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Degenerative Scoliosis

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Abstract

Purpose of Review The purpose of this review is to provide an updated review of adult degenerative scoliosis (ADS). Epidemiology, classification, pathophysiology, and natural history are discussed along with a summary of commonly used outcome measures. Operative vs non-operative outcomes and new surgical techniques are discussed.

Recent Findings The SRS-Schwab classification (2012) combines clinical and radiographic evaluation including overall global alignment. Current evidence regarding risk factors and efficacy of non-surgical modalities are discussed. Recent studies have reported surgical management to provide superior outcomes to non-operative modalities. New surgical techniques provide promising early data in regard to decreasing perioperative morbidity.

Summary ADS is a potentially debilitating condition that occurs with asymmetric spinal degeneration. This can produce global sagittal malalignment and central and foraminal stenosis and can lead to significant impairment often necessitating surgery. The surgeon must be aware of the perioperative risks in this population and implement appropriate age-specific alignment goals to achieve the best outcome for patients.

Keywords Adult scoliosis · Degenerative spine · Spinal stenosis · Spinal deformity

This article is part of the Topical Collection on *Treatment of Lumbar Degenerative Pathology*

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Introduction

Adult scoliosis is defined as a coronal Cobb measurement ≥ 10° in a skeletally mature patient [1]. Two common forms include adult idiopathic scoliosis (AdIS) and de novo adult degenerative scoliosis (ADS). While AdIS is the continuation of adolescent idiopathic scoliosis, ADS develops during adulthood due to a cascade of progressive degenerative changes [2].

ADS has similar gender distribution and typically begins around the age of 50 with an average age of presentation of 70.5 years [1]. Scoliosis is primarily lumbar with distal fractional curves, occasional compensatory thoracic curves, and rotation typically limited to the apex of the deformity. Lateral subluxation, or "lateralisthesis," is common and concurrent spondylolisthesis can also be present [3]. Cobb angles typically measure below 40° in ADS, compared to measurements of > 50° commonly seen in AdIS [4].

A 2005 study suggested that ADS occurs in up to 68% of asymptomatic individuals over 60 with increasing prevalence with age [5]. Operative intervention is met with the challenge of increased medical comorbidities as well as frequent osteoporosis. Patients tend to have declined baseline physical and mental health scores and decreased functional capacity, with increased baseline pain scores compared to similar patients with other pathology undergoing fusion procedures [6]. The economic burden for ADS is growing. From 2000 to 2010, there was a fourfold increase in the number of surgeries performed for adult spinal deformities in the Medicare population, an increase greater than any other spine condition. Additionally, there was nearly a 16-fold increase in Medicare charges (from $56 million in 2000 to $958 million in 2010) and a fourfold increase in the managed care population ($344 million to $1.7 billion) [7].

Classification

In 2005, Aebi presented an etiology-based classification for adult scoliosis. This included deformities caused by asymmetric degenerative changes (Type I), AdIS scoliosis (Type II), and secondary scoliosis caused by extravertebral abnormalities such as pelvic inclination or resulting from osteoporotic compression fractures (Type III) [8]. While this classification assisted in predicting the natural progression, it lacked the ability to relay specific features of individual deformities [3].

In 2006, the Scoliosis Research Society (SRS) described another classification system based on radiographic features [9]. In the same year, the initial Schwab classification was presented focusing on the relationship between radiographic and clinical evaluation [10]. It emphasized defining the apex of the curve, evaluating lumbar lordosis, and categorizing vertebral subluxation. It was the first to report that a lower apex combined with loss of lumbar lordosis resulted in poor health-related quality of life (HRQOL) scores. Finally, in 2012, the latter classifications were combined and updated as the SRS-Schwab classification [11•]. This system took into consideration the relationship between spinopelvic parameters and the global sagittal balance. They identified that patients with lumbar curves resulting in sagittal deformities generally have declined health status and greater disability than patients with thoracic or even double curves. The classification has been widely accepted and implemented due to its ability to describe the nature of the curve, and reflects its severity and correlation to health-related quality of life (HRQOL) measures (Fig. 1).

Pathophysiology and Natural History

With normal aging, the disc naturally increases protease activity and loses proteoglycan content causing decrease in osmotic pressure and, thus, decrease in fluid content. Further, it has been shown that microscopic annular tears are common after the age of 15 [12]. Disruption in the annulus has been shown to result in vascular ingrowth which supplies sensory fibers, a plausible etiology for discogenic pain [12, 13]. As nuclear cell density decreases over time, decreasing not only the structural integrity but also the potential for metabolic activities and osmotic balances are altered [14]. ADS is thought to initiate from degeneration first of the intervertebral discs followed by the posterior column [1]. In a healthy spine, the facet joints provide stability in flexion and extension and protect the disc from excessive torsion. When discs begin to degenerate, resulting in loss of height and segmental instability, increased loads are placed on the facets. It is generally accepted that degenerative changes lead to asymmetric loads on the disc and facet joints leading to progressive deformity with the potential for foraminal or central canal stenosis due to osteophytes and ligamentum buckling. Axial rotation can then ensue putting stretch on surrounding ligaments and instability and lateralisthesis can ensue. In terms of supporting structures, extensor muscles of the spine decrease in density and increase in fatty infiltration with increasing age, a process that begins in the lower segments and extends proximally with increasing age [15].

