentially, we observe that instability is the cause and stabilization of the affected segments is the treatment of spinal deformities. We believe that the authors will acknowledge these concepts and consider modification in their classification scheme.

- **Conflict of Interest:** The author has nothing to disclose.

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Reply to Commentary on “Classification(s) of Cervical Deformity”

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To the editor,

We thank Dr. Goel for his interest in our article and appreciate the comments made regarding our manuscript. As acknowledged in our original submission, the classification of cervical deformities is still a nascent field.\textsuperscript{1} In recent years, significant progress has been made towards creating statistically validated classification schema for cervical deformities; however, there is still work to be done.\textsuperscript{2-4} We agree with Dr. Goel that current classification schema, including the Kim Classification, do not address cases of craniovertebral junctional instability. We also acknowledge that this instability can be an important consideration when managing patients with complex cervical deformities. While Dr. Goel’s proposed classification schema is appreciated,\textsuperscript{5} the Kim Classification cannot reasonably be modified to include craniovertebral junctional instability given the rigorous statistical methodology used in the classification’s creation.

The Kim Classification was created utilizing a 2-step cluster analysis of dynamic spine radiographs (a combination of hierarchical and kappa cluster analyses). This machine-learning-based statistical analysis requires high sample sizes to adequately power conclusions. Given the rarity of craniovertebral junctional instability, these cases were excluded in original analysis of Kim et al.\textsuperscript{2} If they were included, the small sample size would make any derived classification schema inherently unreliable. The exclusion of these cases should not signify that craniovertebral junctional instability was considered unimportant or irrelevant in surgical decision making.

Overall, the classification of cervical deformities is still an evolving field, and we acknowledge that the Kim Classification does not appropriately describe every case of complex cervical spine deformity. It does, however, serve as an additional tool for surgeons to utilize when describing and managing cervical spine deformities. Further, it is the first validated classification schema designed to guide surgical management of different cervical deformities.\textsuperscript{6,7} As we develop more nuanced approaches to treating cervical deformities, we appreciate the continued discussion being had on this important topic.

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REFERENCES

Commentary on “Cervical Inclination Angle: Normative Values in an Adult Multiethnic Asymptomatic Population”

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The incidence of adult spinal deformity (ASD) increases with age. The current incidence of spinal deformity ranges from 29% in adults aged up to 54 years to more than 65% in adults aged ≥ 65 years.¹ A better understanding of the sagittal alignment of the spine allows for comprehensive surgical planning for ASD. This is the key to achieving optimal surgical alignment and improving results.² A recent study of ASD postoperative outcomes reported high complication (8.4%–42%) and mortality (9%–17.6%) rates.³

The roles of the craniocervical complex (CCC) and upper thoracic spine have rarely been analyzed as mechanical complications of ASD. Cerpa et al.⁴ recently suggested that a posterior skull plumbline in front of the instrumented upper spine on postoperative standing radiography may be a risk factor for proximal junctional kyphosis (PJK). Passias et al.⁵ reported that age-adjusted alignment goals and distal inclination angle are important parameters for distal junctional kyphosis in cervical deformity surgery. Le Huec et al.⁶ reported on the cervical inclination angle (CIA) in 2018, a new angle proposed to analyze the role of CCC in global spinal alignment and PJK risk. CIA was defined as the angle between the center of the dentate process, the midpoint of each thoracic upper endplate, and a horizontal line starting at the center of each thoracic endplate. They analyzed, based on ergonomics, that the thoracic and cervical spine should be aligned and have a small anterior lever arm to maintain sagittal alignment and reduce strain on the spinal muscles. For every 1-cm forward displacement of the line of gravity, a bending moment of +3.5 Nm occurs. This increases the risk of spinal and intervertebral disc injuries.

Le Huec et al.⁶ reported that the CIA is the angle whose mean value varies little between T1 and T5 (74.9°–76.85°) and gradually increases from T6 to T12. The T1–5 vertebrae always align within each participant’s thoracic vertebrae and can be viewed as linear T1–5 segments. The vertical slope of the T1–5 segment is correlated with the C7 slope. They analyzed the normative value of the CIA angle in an adult asymptomatic multiethnic cohort. A total of 468 asymptomatic adult patients were included in this study (176 Caucasian, 119 Japanese, 91 African American, 80 Arab-Berber, and 81 Asian).⁷ The mean overall CIA value was 80.12° ± 2.8°, while the maximum difference between all thoracic vertebrae was 9° (minimum T5 = 77.05°; maximum T12 = 86.05°).⁷ An analysis of the CIA every few decades
revealed a significant decrease after 60 years of age; however, it remained constant until 60 years of age and then decreased at all thoracic levels from a mean of 82.25° to 73.65°. Considering ethnicity, there were differences between the Arab-Berber and other groups. Arab-Berbers had a statistically lower mean CIA at each thoracic level.7

In this study, CIA was suggested as a factor related to mechanical complications after ASD.7 Thoracic kyphosis (TK) is known to increase with age due to degeneration of the intervertebral discs and decreased spinal wedge and paraspinal muscle strength.6 An increase in TK corresponds to a major C7 tilt and anterior displacement of the trunk, resulting in a larger odontoid–hip axis angle and a larger odontoid-thoracic distance.6 As the torso moves forward, the bending moment increases, increasing the risk of spinal fractures or PJK.6 In the future, more research on the relationship between CIA and clinical results is needed; if this is proven, it is expected to be a meaningful parameter for ASD surgery.

- **Conflict of Interest**: The authors have nothing to disclose.

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