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Clinical Evaluation, Imaging, and Management of Adolescent Idiopathic and Adult Degenerative Scoliosis

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A B S T R A C T

We provide a comprehensive review of the clinical presentation, imaging evaluation, classification, and management of adolescent idiopathic and adult degenerative scoliosis.

Introduction

Scoliosis represents a tridimensional (3D) spinal deformity with lateral curvature of the spine (Cobb angle) greater than 10° in the coronal plane, often with an associated rotatory component.[1,2] It can occur in any age group and can be idiopathic or have an identifiable etiology (nonidiopathic).[3,4]

The 2 major types of scoliosis—adolescent idiopathic scoliosis (AIS) and adult degenerative scoliosis (ADS)—are easily distinguished from one another based on age of presentation.

Clinical Presentation

Adolescent Idiopathic Scoliosis

AIS affects adolescents and, as the name implies, is of unknown etiology.[1] The estimated prevalence of AIS ranges from 0.47% to 5.2%.[3,4] There is a female to male ratio of 1.5:1-3:1, increasing with age. Females also tend to have more severe curvature than males.[3]

AIS may present as a deformity of the back and waistline. Patients do not typically have pain or neurologic deficits. Instead, common complaints include ill-fitting shirts, leaning to one side, and rubbing of one arm with the ipsilateral pelvis.[1] Screening programs for AIS are common in North America and Europe and often lead to the initial clinical and imaging referral.

Rightward thoracic curves predominate with AIS (80% of cases).[4] Pain, atypical scoliosis curve patterns such as a left thoracic curve, short curve (4-6 segments), reduced vertebral rotation, absence of apical vertebral lordosis, and rapidly progressing curves raise concern for an underlying lesion. Note, the apical vertebra is the vertebra most laterally deviated from the patient's vertical axis. Additionally, neurologic symptoms, including radicular pain, bowel or bladder incontinence, and sensory disturbances, are rare in AIS, and should prompt an investigation for an underlying lesion.[1] The incidence of underlying neuroaxis abnormalities, including but not limited to tumors, accounting for scoliosis in patients with an initial diagnosis of AIS is reported to range from 3% to 4%.[5,6]

Adult Degenerative Scoliosis

ADS, also referred to as de novo or type I adult scoliosis, occurs in skeletally mature individuals as the sequela of asymmetric degenerative changes of the spine. In ADS, asymmetric loading on the intervertebral disks or facet joints leads to coronal and/or sagittal deformity and axial rotation, which further contributes to the asymmetric degenerative changes, and therefore to worsening deformity, in a cyclical manner. The spinal curvature can be accentuated in osteoporotic individuals with compression fracture or asymmetric vertebral body height loss.

In contrast to AIS, ADS has a relatively equal gender distribution, with typical onset after 50 years of age and average age of 70.5 years. ADS can be found in up to 68% of asymptomatic individuals over 60, and its prevalence increases with age.[7-10] ADS commonly presents with back pain. There is an association with smoking and obesity, while depression, nicotine use, and substance abuse all pose risk factors for suboptimal treatment outcome.[11]

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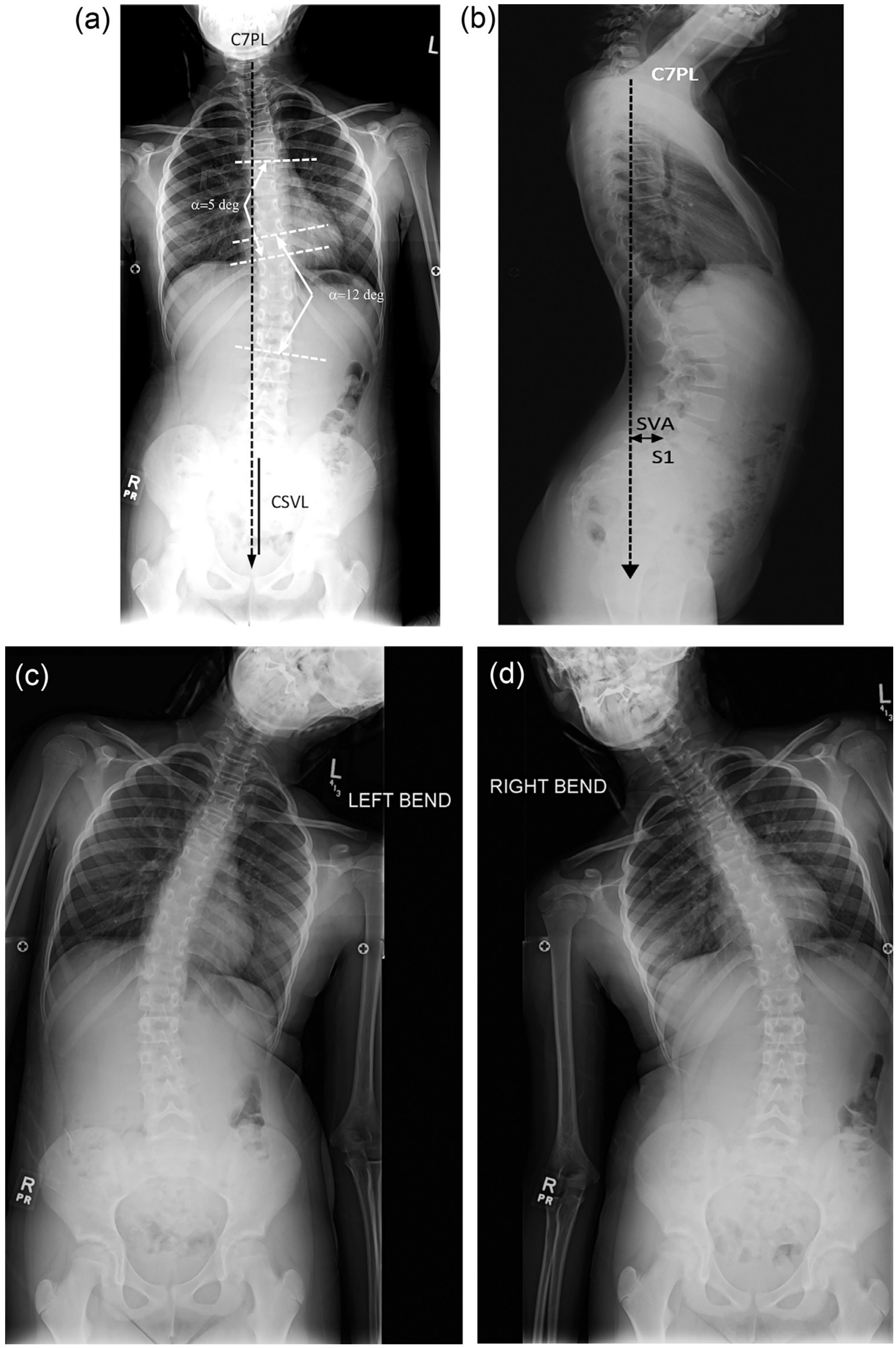

FIG 1. Radiographic evaluation of adolescent idiopathic scoliosis (AIS). Standing (a) AP and (b) lateral radiographs of the spine demonstrate S-shaped curvature with thoracic Cobb angle curvature of 5° from T6 to T10, and thoracolumbar levoscoliosis with Cobb angle of 12° from T10 to L2. In (a) the C7 plumb line (PL) falls within 2 cm of the central sacral vertical line (CSVL), consistent with coronal balance. In (b) there is exaggerated lumbar lordosis and the sagittal vertical axis (SVA) is −2.4 cm, consistent with negative sagittal imbalance. (c) Left and (d) right side-bending standing AP radiographs of the thoracolumbar spine are obtained for evaluation of structural curve. In (d) right-bending view, the curvature reverses, consistent with a nonstructural curve.

ADS typically affects the lumbar spine, with rotation limited to the apex of the deformity. Lateral listhesis (subluxation) of the vertebral bodies is more common than with AIS.[2,4,5,7,10,11] Approximately 55% of cases of ADS will have degenerative spondylolisthesis, and up to 34% have rotatory listhesis. The lumbar curvature and/or Cobb angle typically does not exceed 40° (average 28°) and progresses on average 3° per year (range 1-6°). At the time of initial presentation, prognostic factors for curve progression include degree of apical vertebral rotation, Cobb angle greater than 30°, lateral listhesis (subluxation) of at least 6 mm, and an interiliac crest line (a line joining the superior aspect of the iliac crests) crossing through the L5 vertebra as opposed to L4.[9-13]

Spinal stenosis is present in up to 90% of patients. Axial back pain is common, most often occurring on the convex side of the spinal curve, and is related to the radiographic degree of lateral listhesis (subluxation) and sagittal imbalance. Pain on the concave side of the spinal curve may be caused by radiculopathy, and is reported to occur in 47-78% of patients.[2,7,10,12]

Patients are assessed clinically in sequential supine, sitting, and standing positions, and their gait is observed.[14] The workup for ADS should include a neurologic evaluation. Neurologic deficits may prompt evaluation with MRI to exclude an underlying lesion such as tumor.