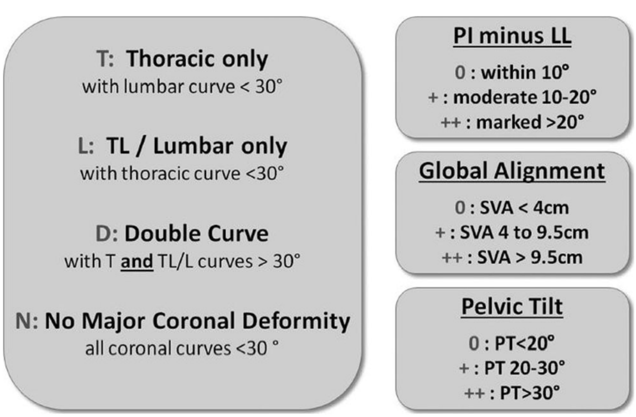


Fig. 1 The SRS-Schwab classification system. The system describes curve type with three sagittal modifiers. PI indicates pelvic incidence; LL, lumbar lordosis; PT, pelvic tilt; SVA, sagittal vertical axis. From Schwab et al. 2012 [11•]

While degenerative processes are seen in a vast majority of the population with normal aging, what varies are the mechanical, nutritional, and inherited factors that can lead to more rapid progression potentially resulting in significant pathology [16]. A recent genetic study revealed a correlation between COL2A1 polymorphism and ADS in Korean patients suggesting a genetic component [17•]. Smoking has been shown to increase catabolic activity within the annulus and nucleus pulposus resulting in the destruction of cell architecture and matrix. Likewise, obesity results not only in increased mechanical load but also in altered disc homeostasis. Leptin, which is a peptide hormone secreted by fat, increases matrix metalloproteinase activity and activates numerous cytokine pathways that ultimately result in proliferation of abnormal nucleus pulposus cells thought to be detrimental to disc integrity [13].

It was previously thought that osteoporosis played a role in the progressive deformity [3]. This theory has been refuted with evidence in recent studies that suggests that the prevalence of osteoporosis in the ADS population is similar to the normal population with no correlation between curve magnitude and degree of osteopenia [18]. Varying bone mineral density (BMD) has been shown with increased density on the concavity of the curve [19] with similar effects seen even in the femur with decreased BMD on the convex side [20].

Typical progression seen in ADS averages 3° per year (range = 1°–6°) [1]. Risk factors for progression include a Cobb angle > 30°, asymmetric disc above and below the apical vertebra, lateral subluxation of the apical vertebra > 6 mm, and L5 located above the intercrestal line [21].

Clinical Presentation

Patients typically present in the sixth decade of life and often with symptoms of spinal stenosis, reported in up to 90% of symptomatic patients [22]. Patients with neurogenic claudication typically do not report relief with a forward posture as in typical neurogenic claudication, but rather if they sit with their trunk supported by their arms [1]. Often symptoms are due to multilevel foraminal stenosis rather than central stenosis (Fig. 2). Back pain is reported by 60–80% of patients with symptomatic ADS and most commonly on the convex side of the curve. This is due to degenerative changes within the spine as well muscle fatigue as a result of spinal imbalance [3] (Fig. 3). This pain is often worsened by exertion and not relieved simply by sitting, often requiring the patient to lie down to obtain relief [23]. Symptomatic radiculopathy has been reported to occur in 47–78% of patients [24]. Foraminal stenosis is common on the concave side and is associated with facet joint hypertrophy and lateral subluxation. Pedicular kinking of the concave nerve between the disc and the pedicle can cause radiculopathy [3].

Clinical Evaluation

The goal of the initial evaluation is to determine pain generators. This requires meticulous attention to the history including onset, location and radiation of pain, and aggravating and alleviating factors [24]. Exam includes visual inspection of the spine for waist and/or rib asymmetry, pelvic obliquity, shoulder asymmetry, and for overall spinal alignment in the coronal and sagittal planes [3]. Obvious deformity should prompt evaluation of possible leg length discrepancy (LLD) or for hip and/or knee flexion contractures that might occur with longstanding compensation. Additionally, a thorough neurologic evaluation to test for strength, sensation, and reflexes can provide additional information on the underlying pathology.

In patients that present with symptoms of spinal stenosis, it is important to evaluate for tandem stenosis in the cervical spine as an association has been shown in patients with congenital lumbar stenosis on anatomic studies [25]. Additionally, studies have shown that asymptomatic thoracic stenosis is present in approximately 30% of patients undergoing lumbar decompressive surgery with the potential for significant impairment if missed [26].

Radiographic Evaluation

Obtaining the necessary imaging is crucial. Thirty-six-inch posteroanterior (PA) and lateral scoliosis radiographs from the base of the skull proximally to the femoral heads distally are a minimal requirement for evaluating patients with a spinal deformity and should, ideally, be obtained with the patient standing, free of supports to evaluate all compensatory mechanisms [27]. Radiographic measurements such as loss of lumbar lordosis, thoracolumbar kyphosis, olisthesis, and L3 and L4 end plate obliquity angles have been shown to be correlated with increased pain levels [28].

