REVIEW

Adolescent Idiopathic Scoliosis; a review and summary of contemporary practice

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Abstract

Adult Idiopathic Scoliosis is a three-dimensional spinal deformity with an aetiology that remains largely unknown. The development of an ideal classification system, identification of risk factors for curve progression, and determination of optimal treatment methods continue to present challenges in the field. Although various surgical and nonsurgical interventions have been employed, the efficacy and advancement of these techniques over recent decades remain uncertain. This narrative review examines these factors to elucidate current best practices in the management of Adult Idiopathic Scoliosis.

Introduction

Adolescent Idiopathic Scoliosis (AIS) is a three-dimensional spinal deformity that occurs in adolescents, characterized by abnormalities across the sagittal, coronal, and axial planes [1]. The Scoliosis Research Society (SRS) defines scoliosis as a spinal curve measuring at least 10 degrees, along with associated vertebral rotation [2].

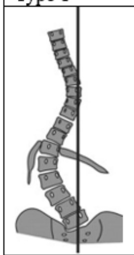
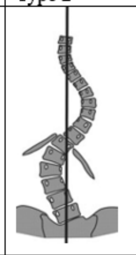
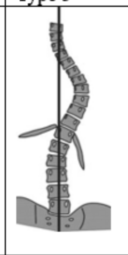
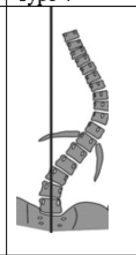
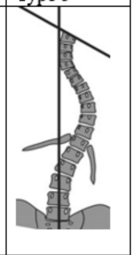
AIS is the most common form of scoliosis, with a reported incidence ranging from 0.47% to 5.2% [3,4]. It is the leading spinal deformity in adolescents, affecting approximately 2–4% of this population and accounting for about 90% of all scoliosis cases in this age group [5]. While mild spinal curves occur at similar rates in both males and females, more severe deformities are observed more frequently in females [4,6].

Classifications

In 1948, John Cobb introduced the first classification system for scoliosis. He distinguished between major and minor curves, as well as structural and non-structural curves, offering a framework to guide appropriate treatment of these deformities [4].

With the popularity of Harrington rod instrumentation for scoliosis correction, Howard King presented a King classification system for AIS in 1983. (Table 1) Important terminology for describing scoliosis, such as Stable Vertebra and Structural vs. Compensatory curves based on side-bending radiographs, was introduced within this classification. Curves were divided into five types, and surgical fusion levels were determined based on curve type, with greater emphasis on motion preservation. [5]

Table 1: The king classification (1983) [4,5]

Type 1	Type 2	Type 3	Type 4	Type 5
				
''S'' shape deformity, in which both curves are structural and cross the CSVL, with the lumbar curve being larger than the thoracic one.	''S'' shape deformity, in which both curves are structural and cross the CSVL, with the thoracic curve being larger or equal to the lumbar one.	Major thoracic curve in which only the thoracic curve is structural and crosses the CSVL.	Long ''C'' shape thoracic curve in which the fifth lumbar vertebra is centered over the sacrum and the forth lumbar vertebra is tilted into the thoracic curve.	Double thoracic curve.

Due to relatively low inter- and intra-observer reliability and the subsequent popularity of segmental instrumentation for scoliosis correction over Harrington rods, the King classification failed to provide reliable advice for selecting accurate fusion levels. Hence, Lawrance Lenke introduced the Lenke classification in 2001 with six curve types based on the number of Major or Minor curves in the deformity, a Lumbar modifier, and, for the first time, the severity of the sagittal deformity. [6] (Table 2)

The Lenke classification is regarded as more comprehensive and reliable than the King classification; however, it remains imperfect, as it does not adequately account for the rotational component of the deformity [7].