Imaging Evaluation

Radiography

Standing frontal (PA or AP), lateral, and side-bending radiographs are the standard for AIS and ADS evaluation (Figs 1-3). Standing radiographs should include the entire spine as well as the pelvis including the iliac crests. The following section reflects the most commonly acquired radiographic measurements during the evaluation of scoliosis.

Cobb Angle

The Cobb method is used to measure the degree of lateral spinal deformity. To calculate the Cobb angle from standing AP or PA radiographs, a line is drawn along the superior endplate of the cranial vertebra (vertebra with greatest inclination angle above the apex of the scoliotic curve) and the inferior endplate of the caudal vertebra (vertebra with greatest declination angle below the apex of the scoliotic curve; Figs 1a, 2a, 3c, and 4). The pattern (laterality) of a scoliotic curve is described by the apical vertebra (vertebra at the apex of the curve)—dextroscoliosis for rightward directed curves and levoscoliosis for leftward directed curves.[1,4,15] In common practice, the margin of error of Cobb angle measurement is assumed to be approximately 5° when measured manually.[16] The definition of curve progression is an increase in Cobb angle, ranging from 0 to 10° in the literature, but most commonly by 5°.[13,17] Mild scoliotic curvature can be defined as a Cobb angle between 11° and 30°, moderate as 30°-50°, and severe as greater than 50°.[18]

Structural vs Nonstructural Curves

A structural curve is relatively inflexible and usually larger in magnitude than a nonstructural curve, often measuring more than 25° (Fig 3c-e). The structural nature of the curve is determined through the acquisition of frontal sideward-bending radiographs (Fig 1c-d).[11] Sideward-bending radiographs are obtained upright with the patient leaning maximally to one side or the other. For a curve to be deemed structural, the Cobb angle remains greater than 25° on sideward-bending radiographs (Fig 3c-e). Conversely, a nonstructural curve will reduce on bending radiographs to less than 25°.[5]

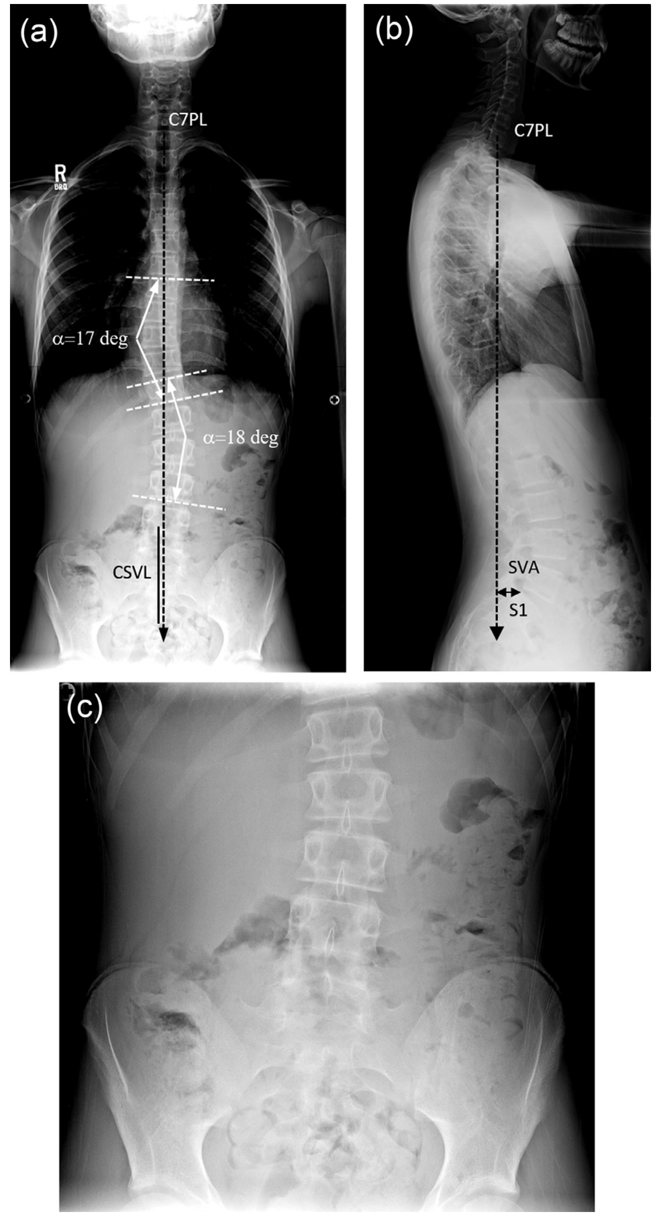

FIG 2. Radiographic evaluation of adolescent idiopathic scoliosis (AIS), with coronal and sagittal balance and Risser grading. Standing AP (a) and lateral (b) radiographs of the spine in a 15-year-old male show biphasic curvature with thoracic dextroscoliosis with Cobb angle of 17° from T8 to T12, and lumbar levoscoliosis with Cobb angle of 18° from T12 to L3. The C7 plumb line (PL) falls within 2 cm of the central sacral vertical line (CSVL), consistent with coronal balance. The sagittal vertical axis (SVA) is −1.8 cm, below threshold for negative sagittal imbalance. (c) Standing AP radiograph of the lumbar spine including the iliac bones shows bilateral iliac crest apophyses which are 50% ossified, consistent with US Risser grade 2.

Skeletal Maturity

An immature skeleton is a key risk factor for scoliosis progression and can be assessed on radiographs by the Risser classification system, which grades the ossification of the iliac crest apophysis (Fig 2c).[4] The US Risser classification, which divides the iliac apophysis into quadrants, ranges from:

- 0 (no ossification)
- I (25% ossified)
- II (50% ossified)
- III (75% ossified)
- IV (100% ossified)
- V (100% ossified and fused to the iliac crest)

The Risser classification has both high inter and intraobserver reliability.[15] During the acceleration phase of puberty, a Cobb angle that increases by 12°/y is likely to require surgical treatment, whereas fewer than one-third of patients who progress by 6°/y or less will require surgery.[19]

Global Spinal Balance

There are numerous radiographic parameters used to assess global spinal balance, which focus on the thoracic and lumbar spine, as well as the relationships of the sacrum, pelvis, and femoral heads.[20] We present the most commonly used measurements acquired clinically.

