Scoliosis Instrumentation Systems

33

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Contents

Abstract

Adult spinal deformity is a complex deformity that involves three-dimensional deformation in coronal, sagittal, and axial planes. Spinal and spinopelvic parameters such as SVA, pelvic tilt, pelvic incidence, and lumbar lordosis are important in understanding, characterizing, and treating adult spinal deformity. Treatment of adult spinal deformity needs to be tailored to each patient with respect to the nature of the curve and the patients' overall medical health. Operative techniques have changed substantially with time, from the early use of

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Harrington rods to modern pedicle screws. Multiple osteotomies (SPO, PSO, and VCR) can be applied for the desired level of spinal correction. Operative management of adult spinal deformity is wrought with complexity and severe complications. Newer techniques involving minimally invasive surgery and interbody fusions are being increasingly used for deformity correction. In this chapter, we will discuss such operative techniques for spinal deformity correction.

Keywords

Adult deformity · Scoliosis correction · Corrective osteotomy · Minimally invasive surgery (MIS) correction

Introduction

Adult spinal deformity (ASD) is an expansive term that covers a wide variety of conditions that involve deformation or malalignment of the adult spine. Among others, terms for various forms of deformity include scoliosis, sagittal imbalance, and spondylolisthesis (regional deformity). Normal anatomic variation does exist that can account for small regional curves of the spine. Adult spinal deformity, however, exceeds this normal anatomic variation and can possibly impair horizontal gaze or the neutral center of the spine over the pelvis and femoral heads. Impairment of horizontal gaze has a dramatic impact on the quality of an individual's life and has associated morbidity. Prevalence of adult deformity does appear to vary based on multiple factors. The overall prevalence in US adults aged 25–74 is about 8.3% with women having twice the rate as men (10.7% and 5.6%, respectively) (Carter and Haynes 1987). Furthermore, the prevalence appears to increase with advancing age. In a 2005 study by Schwab et al., they suggest prevalence rates of adult scoliosis (Cobb angles >10°) may be as high as 68% among adults 60 and older (Schwab et al. 2005). While in some cases adult spinal deformity can be asymptomatic, severe spinal deformity can present in multiple ways including back pain, hip pain, functional decline, radiculopathy, neurogenic claudication, and other neurologic symptoms.

Spinal deformity was initially simplified to deformity in the coronal plane. In particular, scoliosis was described as a lateral curvature of the spine resulting in a deformity in the coronal plane. As knowledge of deformity has grown, we have learned that deformity consists of complex three-dimensional changes that can result in changes in coronal, sagittal, and axial (rotational) planes (Stokes 1994). As understanding of the adult spinal deformity has grown, operative management has also advanced. Various corrective osteotomies can be applied for deformity correction including Smith-Petersen/Ponte osteotomy, pedicle subtraction osteotomy, and vertebral column resection. Instrumentation techniques involving wires and hooks have given way to constructs using pedicle screws and cortical screws (Fig. 1).

In this chapter we briefly discuss adult scoliosis including etiology, presentation, clinical evaluation, radiographic assessment, spinopelvic parameters, and overview on treatment. The primary focus of the chapter, however, relates to operative correction of deformity. In particular, we will discuss the corrective osteotomies that can be employed to improve spinal deformity in adult patients.

Adult Scoliosis: Definition and Etiology

Scoliosis consists of a three-dimensional deformity involving the coronal, sagittal, and axial (rotational) planes. In the sagittal planes, this can manifest as kyphotic changes impacting sagittal imbalance (Stokes 1994; Aebi 2005). The three-dimensional nature of the deformity can substantially impact the position of the head, horizontal gaze, and general positioning of the spine in relation to the pelvis.

The etiology of adult spinal deformity can be multifactorial. Some cases of ASD relate to congenital abnormalities of the vertebrae or spinal cord such as Chiari malformations or myelomeningocele (spina bifida). Neuromuscular conditions that may involve spinal deformity include cerebral palsy, Friedreich's ataxia, Charcot-Marie-Tooth, spinal muscular atrophy, muscular dystrophy, and arthrogryposis (Berven and Bradford 2002). Adult deformity can also

Fig. 1 Standing anteroposterior (AP) and lateral full-length spinal radiographs. AP radiograph demonstrates the deformity in the coronal plane as seen by the lateral curvature of thoracolumbar spine. Lateral radiograph demonstrates the sagittal deformity as seen by the positive sagittal imbalance

represent a progression of idiopathic scoliosis from childhood (infantile, juvenile, adolescent idiopathic scoliosis). Spinal deformity arising and developing in the adult population is often termed de novo or degenerative scoliosis. As the name suggests, this form of scoliosis is thought to relate to degenerative changes to spinal elements including the vertebral discs and zygapophyseal joints (Birknes et al. 2008). Other factors that can contribute to adult deformity include infection (poliomyelitis), spinal cord tumor, post-traumatic, and iatrogenic (post-surgical) (Berven and Bradford 2002; Birknes et al. 2008; Berven and Lowe 2007).

Clinical Evaluation

As with any complex condition of the spine, a complete history and physical examination is imperative. Pain is often a common presenting complaint that can vary from mild to severe and is often diffuse and ill-defined. The etiology of pain may be degenerative changes within the vertebral column (discs, facet joints), as well as paraspinal musculature (Birknes et al. 2008; Kostuik et al. 1973; Smith et al. 2009a, b). Given the imbalance of the spine over the pelvis and subsequently femoral heads, patients may also present with buttocks, hip, or leg pain. Patients may also present with symptoms of radiculopathy and/or stenosis (neurogenic claudication). Severe deformity may impair an individual’s ability to maintain horizontal gaze. Different classification schemes, such as the Scoliosis Research Society (SRS) classifcation for adult spinal deformity, have been developed to help direct evaluation and management (Lowe et al. 2006). We will look at various spinal parameters below that can help guide evaluation and management. As part of the clinical evaluation, a full neurological exam should be performed to assess for weakness as well as additional issues such as myelopathy and cauda equina syndrome.

