History of Spinal Deformity Surgery Part II: The Modern Era
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Following Dwyer introduction of anterior spinal instrumented fusion surgery, Zielke, Moss-Miami, and Kaneda had made a significant progression on anterior spinal instrumented fusion which allowed excellent correction without significant loss of correction or implant failure. King and Moe developed classification of thoracic major curve following Harrington rod instrumentation. King classification presented a stable vertebra concept and selective fusion concept. Surgical classification of Adolescent Idiopathic Scoliosis (AIS) developed by Harms study group provided a more sophisticated two dimensional understanding of curve nature. Surgical intervention of adult scoliosis and sagittal imbalance is still challenging and evolving. Several evidences such as sacropelvic fixation and bone morphogenetic protein helped us to deal with adult deformity. The surgical decision making on spinal deformity surgery is still yet evolving.

Key Words: Anterior spinal instrumentation • King and Moe • Adolescent Idiopathic Scoliosis • Sacropelvic fixation

INTRODUCTION

Harrington’s introduction of the internal fixation device to treat paralytic scoliosis in 1960’s started revolution on deformity correction surgery. Luque developed a segmental spinal using sublaminar wiring technique in 1976 and Cotrel developed Cotrel-Dubousset (CD) instrumentation, which was a posterior segmental instrumentation system that used pedicle and laminar hooks on either thoracic or lumbar spine and pedicle screws on the lumbar spine. Following Dwyer introduction of anterior spinal instrumented fusion surgery, Zielke, Moss-Miami, and Kaneda had made a significant progression on anterior spinal instrumented fusion which allowed excellent correction without significant loss of correction or implant failure. Both of them set the next milestone in modern spinal deformity surgery.

POSTERIOR SPINAL SURGERY

Harrington Instrumentation

The modern era of spinal deformity surgery began with the introduction of Harrington spinal instrumentation in 1960⁴⁹. Paul R. Harrington treated poliomyelitis patients who were suffering from scoliosis with his newly-developed instrumentation that provided an internal traction mechanism (distraction) to correct the scoliotic spine, applied to the concavity of the curve, and in some cases with compression applied to the convexity. Russell A. Hibbs first reported successful surgical treatment of patients with tuberculous spinal deformities by fusing the spine in 1911⁵⁷. The addition of copious bone graft subsequently allowed better fusion rates⁵⁶, especially in long spinal fusions⁵⁰. However, patients were often bedbound in a corrective cast for many months postoperatively. The advent of Harrington instrumentation not only provided a greater magnitude of force application than could be mediated through the skin, but it also allowed the patients to ambulate in a cast or well-fitting brace promptly after surgery without significant loss of correction until healing of the fusion⁵⁵.

Although the majority of patients had significant correction of the coronal plane deformity with satisfactory results, some unfortunately developed sagittal imbalance, namely “flat back syndrome”⁵¹, as the combination of a straight rod and distraction of the spine to correct the curve in the coronal plane caused an obligatory loss of lumbar lordosis with subsequent anterior translation of the vertical axis and the body’s center of gravity in the sagittal plane⁵². Interestingly, the iatrogenic loss of lumbar lordosis was not a significant problem following fusion for treating scoliosis prior to the advent of corrective surgical instrumentation⁵³.

Another potential complication of Harrington instrumentation was progression of scoliosis following posterior fusion...
of the spine in young patients whose spine continued to grow anteriorly. Dubousset published an article in 1973 that first recognized this problem and termed it “crankshaft” phenomenon66. He later recommended combined anterior and posterior spinal fusion for young patients who still had significant growth left34,35, and others have echoed Dubousset’s recommendations and observed less occurrence of crankshaft phenomenon with combined anterior and posterior surgery97,190,156. It was generally agreed that very young patients were more likely to develop crankshaft phenomenon, and some of the associated factors were: age90, peak height velocity133, Risser stage130,132, and open triradiate cartilage48,132. Further, crankshaft phenomenon was also seen later with Luque spinal instrumentation131 but not with Cotrel-Dubousset instrumentation23.