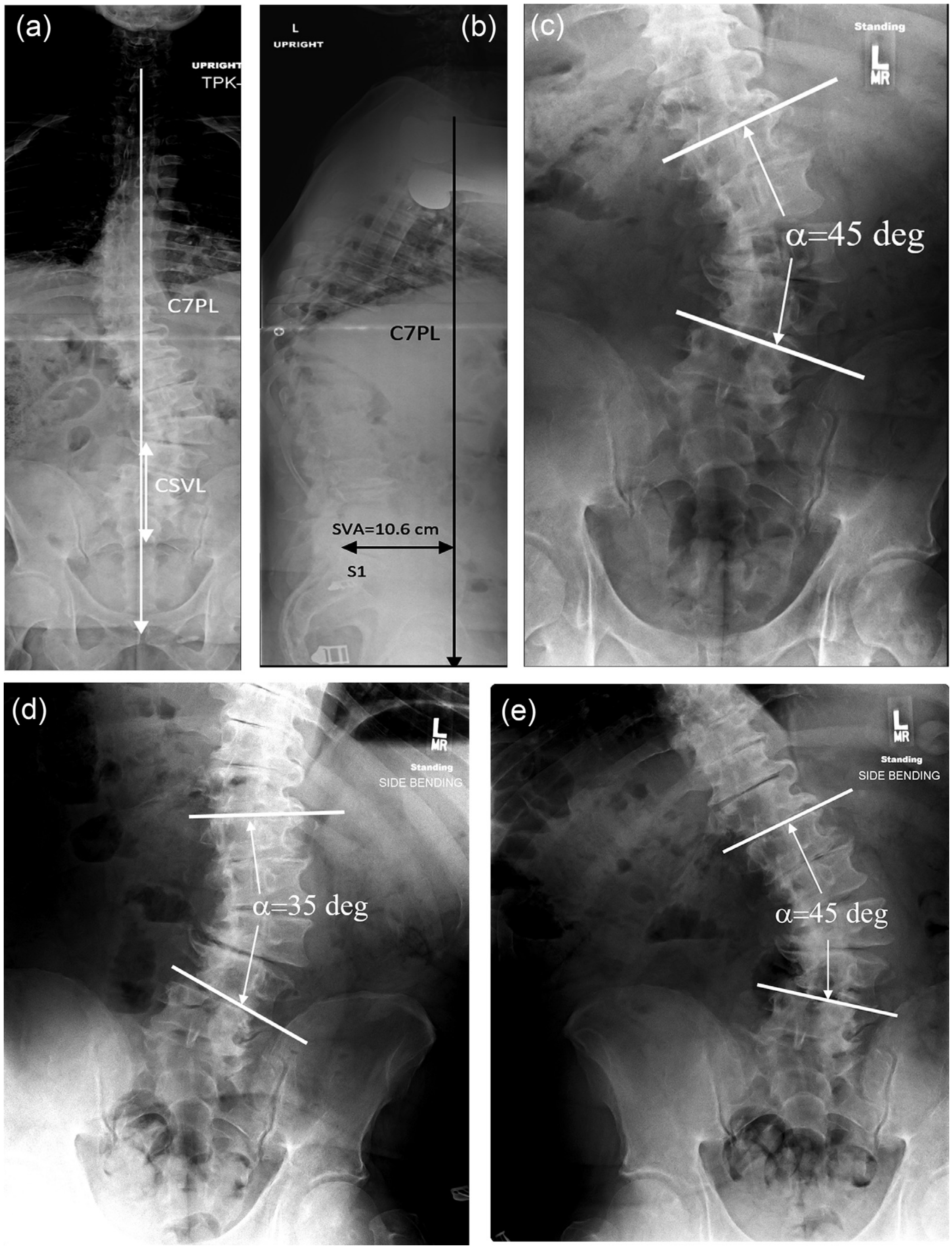

FIG 3. Radiographic evaluation of adult degenerative scoliosis (ADS) in a 54-year-old male with severe lumbar central canal stenosis and radiculopathy with bilateral lower extremity weakness. (a) Standing AP radiograph of the thoracolumbar spine demonstrates the C7 plumb line (PL) nearly aligned with the central sacral vertical line (CSVL), indicating no coronal imbalance. (b) Standing lateral radiograph of the thoracolumbar spine demonstrates sagittal vertical axis (SVA) of 10.6 cm, consistent with positive sagittal imbalance. (c) Standing AP radiograph of the lumbar spine demonstrates Cobb angle between L1 and L4 of 45°. (d) Standing left side-bending AP radiograph of the lumbar spine demonstrates decreased Cobb angle measuring 35°, consistent with a structural curve. (e) Right side-bending AP radiograph of the lumbar spine demonstrates Cobb angle measuring 45°.

Coronal Trunk Balance. The coronal trunk balance is measured on the PA or AP views as the horizontal distance between a vertical plumb line from the center of the C7 vertebral body and a vertical line through the central sacrum, or the central sacral vertical line (CSVL) (Figs 1a, 2a, 3a, and 5). Negative coronal balance indicates the C7 plumb line (C7PL) is to the left of the CSVL; a positive value indicates the vertical plumb line lies to the right of the CSVL (Fig 5).[5,15]

Pelvic Obliquity. Pelvic obliquity (Fig 6) is measured in the coronal plane as the angle formed between a horizontal reference line and a pelvic coronal reference line. The pelvic coronal reference line can be formed as the line through the superior margin of the sacral ala, the line through the superior margin of the bilateral iliac crests, or the line through the superior margin of the bilateral greater sciatic notches. Detection of pelvic obliquity should prompt lower extremity scanograms to assess for limb length discrepancy.[14]

Sagittal Vertical Axis. The sagittal vertical axis (SVA) is the horizontal distance between the C7PL (drawn vertically from the middle of the C7 vertebral body) and the posterior superior corner of S1 (Figs 1b, 2b, 3b, and 7).[14,21] Sagittal imbalance is defined as positive (Fig 3b) when the SVA is greater than 2 cm (C7PL anterior to the

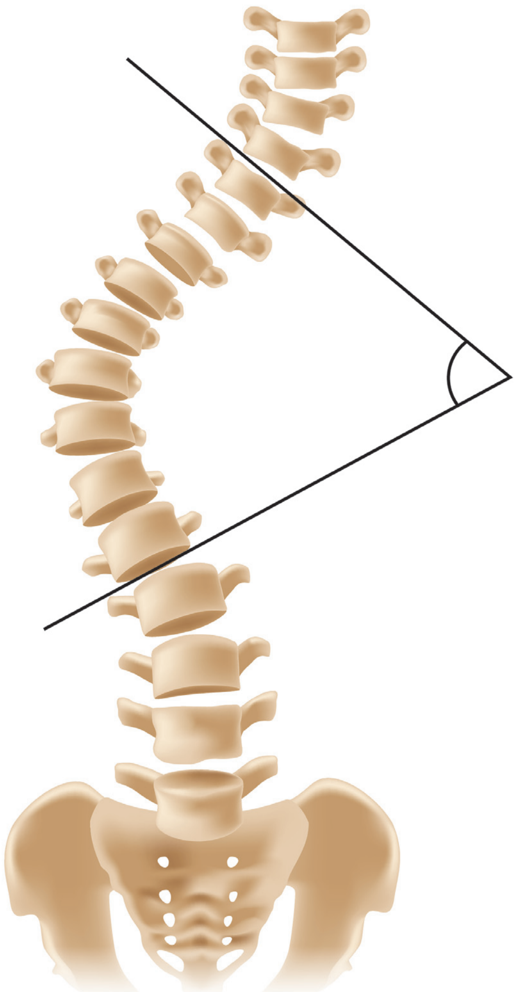

FIG 4. Artist drawing of Cobb angle measurement. Lines are drawn from the superior vertebral endplate of the vertebra with greatest inclination angle above the apex of the scoliotic curve and inferior endplate of the vertebra with greatest declination angle below the apex of the scoliotic curve.

posterior superior corner of S1) or negative (Fig 1b) when the SVA is less than −2 cm (C7PL posterior to the posterior superior corner of S1). Positive sagittal imbalance has been found to correlate with adverse scores on multiple health status measures.[22,23] Additionally, the combination of an accentuated thoracolumbar lordosis with a positive sagittal imbalance increases the likelihood of low back pain.[6,12]

Thoracic Kyphosis. Thoracic kyphosis is commonly measured as the angle between the vertebral endplates from T2 to T12 or from T5 to T12 (Fig 8) (mean 46° in adolescents, standard deviation 10°[24]; mean ranging from 28 to 39° in normal adults up to 60 years old, standard deviation up to 11°[15,25-27]; mean approximately 35° in elderly population, standard deviation up to 14°[28]), with the lines drawn tangent to the superior endplate of the upper vertebra and the inferior endplate of the lower vertebra. The thoracolumbar junction alignment is measured from the superior endplate of T10 and inferior endplate of L2 (Fig 8), while lumbar lordosis (mean approximately 58° in adolescents, standard deviation 11°[24]; 50-54° in normal adults, standard deviation up to 10°[25-27]; approximately 40° in elderly population, standard deviation up to 16°[28]) is the angle between the superior endplate of T12 and inferior endplate of S1 (Fig 9a).[14]