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Table 2: The Lenke classification (2001) [4,6]

Type I	Type II	Type III	Type IV	Type V	Type VI
Single Thoracic	Double Thoracic	Double Major	Tripple Curve	Thoraco lumbar or lumbar	Thoraco lumbar or lumbar
main thoracic (MT) is the only structural curve while the others (proximal thoracic and lumbar or thoracolumbar) are nonstructural.	double thoracic in which the MT is the major curve, the proximal thoracic (PT) is the minor curve but is structural and the thoracolumbar (TL) or lumbar (L) curves are minor and nonstructural.	double major curve pattern in which the MT is the major curve and the lumbar is the minor one but is structural whereas the PT is nonstructural.	triple major curve pattern when the MT is the major curve but all three curves are structural.	the TL or L curve is the major and only structural curve, with the PT and\or MT curves being minor and nonstructural.	the TL or L curve is the major curve measuring at least 5_ more than the MT which is the minor but structural curve.
lumbar spine modifier (defined by the location of the Center Sacral Vertical Line - CVSL on the apical vertebra of the lumbar curve)			Thoracic sagittal profile modifier (Thoracic kyphosis is measured between T5–T12)		
Modifier A	when the CSVL runs between the pedicles of the lumbar apical vertebra.		(+) Plus	when thoracic kyphosis measures >40°	
Modifier B	when the CSVL runs between the medial border of the lumbar concave pedicle and the lateral margin of the apical vertebral body		(N) Normal	when thoracic kyphosis measures between 10° and 40°	
Modifier C	when the CSVL falls completely medially to concave apical vertebra's body.		(-) Negative	when thoracic kyphosis measures < 10°	

Contemporary stereo-radiographic techniques assess spinal deformity by incorporating the Cobb angle, apical vertebra, axial rotation, and the orientation of the apical vertebra relative to the sagittal plane, enabling evaluation in all three dimensions. Nevertheless, a fully comprehensive classification system that encompasses all three dimensions has yet to be established [8].

Aetiology

Genetics

As the name implies, the pathophysiology of AIS remains unclear. However, some studies suggest a genetic predisposition, supported by the increased risk observed among first-degree relatives [9] and monozygotic twins [10].

Biochemical and hormone theories

Although the prevalence of scoliosis is equal among males and females at younger ages, in puberty the female-to-male ratio rises to 8:1, denoting a role for sex hormones in the development of AIS. [11] Specifically, some studies have identified reduced oestradiol levels in girls with AIS [12]. Additional research has suggested associations between elevated platelet calmodulin levels, decreased serum melatonin levels, and scoliosis progression. Zhang et al. reported that genetic variants in the CALM1 gene are associated with AIS susceptibility [13,14], while Sadat-Ali et al. found significantly lower serum melatonin levels in AIS patients [15].

Low bone mineral density (osteopenia)

Osteopenia involving both the axial and peripheral skeletons has been reported in approximately 30% of patients with AIS. Evidence suggests that those with osteopenia have a significantly higher likelihood of requiring surgical intervention [16, 87].

Recent studies have also identified a link between low bone density and polymorphisms in the vitamin D receptor (VDR) gene [17]. Suh et al. found that the VDR BsmI polymorphism is associated with reduced lumbar spine bone mineral density (LSBMD) in girls with AIS [18].

Abnormal skeletal growth and biomechanical theories

Some authors have reported that girls with severe AIS experience delayed menarche and accelerated skeletal growth rates between ages 12 and 16. These individuals are generally taller and have higher body weight compared to healthy controls [19].

Relative anterior spinal overgrowth (RASO), also referred to as asynchronous neuro-osseous growth between the spinal column and the spinal cord, has been proposed as another explanation for AIS. In affected individuals, the thoracic spine is typically longer anteriorly than posteriorly [20]. One hypothesis proposes that longitudinal growth of the vertebral bodies is accelerated and disproportionate compared with that of age-matched controls, primarily occurring through endochondral ossification. In contrast, circumferential growth—mediated by membranous ossification—appears to be reduced in both the vertebral bodies and the pedicles [21].

The Hueter–Volkmann theory is widely accepted as an explanation for the pathogenesis of AIS. It proposes that increased pressure on a vertebral epiphyseal growth plate suppresses growth, whereas reduced pressure promotes it. In AIS, the concave side of the curve is subjected to elevated pressures, resulting in reduced growth rates, whereas the convex side experiences lower pressure and accelerated growth [22].

Postural somatosensory function theories

Previous studies have reported subtle neurological abnormalities in patients with AIS. A comprehensive review by Wang et al. indicated that children with AIS exhibit impairments in postural balance, somatosensory function, equilibrium, and proprioception. It has been suggested that the rapid growth seen in these children may exceed the ability of the somatic nervous system to regulate the developing spinal deformity [23, 24].