### Luque Instrumentation

In 1976, Eduardo R. Luque conceived of and later developed a segmental spinal instrumentation based on the principle of lateral translation as the predominant corrective force105. The rods were fixed proximally and distally with sublaminar wires. After facetectomies on both sides, the wires that encircled the lamina and the rod at each segment were tightened to straighten the spine in the coronal plane. Luque’s initial report on sixty-five consecutive patients with scoliosis who were treated with his instrumentation noted improved curve correction, and although there were no significant outcome data on sagittal plane correction and balance, he hypothesized that segmental instrumentation of this type may help to improve the magnitude of correction and the rigidity of the construct while preserving sagittal curvature36. A biomechanical analysis confirmed that, when compared to Harrington instrumentation, Luque instrumentation with segmental sublaminar wiring provided superior fixation, less risk of loss of lumbar lordosis and thoracic kyphosis, and superior rotational control and resistance against construct failure155. Subsequent clinical studies by others further supported Luque’s hypothesis and reported better preservation of sagittal balance with Luque instrumentation79,124.

Although Luque instrumentation with sublaminar wiring provided powerful translational force (in fact, sublaminar wiring has been shown to be as powerful as pedicle screws when used at the apex of the curvature, albeit at the cost of increased blood loss)26, it also had associated surgical risks including, but not limited to, potential for neurologic complications. Sublaminar wires could directly traumatize the spinal cord62,22,24,55,63,100, the weight of the wires caused by wire position107, Luque himself reported 9% minor complications (paresthesia) that completely resolved after two weeks postoperatively36. In 1987, the Morbidity Report of the Scoliosis Research Society described an incidence of cord injury in 0.26% of operatively treated patients with idiopathic scoliosis of which sublaminar wiring was responsible for 39% of the total101. Published studies by others reported similar injury rates, most of them transient neurologic deficits but certain instances of true cord lesions148,157,159.

### Cotrel-Dubousset Instrumentation

In 1984, Yves Cotrel and Jean Dubousset introduced Cotrel-Dubousset (CD) instrumentation and set the next milestone in modern spinal deformity surgery29. It was a posterior segmental instrumentation system that used multiple transverse, pedicle, and laminar hooks on either thoracic or lumbar spine and later pedicle screws on the lumbar spine, instead of sublaminar wires, to achieve three-dimensional correction of spinal deformities. The correction principle was based on placing the rod on the concave side of the curvature with multiple hooks and then derotating the rod to increase the thoracic kyphosis and translate the curved spine into the midline. Following the rod derotation maneuver on the concave side, a second rod was place on the convex side for sequential compression/distraction at various levels. In addition, the rods were secured to each other with transverse connectors, thereby forming a frame that resisted rotational and torsional forces. Patients were mobilized one day after surgery and did not require any external immobilization.

Early and midterm results (at less than ten years) comparing CD with Harrington instrumentation have demonstrated better correction of thoracic curves with CD instrumentation35,94,95,62. Further, CD instrumentation yielded better long-term (more than ten years) functional and radiographic outcomes in patients with adolescent idiopathic scoliosis than did Harrington instrumentation43.

As more surgeons gained experience, it was clear that pedicle screws were superior in achieving fixation of all three spinal columns and correcting the deformity in all three dimensions. In the beginning, pedicle screws were only used in the lumbar spine since there was less risk of neurologic damage below the level of conus medullaris. Predictably, the next step was to attempt using pedicle screws in the thoracic spine. In 1995, Suk and his colleagues from Korea reported on their experience of using thoracic pedicle screws to treat thoracic idiopathic scoliosis348. Following the introduction of thoracic pedicle screws, four different CD constructs were now possible: all hooks, thoracic hooks and lumbar pedicle screws (hybrid), proximal thoracic hooks, mid-thoracic Luque sublaminar wiring and lumbar pedicle screws, or all pedicle screws. Subsequent analysis comparing the pedicle screw only construct versus hook
or hybrid construct demonstrated superior curve correction and postoperative pulmonary function values\(^7\), as well as lower surgical revision rates\(^8\), without increased risk of neurologic complications with all pedicle screw constructs.