Imaging Evaluation

Initial imaging consists of standing full-length spinal radiographs, both PA and lateral views. Many of the spinopelvic parameters that are discussed below can be assessed on these radiographs alone. The PA view allows for evaluation of coronal alignment through measurements involving the central sacral vertical line (CSVL) and Cobb's angle. Pelvic obliquity can also be assessed on the PA radiograph. If the pelvic obliquity is related to a leg length discrepancy, repeat standing radiographs with blocks under the short leg may be needed. This is important in unmasking any perceived spinal deformity that may just relate to pelvic obliquity. The lateral radiograph allows for evaluation of the sagittal balance including any variation in lordosis and kyphosis in each spinal segment. The lateral radiographs also help to assess the sacral slope, pelvic tilt, and pelvic incidence. Additionally, the chin-brow to vertical angle, the angle formed between a line connecting the patient's chin to brow and a vertical line, can be measured in this view. Increasing chin-brow to vertebral angle suggests difficulty with maintaining horizontal gaze.

CT scans can prove useful in assessing bony morphology as part of planning for corrective osteotomies or placement of instrumentation such as pedicle screws. Being a supine study, CT scans can also be used to evaluate the flexibility of the curve in the sagittal plane when compared to upright x-rays. Given that patients may present with radicular or other neurological symptoms, an MRI can provide details regarding the location and etiology of areas of compression on the spinal cord and spinal nerves. If patient cannot undergo an MRI, a CT myelogram can be considered.

Spinal and Spinopelvic Parameters

Introduced in 1948, the Cobb method provides a quantitative measure of spinal curve on the coronal plane as seen on PA radiographs (Cobb 1948). The method consists of identifying the vertebral segment at the apex of the curve and most tilted vertebral bodies cephalad and caudal to the apex. Parallel lines are drawn along the superior end plate of the cephalad vertebral body and along the inferior end plate of the caudal vertebral. Perpendicular lines are subsequently drawn to each of the previously formed lines along the end plates. The angle formed between the intersections of the perpendicular lines is the Cobb angle. Traditionally, scoliosis is defined as a Cobb angle greater than 10° (Aebi 2005). The inter-observer error using the Cobb's method is about 5% (Mehta et al. 2009). Furthermore, studies suggest that an inherent error of up to 5° exists using the Cobb's method, meaning that only a change in the Cobb's angle of 5° or more is considered a real change (Morrissy et al. 1990). The Cobb's method can also be applied to lateral radiographs as a method of quantifying lordosis and kyphosis (Fig. 2).

While the Cobb method measures degree of curvature with respect to regional curves, the central sacral vertical line (CSVL) assesses overall coronal alignment (Lenke et al. 2001; Angevine and Kaiser 2008; O'Brien et al. 2004). A vertical line is made through the center of the sacrum. A second vertical line, C7 plumb line, is made centered on the C7 vertebral body. The difference between these two lines is the CSVL. A negative

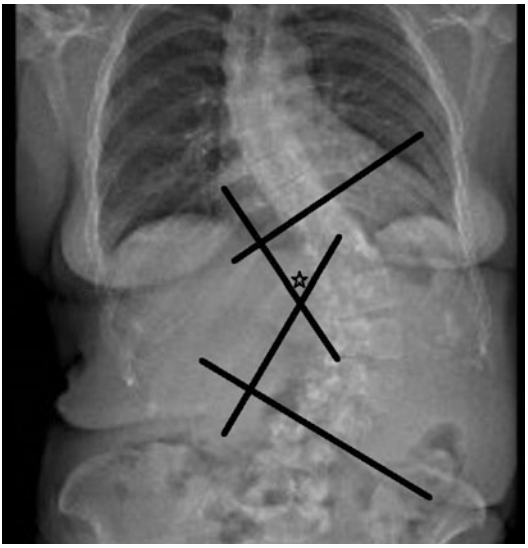

Fig. 2 Cobb's method for quantifying a curve. The star represents the Cobb's angle

value denotes that the C7 plumb line is to the left of the sacral line, while a positive value denotes that the C7 plumb line lines to the right.

The lateral radiograph provides crucial insight into the nature of the spinal deformity. Several parameters can be measured on the lateral radiographs including pelvic incidence (PI), sacral slope (SS), pelvic tilt (PT), sagittal vertical axis (SVA), and T1 pelvic angle (TPA). Pelvic incidence is the angle formed between a line perpendicular to the S1 end plate and a line between the center of the sacral end plate and the center of the femoral head (Legaye et al. 1998). Pelvic incidence also describes the sum of the sacral slope and the pelvic tilt. As a formulaic representation, $PI = SS + PT$. Sacral slope is the angle formed between a pure horizontal line and a line parallel to the sacral end plate. Pelvic tilt is the angle formed between a pure vertical line and a line between the center of the femoral head to the center of the sacral end plate. Of note, the pelvic tilt and sacral slope can change depending on position of the pelvis. Any movement leading to a change in pelvic inclination (i.e., increasing retroversion) will impact the pelvic tilt and sacral slope (Lafage et al. 2008; Boulay et al. 2006a; Jackson and McManus 1994; Schwab et al. 2009).

The sagittal vertical axis is also measured on the lateral radiograph. A vertical plumb line is drawn down from the center of C7 vertebral body. The distance between this plumb line and a point at the posterior-superior aspect of the sacral end plate is measured. A plumb line that lies anterior to the point on the posterior superior sacral end plate is denoted as a positive value. Normative values for the SVA are +2 to −2 cm; values outside of this range are considered positive or negative sagittal imbalance (Schwab et al. 2009; Boulay et al. 2006b; Roussouly and Nnadi 2010; Bernhardt and Bridwell 1989; Berthonnaud et al. 2005). The SVA, however, does not account for pelvic parameters and as such can be impacted by positioning and tilt of the pelvis. The T1 pelvic angle may provide more accurate insight into the overall sagittal alignment as it incorporates elements from the abovementioned pelvic parameters. The T1 pelvic angle is formed at the intersection of a line drawn from the T1 vertebral body to the center of the femoral head and a line drawn from the center of the femoral head to the center of the sacral end plate (Ryan et al. 2014). Lafage et al. introduced the TPA in 2014 as part of the International Spine Study Group. They proposed a goal/normative TPA of 10°, with a TPA greater than 20 representing a severe sagittal deformity (Ryan et al. 2014).