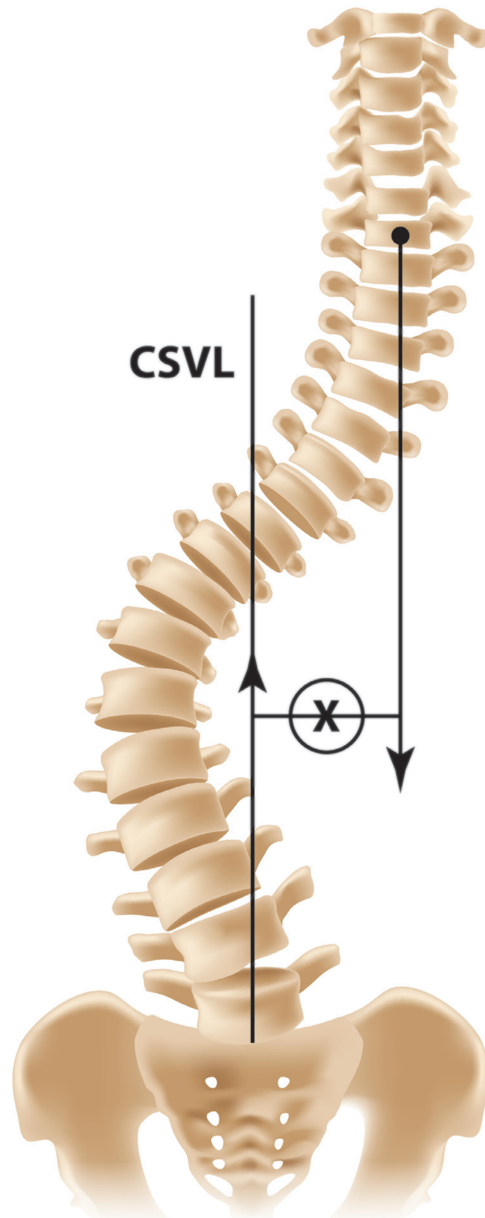

FIG 5. Artist drawing of coronal balance measurement (X). The C7 plumb line (PL) lies to the left of the central sacral vertical line (CSVL), consistent with positive coronal imbalance.

Pelvic Incidence. Pelvic incidence (PI) (Fig 9b) is a parameter that is fixed with age after skeletal maturity. On the lateral view of the pelvis, the PI is defined by the angle between a line drawn from the mid bi-femoral head axis (the imaginary line connecting the centers of the bilateral femoral heads) to the midpoint of the S1 superior endplate and a vertical line drawn perpendicular to the center of the S1 superior endplate (mean ranging from 41 to 48°, standard deviation up to 11°[24-28]).

On the lateral view, the pelvic tilt (PT) (Fig 9b), a measure of retroversion, is the angle formed between a vertical line through the mid bi-femoral head axis and a line drawn from the center of the femoral head to the midpoint of the S1 superior endplate (mean 5-13°, standard deviation up to 8°[24-27]).

On the lateral view, the sacral slope (SS) (Fig 9b) is the angle formed between a line drawn along the S1 superior endplate relative to a reference horizontal line (mean 39° in adolescents, standard

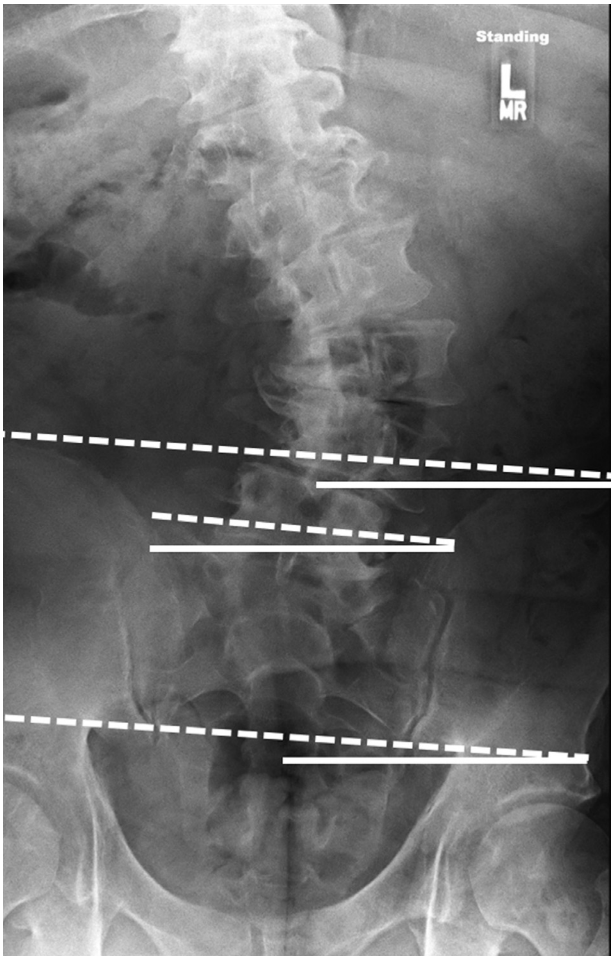

FIG 6. Radiographic assessment of pelvic obliquity. Standing AP radiograph of the lumbar spine of a 54-year-old male with ADS and mild leftward pelvic obliquity. Pelvic obliquity is measured between the horizontal reference line (solid lines) and the pelvic coronal reference line (PCRL). The PCRL can be obtained through the superior margin of the sacral ala, superior margin of the bilateral iliac crests, or through the superior margin of the bilateral greater sciatic notches (dashed lines), as shown in the figure.

deviation 7°[24]; mean 34-38° in adults, standard deviation 7°,[25-27] mean 30° in elderly, standard deviation 11°[28]).

These 3 parameters are geometrically related by the following equation, PI = PT + SS (Fig 9b).[14,21] A PI − LL mismatch (PI − LL greater than 11°, that is, hypolordosis, or a diminished lordotic curve) correlates with pelvic retroversion (PT greater than 22°) and SVA, and is associated with higher disability scores, particularly in patients who will undergo surgery.[22]

Shoulder Balance and/or Clavicle Angle

The clavicle angle is measured between a line drawn tangential to the superior aspect of the bilateral distal clavicles and the horizontal line. If the patient has a clavicle angle that is neutral or shows elevation of the right shoulder, correction of a major thoracic dextroscoliosis results in symmetric shoulder position. In contrast, elevation of the left shoulder would be exaggerated by surgical correction of a thoracic dextroscoliosis and may require surgical fusion of the proximal thoracic curve to prevent this occurrence.[5]

Vertebral Rotation

Rotation of vertebral bodies occurs with the pedicles directed toward the concave side of the curve. The Nash-Moe method, in addition to several other radiographic methods, can be used to estimate the severity of rotation on a 5-point scale by noting the position of the convex pedicle shadow with respect to 3 vertical zones of the

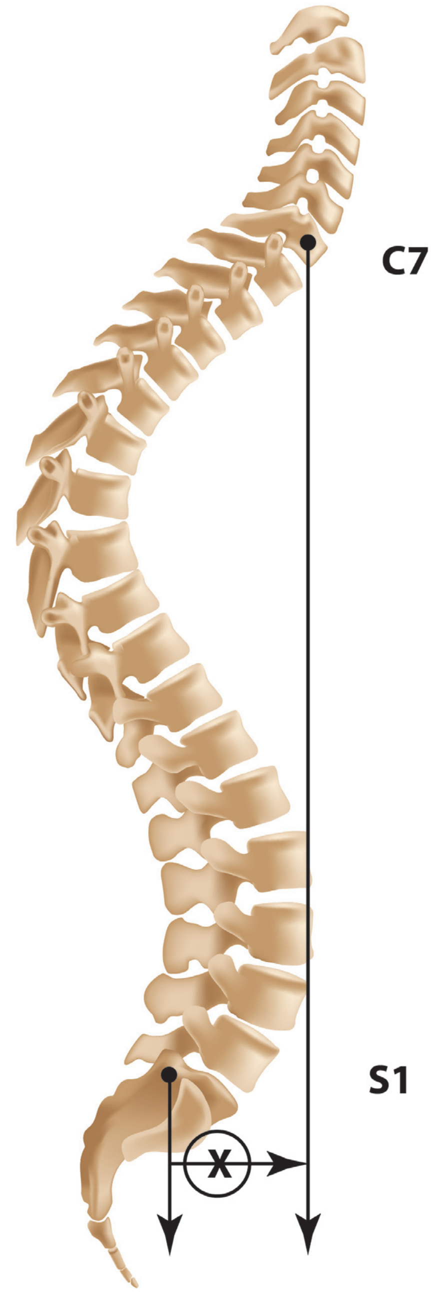

FIG 7. Artist drawing of sagittal imbalance measurement. The sagittal vertical axis (SVA) (X) is measured from the C7 plumb line (PL), a line drawn vertically from the center of the C7 vertebral body, to the posterior superior corner of S1. This case demonstrates a positive SVA, as seen with positive sagittal imbalance.