As with previous internal fixation systems, the use of CD instrumentation introduced a whole new set of surgery-related complications. Combined effect of rigid, three-column fixation with pedicle screws and surgical techniques that unintentionally decreased thoracic kyphosis when performing corrective maneuvers to straighten the scoliotic spine in the coronal plane caused high incidence of proximal junctional kyphosis in both adolescent\(^5\,\,\,7\) and adult patients\(^4\,\,\,5\). Maintenance or thoracic kyphogenion technique using posterior translational instrumentation by sub-laminar wiring technique or rod derotational technique can prevent proximal junctional kyphosis.

**Moss-Miami Instrumentation**

The Moss-Miami System instrumentation (DePuy, Warsaw, IN) was introduced in 1994. It was a posterior segmental spinal instrumentation that had biomechanical and metallurgical attributes similar to other posterior systems. However, it offered advanced characteristics such as low profile implants, smaller rod diameter (five millimeters), all top opening implants permitting straight-forward rod placement, a simplified and strong closure mechanism (which can be easily removed or altered if necessary), different hook styles, and pedicle screws. Clinical reports using this system is rather scant\(^3\), but in a comparative study, Luk and colleagues found no significant difference between the amount of correction possible using Texas Scottish Rite, Isola, CD-Horizon, or the Moss-Miami systems\(^10\).

**Posterior based instrumentation**

1. Harrington Rod Instrumentation (Fig. 1).
2. Sublaminar wiring with hooks only and hybrid (proximal hooks and distal screws) (Fig. 2).
3. Pedicle screws (Fig. 3).

**KING-MOE AND LENKE CLASSIFICATION**

The goals of surgery for adolescent idiopathic scoliosis are: 1) halt curve progression and correct deformity, 2) maintain a balanced spine in the coronal and sagittal planes, 3) preserve as many mobile spinal segments as possible, and, 4) prevent surgical complications such as junctional kyphosis, adding on, and revision surgery. To preserve as many mobile spinal segments as possible, identification of the primary curve(s) is mandatory. It was easy to detect primary curve in primary thoracic and lumbar curves. Difficulty to differentiate primary curve came from double major or false double major curves in which both thoracic and lumbar curves crossed the midline. The concept of selective thoracic fusion to treat adolescent idiopathic scoliosis has been brewing over the years with no agreement among different schools. It finally came to the fore with the introduction of the King-Moe classification system in 1983\(^7\). This classification was based on data gathered from 405 adolescent idiopathic scoliosis patients who underwent surgical correction.
of the spine using Harrington instrumentation. The authors suggested that, for a type II curve (major thoracic, compensatory lumbar), selective thoracic fusion should extend to the lower vertebra that is both neutral (no rotational deformity with both pedicles appearing equal in size and shape on a posteroanterior radiograph) and stable (bisecting the center sacral line that is perpendicular to the iliac crests). When the neutral vertebra and the stable vertebra are not the same, they recommended choosing the stable vertebra as the caudal end of the fusion. Before the appearance of this article, the stable zone as defined by Harrington was the area between two vertical lines drawn through the lumbosacral facet, and Harrington has stated that the lower level of fusion should fall within this zone\textsuperscript{51}. In recent years, some surgeons noted that the ver-
tebra that bisects the center sacral line (stable vertebra) changes based on whether the radiographs are taken with the patient standing or supine with side bending/in traction and introduced the idea of a “dynamic” stable vertebra.

Quite naturally, there was concomitant interest in the behavior of the unfused lumbar spine with variable results and introduced the idea of a “dynamic” stable vertebra. Decompensation of the lumbar spine, or “adding-on” phenomenon, was quite rare (4%) with Harrington instrumentation compared to the new CD instrumentation (41%)\(^{108}\). This led to the realization that selective thoracic fusion with CD instrumentation required a whole different set of criteria\(^ {15,96,109}\).