Scoliosis was initially viewed as a lateral curvature in the coronal plane; however, studies have not found a link between patient disability or perceived pain and degree of coronal deformity (Glassman et al. 2005a; Schwab et al. 2006a; Lazennec et al. 2009). Sagittal imbalance has been found to correlate with patient-reported pain and disability across several studies as measured by health-related quality of life measures (HRQOL). Sagittal imbalance as measured by pelvic tilt, TPA, T1 spinopelvic inclination, and SVA has been associated with worse scores on surveys such as the Oswestry Disability Index (ODI), SRS 23 Patient Questionnaire, and12-Item Short Form Health Survey (SF-12) (Glassman et al. 2005a, b; Schwab et al. 2006a; Lazennec et al. 2009; Lafage et al. 2009). In lieu of these HRQOL studies, Schwab et al. outlined ideal thresholds with regard to key spinopelvic parameters. They found severe disability with regard to ODI with SVA exceeding 47 mm, pelvic tilt greater than 25°, and pelvic incidence minus lumbar lordosis being above 11° (Schwab et al. 2006b, 2010, 2013).

Management

Non-operative management of adult spinal deformity is usually limited to patients with mild deformity, minimal to mild pain, little disability in daily functional activities, nonprogressive symptoms, and lack of worrisome symptoms such as those of cauda equina. Non-operative management can also be applied to poor surgical candidates who have high anesthetic risks given profound comorbidities. Non-operative management modalities include massage, aqua therapy, and physical therapy which can serve to strength the surrounding paraspinal muscles and core as a whole. Additional modalities include nonsteroidal anti-inflammatory drugs, neuropathic medications (gabapentin), and epidural steroid injections (Cummins et al. 2006). The impact of non-operative modalities in improving pain and disability, however, is controversial. In 2010, Glassman et al. presented a prospective cohort study of 123 patients. Sixty-eight patients proceeded with conservative management consisting of physical therapy, bracing, bed rest, injections, and chiropractic care. Despite a mean cost of $10,815 over the course of 2 years, no significant change was found with regard to HRQOL outcomes (Glassman et al. 2010).

Indications for operative management include worsening pain, progressive deformity, declining neurological function, and failure of non-operative interventions. The spinopelvic parameters discussed earlier can help to assess the degree of deformity. Severe disability (measured with ODI) is correlated with SVA exceeding 47 mm, pelvic tilt greater than 25°, and pelvic incidence minus lumbar lordosis being above 11° (Schwab et al. 2010, 2013). In a 2009 prospective observational cohort, Bridwell et al. followed symptomatic adult scoliosis patients for 2 years. One hundred sixty patients treated either non-operatively or operatively were followed for 2 years. The non-operative cohort had no significant change in quality of life measures such as SRS and ODI. The operative cohort, however, did experience a significant improvement across all quality of life metrics (Bridwell et al. 2009). While each case of adult spinal deformity is unique, these findings do suggest that those with severe deformity and poor QOL scores may benefit from operative intervention (Bridwell et al. 2009; Smith et al. 2009c).

Operative intervention needs to be tailored to the specifics of each adult spinal deformity patient. Factors such as clinical symptoms, age, and overall medical health can help to steer direction of management. Operative modalities can include decompression, decompression with limited instrumentation, long-segment instrumentation, and corrective osteotomies. Decompression alone has a limited but important scope. Studies have shown that decompression alone may help radicular and compressive relative symptoms but risks progression of deformity (Kelleher et al. 2010). As such, decompression alone may help to address primarily compressive or radicular symptoms in an elderly individual, who may not otherwise be a candidate for extensive instrumentation or deformity correction given osteoporosis or medical comorbidities. In the following sections, we will discuss various methods of instrumentation, decision-making regarding what levels to include, and corrective osteotomies.

Early Fixation Constructs: Harrington Instrumentation, Wires, and Hooks

A key in the early development of spinal instrumentation involved the use of Harrington rods and instrumentation technique (Drummond 1988). Initially, Harrington rods were applied with the use of facet screws. However, Harrington constructs involving the use of facet screws did not prove viable in the long term as the screws were unable to accommodate the forces needed to correct spinal deformity (Harrington 1972, 1973). Subsequently, attention was directed toward new forms of spinal fixation involving sublaminar wiring and hooks. One such wiring technique, Luque wiring, was developed in Mexico. Luque wiring consisted of sublaminar wires that were twisted around rods posteriorly (Luque 1982). Since they are sublaminar, Luque wiring does place neural structures at risk during placement (Zdeblick et al. 1991). During the development of these early constructs, however, deformity was primarily understood as a problem in the coronal plane. As such, Harrington instrumentation and these early fixation models did not take into account the importance of sagittal. In the 1970s, various publications described the loss of lumbar lordosis and the development of a “flat back” resulting from Harrington distraction techniques (Doherty 1973; Grobler et al. 1978). The resultant flat back (iatrogenic fixed sagittal imbalance) made it a challenge to maintain upright posture and a horizontal gaze. To accommodate for the flat back, patient often flexes the hips and knees while extending the mobile cervical and thoracic segments (Potter et al. 2004).

Subsequent development focused on hooks as a means of providing segmental fixation that accommodated for lumbar lordosis. Examples of hooks include pedicle, laminar, supralaminar, and transverse process hooks. While adult spinal deformity is a complex malalignment involving all three vertebral columns in multiple planes, hooks primarily rely on fixation to the posterior column. Fixation through the posterior column alone may be unable to overcome the forces associated with the underlying spinal deformity required in obtaining and maintaining a correction (Rohlmann et al. 2006; Hackenberg et al. 2002). As such, these earlier techniques often involved additional anterior releases and correction to supplement the posterior fixation.