EOS imaging is a relatively new method of obtaining perpendicular, whole-body radiographs that allow improved analysis of the global sagittal alignment including the lower extremities, pelvis, spine, and head position. This has been shown to reliably provide a global 3D quantitative analysis of spinal deformities [29]. EOS provides increased image quality for nearly all structures with ×6–9 decreased radiation compared to standard thoracolumbar radiographs [30] with excellent intraobserver reliability and increased interrater reproducibility compared to standard radiographs [31].

To assess the flexibility of a curve, upright images can be compared to supine images, taking out the effect of gravity. Additional information can be obtained via traction, push-prone, or side-bending radiographs as well as images taken with a bolster under the apex of a deformity. All of these techniques provide information that can be helpful preoperatively as it relates to what intraoperative techniques might be required for deformity correction.

Coronal Evaluation

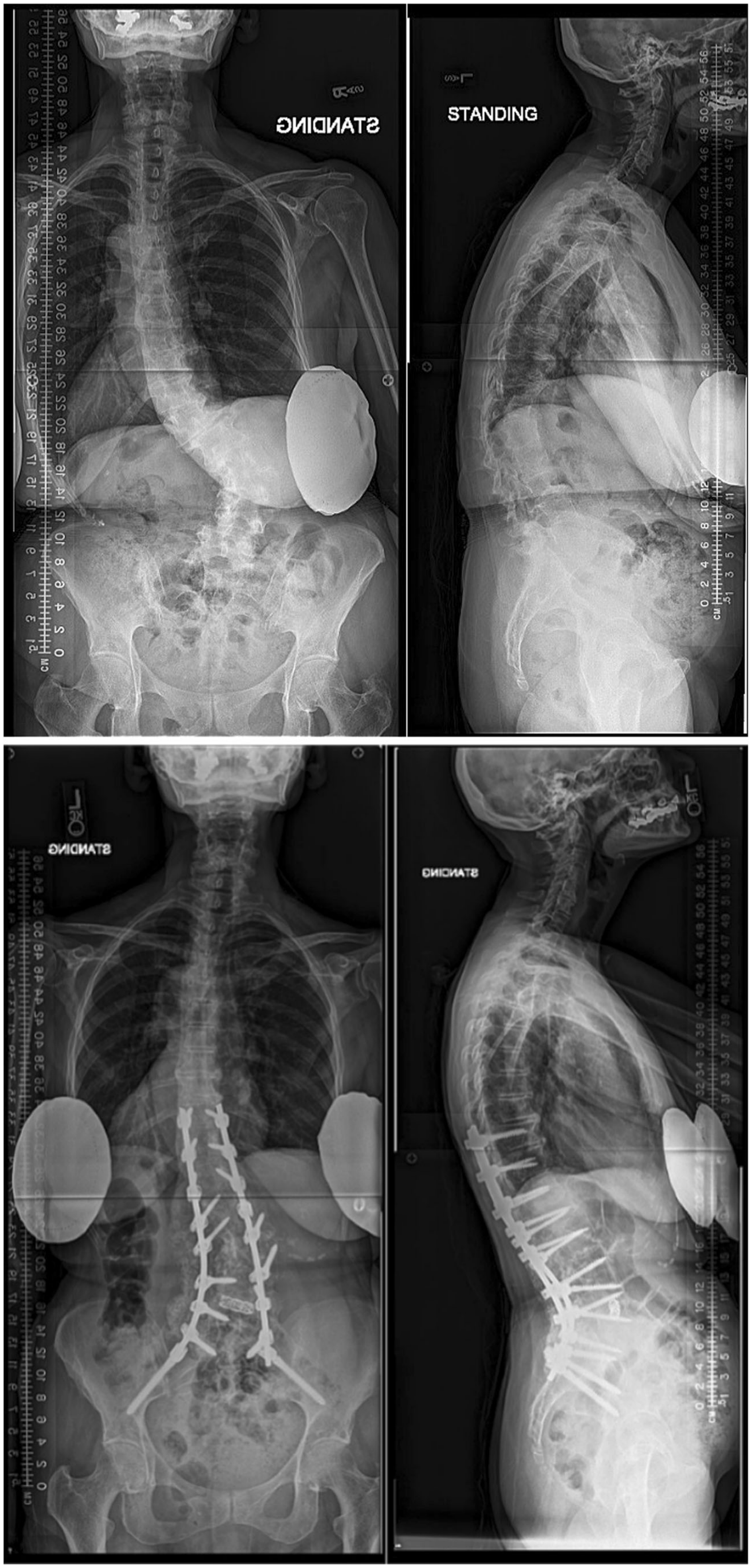
Coronal decompensation should be evaluated by measuring the horizontal distance between the C7 plumb line (C7PL, a line drawn down vertically from the center of the C7 body) and the center sacral vertical line (CSVL, a line drawn up vertically through the center of the sacrum).

Pelvic obliquity can be assessed on the PA view and, if present, should prompt evaluation for LLD with bilateral hip to ankle radiographs.