In 2001, Lenke and colleagues\(^ {92}\) described a new surgical classification system for adolescent idiopathic scoliosis that specifically quantified the structural aspects of regional scoliotic curves based on relative curve magnitude, flexibility, and position. Lenke classification proposed structural minor curve concept for fusion in addition to the Major (primary or biggest) curve, lumbar/thoracolumbar major curve, and sagittal profiles. According to this system, curves are classified according to: 1) curve pattern; 2) lumbar apical vertebral translation; and 3) sagittal alignment. In general, for main thoracic curves in which the lumbar apical vertebral body is incompletely translated from the midline (lumbar modifier A and B), selective thoracic fusion is recommended. The more challenging main thoracic curves in which the lumbar apical vertebra is totally translated from the midline (lumbar modifier C) may also be treated with selective thoracic fusion, but are considered to be at greater potential for subsequent decompensation. However, there was 10% rule breaker (usually lumbar C modifier) which meant the thoracic and lumbar curves fused in the Lenke 1C, 2C, and 5C curves and only thoracic curve fused in the Lenke 3C and 4C as well as only lumbar or thoracolumbar curve fused in the Lenke 6C curve. Recently, selective thoracic fusion surgeries have been successfully performed on double major curves (Lenke type 3) with lumbar modifier C when there was more than 40% derotation of lumbar apical vertebrae observed when comparing the standing anteroposterior film with the lumbar supine side-bending films\(^ 5\).

The most important factors to decide whether or not to perform selective thoracic fusion consist of patient lifestyle and clinical patient status including activity level, age, and preference to sports. Some patients such as professional dancers or athletes require more lumbar flexibility for their activity and thus require selective thoracic fusion if indicated. The patient and family need to understand the potential for lumbar curve progression, junctional problem, and revision surgery to extend the fusion. Physical examination such as Adams forward bending test is very important. Thoracic rotational prominence should be larger than the lumbar prominence with a scoliometer. Flexibility on thumb abduction testing is also important. If a patient is very flexible, a selective fusion may not be a good choice. Radiographic criteria proposed by Lenke et al is more to consider when evaluating a patient for possible selective thoracic fusion. The thoracic apical vertebral translation (AVT) is the distance between the C-7 plumb line and the center of the apical vertebral body of the thoracic curve. The thoracolumbar/lumbar AVT is the distance between the center of the apical vertebral body of the thoracolumbar/lumbar curve and the center sacral vertebral line. A ratio of thoracic AVT to thoracolumbar/lumbar AVT is very important to perform selective fusion. The second factor that helps to determine if selective thoracic fusion is feasible is apical vertebral rotation (AVR). This is based on the Nash-Moe grading for vertebral rotation based on the radiographic pedicle appearance of the thoracic or thoracolumbar/lumbar apical vertebrae. The third factor is the magnitude of the curves on Cobb measurements (Fig. 4, 5).

### ANTERIOR SPINAL SURGERY

Surgical treatment for thoracolumbar or lumbar adolescent idiopathic scoliosis typically has been performed with anterior correction and fusion. The demonstrated advantage of anterior surgery, when compared to posterior surgery, traditionally has

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**Fig. 4.** The thoracic apical vertebral translation (A) is the distance between the center of thoracic apical vertebra (A) and the C7 Plumb Line (solid line). The lumbar apical vertebral translation (B) is the distance between the center of lumbar apical vertebra and Central Sacral Vertical Line (dashed line).
Fig. 5. TF is a 13 year old boy with idiopathic scoliosis. Preoperative standing AP radiograph showed a right thoracic curve of 47º and a left thoracolumbar curve of 80º. Lumbar apical vertebral rotation of T13 was 40º and thoracic apical vertebral rotation of T7 was 5º according to Perdriolle. Thoracic apical vertebral translation was 18 mm and lumbar apical vertebral translation was 77 mm. C7 plumb was 44 mm toward the left side. Preoperative standing lateral radiograph showed thoracic kyphosis at T5-T12 of 3º, thoracolumbar kyphosis at T10-L2 of 23º, and lumbar lordosis at T12-S1 of 42º. Left side bender of the thoracolumbar curve was 58º and right side bender was 22º. He also had left-side only synostosis of L5-S1. His curve is 6C according to Lenke classification system. He underwent posterior osteotomy at L5-S1 and selective posterior thoracolumbar instrumentation and fusion at T10-L3 and presented at 12 months follow up with satisfactory frontal and sagittal spinal alignment.

been shorter fusion levels whereby the cranial and caudal ends of the fusion are the end vertebrae\(^{154}\). Cranial end vertebra is the first vertebra in the cranial direction from a curve apex whose superior surface is tilted maximally toward the concavity of the curve, whereas caudal end vertebra is the first vertebra in the caudal direction from a curve apex whose inferior surface is tilted maximally toward the concavity of the curve.