With the advent of pedicle screws, fixation could be placed across all three columns of the vertebra making it useful in deformity correction (Chang et al. 1988). Studies comparing pedicle screws versus hooks suggested that hooks had less pullout strength compared to pedicle screws (Liljenqvist et al. 2001). Clinically, pedicle screw constructs have been shown to lead to greater improvement in Cobb angles and sagittal alignment (Hamill et al. 1996). Some reports suggest increased rates of postoperative fusion with pedicle screws (Hamill et al. 1996; Gaines 2000; West et al. 1991; Thomsen et al. 1997). Multiple studies have suggested a decreased need for postoperative immobilization and bracing with the use of pedicle screws, as well as earlier process of rehabilitation (Marchesi and Aebi 1992; Suk et al. 1994, 1995). Pedicle screw placement has become safe and efficient. In particular, use of intraoperative fluoroscopy and intraoperative computed tomography and navigation has allowed for increased precision when placing pedicle screws (Miller et al. 2016; Gelalis et al. 2012).

Proximal and Distal Extent of Instrumentation

The proximal extent of the instrumentation is referred to as the upper instrumented vertebra (UIV). Generally, the UIV segment should not be at a level of segmental rotation or translation. Additionally, the UIV should not be at the apex of the curvature. Ending at a level of junctional kyphosis should be avoided. Mardjetko suggests that the UIV should be at a level within 2 cm of the coronal vertical axis and sagittal vertical axis (Shufflebarger et al. 2006). Given that spinal deformity curves may extend from the lumbar to the thoracic spine, the proximal instrumentation may need to extend to the thoracic spine. Extension to the thoracic spine, however, does raise concerns of proximal junctional kyphosis. As such, the most kyphotic range of the thoracic spine is avoided. This leaves two options for the upper instrumented vertebra: upper thoracic (T1–T6) and lower thoracic (T9–L1) (Kim et al. 2008, 2013, 2014; McCord et al. 1992). Proximal instrumentation to the upper thoracic versus the lower thoracic in adult scoliosis patients has increased operative times and blood loss but had similar levels of proximal junctional kyphosis and revision surgeries compared to UIV to the lower thoracic levels (T9–L1) (Kim et al. 2014). Mode of proximal junctional failure in the upper thoracic UIV is often ligamentous disruption compared to lower thoracic UIV in which failure is bony. While not reaching clinical significance, the total number of complications was greater with upper thoracic group, including substantial complications such as pseudoarthrosis (Kim et al. 2014).

The distal instrumented vertebra (DIV) has evolved over the years. McCord et al. defined the lumbosacral pivot point as the “intersection of the middle osteoligamentous column in the sagittal plane and the lumbosacral intervertebral disc in the transverse plane.” They discuss concerns that DIV to sacrum is potentially less resistant to flexion moments and advocate for longer constructs distal to S1 and anterior to the pivot point (McCord et al. 1992). Constructs such as iliac bolts and S2-alar-iliac screws subsequently evolved to accommodate these principles. In a 2001 study, Lenke et al., they found a 95.1% fusion rate when using iliac screws for long fusions to the sacrum and severe spondylolisthesis (Kuklo et al. 2001). Another option is that of the S2-alar-iliac screws, which has a starting point at S2 with extended through the sacral ala into the ilium (Burns et al. 2016). Biomechanical studies suggest similar load to failure in comparing iliac screws to S2AI screws with the S2AI screws having the benefit of being lower profile and lining up with the lumbosacral screws obviating the need for offset connectors. Overall, such longer constructs can potentially better resist flexion moments with lower rates of failure compared to fixation ending at L5 or S1 (Kuklo et al. 2001; Burns et al. 2016; Kebaish 2010).

Osteotomies

In cases of rigid and severe spinal deformity, instrumented fusion alone may not fully correct the deformity, and additional correction through osteotomies of the vertebral column may be needed. Several osteotomies are available to aid in deformity correction including Ponte, Smith-Petersen osteotomy (SPO), pedicle subtraction osteotomy (PSO), and vertebral column resection. These osteotomies should be viewed as a spectrum with the more complex osteotomies built on the foundation of simpler osteotomies giving a greater correction. Choice in osteotomy depends on the amount of correction that is desired. Goals for deformity correction in the sagittal plane are an SVA under 5 cm, pelvic tilt less than 25°, and pelvic incidence minus lumbar lordosis being less than 11° (Schwab et al. 2010, 2013). In 2014, Schwab et al. created the comprehensive anatomical spinal osteotomy classification, which is a system to understand vertebral osteotomies. This system classifies the osteotomies into six categories based on increasing vertebral resection and destabilization; a graphic illustration can be seen in Fig. 3 (Schwab et al. 2015). While Schwab's classification system provides a systemic framework for understanding osteotomies, we will focus the discussion on the above classically described osteotomies.

Smith-Petersen Osteotomy

Developed in 1945, the Smith-Petersen osteotomy was initially developed to address flexion deformity in patients with ankylosed spines and rheumatoid arthritis (Smith-Petersen et al. 1945). As outlined in their original paper in 1945, the SPO involves removal of elements from the posterior column. The SPO does not extend into the vertebral body itself. The overall principle behind the SPO relies on an axis of rotation through the middle column. In effect, the removal of the posterior column and subsequent closing of the posterior void lead to elongation of the anterior column through osteoclasis of the anterior disc space and anterior longitudinal ligament.

Although the terms are often used interchangeably, Ponte osteotomies are distinguished from Smith-Petersen osteotomies in patient selection. A Ponte is performed in patients with an open disc space. Although it still results in a lengthening of the anterior column, it does not involve an osteoclasis of the anterior column. It is often used in conjunction with an interbody cage which serves as a fulcrum assisting to get angular correction with posterior compression. For the purposes of this chapter, we will refer to both these techniques as SPO. A SPO consists of a standard laminectomy and resection of the inferior articular facet of cranial level and superior articular facet of caudal level. They are usually performed at multiple consecutive levels in order to achieve a gradual correction. Classically these are performed for pathology such as Scheuermann's kyphosis (Ponte et al. 2018).

SPO technique differs slightly based on location: thoracic versus lumbar spine. Overall the concept is the same, resection of posterior elements allowing for compression and angular correction of approximately 5–10°. Anatomic differences particularly in facet orientation alter the sequence of steps depending on the location.