Aortic arch vascular theory

Taylor's 1986 paper was the first to propose that vascular asymmetries contribute to the sidedness of thoracic scoliosis, with left-sided curves in infantile scoliosis and right-sided curves in adolescent scoliosis. In adolescents, this phenomenon may result from the rotational forces exerted on the growing thoracic vertebrae by the asymmetrically positioned descending thoracic aorta [25].

Clinical features

The typical presentation of AIS is a back deformity, often detected incidentally by a family member or during a school medical or nursing inspection. Usually, children present with a prominent rib hump, unequal shoulder levels, and waistline asymmetry [26].

Traditionally, back pain has been considered uncommon in AIS [27]. However, a large cross-sectional study of school-aged children (9–15 years) reported a back pain prevalence of 58.8% among AIS participants, compared with 33% in those without AIS [28]. The presence of persistent, nighttime, or radicular pain warrants further investigation to rule out underlying pathology [26, 29].

In AIS, a typical curve is a right thoracic curve, which is the majority of cases; atypical curves, rapidly progressing curves, or scoliosis with neurological symptoms should be further investigated to exclude possible underlying pathology [30].

In the assessment of AIS, a thorough history should include birth details, developmental milestones, family history of spinal deformity, and evaluation of physiological maturity. Complicated labor can result in cerebral palsy, which may lead to neuromuscular scoliosis, while a history of developmental delays may suggest a non-idiopathic cause. Assessing maturity—such as menarchal status in girls—is crucial for determining the stage of the growth spurt and, consequently, the risk of curve progression [26].

Physical examination involves evaluating curve patterns and truncal asymmetry, particularly at the shoulder and pelvic levels [1].

Any leg length discrepancy should be addressed by placing blocks under the shorter leg until the pelvis is level. During the examination, the location and direction of visible spinal curves should be documented. Skin findings such as café-au-lait spots, subcutaneous nodules, and axillary freckles may suggest neurofibromatosis, while midline lower back hairy patches or skin dimples can indicate underlying spinal dysraphism rather than idiopathic scoliosis.

Upper body balance over the pelvis is assessed by dropping a plumb line from the C7 spinous process, which typically aligns with the gluteal cleft. In cases of coronal imbalance, the distance between the plumb line and the gluteal cleft is measured in centimeters, and the direction of deviation is recorded [26].

The Adams forward bending test may reveal the structural component of the curve and a rib rotational deformity (rib hump) on the convex side of the curve. A scoliometer is used to measure the angle of vertebral rotation in a patient bent forward. A 7° rotatory asymmetry angle suggests referral for evaluation of scoliosis [1].

A thorough neurological examination should be conducted, assessing motor and sensory function as well as reflexes. Asymmetrical reflexes may indicate an underlying intraspinal disorder [31]. The abdominal reflex, elicited by stroking the abdomen around the umbilicus, normally causes contraction of the abdominal muscles and movement of the umbilicus toward the stimulus. An abnormal abdominal reflex—often absent on the convex side of the curve—can signal an intraspinal pathology [26].

Since ongoing spinal growth increases the risk of curve progression in AIS, monitoring growth velocity at each clinical visit is crucial. One of the simplest and most reliable methods for this is regular measurement of height [32].

Investigations

Standard radiographic evaluation for AIS typically includes upright standing posteroanterior (PA) and lateral X-ray views. The apex vertebra of the curve should be identified, as its location determines the curve classification: cervical, thoracic, thoracolumbar, or lumbar [27].

Lateral bending films or traction films are used to determine the flexibility of the curves and to identify true structural vs. non-structural curves in the deformity. [26]

The central Cobb angle is measured by first identifying the primary curve and its two end vertebrae (EV)—the vertebrae with the greatest tilt above (cephalad) and below (caudal) the curve's apex. Lines are then drawn along the superior border of the upper end vertebra and the inferior border of the lower end vertebra to determine the Cobb angle [1]. Today, this measurement is often performed using digital imaging software.

Additional imaging, such as magnetic resonance imaging (MRI), is generally reserved for AIS patients with atypical features that may suggest underlying pathology, including tumors, other lesions, or neural axis abnormalities like syrinx or Arnold–Chiari malformations [27, 4]. Some centers, however, perform MRI routinely before surgical correction.