Coronal curvature should be evaluated by identifying the apex of the major curve, determining if minor curves appear structural or compensatory (at times requiring side bending films), and noting the direction of the concavity. Cobb angles of the curves are measured at the end vertebrae of the curve. The neutral and stable vertebra should be identified [27].

Sagittal Evaluation

Lateral radiographs allow for evaluation of the global sagittal alignment. The most important measurement is the sagittal vertical axis (SVA) which is the horizontal distance from the C7PL to the posterior superior corner of the S1 vertebral end plate. Additionally, regional alignment measures include thoracic kyphosis (TK; T5-T12) and lumbar lordosis (LL, superior end plate of L1 to superior end plate of S1). Important spinopelvic parameters to include are pelvic incidence (PI,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◀ **Fig. 2** Preoperative (top) and 3-year postoperative (bottom) radiographs of a 73 year old female with debilitating back pain and progressive coronal and sagittal decompensation

angle between a line perpendicular to the sacral end plate and a line drawn from the center of the femoral heads to the mid-point of the end plate), pelvic tilt (PT, angle between a line perpendicular to the sacral end plate and a vertical line extending down from the end plate), and sacral slope (SS, the angle between a line perpendicular to the sacral end plate and a horizontal line).

According to the SRS-Schwab classification, there are a number of thresholds that are predictive of disability (i.e., ODI ≥ 40). These include PT of 22°, SVA of 46 mm, and PI-LL of 11°. Accordingly, the classification system includes the sagittal modifiers identifying moderate global malalignment as PT > 20, SVA of 4–9.5 cm, or PI-LL of 10–20 and identifying severe deformities being over those values [11]. Recent data has suggested that these goals change

