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ADOLESCENT IDIOPATHIC SCOLIOSIS

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Abstract

Adolescent Idiopathic Scoliosis (AIS) is considered as a complex, three-dimensional structural deformity of the spine, occurring in the transition from childhood to skeletal maturity. This review synthesizes data from leading global authorities (SRS, USPSTF, SOSORT) and seminal investigators such as Weinstein, Lenke, and Negrini, analyzing the pathology through the lens of neurophysiological dysregulation, genetic determinism, and biomechanical progression. The review emphasizes the importance of early detection and the effectiveness of evidence-based non-operative and operative interventions in preventing long-term pulmonary and psychosocial complications.

Keywords: Adolescent, idiopathic, scoliosis, AIS, teenage, deformity, vertebrae, spine, curve, degree, cobb angle, painless, bracing, screening, surgical intervention, physical therapy.

Introduction

Adolescent Idiopathic Scoliosis (AIS) is more than just a simple curve, it is a three-dimensional spine deformation where the Cobb angle reaches or even exceeds 10 degrees. It often results in a twisting of the vertebrae, causing visible physical asymmetry.

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The condition affects 1.65% to 3.1% of the teenage population worldwide, while the impact on females is inappropriately high. Females are not only diagnosed twice as often but are also significantly 10 times more likely to suffer from severe curve progression during pubertal growth.

In Uzbekistan, AIS is recognized as a serious health challenge. Nowadays specialized centers in the capital are carrying out global treatment guidelines, prioritizing early detection to improve long-term patient health.

The central issue remains the risk of progression: while most curves remain mild, approximately 10% of diagnosed cases require clinical intervention to prevent severe thoracic cage deformity, diminished pulmonary function, and secondary cardiovascular strain.

The aim is to systematically evaluate the current scientific literature on Adolescent Idiopathic Scoliosis (AIS). In particular, to evaluate the multifactorial etiopathogenesis including the role of genetics (LBX1, GPR126) and neurophysiological factors; to summarize diagnostic and screening standards based on the newest US Preventative Services Task Force (USPSTF) and SRS recommendations; to describe the treatment spectrum including: Physiotherapy Scoliosis Specific Exercises (PSSE), and/or rigid bracing (BrAIST trial basis) and/or reconstruction surgery; and finally, to evaluate the long-term psychosocial and physiological outcomes so that patients successfully integrate into mainstream society upon reaching adulthood.

Epidemiological Profile and Sexual Dimorphism

The epidemiological landscape of Adolescent Idiopathic Scoliosis (AIS) is characterized by significant variability in prevalence and a distinct, age-dependent sexual dimorphism. According to the foundational meta-analysis provided by Konieczny et al., the overall prevalence of AIS in current global literature ranges from 0.47% to 5.2%. This wide range is attributed to differences in screening methodologies, geographical variations, and the specific age cohorts

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studied, typically focusing on children from age 10 until the achievement of skeletal maturity.

The Phenomenon of Sexual Dimorphism. One of the most striking features of AIS is the disproportionate impact on the female population as the severity of the deformity increases. The curve Magnitude and Gender Correlation: While the male-to-female ratio is nearly 1:1 to 1.5:1 for minor curves (Cobb angle between 10∘ and 20∘), large-scale longitudinal studies by Stuart Weinstein and Marc Asherconfirm a sharp divergence as the angle grows. For curves exceeding 30∘, the risk of progression is significantly higher in females. About risk Factors: Clinical data indicates that females are ten times more likely than males to experience curve progression that reaches a treatment-requiring threshold (>30∘). This dimorphism is closely linked to the timing of the pubertal growth spurt; females generally experience an earlier and more rapid "peak height velocity," which provides a critical window for the "vicious cycle" of biomechanical vertebral wedging to accelerate.