Reducing radiation exposure is particularly important in AIS, as repeated imaging of growing spines raises concerns about long-term cancer risk. The EOS slot-scanning 2D/3D imaging system is increasingly used because it delivers 50–80% less radiation than conventional radiography and provides simultaneous bi-planar images, allowing for 3D reconstruction of the spinal deformity [33]. A CT scan may be helpful when planning surgery to assess pedicle size and when the intraoperative navigation system relies on preoperative CT scans.

Risk factors for curve progression

Skeletal maturity and curve severity are the two most important factors in evaluating the risk of curve progression. Generally, the younger the child and the larger the curve, the higher the likelihood that the curve will progress [34] (Table 3).

The scoliosis curve will markedly worsen during the adolescent growth spurt. The total pubertal growth spurt typically lasts approximately 2.5 to 3.0 years, with the mean age at peak height velocity around 14 years for boys and 12 years for girls [35].In a retrospective case series of over 200 patients with AIS, at the onset of puberty, the risk of a 20-degree curve progressing was 16%, but when the curve was 30 degrees, the risk increased to 100%. [36, 26]

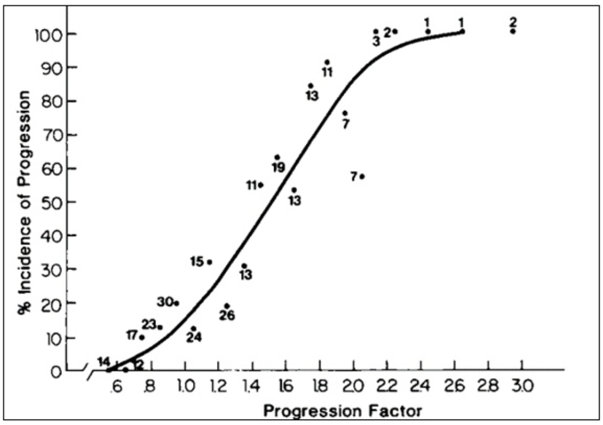
Table 3: Risk factors for curve progression in adolescent idiopathic scoliosis

Age	The younger the age at diagnosis, the greater the potential for curve progression at the onset of an adolescent growth spurt
Sex	Progression is more common in girls
Menarche	Progression is least common after menarche
Remaining Skeletal Growth	The more skeletally immature the greater the risk of curve progression
Curve Pattern	Double curves are more likely to progress than single curves
Curve magnitude	The risk of progression increases with the curve magnitude

As spinal growth is closely associated with height, sequential height measurements can be used to determine the patient's growth stage and the timing of peak growth velocity. Skeletal age provides a more accurate measure of maturity than chronological age. The Risser sign is commonly used to assess skeletal age, comprising six stages (0–5) that reflect the progression of the iliac apophysis from the anterior to the posterior iliac spine, followed by fusion with the iliac bone.

According to Lonstein et al., curve progression is influenced by several factors, including the patient's age, curve pattern and magnitude, Risser stage, and menarchal status at presentation. In immature children with a Risser sign of 0 or 1, curves measuring 20°–29° had a 68% likelihood of progression [37] (Figure 1).

Figure 1: Evidence of curve Progression according to the 'progression factor', which is calculated by the formula: [(Cobbs angle – 3) × Risser stage] ÷ Chronological age [37]



The Risser sign has limitations, including its variable correlation with skeletal age between boys and girls and its typical appearance after peak height velocity [26].

Skeletal age can also be assessed using left-hand and wrist radiographs, which are compared with a standard atlas developed by Greulich and Pyle [38]. Sanders demonstrated that scoring the metacarpals and phalanges provides a closer correlation with scoliosis progression than either Tanner staging or the Risser sign [26, 39, 40] (Table 4).

A recent study from Poland by Tschurl JR et al. further described the strong correlation between the Sanders Maturity Scale and the Risser method. The main advantage of the Sanders Maturity Scale was found to be its wider range of stages compared to the Risser method, while clearly distinguishing maturity levels prior to Risser stage 1. This assessment is essential for determining a patient's eligibility for either surgical intervention or brace treatment [41].