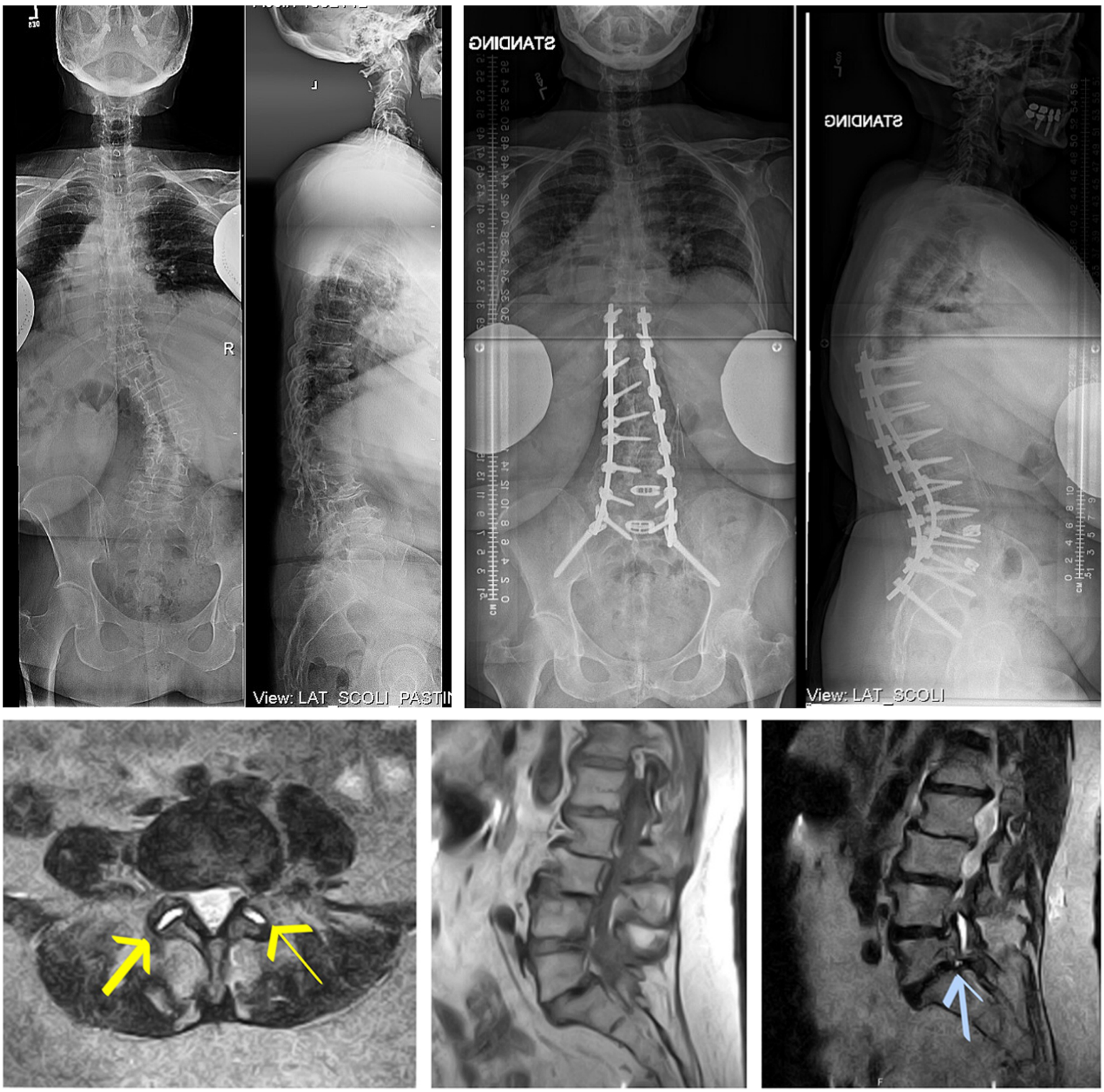

Fig. 3 **a** Preoperative (left) and 2-year postoperative (right) radiographs of a 71-year-old female who presented with debilitating right leg pain and back pain resulting in limited ambulation and decreased functional capacity for activities of daily living. **b** MRI of the same patient revealing L5-S1 right foraminal stenosis (blue arrow), L5-S1 isthmic spondylolisthesis, and L4–5 facet joint effusions (yellow arrows)

over time and that ideal spinopelvic values increased with age, ranging from PT = 10.9°, PI-LL = 10.5°, and SVA = 4.1 mm for patients under 35 years to PT = 28.5°, PILL = 16.7°, and SVA = 78.1 mm for patients over 75 years. This suggests that older patients may not need to be held to as rigorous alignment goals to obtain satisfactory functional improvement as it may be natural for elderly patients to have some degree of positive SVA and compensatory pelvic retroversion [32].

Outcome Measures

There are several outcome measures that are utilized to compare various treatments in degenerative scoliosis. Some tests measure a single variable, while others attempt to measure multiple variables such as the effect that a particular condition has on a patient's health-related quality of life (HRQOL). HRQOL is multidimensional and encompasses multiple domains such as physical, emotional, mental, and social functioning. The SF-36 is the most commonly used HRQOL measure and attempts to quantify a patient's general health status. A similar measure that was developed for patients treated for spine conditions is the SRS questionnaires which, in addition to the above domains, add components related to a patient's self-image (initially used for patients with AIS) as well as a patient's satisfaction with treatment or surgery [33]. Other instruments have been created to determine that the amount of disability is induced by a specific condition. These include the Oswestry Disability Index (ODI) and the Rowland-Morris disability questionnaire (R-M). These attempt to focus strictly on physical impairment and not on the consequences (psychological, chronic pain, etc.) of that impairment [34]. While the ODI and R-M scores have been shown to correlate, the ODI has been shown to be more sensitive in detecting change in more severe symptoms compared to minor disability. Compared to the ODI, the SRS-22 has been shown to be more sensitive to detecting changes induced by surgery and has been suggested to have a minimum clinically important difference (MCID) of 0.4 points which corresponds to a change in one interval in two of five questions in a single domain [35]. Further, thresholds for substantial clinical improvement values have been suggested as goals for improvement in regard to the SRS-22R total score and for each domain in order to improve the quality of data interpretation in the literature. The SRS-22R is the current version and has been shown to be responsive, reliable, and valid in the adult spinal deformity population. The SRS-30 consists of the SRS-22R questions with the addition of eight questions aimed at identifying postoperative perceptions of pain, appearance, and activity [36, 37].

In terms of pain, one of the most straightforward means of attempting to measure a patient's degree of pain is to ask them to quantify it on a presented scale such as the Visual Analog Scale (VAS) or the Numerical Rating Scale (NRS). An even simpler form is to ask them whether they have no pain, mild pain, some pain, a lot of pain, or their worst pain which is known as the Verbal Rating Scale (VRS). These scales attempt to measure pain intensity, while other tests (ex. SF-36 bodily pain domain) combine questions related to pain intensity and on how that pain interferes with activities [38].

Non-Operative Treatment

Currently, there is little evidence that conservative measures in ADS are effective in improving quality of life (QOL) or associated symptoms. The existing evidence for physical therapy, chiropractic intervention, or manipulation is weak and consists of level IV evidence only [39]. Some would suggest that in the absence of neurologic compromise, or in patients that are not fit for surgery, there is a benefit to increasing their physical activity via modalities such as supervised exercise programs focusing on core strengthening and postural training in order to keep the patients as active and fit as possible—if surgical intervention might be undertaken at a future time point. It has been suggested that a trial of non-operative treatment is safe and reasonable in patients with curves < 30° with < 2 mm subluxation with anterior osteophytes [1]. Additionally, patients should be evaluated for osteoporosis via BMD tests with appropriate referral for treatment if indicated.

While there is very weak evidence that bracing can provide temporary pain relief, this is generally not recommended due to significant deconditioning that can occur in a short period of time in this patient population. A recent study suggested that brace wear of > 6 h/day could slow the rate of progression of ADS from 1.47°/year prior to bracing to .24°/year with bracing. The study included 29 women with ADS with a mean age of 62 and Cobb angle of 45.3°. However, there was no mention of clinical outcomes, deconditioning, or pre/postbracing symptom severity [40].

Injections can be considered for both diagnostic and therapeutic intervention, especially in patients presenting primarily with leg pain ipsilateral to the concavity of the curve. While the current evidence for the use of injections as a treatment modality for ADS is weak [39], they are often considered beneficial for presurgical planning in determining the extent of decompression necessary. For therapeutic purposes, it has been suggested that the time delay between injections should be at least 3 weeks with a maximum number of injections ranging between three and four in a 6–12-month period [41].