convex half of the vertebral body on a frontal radiograph (Fig 10).[6,15,29] Grades in the Nash-Moe method range from 0 (neutral, no asymmetry), 1 (+, convex pedicle migrates within the first segment and concave pedicle starts to disappear), 2 (++, convex pedicle migrates to the second segment and concave pedicle disappears), 3 (+++, convex pedicle migrates to the medial segment), to 4 (++++, convex pedicle shadow rotates past the midline of the vertebral body shadow).[29] However, estimating vertebral body rotation on a single coronal radiograph is relatively inaccurate when compared with 3-D imaging.[30]

In ADS patients, curves typically have an L2-L3 apex and have lateral listhesis (subluxation) with rotatory subluxation of the apical vertebra. Patients tend to have lumbar hypolordosis, no significant thoracic compensatory curve (a minor curve above or below a major curve), and degenerative disk disease commonly at L5-S1.[10-12]

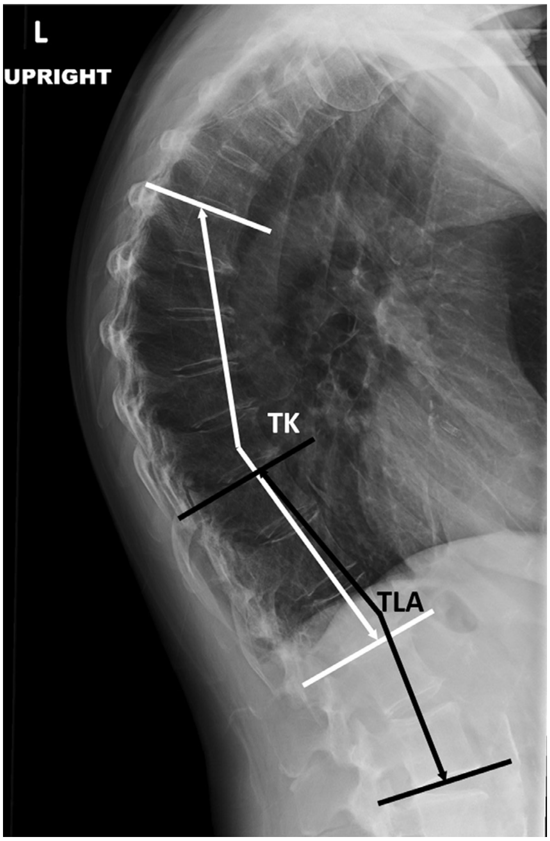

FIG 8. Radiographic assessment of thoracic kyphosis and thoracolumbar kyphosis angles in a 75-old-female with back pain. On the lateral standing radiograph, the thoracic kyphosis angle (TKA) is measured between the superior endplate of T5 and inferior endplate of T12 (white lines). Thoracolumbar junction alignment (TLA) is measured between the superior endplate of T10 and inferior endplate of L2 (black lines).

Computed Tomography (CT)

The main roles of CT are to assess for an underlying occult pathology causing a scoliosis, and for preoperative planning (Fig 11). In AIS, there are currently no clear guidelines regarding which children with scoliosis would benefit from this more expensive study with much higher dose of ionizing radiation compared to radiographs.[1,6]

Dual-Energy X-ray Absorptiometry

Low bone mineral density for age is associated with a higher risk of curve progression in AIS. The Cobb angle was found inversely related to bone mineral density in peripubertal females. However, in ADS there is no association between curve progression or severity with osteopenia.[13,31] In patients with suspected osteopenia, dual-energy x-ray absorptiometry can be obtained to determine bone mineral density.[6]

Magnetic Resonance Imaging (MRI)

MRI is often acquired in patients with ADS presenting with either radicular pain, which may be attributable to neural foraminal or far lateral root compression, or neurogenic claudication symptoms that may be related to central, foraminal, or subarticular spinal stenosis (Fig 12).[5] MRI can also be obtained when interrogating for a potential underlying lesion responsible for the scoliosis.

Reducing Radiation Dose in AIS

AIS patients are at increased risk of cancer from repeated radiographic examinations. The cancer rate in AIS patients may be 5 times higher than the age-matched population.[32] Additionally, surgically treated patients may receive 8-14 times more radiation than braced and observation patients.[33]

If possible, radiographs should be performed in right lateral and PA projections to reduce the effective radiation dose. A PA radiograph reduces both the risk of breast and thyroid cancer for scoliosis patients exposed to repeated radiographs.[34] Follow-up radiographs can be limited to the areas of interest, and the cervical spine, ribs, and lower pelvis excluded to reduce radiation exposure. Shielding of genitalia should also be performed.[6] Unless the patient has a marked thoracic hypokyphosis (less than 10°)[15] or lumbar hypolordosis, lateral views are unnecessary for each follow-up examination. If no progression in the curvature is apparent, radiographs can be limited to once a year.[6]

EOS

One method to reduce radiation dose is to use the low-dose 3D imaging system by EOS. EOS uses low-dose radiographic equipment with an ultra-sensitive multiwire proportional chamber detector to simultaneously take AP and lateral images of the whole body in a standing position, and uses this data to create 3D reconstructions of the spine. The 3D measurements from the EOS have been shown to have high intraobserver reproducibility for the Cobb angle, thoracic kyphosis, and lumbar lordosis measurement acquisition, and superior interobserver reproducibility than the 2D method.[6] The radiation dose of low-dose EOS is significantly lower than that of conventional radiography. For frontal radiographs, the radiation dose with low-dose EOS is 0.07 mGy as compared to 0.92 mGy for conventional radiography. A microdose protocol can also be utilized, where the radiation dose is even lower and is approximately 1/45th that of conventional radiographs.[35] Drawbacks of this system include its proprietary nature, added cost, and lack of widespread use.[36]

3D-ultrasound

Another potential method to reduce radiation dose in AIS is 3D-ultrasound, which can be used to determine spinal curvatures, vertebral rotation, and Risser sign.[6] However, 3D-ultrasound may have limited efficacy in cases of severe back deformity (large hump or winged scapulae) or high body mass index (> 25 kg/m^2). Ultrasound also underestimates the spinal curvature compared to radiographs in patients with a high Cobb angle.[6]

Classification Systems

AIS—Lenke Classification System

For AIS, the Lenke classification system is the most commonly used. The Lenke classification requires frontal and lateral full spine radiographs and left and right sidebending supine views. The curve type is assessed on the AP or PA view, with the largest Cobb angle designated as the major curve (Table 1). Notably, the major curve is always structural. Minor curves are defined as all other curves, and are considered structural if they exceed 25° in the coronal plane on standing frontal radiographs and do not decrease to less than 25° on bending radiographs (Table 2), or if the curve is greater than 20° in the sagittal plane. The apical vertebral location of the curve is denoted as proximal thoracic, thoracolumbar, or thoracolumbar and/or lumbar, per the Scoliosis Research Society (SRS) guidelines (Table 3). Once these parameters have been determined, a lumbar modifier is assigned based on the criteria presented in Table 4 in order to guide the surgeon as to whether a selective thoracic fusion may be performed. A sagittal thoracic modifier is also assigned, with criteria presented in Table 4, in effort to help identify patients who have