**Dwyer Instrumentation**

In 1964, Allen F. Dwyer attempted surgical correction of scoliosis via an anterior approach and conducted a two-stage surgery in which he first performed posterior release, resecting the ligaments and capsular structures overlying the facet
joints on the concave side and excising any fibrous and bony ankylosis between the laminae, followed by corrective instrumentation anteriorly. Screws were placed into the lateral wall of the vertebrae on the convex side, and a cable was then threaded through the screw heads and was tightened by compressing the screws together to straighten the curve. Unfortunately, high rate of late curve progression secondary to ineffective derotation and cable fracture with pseudarthrosis, as well as lack of surgical expertise in anterior approaches, caused many spine surgeons to avoid using this method. Further, these anterior deformity correction surgeries resulted in increased thoracic kyphosis on long-term follow-up.

Zielke Instrumentation

Klaus Zielke and his colleagues modified the Dwyer system by substituting a threaded rod and nuts for the cable and introduced a derotator designed to correct rotation and to prevent instrumentation-induced kyphosis. Over time, Dwyer instrumentation was replaced by Zielke (ventral derotation spondylodesis [VDS]) instrumentation in treating thoracolumbar and lumbar scoliosis with the following advantages: effective correctibility of the coronal curvature, the ability to correct deformity by instrumenting shorter segments of the spine (shorter fusion levels) than would normally be necessary with the posterior approach, and derotation capability. However, some reports noted a high incidence of implant breakage, loss of correction, progression of kyphosis, and pseudarthrosis with the Zielke system as well.

The Halm-Zielke instrumentation was developed as a modification of the VDS system, in which an additional fluted rod was introduced to better derotate the spine while improving postoperative sagittal alignment. Clinical studies have demonstrated superior results with Halm-Zielke instrumentation in eliminating the kyphogenic effect while maintaining primary stability.

Kaneda Instrumentation

Kaneda recognized a number of shortcomings with Zielke instrumentation, namely, mechanical weakness of the implants because of the small diameter of the rod, less than optimal correction of the sagittal plane even with vertebral derotation, and loss of three-dimensional correction obtained (stability). He introduced a new multisegmental instrumentation system which was originally developed to treat spinal fractures, tumors, and other disorders. The Kaneda system consisted of a vertebral plate and two vertebral screws for individual vertebral bodies and two semirigid rods to interconnect the vertebral screws. Kaneda reported excellent correction of thoracolumbar and lumbar scoliosis in both coronal and sagittal planes without significant loss of correction or implant failure. Other surgeons also reported similar excellent clinical results using the Kaneda system.

Anterior based instrumentation

1. Dwyer and Zielke Instrumentation (Fig. 6).
2. Modern anterior spinal instrumentation: single rod and dual rod (Fig. 7).
ADULT SCOLIOSIS

There are a number of etiologies for developing a scoliotic deformity as an adult. These include, but are not limited to, progression of infantile or adolescent idiopathic scoliosis, degenerative disc disease below the previous spinal fusion, a compensatory spinal deformity, and degenerative changes without preexisting scoliosis typically manifested in the lumbar spine. Of these, adult degenerative or de novo scoliosis is thought to arise from asymmetric degeneration of discs, osteoporosis, and vertebral body compression fractures. Adult degenerative scoliosis patients typically present with symptoms of low back pain, which may be accompanied by neurogenic claudication and/or progressive deformity with imbalance in either coronal or sagittal plane. Recently, there have been attempts to develop a meaningful classification system for adult scoliosis by a multicenter prospective study group based on studies showing specific radiographic parameters that bore significant impact on outcome scores. Surgery is a good option for adult patients with pain-related deformity who have failed conservative treatment. There are several options for surgical treatment: 1) decompression only, 2) decompression with limited lumbar fusion, 3) whole lumbar fusion with or without decompression, 4) both thoracic and lumbar fusion, or 5) lumbar or thoracolumbar fusion with corrective spinal osteotomies. In general, patients with curves that are at risk for progression (i.e., >50 degrees of thoracic and >40 degrees of lumbar curves), along with overall sagittal imbalance, should be considered for surgical correction.

Thoracic kyphosis greater than 75 degrees is amenable to surgical treatment, as well as any patient who has a persistent neurological deficit.