Ultimately, the treating physician must have realistic expectations regarding the likelihood of long-term success with non-operative options as these can be costly and time-consuming for the patient, the provider, and for the health care system with little long-term benefit [24].

Surgical Treatment

There are numerous challenges to approaching ADS surgically. As stated earlier, surgical intervention for ADS poses a significant economic burden [7, 42]. Surgeons must be conscientious of their utilization of health care dollars and make concerted efforts to decrease unnecessary spending. Surgical intervention in this population poses unique challenges and is technically demanding which has impacts on clinical outcome. For example, it has been shown that outcomes in surgery for spinal stenosis are worse in patients with concurrent ADS [43], particularly in patients over the age of 60 [41]. Additionally, fusion rates in ADS are lower than in cases of degenerative disc disease [23]. One of the greatest challenges relates to the high morbidity of these surgeries in a patient population with significant medical comorbidities. Recent work has been done to advance the field of minimally invasive surgery (MIS) in an attempt to decrease risks and improve outcomes.

An understanding of the risks must be balanced with knowledge that patients who undergo surgical correction for ADS have the potential for significant gains in terms of functional capacity, pain improvement, and overall QOL. In a large prospectively collected series of all patients who underwent lumbar fusion, patients with ADS had the greatest improvement in HRQOL scores behind patients with spondylolisthesis. Improvement was greater than that seen in patients with diagnoses of disc pathology, instability, stenosis, postdiscectomy revision, adjacent level degeneration, or non-union [44].

There has been a collective effort in the literature to determine how to balance obtaining the maximal benefit for patients while reducing risks and optimizing economic costs. For example, the alignment thresholds in the SRS-Schwab classification (outlined previously) have been considered by many to be the goals for achieving adequate correction in ADS. Achieving this degree of correction can require larger surgeries that include long fusion and osteotomies which can be difficult in older patients with increased perioperative risks. With the recent work to define age-appropriate alignment goals, it is becoming more apparent that elderly patients may benefit from surgical intervention in the form of a lesser correction with decreased perioperative complications [32].

Recognizing the importance of decreasing surgical morbidity in this population, Wang et al. recently published a prospective randomized study investigating the intraoperative use of a bipolar sealer device (Aquamantys; Portsmouth, NH) and found that this device significantly decreased surgical time (mean 25 min shorter), blood loss (nearly 300 cc less), and transfusion requirement (0.4 U/patient compared to 1.1 U/patient) [45].

Preoperative Considerations

A patient's general medical condition requires thorough investigation preoperatively. Surgical intervention in ADS has historically been wrought with significant complications due to length of surgery, blood loss, and prolonged recovery time amongst a population that typically has high rates of significant medical comorbidities. Complications such as cardiopulmonary insufficiency, DVT, and infection are not uncommon [3]. Additionally, other factors such as nicotine use and depression have both been shown to be related to poor clinical outcomes following major surgical intervention [24]. It is important to inquire about surgical history, particularly any history of prior spine surgeries or previous abdominal surgeries if an anterior surgery is being considered [24].

Indications for Surgery

The most commonly reported indications for operative intervention are leg pain and/or intermittent claudication [3]. Other suggested indications include L3 or L4 end plate angulations, lumbar curves > 30°–40°, and/or > 6 mm of lateral olisthesis [1]. It is important to understand that decompression alone can lead to progression of the deformity. Further, restoration of sagittal imbalance, disc height, and correction of lateral subluxation can improve symptoms and overall functional capacity. Surgery should attempt to relieve back pain, decompress affected nerves to decrease radiating pain and claudication, and correct the overall deformity [46].

Outcomes

Bridwell et al. in 2009 [47] reported on 160 patients treated for ADS (85 operative, 75 non-operative) and showed significant improvement in QOL scores and NRS back and leg pain scores in the operative group at 2 years postoperatively. This study was unique in that it included only patients with the diagnosis of ADS. Non-operative patients comparatively showed deterioration of QOL scores with no significant improvement in pain ratings seen in patients treated with observation alone, with medications, or with any combination of non-operative interventions. In terms of outcomes following an adverse event (with 36% [31/85 patients] complication rate reported), patients with major and minor complications still showed a significant improvement in all scores at 2 years with a trend toward smaller incremental improvement in patients with major complications compared to those with minor or no complications.

Recently, Smith et al. [48•] conducted a similar comparison of 286 operative and 403 non-operative adult patients with spinal deformity (including ADS). While non-operative patients showed modest improvement in SRS-22 pain and satisfaction scales at 2 years, the operative group showed significant improvement in all HRQOL scales investigated, improvements significantly better than matched non-operative cohorts on nearly every scale. However, they reported that a surprising 71.5% of patients had experienced ≥ 1 complication at 2-year follow-up—although they reported most complications did not impact long-term outcomes.