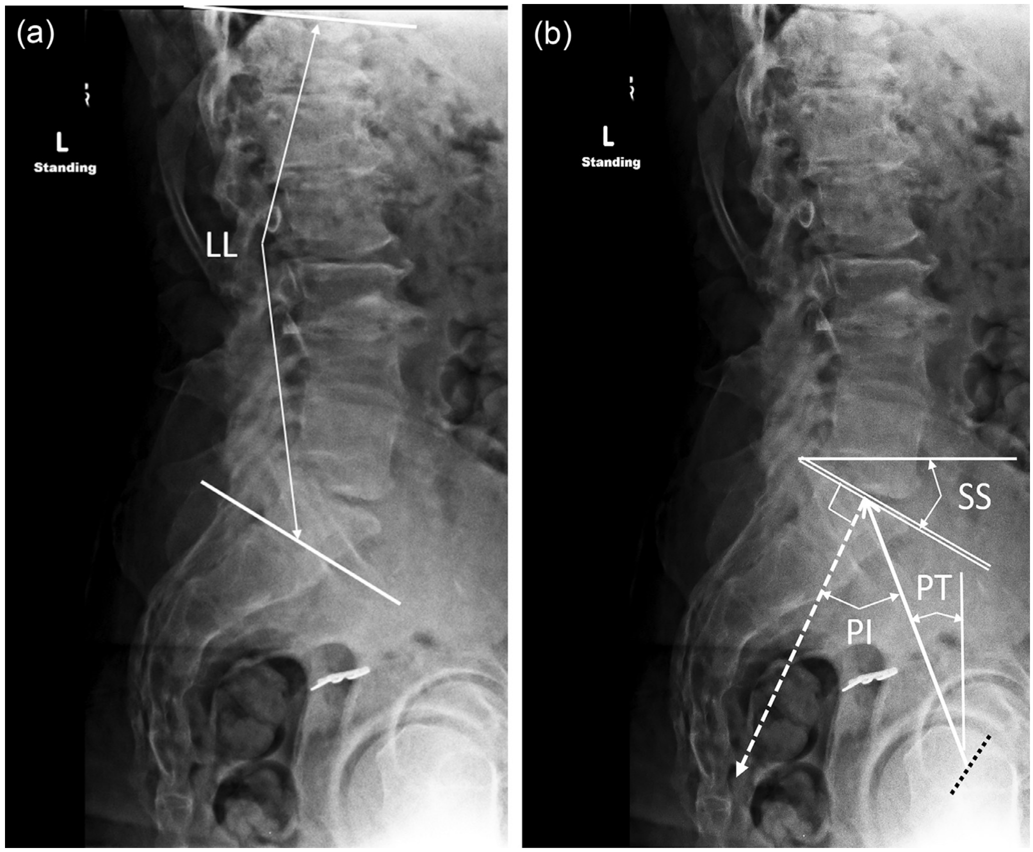

FIG 9. Radiographic assessment of lumbar lordosis (LL), pelvic incidence (PI), pelvic tilt (PT), and sacral slope (SS). (a) Lateral standing radiograph of the lumbar spine of a 54-year-old male with ADS demonstrates the LL angle of 25 degrees, measured between the superior endplate of T12 and inferior endplate of S1. (b) Lateral radiograph of the lumbar spine demonstrates a PI of 46 degrees measured between a line perpendicular to the center of the superior endplate of S1 (dashed white arrow) and a line from the mid bi-femoral head axis (black dashed line) to the center of the S1 superior endplate (solid white arrow). The SS measures 27° between the horizontal reference line and a line tangent to the S1 superior endplate (double white line). The PT measures 19° between the line connecting the mid bi-femoral head axis and the midpoint of the superior endplate of S1 (solid white arrow) and the vertical axis. These are related geometrically by PI = SS + PT. Here, PI − LL = 21°. PI − LL > 11° and positive sagittal imbalance in patients are associated with higher disability scores.

profound thoracic hypokyphosis and would benefit from restoration of thoracic kyphosis to improve their thoracic anteroposterior dimension and thus chest capacity.[1,5]

ADS—SRS-Schwab Adult Spinal Deformity Classification

The most commonly used classification for ADS is the SRS-Schwab Adult Spinal Deformity Classification. This classification is based on a multicenter, prospective, and clinical series of spinal deformity in which radiographic parameters such as Cobb angle, apical level, lumbar lordosis, and intervertebral listhesis were correlated with clinical outcome measures.[37] Patients are classified according to coronal curve type (Table 5), and sagittal pelvic modifiers (Table 6). Significant differences in health related quality of life were identified based on SRS-Schwab curve type, with thoracolumbar and primary sagittal deformities associated with greater disability and poorer health status than thoracic or double curve (2 approximate equal magnitude structural curves).[38]

Scoliosis Management

Management of AIS

AIS is a benign process without an increase in mortality.[17] Many mild scoliotic curves in AIS can be observed and followed with serial radiographs or clinical examinations at 6-month intervals until skeletal maturity. In some countries, exercise therapy is utilized. For moderate curves in a skeletally immature patient with Risser grades 0-1, bracing may be attempted. Some advocate bracing with Cobb angle 30-45° and Risser grades 2 or 3.[1,39,40]

Multiple studies have shown the efficacy of bracing in preventing curve progression in moderate AIS, including the BRAIST randomized control trial which recorded a NNT (number of patients needed to treat) of 3.[41] Two types of braces are used for treating AIS, a thoracolumbosacral orthosis, and a cervicothoracolumbosacral orthosis.[1]

Most recommend braces be worn at least 16 hours per day with bracing treatment protocols lasting anywhere from 2 to 4 years or until skeletal maturity. Standing radiographs are often taken at 6-month intervals to assess bracing efficacy.[1]

When a brace is indicated, baseline prebrace radiographs are required for future comparison. Once the brace has been fitted, additional in-brace radiographs are required to determine the frontal and lateral balance of the spine together with the degree or percentage of curve correction. An in-brace curve correction of at least 30% and up to 70% is required to achieve a lasting effect once the patient reaches skeletally maturity.[17,40] There is some evidence that early bracing can cause curve regression under select circumstances. For example, in premenarchal females with good brace compliance, an in-brace correction of at least 40% was associated with improvement in Cobb angle of 7° at skeletal maturity .[42]

There is no standard practice regarding timing of follow-up radiographs and if they are to be taken in or out of the brace. Some providers have the initial out-of-brace radiographs taken the day the patient has been fitted, whereas some advocate waiting 2-4 weeks while in brace.[43] Out-of-brace radiographs used to evaluate progress should be taken 24-48 hours out of brace.[6]

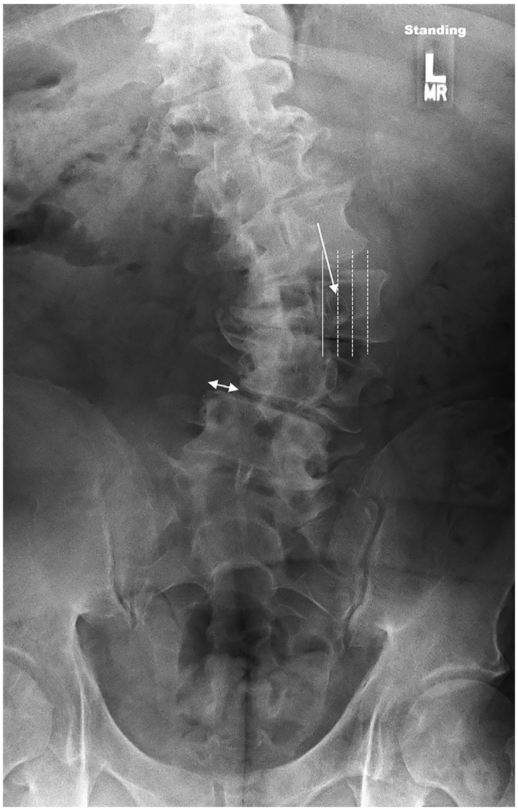

FIG 10. Radiographic assessment of lateral listhesis (subluxation) and apical vertebral body rotation using the Nash-Moe method. AP radiograph of the lumbar spine demonstrating lateral listhesis (subluxation) of L4 on L5 (double-ended arrow) of 1.5 cm. The apical vertebra, L3, is rotated. Nash-Moe divides the convex half of the vertebral body into 3 zones (denoted by vertical dashed line borders). The L3 convex-sided pedicle projection has migrated into the middle zone (arrow), but has not migrated past the midline, consistent with Nash-Moe grade 3.

Relative indications for surgery in AIS are severe curves of Cobb angle > 40-50° or rapidly progressing curves. The goals of surgery are to correct spinal balance and prevent progression through solid fusion.[1,39,44]

Pedicle screw instrumentation is considered optimal to stabilize the correction, and arthrodesis is augmented with biologics, preferably local autograft. End hooks may be used in certain cases to augment the fusion, particularly in those which require purchase in the thoracic spine. Ponte osteotomies, which resect the thoracic facet joints, lamina, and ligamentum flavum to shorten the posterior column, may be useful in certain cases with large rigid curves, however their efficacy has been questioned. The effect of concomitant thoracoplasty on rib hump, cosmesis, curve correction, and pulmonary function is unclear.[44,45]

Anterior spinal fusion is typically indicated for skeletally immature patients to arrest vertebral growth and prevent progressive rotational and angular spinal deformity after posterior spinal surgery (a.k.a. crankshaft phenomenon), reduce the number of vertebral bodies included in the fusion construct, and increase flexibility for the correction of rigid curves.[1,46]

Management of ADS

In ADS, a trial of nonoperative treatment may be acceptable in patients with curves < 30° with < 2 mm lateral listhesis (subluxation) associated with anterior osteophytes, the latter of which may contribute to spinal stability and decrease curve flexibility.[47,48] However, the actual biomechanical significance of anterior osteophytes is unresolved and is a subject of active investigation.[49] Additionally, patients should be evaluated for osteoporosis via bone mineral density tests with appropriate management if indicated.[7,12]