Perhaps the single most important principle in the surgical treatment of adult scoliosis is achieving and maintaining proper sagittal and coronal balance such that the spine is oriented to have the head placed over the pelvis. Unlike adolescent idiopathic scoliosis whereby successful fusion can be obtained without supplemental allograft or nonlocal autograft, adult scoliosis carries a significant risk of pseudarthrosis. The reported incidence of pseudarthrosis in long fusions to S1 is 3% to 83%, which has shown a large disparity according to diagnosis, surgical approaches, and instrumentation types. In one recent study, Kim and colleagues reported a 24% pseudarthrosis rate and identified several associated risk factors: thoracolumbar kyphosis, hip osteoarthritis, use of a thoracoabdominal (versus paramedian) approach, positive sagittal balance greater than 5 cm, age greater than 55 years, and incomplete sacropelvic fixation.

Bone Morphogenetic Protein

The use of autograft, either the local bone harvested from the operative site or iliac crest, is the gold standard material to achieve a solid arthrodesis for adult spinal deformities. One possible confounder that may prevent the surgeon from harvesting iliac crest graft is planned iliac instrumentation. When the amount of autograft is insufficient, there exists a plethora of alternatives that include allograft products, synthetics, ceramics, bone graft extenders, as well as bone morphogenetic protein (BMP). In two recent studies, adult patients under...
went surgical fusion for degenerative scoliosis with anterior or posterior BMP-2 application, either with local bone graft only (posterior) or no bone graft (anterior), which obviated the need for rib, iliac crest, or other autograft harvest and its associated morbidity. Fusion rates were excellent, with mid-90% fusion success. Caution should be exercised when using BMP, however, as there have been reports of undesirable effects such as ectopic bone formation, accelerated resorption of interbody grafts, and radiculitis.

**Sacropelvic Fixation**

A frequent decision-making dilemma in deformity surgery is determining the caudal end of the fusion reconstruction. Typically, fusions are extended to the sacrum in the presence of spondylolisthesis or previous laminectomy at L5-S1, stenosis requiring decompression at L5-S1, severe degeneration, or an oblique takeoff (>15 degrees) of L5 to the sacrum. Unfortunately, there is a high rate of pseudarthrosis (and other complications) following stand-alone posterior L5-S1 fusion with long constructs in scoliosis patients, requiring more surgical procedures than those that end at L5. For these reasons, some authors have advocated avoiding fusion to the sacrum whenever possible, although fusions ending at L5 were associated with adjacent segment disease in 61% of the time and adverse changes in the patient’s sagittal balance.

Augmentation of the lumbosacral reconstruction in long constructs with anterior column support in the form of interbody fusion at L5-S1, which can be applied anteriorly (anterior lumbar interbody fusion) through a separate anterior approach or posteriorly (transforaminal or posterior lumbar interbody fusion), improves biomechanical stability and reduces the risk of lumbosacral pseudarthrosis. An anterior structural graft at L5-S1 can also recreate the lordosis, which is typically lost in these patients, partially restoring sagittal balance, and may also diminish stenosis by restoring the intervertebral height. In addition, BMP may be used to further increase the chances of achieving solid fusion.

When performing fusion to the sacrum, iliac fixation should be considered, particularly if the fusion extends beyond the upper lumbar spine. Methods of sacropelvic fixation have included the Galveston (L-rod) technique, Dunn-McCarthy (S-rod) technique, transiliac screws, intrasacral rods, iliosacral fixation, and iliac screws. Several biomechanical studies have shown increased rigidity of lumbosacral fixation techniques using iliac screw fixation. When various pelvic fixation techniques were compared in patients with neuromuscular scoliosis, iliac screws afforded equivalent maintenance of pelvic obliquity and scoliosis correction compared to the Galveston technique with less complications.