As per Dimeglio et al elbow is more precise than the hand in determining maturation [36].

Treatment

The management of adolescent idiopathic scoliosis (AIS) depends on multiple factors, including the type and magnitude of the curve, its progression, skeletal maturity, and additional considerations such as cosmetic deformity [42, 5].

Non operative management

The effectiveness of conservative treatments for scoliosis remains a topic of debate. Alternative nonsurgical approaches—such as chiropractic or osteopathic care, acupuncture, specific exercises or manipulative therapies, and dietary interventions—have not been shown to alter the natural course of spinal deformities [5].

However, physiotherapy-specific scoliosis exercises (PSSE) have shown some recent promise, at least in the short term. One study reported that incorporating physiotherapeutic scoliosis-specific exercises (PSSE) into the SRS standard of care improved Cobb angle outcomes in adolescents with AIS after six months, as demonstrated in a randomized controlled trial [43].

Schreiber et al., in a 2023 systematic review of methods used in published PSSE trials, acknowledged that, to date, methodological standardization and rigor have been equivocal and recommended minimum standards for future research and reporting in this field. [44]

Observation is the most common management strategy for AIS patients with mild deformities, such as a Cobb angle below 25°. Depending on skeletal maturity, these patients are typically reassessed every 4 to 6 months at a specialist clinic to monitor for curve progression [26].

Bracing

Multiple studies have shown that bracing can effectively manage the natural progression of adolescent idiopathic scoliosis (AIS) [5, 6]. Rigid bracing is the most effective non-surgical treatment for adolescents with AIS who have Cobb angles between 20° and 40°. A randomized controlled trial reported a 72% success rate for bracing in this group [45, 46]. Furthermore, a recent meta-analysis indicated that bracing may help control curve progression even in patients with curves greater than 40° [37].

Indications for brace treatment include:

- Growing children with spinal curves of 25°–40°

Table 4: Correlation of sanders and risser stage during phases of bone growth [40]

Sanders stage	Radiographic features	Risser stage	Radiographic features
Juvenile slow (1)	Digital epiphyses are not covered	0	No ossification of the apophysis
Preadolescent slow (2)	All digital epiphyses are covered	0	No ossification of the apophysis
Adolescent rapid (early) (3)	Most digits are capped. 2nd-5th MC epiphyses are wider than metaphyses	0	Triradiate cartilage open (peak height velocity)
Adolescent rapid (late) (4)	Any of distal phalangeal physes are clearly beginning to close	0	Triradiate cartilage remains (open growth plates in the long bones)
Adolescent steady (early) (5)	All distal phalangeal physes are closed, while others are open	0	Triradiate cartilage closed (menarche in female patients)
Adolescent steady (late) (6)	Middle or proximal phalangeal physes are closing	≥1	Ossification of the iliac apophysis ranges from 25% to 75%
Early mature (7)	Only distal radial physis is open. MC physeal scars may be present	4	100% ossification of the iliac wing, with no fusion to iliac crest
Mature (8)	Distal radial physis is completely Closed	5	Fusion of the iliac apophysis to the iliac crest (cessation of growth)

- Curves under 25° with documented progression of 5°–10° over six months (i.e., >1° per month)
- Curves of 20°–25° in children with significant skeletal immaturity (Risser 0; Tanner stage 1 or 2), who should begin bracing immediately

Braces are typically worn full-time, 22–23 hours per day, for 2–4 years, continuing until skeletal maturity and the completion of bone growth [5].

Contraindications for bracing include:

- Skeletally mature children
- Growing children with curves exceeding 45°
- Curves under 25° without documented progression
- True thoracic lordosis, as bracing may worsen thoracic flattening
- Patients without adequate family support or those unwilling to comply with brace wear [1, 3, 5, 21, 48]

AIS occurs approximately seven times more frequently in girls than in boys. However, girls generally achieve better outcomes with bracing, likely due to greater spinal flexibility, a shorter pubertal growth spurt, and a reduced duration of required treatment. Additionally, girls tend to show higher compliance with brace use.

Body habitus affects brace outcomes: overweight adolescents are at higher risk of curve progression and lower bracing success. In these patients, the brace may have difficulty transmitting corrective forces through soft tissues and the rib cage, which should be considered during treatment planning [49].