Spinal injections can be considered for both diagnostic and therapeutic use, especially in patients presenting primarily with leg pain ipsilateral to the concavity of the curve. The current evidence for the

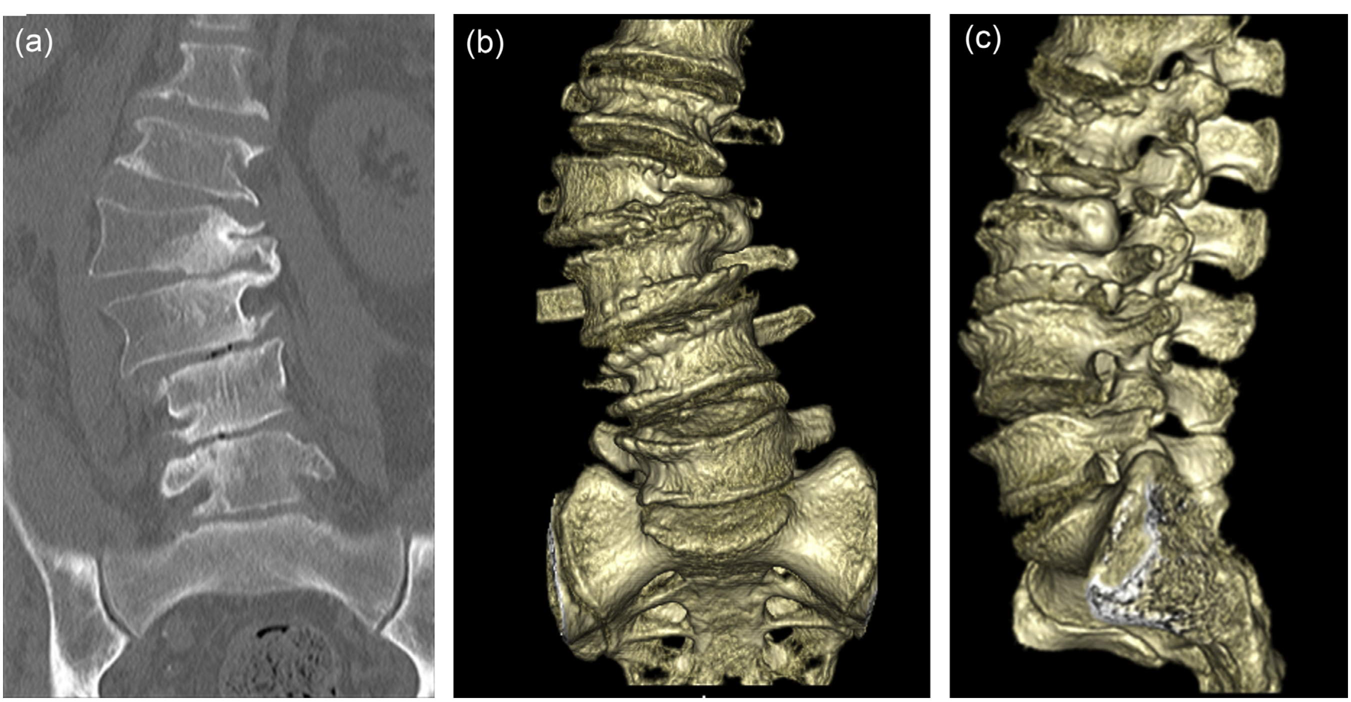

FIG 11. Computed tomography of the lumbar spine performed for preoperative assessment. (a) Coronal reformatted and (b) and (c) surface-rendered 3D-reconstruction CT images demonstrate moderate rotatory dextroscoliosis of the lumbar spine with apex at L2 with associated marked multilevel degenerative disk disease and L3 on L4 lateral listhesis (subluxation).

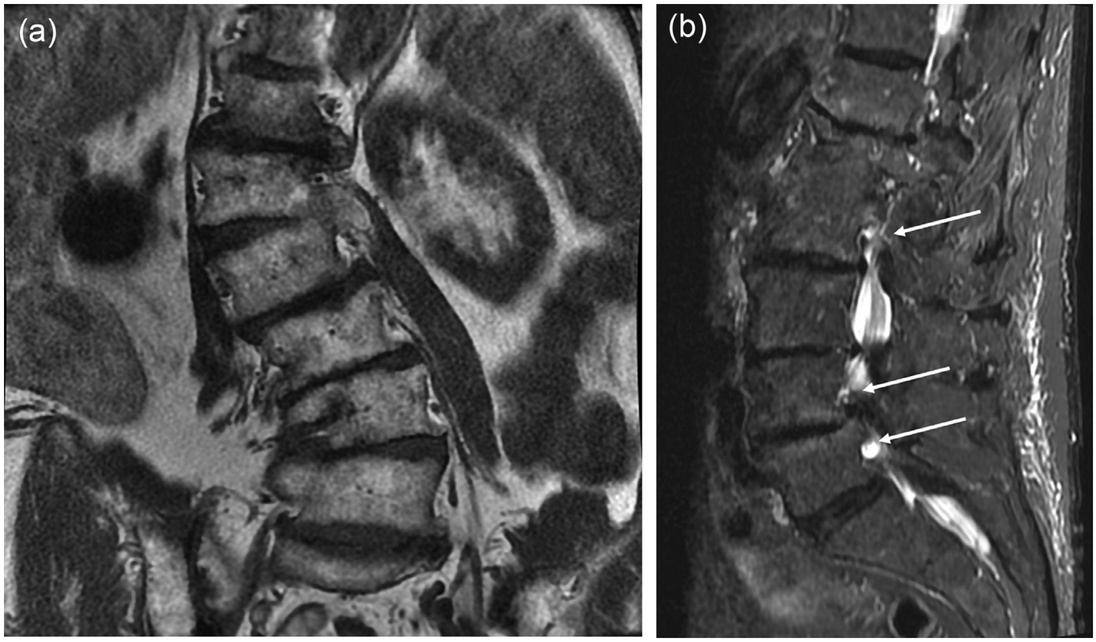

FIG 12. MRI assessment of the lumbar spine in an 87-year-old female with ADS and severe low back pain. (a) Coronal T1-weighted MR image of the lumbar spine demonstrates S-shaped scoliosis of the thoracolumbar spine with moderate levoconvex curvature of the lumbar spine and apical vertebra at L4. In (b), sagittal STIR MR image of the lumbar spine, note severe multilevel degenerative disk disease with spinal stenosis and neural foraminal narrowing at multiple levels (arrows).

TABLE 1
Lenke classification of thoracolumbar scoliosis

Curvetype				
Type	Proximal thoracic	Main thoracic	Thoracolumbar/lumbar	Description
1	Nonstructural	Structural (major)	Nonstructural	Main thoracic
2	Structural	Structural (major)	Nonstructural	Double thoracic
3	Nonstructural	Structural (major)	Structural	Double major
4	Structural	Structural (major)	Structural (major)	Triple major
5	Nonstructural	Nonstructural	Structural (major)	Thoracolumbar/lumbar
6	Nonstructural	Structural	Structural (major)	Thoracolumbar/lumbar-main thoracic

Note: The major curve is the largest Cobb measurement, and is always structural. The minor curve represents all other curves, and can be structural or nonstructural. In Type 4, the structural curve can be either main thoracic or thoracolumbar/lumbar depending on which Cobb angle is larger.

TABLE 2
Structural criteria for Lenke classification of thoracolumbar scoliosis

Structural criteria (minor curves)	
Proximal thoracic	Side bending cobb ≥ 25° T2-T5 kyphosis ≥+20°
Main thoracic	Side bending cobb ≥ 25° T10-L2 kyphosis ≥+20°
Thoracolumbar/lumbar	Side bending cobb ≥ 25° T10-L2 kyphosis ≥+20°

TABLE 3
Lenke classification of thoracolumbar scoliosis—apex location

Location of apex	
Curve	Apex
Thoracic	T2-T11/12 disk
Thoracolumbar	T12-L1
Thoracolumbar/lumbar	L1/L2 disk—L4

TABLE 4
Modifiers for Lenke classification of thoracolumbar scoliosis

Modifiers			
Lumbar spine modifier	CSVL to lumbar apex	Thoracic Sagittal Profile T5-T12	
A	CSVL between pedicles	– (hypo)	<10°
B	CSVL touches apical body	N (normal)	10°-40°
C	CSVL completely medial	+ (hyper)	>40°

CSVL = central sacral vertical line.