In the thoracic spine, the first step is using an osteotome to resect the inferior articular facet of the cranial level, exposing the cartilage of the superior articular facet. Next, the spinous process of the osteotomy level is removed, exposing the interlaminar space. The amount of resection of the lamina is based on the desired angular correction. More resection will potentially lead to more correction. Ideally, after the osteotomy is performed, the lamina which is resected and the

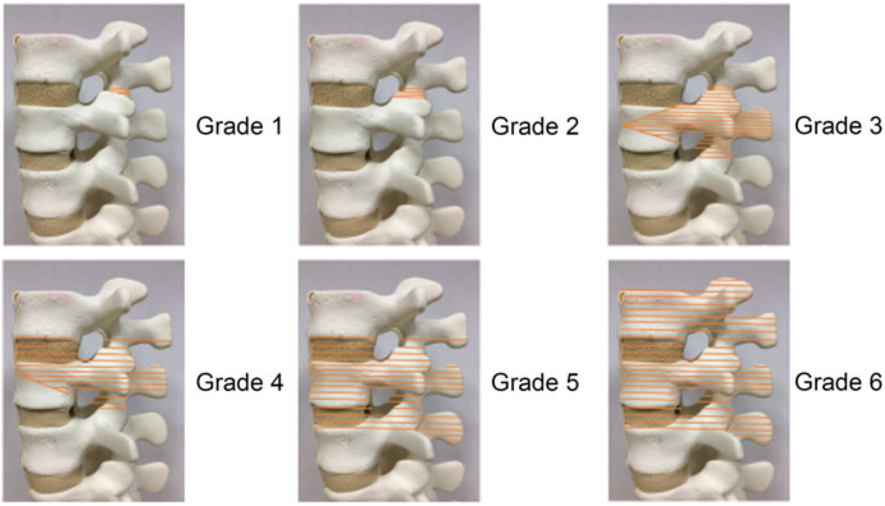

Fig. 3 Graphic illustration of Schwab et al. anatomical spinal osteotomy classification. Grade 1 involves partial resection of facet joint. Grade 2 involves complete facet joint resection. Grade 3 resects posterior elements, pedicles, and portion of vertebral body. Grade 4 resects posterior elements, pedicles, portion of vertebral body, intervertebral disc, and adjacent end plate. Grade 5 involves complete resection of vertebral segment and the adjoining intervertebral discs. Grade 6 involves complete resection of multiple vertebral segments (Schwab et al. 2015)

lamina of the caudal level should be in contact, providing a surface area for fusion. The lamina should be resected in a superiolateral direction on the midline creating a “V”-shaped bony defect. Due to the shape of the resection, these osteotomies are often referred to as chevron osteotomies. Next, the exposed ligamentum flavum is resected in the same direction exposing the spinal cord. Access to the canal can be gained through a midline defect in the ligament. After the ligament is resected, the superior articular facet of the caudal level is resected by continuing laterally with a Kerrison. Thorough excision of the ligament and superior articular facet is critical. Failure to remove these structures will lead to compression of either the spinal cord or nerve root, potentially leading to postoperative complications. If these osteotomies are performed after pedicle screws are placed, the heads of the screws may obstruct the resection of the superior articular facet. In such instances, one can either perform the osteotomy prior to placing in the screws or using a modular system where the heads are attached after the osteotomy.

In the lumbar spine, the screw heads do not interfere with the resection and therefore be inserted prior to performing the osteotomy. Additionally, due to the bony anatomy, it is not typically possible to have the resected lamina contact the caudal lamina. Therefore, a more generous laminectomy is performed. Since there is often spinal stenosis in the lumber spine which needs to be addressed as well, lamina resection at least to the origin of ligamentum flavum is recommended. Additionally, most lumbar SPOs/Ponte are performed caudal to the conus, allowing an interbody cage to be safely placed posteriorly. An appropriately placed cage can provide a pivot point to gain more angular correction. The laminectomy is performed in the usual standard fashion. Subsequently, the pars on both sides are identified and resected with a Kerrison or a drill. Our preference is to place a Woodson in the foramen, serving to protect the exiting nerve root. Subsequently, we drill away the pars in its entirety until the Woodson is visualized. The inferior articular facet is then removed as it is no longer attached to any bony or soft tissue structures. The final step is to resect the overhanging portion of the superior articular facet. Removal with a Kerrison can be challenging given overgrowth. It is our preference to use a straight osteotome and place it in line with the superior aspect of the pedicle and remove it en bloc. There is usually venous bleeding in the foramen which can be stopped with bipolar cautery. We find this technique to be safe as the exiting nerve root typically lies in the superior third of the foramen. Therefore, even in the event of plunging with the osteotome, the exiting nerve root is safe from harm. The posterior void is subsequently closed via spinal instrumentation (Schwab et al. 2015; Bridwell 2006).

Smith-Petersen/Ponte osteotomies are best for deformities that have larger radius of curvatures as opposed to sharp curves (Cho et al. 2005). Since the anterior column is elongated, they should be avoided in cases where there is less than 5 mm of intervertebral disc present. These osteotomies allow for about 10° of correction per level performed (Cho et al. 2005).

Pedicle Subtraction Osteotomy

The pedicle subtraction osteotomy requires more resection than that for an SPO/Ponte osteotomy. While the SPO only involves the posterior column, pedicle subtraction osteotomies extend into the vertebral body at the desired level of correction, and as such is a three-column osteotomy. A PSO generally creates a triangular wedge through the vertebral body with removal of the posterior column. The osteotomy has an axis of rotation at the anterior aspect of the vertebral and shortens the posterior column without elongating the anterior column. The PSO can prove useful in patients with a rigid ALL or immobile vertebral disc, where an SPO/Ponte is usually contraindicated. Furthermore, a PSO can address sharp curves and curves that exceed 25° (Cho et al. 2005; Berjano and Aebi 2015; Chen et al. 2001). A PSO can provide 25–35° of correction (Berjano and Aebi 2015; Chen et al. 2001; Bridwell et al. 2003). Figure 4 demonstrates a case involving a PSO at L3 in conjunction with Smith-Petersen osteotomies at adjacent segments resulting in significant deformity correction.