**CORRECTIVE OSTEOTOMIES IN SPINE SURGERY**

A substantial imbalance in the sagittal plane sometimes cannot be corrected solely with spinal arthrodesis and instrumentation. In these unique cases, spinal osteotomies must be performed to achieve balance in both the sagittal as well as the coronal plane. There are two general types of spinal imbalance in the sagittal plane: type 1 and type 2. A type-1 imbalance refers to a condition in which the patient has a segmental or regional imbalance in the sagittal plane of the spine but still has a balanced spine as defined by the C7 plumb line falling over the L5-S1 disc. On the other hand, a type-2 imbalance refers to a global imbalance whereby the C7 plumb line falls more than 5 cm in front of the L5-S1 disc. A spine with a type-2 imbalance cannot compensate for the deformity, and the patient tends to flex the hips and knees to maintain a proper balance and horizontal gaze. Patients with type-2 imbalance are the ones who generally need corrective osteotomies of the spine in addition to fusion and instrumentation.

**Smith-Petersen Osteotomy (Posterior Element Wedge Resection)**

This osteotomy was first described by Smith-Petersen and colleagues as an operative technique to treat kyphotic deformity caused by ankylosing spondylitis. In general, once the appropriate level for the osteotomy is identified, the lamina, ligamentum flavum, and superior and inferior articular processes are removed bilaterally. Smith-Petersen osteotomy (SPO) has a chevron arrangement in the coronal plane and the width of the osteotomy is typically 7-10 mm. A rough guideline to follow is that every 1 mm of resection results in 1 degree of correction, resulting in approximately 10 degrees of correction per level. An open disc space is a prerequisite for closure of the osteotomy site, and if the disc is collapsed, it may limit the amount of correction obtained. Once the SPO site has been closed through gradual compression, it is important to ensure that the neural elements are free and not compressed.

SPO is typically performed in the thoracic spine for sagittal imbalance that requires <30 degrees of correction. Multiple SPO's can usually achieve the desired amount of lordosis, and, in some cases, can be extended to the lumbar spine. The advantages of using SPO are that it can be performed relatively easily and rapidly with less blood loss than the other osteotomies described below, that it does not necessitate neural element manipulation, and that it can be performed safely at the cord, conus, or caudal levels. However, if there is a concomitant coronal curve, one study showed that multiple SPO's...
may exacerbate the concavity of that coronal curve\textsuperscript{106}.

Specific to SPO are complications such as intraspinal hematoma, intestinal obstruction, and superior mesenteric artery syndrome\textsuperscript{121,125,152,161}. The most frequent complications following SPO, however, are superficial wound infections and substantial coronal imbalance of >4 cm when three or more SPO’s had been performed\textsuperscript{106}.

**Pedicle Subtraction Osteotomy (Posterior Three-Column Wedge Resection)**

In 1985, Thomasen first described pedicle subtraction osteotomy (PSO) for the management of fixed sagittal plane deformities in patients with ankylosing spondylitis\textsuperscript{147}. PSO is typically performed at either L2 or L3, as these vertebrae are the normal apex of lumbar lordosis, and as it is also safer to perform the osteotomy below the conus medullaris\textsuperscript{153}. The technique involves a transpedicular vertebral wedge resection extending from the posterior elements through the pedicles and into the anterior cortex of the vertebral body. The length of the anterior vertebral cortex remains unchanged when the middle and posterior column bony defects are closed. Further, a substantial surface area for fusion is provided upon closure of the osteotomy. On average, PSO can achieve 30 to 40 degrees of lordotic correction at each level\textsuperscript{19}.

Unlike SPO, PSO is mainly useful for deformities with an apex in the lumbar spine. An ideal candidate for this procedure typically has a positive sagittal imbalance >12 cm\textsuperscript{14,17,19,30}. PSO is also indicated for patients who have had a circumferential fusion along multiple vertebrae, which prevents the performance of SPO. The main advantages of PSO are that it can produce substantial correction at a single level, that there is often successful fusion due to the three-column bony contact, and that it does not require a supplemental anterior approach\textsuperscript{27}. According to one study, 39% of patients treated with PSO required a concomitant anterior arthrodesis while 87% of those who had SPO’s done underwent anterior column fusion\textsuperscript{106}. In another retrospective study comparing circumferential fusion to PSO, the authors found that PSO had a shorter operative time, less intraoperative bleeding, and more correction of the kyphosis\textsuperscript{143}.

Major complications of PSO include neurologic deficits, deep wound infection, pulmonary embolus, pneumonia, and myocardial infarction\textsuperscript{15}. Increasing age was a significant predictor of a complication. The prevalence of intraoperative and postoperative neurologic deficits was 11.1% and the prevalence of permanent deficits was 2.8% in a study of 108 patients\textsuperscript{49}. In another study, 15% of patients experienced a transient neurologic deficit following PSO\textsuperscript{58}.