TABLE 5
SRS-Schwab classification of thoracolumbar scoliosis

Coronal curve types
T: thoracic only with lumbar curve <30°
L: thoracolumbar/lumbar only with thoracic curve <30°
D: double curve with at least one T and one thoracolumbar/lumbar, and with both curves >30°
N: No major coronal deformity, all coronal curves <30°

TABLE 6
Sagittal modifiers for SRS-Schwab classification of thoracolumbar scoliosis

Sagittal modifiers
Pelvic incidence (PI) minus lumbar lordosis (LL)
0: within 10°
+: moderate 10°-20°
++: marked >20°
Global alignment
0: SVA < 4 cm
+: SVA 4-9.5 cm
++: SVA > 9.5 cm
Pelvic tilt (PT)
0: PT <20°
+: PT 20-30°
++: PT>30°

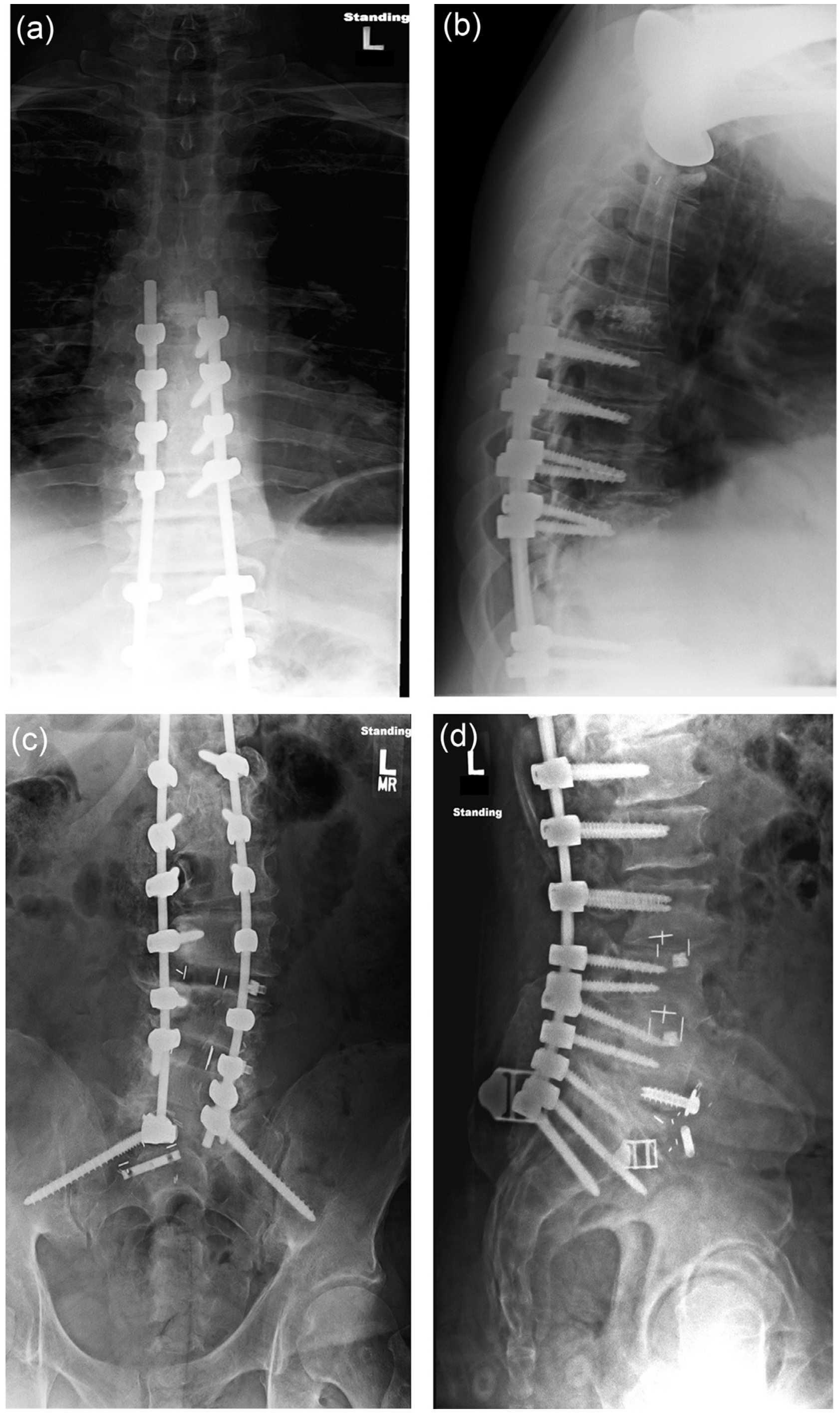

FIG 13. Postoperative radiographic assessment of the thoracolumbar spine in a 54-year-old male following staged L2-S1 posterior lumbar laminectomy and decompression, L3-L4, L4-L5, and L5-S1 anterior lumbar interbody fusions performed through a minimally invasive approach, and T7-S1 posterolateral fusion with bilateral iliac screws, T11 posterior osteotomy, and T6 kyphoplasty. Standing (a) AP and (b) lateral radiographs of the thoracic and standing (c) AP and (d) lateral radiographs of the lumbar spine demonstrate interval improvement in lumbar scoliosis (Cobb angle was measured at 28°, decreased from 45° preoperatively). Note, bilateral posterior rods with multilevel pedicle screws extending from T7 through iliac bones, intervertebral cages and/or spacers at L3-L4 and L4-L5, anterior fusion construct at L5-S1 and kyphoplasty at T6. Also, note multiple additional metallic objects projecting over the pelvis and lower lumbar spine unrelated to the fusion construct. Partially imaged are bilateral shoulder arthroplasties.

use of spinal injections as a treatment modality for ADS is poor, however injections are often utilized for presurgical planning to determine the extent of decompression necessary.[7]

The most commonly reported indications for surgical intervention in ADS are leg pain and/or intermittent claudication. Other indications include L3 or L4 endplate angulations, lumbar curves > 30-40°, and/or >6 mm of lateral listhesis (subluxation). Goals of surgical management include relief of back pain, radiculopathy, claudication, and correction of the spinal deformity.[7,11]

Surgical options include decompression alone, decompression with limited short segment fusion, and decompression with long segment fusion and correction of deformity. Decompression is used for the relief of radiculopathy and claudication, however without fusion is associated with progression of deformity and recurrence of spinal stenosis. It should therefore be considered in cases of milder scoliosis curves (<30°) without lateral listhesis (subluxation; <2 mm), and in elderly patients at higher risk with more extensive surgery.[10,11]

Limited posterior short segment fusion can be considered in mild curves and mild lateral listhesis (subluxation) of the apical vertebra with good spinal balance. Adjacent segment (junctional) disease is a common complication in short segment fusion, however.[10] Furthermore, scoliosis may be accelerated in patients with severe Cobb angle and when fusion to the apical vertebra is included.[9]

Long segment fusion is employed to correct scoliotic deformities in cases of severe lumbar curvature with severe lateral listhesis (subluxation) of the apical vertebra. Correction of deformity, restoration of lumbar lordosis, and restoration of sagittal balance are associated with improvement in back pain and successful fusion. Inclusion of anterior interbody release with anterior column support may help restore lumbar lordosis. Correction of severe sagittal imbalance may be achieved by anterior column support or vertebral osteotomies (Fig 13).[10,12]

The determination of the levels to include in the fusion is crucial and can be controversial. While extending the fusion up to the T10 level cranially may reduce the occurrence of adjacent segment disease in comparison to T11, T12, or L1, it is associated with increased perioperative morbidity due to increased blood loss and length of surgery.[10] The decision to extend the fusion to the sacrum caudally may prove to be difficult as well, because there is a relatively high rate of pseudoarthrosis and higher number of surgical procedures in this group in comparison to those with fusions that terminate at L5, while there is a higher rate of adjacent segment disease in those with fusions that terminate at L5.[7,11]

Conclusions

Scoliosis represents the abnormal curvature of the spine in the coronal plane, and can present in any age group or patient demographic. We summarized the clinical evaluation, diagnostic imaging, and treatment options of the 2 major distinct types of scoliosis—AIS and ADS—and emphasized several useful imaging modalities and measurements to aid the radiologist and clinician in the evaluation of scoliosis.

Competing Interests

None.

Declarations of Interest

None.

Acknowledgments

None.

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