In performing a PSO, the patient is placed prone on the operating table. When possible the PSO is below the level of the conus. There is variability as to where the conus ends; as such, it is imperative to review preoperative MRI or CT myelogram in selecting the level for the PSO. A cord-level PSO is associated with a considerably higher risk of cord injury and should be avoided when possible. The more caudal the osteotomy is performed, the greater the SVA is corrected for the same angular wedge resection. However, the more caudal the PSO is performed, the fewer fixation points will exist. For the stated reasons, L2 and L3 are commonly chosen levels. Due to significant angular correction, laminectomies are usually performed above and below the PSO site in order to prevent compression of the neural elements upon closure of the osteotomy site.

Conceptually, the building blocks of a PSO are two adjacent SPO. This will isolate a pedicle of a single level and is the first step of a PSO. The amount of angular correction is based on the angle of the wedge which is excised. This correlates to the distance between the starting points of the osteotomy along the posterior vertebral body. The limiting structures are the disc space above the pedicle and exiting nerve root below the pedicle to be excised. After two adjacent SPO are performed, these structures are identified bilaterally. The exiting nerve is followed out into the foramen. Prior to performing a PSO, all screw fixation is in place. We will routinely tap the pedicle of the osteotomy level with a large tap removing all the cancellous bone thereby making pedicle resection easier. We will also tap into the vertebral body creating a trajectory for our osteotome. The residual superior articular facet is then resected with a Leksell rongeur until flush with the transverse process. The transverse process is detached from its attachment at the lateral aspect of the pedicle. It is critical that the TP is cut flush with the lateral border of the pedicle. If it is not, when dissecting the psoas off the lateral aspect of the vertebral body, the segmental vessel is at risk. Using a large curette, the lateral wall of the pedicle and vertebral body is exposed. With the pedicle now in view circumferentially, it is removed with a rongeur. Any bony prominences need to be removed as

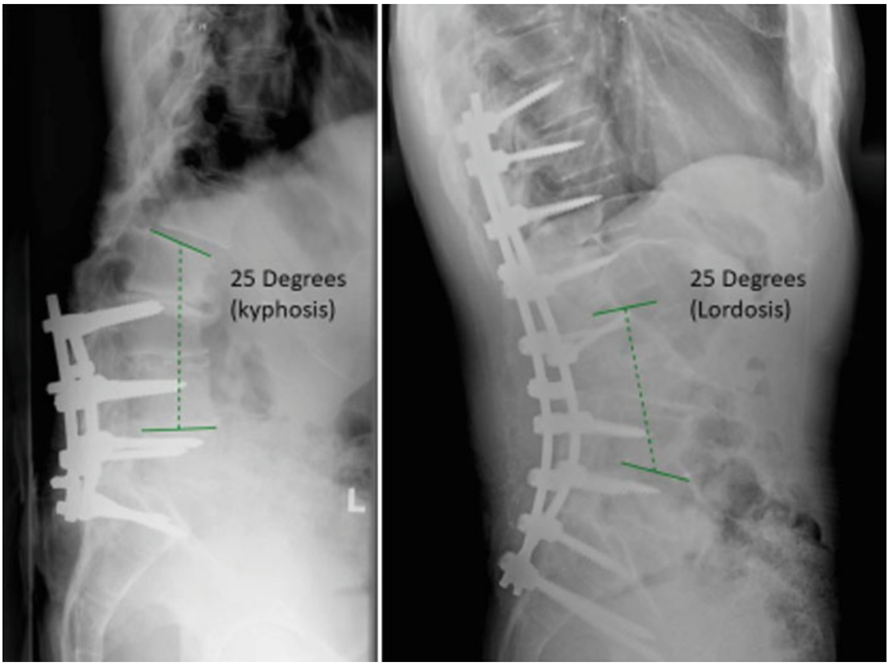

Fig. 4 A 68-year-old patient with persistent back pain status post remote L3 to S1 instrumentation and fusion. At initial evaluation, patient was found to have spinal stenosis and deformity consisting of kyphoscoliosis. Segmental Cobb angle from L2 to L4 demonstrated 25° of kyphosis. Patient underwent extension of instrumentation both proximally to T10 and distally to ilium. Additionally, a pedicle subtracting osteotomy was performed at L3 in conjunction with Smith-Petersen osteotomies at T12 to L2. Postsurgical radiographs demonstrated improvement in segmental lordosis to 25° from L2 to L4, representing an improvement in about 50°

they may cause foraminal stenosis after the osteotomy is closed. The exiting nerve root is protected with a nerve root retractor when removing the inferior wall of the pedicle. By resecting the pedicle, the two foramens have been combined making one large foramen that is housing two nerve roots. This step is performed bilaterally. A temporary stabilizing rod is now placed unilaterally, and an osteotome is used to make a wedge resection on one side. The superior cut is just caudal to the disc space above where the pedicle was, and the caudal cut is just cranial to the exiting nerve root immediately below where the pedicle was. One pass of the osteotome is directed medially and the other laterally, cutting the lateral wall of the vertebral body. The rod is moved to the opposite side, and a contralateral wedge resection is performed. The depth of the osteotome is determined by fluoroscopy or navigation. If using fluoroscopy, in the setting of a rotational deformity, the author prefers to rotate the table, so the osteotomy segment is no longer rotated. This leads to a more accurate assessment of depth of the osteotomy on fluoroscopy. After these cuts are made, a single vertical cut of the posterior vertebral body is made connecting the first two cuts. The resultant wedge is then resected and saved as autograft. Subsequently, a curette is used to remove any cancellous bone behind the remaining posterior cortex ventral to the thecal sac. A Woodson is used to develop a plane between the dura and posterior cortex. An Epstein curette or a Siefert bone tamp is used to impact the posterior wall into the defect created by removing the wedge. With the three-column osteotomy now complete, the spine should be mobile and the deformity ready to be corrected. Compression is applied on the temporary rods on either side closing the osteotomy, and wrinkling of the dura is noticed. Contact between the edges of the osteotomy marks the maximum extent of the correction obtained. If further correction is desired, the fixation is released, and further bony resection is performed. In the osteoporotic spine, if there is concern for screw loosening with compression, the patient's hips can be extended to close the osteotomy either manually or with an axis bed (Cho et al. 2005; Chen et al. 2001; Bridwell et al. 2003; Bianco et al. 2014).