Two studies from the International Spine Study Group [49•, 50] reported on adults with scoliosis (AdIS and ADS) who presented with leg and/or back pain. Patients treated operatively had significantly lower NRS leg pain scores and improved ODI scores than baseline and significantly improved compared to the non-operative cohort at 2 years. In terms of back pain, operative patients had significant improvement despite higher baseline NRS back pain scores than the non-operative cohort. Scheer et al. [51] recently supported these findings, reporting that patients with spinal deformity treated operatively were six times and three times more likely to improve by one NRS pain severity category for back and leg pain, respectively. Importantly, 37 and 33% of operative patients had some residual leg pain at 6 weeks and 2 years, respectively. Interestingly, patients who required osteotomy for correction reported greater improvement in back pain but with an increased rate of new leg pain.

Li et al. reported on outcomes of 49 surgically managed vs 34 non-surgical-managed patients with ADS over the age of 65 [52]. Average levels fused in the operative group were 6.7. While there was no significant difference in the number of patients who reported severe disability as measured by the ODI at final follow-up (21% in non-operative and 18% in operative group), the operative group reported significantly less pain (SRS-22) and higher function/activity scores, self-image scores, HRQOL, mental health scores, and overall satisfaction with treatment with a reported complication rate of 17%.

A 2013 meta-analysis [53•] reported on 24 articles including a total of 883 ADS patients with a mean age of 64.3 years. All studies reported improvement in VAS pain ratings postoperatively. Patients with worse baseline pain scores showed the greatest benefit of treatment in terms of VAS improvement. Additionally, all studies reported improvement in ODI scores with a mean improvement in ODI of − 27 points (a 40% decrease; MCID = 20%). The studies were of relatively low quality, with heterogeneity in outcome measurements, poor description of surgical techniques, and variable baseline score reporting.

To determine which patients tend to have the best outcomes following surgery, Smith et al. [54] compared the patients with the best outcomes to matched patients with the worst outcomes following surgery for adult spinal deformity. They reported an overall minor and major complication rate of 53 and 40%, respectively. While HRQOL scores were all improved at 2-year follow-up, patients who had the worst ODI scores at 2 years were found to have more major complications and were typically patients that had worse baseline pain scores, functional scales, mental function, depression, higher sagittal alignment, and greater BMI. The findings on the SRS-22 scales were similar with the addition that patients with the worst SRS-22 scores had higher prevalence of previous spine surgery, worse PI-LL mismatch, and greater comorbidities. Greater residual deformity also correlated with worse final scores on both scales. Age and smoking status were not related to the outcomes measured by either scale.

Surgical Options

In 2010, Silva and Lenke outlined six levels of surgical intervention in ADS [1]. These include I, decompression alone; II, decompression and limited instrumented posterior spinal fusion; III, decompression with lumbar curve instrumented fusion; IV, decompression with anterior and posterior instrumented spinal fusion; V, thoracic instrumentation and fusion extension; and VI, inclusion of osteotomies.

Decompression alone (level I) is best suited for patients with primarily neurogenic complaints and small scoliotic curves (< 30°) without significant lateral subluxation (< 2 mm) [3]. These curves tend to have anterior osteophytes with relatively normal thoracic kyphosis without global imbalance. The addition of a limited fusion (level II) should be considered if a more extensive decompression is required in similar curves (< 30°), if there is mild apical subluxation of more than 2 mm or if there are no anterior osteophytes in the area of the decompression. Adjacent segment degeneration is common in these limited fusions [55].

When patients complain of back pain, fusion of the symptomatic levels has the potential for addressing the source of pain (level III). Curves > 45° with > 2 mm of subluxation are likely to fall in this category. Posterior interbody techniques can be implemented to maintain or restore both coronal and sagittal alignment in these cases. When a mild sagittal imbalance exists, or in patients at risk for pseudarthrosis with posterior-only instrumentation, the addition of anterior fusion is beneficial (level IV) but comes at the cost of added morbidity. In patients with thoracic hyperkyphosis with marked sagittal imbalance, extension of the fusion into the thoracic spine may be required (level V). Finally, significant sagittal imbalance in stiff curves requires osteotomies (level VI) to correct the global deformity. While there is no doubt that osteotomies increase operative time, blood loss, and perioperative morbidity, in patients that have significant global sagittal imbalance, the ability to correct this deformity can be the single most important prognostic factor in the surgical outcome [55].

A few general principles for selecting the extent of the fusion have been suggested.

Selection of fusion level for deformity correction:

1. Do not stop at the apex of the curve
2. Do not stop at an area of kyphosis
3. Include severe lateral subluxation
4. Include spondylolisthesis or retrolisthesis
5. Upper instrumented vertebra should ideally be horizontal

6. Iliac fixation should be strongly considered in long fusions

If extending the fusion into the lower thoracic spine, T10 is more stable than T11/12 because of true rib attachments. Patients with sagittal imbalance should be fused distally to the sacrum even without existing L5-S1 degenerative changes due to the high risk of subsequent L5-S1 degeneration [56].

Comparison of Surgical Techniques

Li et al. reported on a randomized comparison of outcomes between posterolateral fusion (PLF) and transforaminal lumbar interbody fusion (TLIF) in patients with ADS [57]. Their analysis included 37 patients (mean age 56.5) with an average of 3.2 years follow-up. With a mean of just over six levels fused in each group, the PLF group had significantly less operative time (187 vs 253 min), blood loss (1166 vs 1673 ml), and fewer early complications (11.1 vs 26.3%). While there was no difference in coronal correction, TLIF outperformed in restoring lumbar lordosis and overall sagittal balance. This may have accounted for the significantly better pain and satisfaction outcomes (SRS-22) in the TLIF group. They suggested that even with the higher perioperative morbidity, TLIF outperforms PLF in ADS but cautioned that the PLF is still a reasonable option and may be safer in high-risk patients who may not tolerated the increased morbidity.