Modern brace fabrication involves 3D scanning of the patient using a laser measurement system. The collected data is processed in software to design the final brace shape on a 3D model, providing a more efficient alternative to the traditional plaster-cast method [50].

Operative management

The decision to pursue surgical treatment for an AIS patient is based on multiple factors, including the magnitude and pattern of the spinal curve, the rate of curve progression, and the patient's skeletal maturity.

Surgery is indicated when the curve magnitude is already significant at presentation or when curves progress despite conservative treatment.Hence, a skeletally immature patient with a structural thoracic curve Cobb angle over 40° is a candidate for surgery.

The goals of surgical treatment are to correct the spinal deformity, prevent further curve progression, and restore trunk symmetry and balance, while minimizing the number of fused levels, preserving spinal motion, and reducing pain and overall morbidity [51–53]. For over a century, fusion and instrumentation have been used to treat scoliosis. Surgical options include anterior spinal fusion (ASF), posterior spinal fusion (PSF), or a combination of both approaches [52].

Recognition of AIS as a complex three-dimensional deformity of the spine and pelvis has driven rapid advances in surgical instrumentation and techniques over recent decades. In the 1960s, simple uniplanar distraction using Harrington rods evolved in the 1970s into biplanar segmental instrumentation with Luque wires, and by the 1980s progressed to triplanar Cotrel–Dubousset instrumentation combined with rod-derotation maneuvers [54].

The introduction of segmental pedicle screw instrumentation has allowed more powerful correction of spinal deformities, reduced nonunion rates, and earlier postoperative mobilization [55].

However, a significant challenge with pedicle screws in AIS is the higher rate of screw malposition compared with adult spinal deformities. This is largely due to dysplastic pedicles with smaller diameters in younger AIS patients. The risk is particularly critical on the concave side of severe thoracic curves, where the spinal cord lies in close proximity to the pedicle wall [56, 57].

Modern techniques such as CT-guided navigation, 3D-printed spine models for freehand pedicle screw placement, and robotic-assisted pedicle screw insertion have significantly reduced the risk of pedicle screw malposition. [57-62]

With advances in operative techniques, the volume of AIS surgeries has significantly increased over the past few decades. According to Vigneswaran et al, in the USA, there was a 193% increase in the number of AIS surgeries in 2012 compared to 1997. [63]

Currently, posterior spinal fusion is the most commonly performed surgical approach for AIS, accounting for approximately 75% of cases, followed by anterior fusion (18%) and combined anterior-posterior approaches (7%) [48]. Research indicates that the anterior approach may offer an advantage in thoracolumbar Lenke 5C curves by requiring fewer fused levels compared with the posterior approach. However, studies have reported no significant differences between these surgical approaches regarding blood loss, length of hospital stay, or patient-reported outcomes. The posterior approach may be preferable because it avoids the potential adverse effects of anterior surgery on pulmonary function. Furthermore, posterior-only fusion has been shown to achieve correction comparable to combined anterior-posterior fusion, without entering the thoracic cavity and impacting lung function [64–72].

Because fusion limits spinal motion, fusion surgery in younger, skeletally immature patients with significant growth potential has been discouraged. Hence, when fusion is required in these immature patients, the aim is to fuse the fewest segments possible while achieving an acceptable correction. Several studies have provided recommendations for selecting the upper and lower instrumented vertebrae (UIV and LIV) based on the Lenke classification. Commonly used guidelines include those by Rose and Lenke [73] (Table 4), Trobisch et al. [74] (Table 5), and Ilharreborde et al. [75] (Table 6). Proper selection of fusion levels is also critical for addressing the challenging goal of avoiding postoperative shoulder imbalance.

Table 5: Trobisch et al. Recommendations for Choosing UIV Levels in AIS* [74]

1, 3, and 6	Right shoulder elevated: T4 Level shoulders: T3 Left shoulder elevated: T2
2 and 4	Always T2
5	Upper-end vertebra (UEV) of the curve
	*Adapted from: Trobisch PD, Ducoffe AR, Lonner BS, Errico TJ. Choosing fusion levels in adolescent idiopathic scoliosis. J Am Acad Orthop Surg. 2013 Sep;21(9): 519-28.