If a larger correction is needed, one can perform an extended PSO. The extended PSO involves resection of the posterior aspect of the adjoining disc space and superior end plate. This creates a larger wedge and subsequently a larger correction. In order to increase the likelihood of a fusion, this procedure is often accompanied by a TLIF with the implant placed anteriorly resting on the residual superior end plate. If a patient has a multiplanar deformity, asymmetric wedges can be resected to achieve a correction in the sagittal as well as the coronal plane.

While a pedicle subtraction osteotomy allows for substantial correction of deformity, given the complex and aggressive nature of the osteotomy, it is associated with some notable complications. Several studies have reported complications rate reaching close to 50% (Bianco et al. 2014; Kelly et al. 2014). The International Spine Study Group reported 7% rate of intraoperative complications, 39% rate of postoperative complications, and 42% rate of overall complications. Additionally, they reported an average blood loss of 55% of total blood volume. Age older than 60, a thoracic three-column osteotomy, osteotomies at two or more levels, and major blood loss were all associated with increased complications (Kelly et al. 2014).

Vertebral Column Resection

Vertebral column resection builds on a PSO and allows greater segmental correction. It entails complete removal of a vertebral segment and allows for multiplanar corrections. A VCR can also prove useful in malformed vertebral segments that are not amenable to angular osteotomies such as those encountered in congenital scoliosis. Vertebral column resection was first described in the early 1980s by Bradford as method of addressing severe and rigid spinal deformity (Bradford 1987; Lenke et al. 2010).

Setup and technique for a VCR start similar to that of a PSO. Similar to a PSO, prior to proceeding with the VCR, it is imperative to establish fixation above and below the level of correction, as the VCR will lead to destabilization of the spine. The pedicle is isolated and resected as described above. Deviating from a PSO, the authors next prepare the cranial and caudal disc spaces as one would do for a TLIF. Careful attention is paid to removing all disc material and cartilage on the inferior and superior end plates from the cranial and caudal levels, respectively. This will establish margins for resection required for a VCR and to place a cage. Subsequently, similar to a PSO, the lateral aspects of the vertebral body are accessed and protected, while the vertebral body is resected. The resection can be performed with an osteotome or a drill. Similar to a PSO, the posterior wall is resected last. Subsequently, a spacer is placed where the vertebral body was. In the lumbar spine, this can be challenging as the nerve roots block complete access to the vertebrae to be resected and to the space created during cage insertion. For this reason, we use expandable cages as they can be inserted in the interval between the nerve roots, rotated, and expanded. In the thoracic spine, the nerve roots can be resected allowing for easier access to the anterior aspect of the spine without significant neurologic repercussion. While VCRs do have the potential for significant deformity correction, they are also associated with substantial complications. In 2011 study by the Scoliosis Research Society, VCRs were associated with a complication rate of 61.1%. In contrast, they found a 28.1% complication rate in SPOs and 39.1% in PSOs (Smith et al. 2011). Suk et al. in the early to mid-2000s published several retrospective studies that detailed their preferred technique for a VCR and report outcomes. In their 2002 study, 70 patients underwent a VCR; an average correction of 61.9% in the coronal and 45.2% in the sagittal planes was achieved. Twenty-four of the 70 patients (34.2%) had a complication including 2 complete injuries to the spinal cord (Suk et al. 2002). In Suk's

2005 study, they performed 16 VCRs and achieved an average SVA correction from 4.2 to 1.6 cm. They had complications in 4 of the 16 patients (25%), including 1 involving complete paralysis (Suk et al. 2005a). These studies highlight that the potential deformity correction through a VCR comes at the cost of a technically challenging procedure with high rates of severe complications (Smith et al. 2011; Suk et al. 2002, 2005a, b).

Minimally Invasive Surgery

With technological and surgical advancements, interest has grown in minimally invasive surgery as a route to operatively address spinal deformity. Minimally invasive surgery can include use of interbody fusion through anterior and extreme lateral. A systematic review by Phan et al. in 2015 regarding direct lateral and extreme lateral interbody fusions (DLIF and XLIF) showed promise in correcting coronal deformity and regional lumbar lordosis (Phan et al. 2015). A retrospective review by Anand et al. suggests that MIS deformity correction has the potential for significant deformity correction, with less blood loss and morbidity compared to open procedures (Anand et al. 2010). Figure 5 shows correction achieved with placement of lateral retroperitoneal interbody placement in conjunction with posterior osteotomies and instrumentation.

Newer studies, however, have suggested the possibility of more substantial correction with hyperlordotic cages that can help to correct the global sagittal imbalance and improve lordosis (Gödde et al. 2003; Le et al. 2012). Additionally, the anterior longitudinal ligament resection is increasingly being appreciated as a method for additional correction. In particular, selective releases of the anterior longitudinal ligament through a minimally invasive retroperitoneal transpoas (lateral) approach can help to restore lumbar lordosis while minimizing the complex dissection and resection involved in the various posterior-based osteotomies (Deukmedjian et al. 2012a). In a 2012 cadaveric study, combination of a hyperlordotic cage and ALL releases led to an increase in 11.6° of segmental lordosis (Uribe et al. 2012). In a retrospective review of