**Vertebral Column Resection**

Vertebral column resection (VCR) has been described for the treatment of spinal column tumors, spondylolisthesis, congenital kyphosis, and hemivertebrae excision\textsuperscript{27}. VCR is a resection of one or more vertebral segments, including the posterior elements (spinous process and lamina), pedicles, vertebral body, and discs cephalic and caudal to the vertebral body and is only reserved for cases in which either SPO or PSO will not adequately correct the deformity. VCR can be performed either through a combined anterior and posterior or posterior only approach. If VCR is performed in the thoracic spine, costotransversectomies are usually performed to facilitate removal of the vertebral body. Unlike SPO or PSO, bone-on-bone contact is not provided with VCR, and reconstruction of the spinal column with either a metal cage, structural autograft, or allograft is needed after deformity correction\textsuperscript{17}.

Patients with type-2 sagittal deformity with moderate to severe coronal imbalance requires VCR’s\textsuperscript{17}. Additional indications include congenital kyphosis, a hemivertebra, L5 spondylolisthesis, and resection of a spinal tumor. In one retrospective study, complications following VCR included complete paralysis, hematoma, hemopneumothorax, and proximal junctional kyphosis\textsuperscript{141}. In another retrospective study, 20% of patients experienced a complication (transient radicular pain, compression fractures, pseudarthrosis)\textsuperscript{142}. The investigators also reported a mean blood loss of 2,810 mL, indicating that a substantial amount of blood loss can occur in association with this procedure.

**VIDEO-ASSISTED THORACOSCOPIC (VAT) SPINAL FUSION**

Despite excellent clinical results associated with open anterior thoracotomy and spinal fusion, there still exist significant risks such the development of hyperkyphosis and a higher reported rate of pseudarthrosis and implant breakage in comparison with posterior spinal fusion\textsuperscript{7}. Other potential complications include loss of correction, a large chest wall scar, postoperative pain, and reduced postoperative pulmonary function\textsuperscript{3,77,83,121,125,152,161}. Initially developed as a minimally invasive approach for anterior release and fusion for the treatment of rigid spinal deformities, the use of video-assisted thoracoscopic surgery and instrumentation as a stand-alone treatment for adolescent idiopathic scoliosis has recently emerged as a viable alternative\textsuperscript{14}. This approach offers the advantages of an open anterior spinal fusion but with the potential for less muscle dissection, less pulmonary insult, quicker rehabilita-
tion, and improved cos- messis98,99,122). Another potential disadvantage of open anterior spinal fusion is the early, although transient, diminished upper extremity and pulmonary function, which is theoretically reduced in association with video-assisted thorascopic surgery21,125). Despite a substantial learning curve, a recent matched-pair analysis of thirty-four patients undergoing either video-assisted thorascopic surgery or posterior spinal fusion with thoracic pedicle screws for the treatment of structural scoliosis showed equivalent radiographic results, patient-based clinical outcomes, and complication rates, with the exception that posterior spinal fusion with thoracic pedicle screws may result in better major curve correction97). However, posterior based pedicle screw construct are replacing VAT or open anterior spinal instrumentation and fusion in the north America.

**CONCLUSION**

The modern era of spinal deformity surgery has flourished over the past century. It started with Hibbs’ first surgical fusion of a tuberculous spine. Harrington introduced the first internal fixation system that provided better scoliosis correction while obviating the need for prolonged immobilization. Segmental spinal instrumentation further improved the corrective power of instrumentation. However, all of these surgical endeavors to restore the natural curvature of the spine were not without associated risks and failures. The use of BMP ushered in the age of biologics to spinal surgery. Various corrective osteotomies of the spine are available to restore proper sagittal balance. Newer technologies such as video-assisted thorascopic procedures are still being perfected. Other novel techniques that attempt to perform fusionless correction of scoliosis in growing patients include growing rod constructs, vertebral stapling, and vertical expandable prosthetic titanium rib (VEPTR) instrumentation. Minimally invasive surgery that affords less intraoperative blood loss and soft tissue dissection is evolving as well.

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