Table 6: Ilharreborde et al. Recommendations for Choosing UIV Levels in AIS* [75]

	T1 Tilt and Shoulder Balance in the Same Direction to the Left	T1 Tilt and Shoulder Balance in Opposite Directions	T1 Tilt and Shoulder Balance in the Same Direction to the Right
$\alpha - (\beta/2)$ =/< 15°	T4	T2 or T3	T1
$\alpha - (\beta/2) <$ 15°	T2 or T3	T1	T1
*Note that these recommendations apply only to Lenke-1 and 2 curves. a: Cobb angle of the proximal thoracic curve on the lateral bending radiographs toward the convex side. b: Cobb angle of the main thoracic curve on the lateral bending radiographs toward the convex side. Adapted from: Ilharreborde B, Even J, Lefevre Y, Fitoussi F, Presedo A, Souchet P, Penneçot GF, Mazda K. How to determine the upper level of instrumentation in Lenke types 1 and 2 adolescent idiopathic scoliosis: a prospective study of 132 patients. J Pediatr Orthop. 2008 Oct-Nov;28(7):733-9.			

However, these guidelines are largely based on expert opinion rather than evidence from clinical trials. Consequently, evidence-based recommendations and principles to guide surgeons in selecting fusion levels remain to be established in future studies [53].

Early-onset scoliosis (EOS) is defined as a spinal curve greater than 10° in the coronal plane that develops before the age of 10. EOS may result from idiopathic causes or, less commonly, from other underlying conditions. In 1963, Harrington introduced a surgical distraction technique without spinal fusion to correct deformities in this patient population [76]. Since then, several variations of growing rod (GR) techniques have been advocated by surgeons for the treatment of young skeletally immature AIS patients with severe curves that Bracing cannot control. In these patients, fusion is undesirable because of the substantial remaining growth. Traditional distraction growing rods require surgical lengthening approximately every six months, whereas the newer magnetically controlled growing rod system, MAGEC (magnetic expansion control), allows for non-invasive lengthening in an outpatient setting, eliminating the need for repeated surgeries. [51] However, recent evidence indicates that MAGEC rods are associated with significant titanium wear debris, leading to metallosis. They also have a high rate of implant failure, often necessitating unplanned revision surgeries, which has contributed to their declining use among surgeons [77,78].

Other advancements in fusionless and growth-modulating techniques, such as compression-based Vertebral Body Stapling (VBS) and Vertebral Body Tethering (VBT), have been developed to address concerns associated with early spinal fusion in young AIS patients [48] (Table 7).

Table 7

	VBS [78-80]	VBT [81-83]
Indications	• skeletally immature patients (Sanders bone age of 4 or less Risser grade of 2 or less) • The thoracic curve of <35 or the Lumbar curve of 20-45_ corrects to <20 on side-bending radiographs. (For stiff thoracic curves >35, consideration can be given to the use of VBS, along with a posterior growing rod system (hybrid construct).	• skeletally immature patients (Sanders bone age of 4 or less Risser grade of 2 or less) • Major Cobb angles of 30 - 65 involving thoracic and/or lumbar curves for which bracing has failed or who are intolerant to brace wear. (Curves of more than 65 are thought to be too severe for VBT)
Advantages	• Immediate and reversible cessation of growth of the anterior vertebral physes • Minimally invasive thoracoscopic (Thoracic) or mini-open retroperitoneal (Lumbar)approach • No additional full-time bracing. • Does not preclude future surgery of fusion if necessary	• minimally invasive growth-modulating procedure, • Does not require the frequent rod-lengthening procedures
Disadvantages	May not be possible to fully reverse the Heuter-Volkmann effect, and the long-term effect of the staples on the involved intervertebral discs remains unknown.	• overcorrection, because the ideal tension of the cord has not yet been established. • Tether breakage • require the the assistance of a general or cardiothoracic surgeon for access,
Outcome	Effective at preventing progression and fusion for moderate idiopathic scoliosis in immature patients [78,79]. Although early outcomes after VBS appear to parallel the results of bracing, stapling does not affect the percentage of patients ultimately requiring PSIF[80]	Early results indicate that anterior VBT is a safe and potentially effective treatment option for skeletally immature patients with idiopathic scoliosis. [83]

In Vertebral Body Stapling (VBS), staples made from nitinol—a shape-memory alloy of nickel and titanium—are applied to the anterior vertebral growth plates via open thoracotomy or thoracoscopic techniques. The staples are designed so that their prongs are straight when cooled but clamp into the bone in a “C” shape as they return to body temperature, providing secure fixation. This approach partially restrains growth on the convex side of the curve while allowing natural growth on the concave side [78–80].