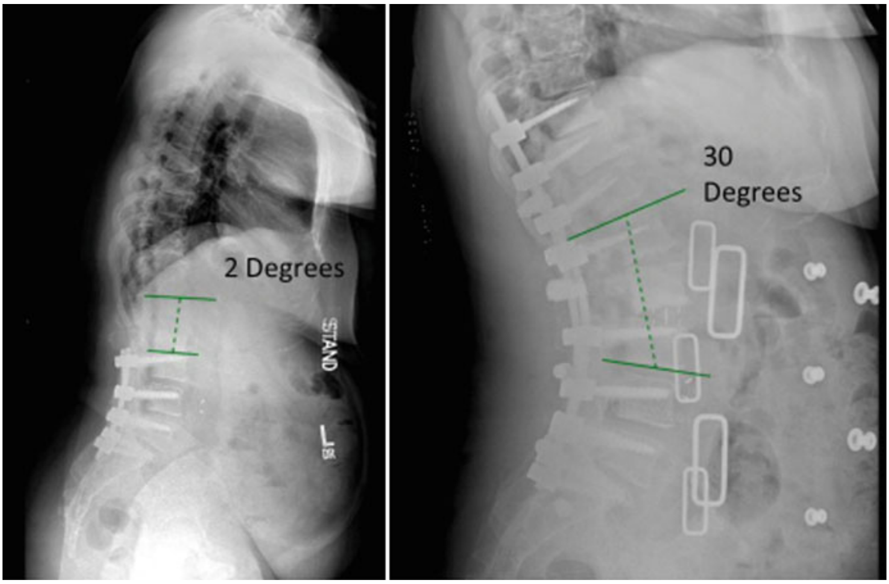

Fig. 5 A 63-year-old patient presented with global sagittal imbalance and stenosis at L2–L3. Initial radiographs on left demonstrate segmental lumbar lordosis measuring at 2° from L2 to L3. Radiographs on right demonstrate extension of fusion proximally to T10 with Smith-Petersen osteotomies at L1 and L2 with lateral retroperitoneal interbody placement at L2–L3. Segmental lumbar lordosis improved to 31°

prospectively collected data, Deukmedjian et al. assess ALL releases in patients with adult spinal deformity. In their study, they found an overall increase in lordosis of 24°, with segmental lumbar lordosis improving by 17° per level of ALL release (Deukmedjian et al. 2012b). In a cadaveric study and presentation of four clinical cases, Uribe et al. found an average increase of 10.2° per level of ALL released and 25° of overall global lumbar lordosis (Deukmedjian et al. 2012c). In a 2016 cadaveric biomechanical study by Hutton et al., they found a placement of 30° lordotic cage in addition to ALL release led to a 10.5° increase in segmental lumbar lordosis (Melikian et al. 2016). When combined with posterior facet resection and compression, one can achieve an even great degree of correction. While the individual correction values may vary in these studies, they do highlight the potential of ALL releases in deformity correction (Le et al. 2012).

Prior to performing an ALL resection, a surgeon must be comfortable performing a standard lateral interbody fusion. After prepping the disc space for the placement of an implant, soft tissue is dissected off the disc space along the anterior border of the spine. There should be a clean plane between the great vessels and the spine. If there is resistance to dissection, it is our recommendation that the ALL release should be abandoned. A retractor is then placed in front of the disc space across the anterior aspect of the spine. With a clear view of the anterior annulus and ALL, a special knife is used to cut the ALL. It is our preference to use an expanding trial to rupture any remaining fibers. We then place in a hyperlordotic implant with integrated fixation and secure it to one vertebral body in order to prevent anterior extrusion of the implant.

While MIS technology has advanced and provides a reasonable method for deformity correction in specific situations, careful patient selection and acknowledgment of MIS limitations are imperative. As in any spine case, extensive preoperative planning is critical in matching patient's diagnosis and pathology with appropriate treatment. The decision to pursue MIS, open deformity correction, or a combination of the two must match the intended degree of correction. Mummaneni et al. as part of the Minimally Invasive Section of the ISSG published an algorithm in 2014 that aimed to help in MIS and deformity decision-making (Mummaneni et al. 2014). The minimally invasive spinal deformity surgery (MISDEF) algorithm separates deformity correction into three different classes.

Class I is defined as patients with compressive symptoms relating to claudication or radiculopathy with minimal deformity. Furthermore, they use several parameters to define class I deformity: SVA less than 6 cm, PT less than 25°, LL-PI less than 10, lateral listhesis less than 6 mm, coronal Cobb angle less than 20°, and a flexible curve. They suggest that MIS techniques using decompression alone or with limited fusion are reasonable for class I deformity. Class II is defined as patients with previously mentioned compressive symptoms with a large component of back pain as well. Parameters for class II include lateral listhesis greater than 6 mm, coronal Cobb greater than 20°, and a LL-PI mismatch of 10–30°. For class II they recommend MIS surgery using decompression with multilevel interbody fusion that extends beyond just the apex of the curve (Mummaneni et al. 2014).

Class III patients are characterized by severe deformity in both coronal and sagittal imbalances. Parameters for this group include inflexible curves, SVA greater than 7 cm, LL-PI mismatch of greater than 30°, PT greater than 25°, and thoracic hyperkyphosis greater than 60. Class III patients are not readily amenable to MIS deformity correction and are better suited for traditional open deformity correction with osteotomies (as described in the previous sections). Mummaneni et al. tested the algorithm by having spine surgeons' complete surveys to classify various cases into the above classes and found MISDEF to have high intra- and interobserver reliability (Mummaneni et al. 2014).

While algorithms like the MISDEF provide a framework to understand treatment options for deformity correction, treatment must accommodate for the unique characteristics of the patient's deformity as well as the surgeon's comfort with various surgical techniques. Furthermore, MIS technology continues to advance, and patients that currently are treated with open corrective techniques may in the future be treated with MIS approaches.

Conclusions

Adult spinal deformity is complex deformity that involves three-dimensional deformation in coronal, sagittal, and axial planes. Spinal and spinopelvic parameters such as SVA, pelvic tilt, pelvic incidence, and lumbar lordosis are important in understanding, characterizing, and treating adult spinal deformity. Treatment of adult spinal deformity needs to be tailored to each patient with respect to the nature of the curve and the patients overall medical health. Operative techniques have changed substantially with time, from the early use of Harrington rods to modern pedicle screws. Multiple osteotomies (SPO, PSO, and VCR) can be applied for the desired level of spinal correction. Operative management of adult spinal deformity is wrought with complexity and severe complications. Newer techniques involving minimally invasive surgery and interbody fusions are being increasingly used for deformity correction.

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