Anterior lumbar interbody fusion (ALIF) has the advantage of anterior release, more thorough decompression, and larger graft placement which can improve sagittal correction compared to posterior interbody techniques. ALIF has been shown to be an effective surgical method for interbody graft placement in ADS with significant improvement in SF-12, ODI, and VAS scores at mean follow-up of 20 months in a recent prospective study [6]. Fusion rates and overall outcomes were not as high in ADS patients as seen in patients with degenerative disc disease or spondylolisthesis.

In an effort to decrease perioperative morbidity in these cases, a number of MIS techniques have been described with increasing literature support. Lateral lumbar interbody fusions have been gaining popularity in recent years. These techniques reportedly offer the benefit of avoiding entry into the spinal canal with the reduced risk of epidural fibrosis, development of adhesions, and a decreased risk of nerve injury. The approach can be performed in obese patients and in select patients with prior abdominal surgeries, both of which can be a relative contraindication to ALIF. Additionally, larger interbody cages can be placed for greater deformity correction, greater initial stability, less risk of subsidence, and enhanced fusion capacity. Disadvantages include difficulty in approaching the L5-S1 disc space due to the iliac crest, psoas weakness due to retraction, or muscle damage with additional risk of lumbar plexus injury. Additionally, there can be a difficult learning curve for surgeons unfamiliar with the anatomy with the potential for vessel, bowel, or ureteral injury. The FDA has approved cages for one- and two-level lateral lumbar interbody fusions with supplemental posterior instrumentation.

Phillips et al. [2] reported on a prospective, multicenter study of 107 patients with ADS who underwent lateral lumbar interbody fusion (XLIF) (mean 4.4 levels fused). Standalone XLIF was performed in 18% (20/107), with anterolateral fixation in 7% (7/107), and supplemental posterior fixation in 76% (80/107, 35% of these were unilateral posterior instrumentation). Lateral operative time averaged 57.9 min per level. Mean length of hospitalization was 3.8 days (2.9 for unstaged and 8.1 for staged procedures). At 2-year follow-up, patients reported significant improvement in ODI, VAS, and SF-36 PCS scores. Mean Cobb angles corrected from 20.9° to 13.5° immediately postoperatively and maintained at 15.2° at 2 years. Supplemental bilateral pedicle screw fixation significantly improved fusion rates (8% pseudarthrosis with all techniques at 12 months) as well as the initial and long-term correction. Importantly, the degree of Cobb correction did not correlate with clinical outcome. XLIF provided the ability to significantly increase lordosis which maintained at 2 years. The number of levels fused was the greatest predictor of complications with an overall rate of 24.3% (16% minor and 12% major). Patients with MIS supplemental fixation had decreased complications compared to open. Some degree of leg weakness was reported in 34% of patients, of which 81% of these had proximal hip flexor weakness thought to be due to psoas retraction.

Anand et al. [58] in 2013 evaluated 71 patients who had undergone either MIS posterior instrumentation, DLIF or AxiaLIF for ADS. Mean Cobb measurement improved from 24.7° to 9.5° at last follow-up. Mean sagittal and coronal balance decreased from 31.7 to 10.7 mm and from 25.5 to 11 mm, respectively. Mean lumbar apical vertebral translation of 24 mm was corrected to 11.8. Overall, 16 complications required reoperation and 4 cases of pseudarthrosis were reported.

While these studies provide some encouraging early data on the use of MIS lateral techniques, they are limited by small heterogeneous populations with outcomes compared to historical controls. Additionally, deformities were of relatively small magnitude and the diagnosis of ADS was not clearly defined [59]. Overall, these techniques are purported to offer comparable outcomes with reduced surgical morbidity compared to previous open procedures. However, there is currently a paucity of good clinical data supporting use in the ADS population.

Conclusion

ADS is a potentially debilitating spine condition due to progressive degenerative changes that result in multiaxial rotational deformity. It can result in significant pain and functional impairment and often warrants surgical intervention as conservative measures have not proven to be effective in most cases. The workup involved thorough physical exam and appropriate radiographic investigation to determine the true pain source, and surgical intervention should be aimed at addressing this source, decompressing affected nerves, fusing painful or unstable segments, and correcting deformity. The treating surgeon must balance alignment goals with risks in light of patient comorbidities and age-specific alignment goals to produce the best outcome for patients with the lowest risk possible. Newer techniques are gaining popularity that show promise in decreasing perioperative morbidity while providing adequate deformity correction. Additional well-designed, long-term studies will further help to determine the roll for these techniques in ADS.

Compliance with Ethical Standards

Conflict of Interest Philip J. York declares that he has no conflict of interest.

Han Jo Kim reports personal fees from ZimmerBiomet, K2M, and AO Spine, outside of the submitted work.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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