Vertebral Body Tethering (VBT) is performed under thoracoscopic visualization. Titanium screws are placed on the convex side of the spinal curve using an anterior approach, and a flexible braided polyethylene terephthalate cord is threaded through the screw heads. When the cord is tightened, it compresses the adjacent screws, straightening the curve, slowing progression, preserving growth potential, and maintaining spinal mobility and flexibility [81–83].

However, some controversy remains about long-term results, degree of correction, the amount of motion retained, particularly in the thoracic spine, and revision rates. Vertebral body tethering most often fails due to mechanical complications, particularly problems with the tether itself. The most common issue is tether breakage or slippage at the screw–tether connection. This happens because the tether is constantly under tension as it guides spinal growth. High stress at the locking mechanism, repetitive loading from daily movement, and excessive intraoperative tightening can all create strain concentrations that eventually cause the tether to snap or loosen. [83]

Complications

In Scoliosis management, it is important to recognize the complications and risk factors for patients and surgeons.

The most common complications of bracing in AIS include curve progression due to poor compliance, skin irritation, temporary reductions in vital capacity, and mild chest wall or lower rib deformities. Adolescents often struggle with brace tolerance, as braces must be worn 18–23 hours per day. Poor compliance is frequently associated with concerns about body image, discomfort from chin and throat contact (especially with Milwaukee braces), or pressure from the pelvic or axillary sections of the brace, particularly in thoracic–lumbar–sacral orthosis (TLSO) braces.

Skin irritation is more common in warm climates or during summer months due to heat and perspiration, so frequent changes of cotton undergarments are recommended to help minimize this problem. TLSO braces may also cause temporary reductions in vital capacity, and mild chest wall or lower rib deformities can develop during treatment. These rib cage changes usually resolve after brace discontinuation, although they may become permanent if bracing begins at a very young age and continues for many years [5].

Despite modern instrumentation, new surgical techniques, and technological advances, complications in scoliosis surgery remain common.

Surgical treatment of AIS is associated with complications in 5% to 23% of patients [4, 52]. A multicenter prospective study reported a 2.6% rate of major perioperative complications and a 4.1% rate of significant complications occurring two or more years after surgery [84].

In a U.S. study using the National Inpatient Sample Database (NIS), Menger et al. reported postsurgical complication rates after AIS correction as follows: 2.8% for cardiopulmonary complications, 3.5% for abdominal complications, 0.9% for neurological complications, 0.4% for infectious complications, 0.1% for thromboembolic events, 0.1% for renal complications, and a mortality rate of 0.1%. The likelihood of these complications is influenced by multiple factors, including patient characteristics and surgeon experience, making precise risk stratification challenging [85].

Despite these risks, contemporary spinal fusion and instrumentation remain the gold standard for surgical correction of AIS. A 2020 study, Patient-reported Outcomes Following Surgical Intervention for Adolescent Idiopathic Scoliosis, provided moderate evidence that spinal fusion can improve quality of life for adolescents with idiopathic scoliosis in medium- and long-term follow-up [86].

Conclusion

Still, ongoing efforts seek to develop an ideal classification, better understand the risks of curve progression, and improve treatment methods for AIS. Diagnosis and classification of AIS, as well as assessment of curve progression, rely on a comprehensive clinical history and physical examination combined with standard radiological imaging. Although many nonsurgical treatment options exist, bracing with good compliance is the most effective. Although surgical techniques for treating AIS have evolved rapidly with the advent of segmental pedicle screw instrumentation, managing skeletally immature patients with significant remaining growth potential remains challenging. Fusionless and growth-modulating techniques, including VBS and VBT, have sought to tackle these concerns. The long-term efficacy and safety of these techniques are yet to be determined by further prospective studies.

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Competing interests

The authors read and approved the final manuscript. None of the authors has competing interests to declare

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