Screening Efficacy and Clinical Necessity. The implementation of school-based screening programs has provided vast amounts of data, yet it has also raised questions about over-diagnosis. Dunn et al., in the systematic evidence report for the US Preventive Services Task Force (USPSTF), emphasize a crucial distinction between "detection" and "clinical necessity": The 10% rule: Of all adolescents identified with a spinal curvature of 10∘ or more during screening, only approximately 10% will ever require active clinical intervention (bracing or specialized physical therapy). About surgical thresholds: The prevalence of severe cases is even lower; only about 0.25% of the screened population reaches the surgical threshold of 45∘ to 50∘.

Predictors of Progression. The epidemiological risk is not static but dynamic, shifting based on skeletal maturity. Using the Risser Sign (a measure of the ossification of the iliac apophysis), investigators have shown that a child at Risser 0 or 1 with a 20∘ curve has a nearly 70% risk of progression, whereas a child at

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Risser 4 with the same curve has less than a 2% risk. This emphasizes that AIS epidemiology must always be interpreted through the lens of "remaining growth potential," a concept central to the natural history studies conducted at the University of Iowa.

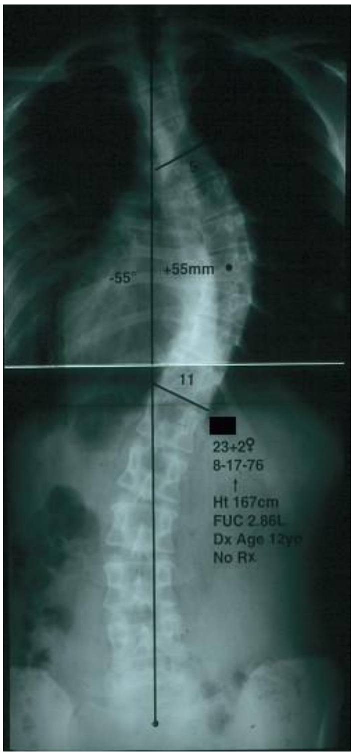

Figure 1 Posterior-anterior radiograph of a woman with right thoracic idiopathic scoliosis of 55 degrees at age 23 years

Molecular Mechanisms and the Neurophysiological Substrate

In contemporary orthopedics, the understanding of Adolescent Idiopathic Scoliosis (AIS) has undergone a fundamental paradigm shift. Moving beyond

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purely mechanical or orthopedic theories that viewed the condition as a simple bone deformity, researchers such as Paramento et al. (2024) and Peng et al. redefine AIS as a complex failure of sensorimotor integration and central postural control. This perspective suggests that the spinal curvature is a secondary manifestation of an underlying neurological or molecular dysregulation.
Neuroplasticity and Connectivity: Neural Signaling Deficits. The integration of advanced neuroimaging has provided objective evidence for the neurological basis of AIS. The white matter alterations which studies utilizing Diffusion Tensor Imaging (DTI) have identified significant microstructural changes in the white matter of the spinal cord and specific regions of the brain (such as the corpus callosum and internal capsule) in AIS patients. These changes in fractional anisotropy suggest a decrease in the integrity of neural fibers. The systemic signaling failures: Such deficits imply that AIS involves systemic neural signaling impairments. When the brain receives suboptimal or asymmetric sensory feedback, it cannot maintain a perfectly vertical spinal alignment during the rapid growth phase of puberty. This leads to an "erroneous" motor output that gradually forces the spine into a three-dimensional deformity.
The Genetic Landscape: From LBX1 to Proprioception. The genetic architecture of AIS is increasingly linked to the development of the somatosensory system. The role of LBX1: Research led by Takahashi et al. has identified specific risk loci in proximity to the LBX1 the - Ladybird Homeobox 1 gene. This gene is functionally essential for the developmental patterning of the dorsal horn neurons in the spinal cord, which are responsible for processing sensory input. Impaired proprioception: By linking LBX1 to AIS, scientists have established a direct genetic bridge between spinal deformity and impaired proprioception . If the dorsal horn neurons do not develop correctly, the adolescent may have a subclinical "spatial disorientation" of the spine, which becomes physically apparent only during the growth spurt. About additional loci: Other genes, such as GPR126 and CHL1, have been implicated in chondrogenesis and axon

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guidance, further supporting the theory that AIS is a multi-system genetic disorder affecting both bone and nerve tissue.

The Biomechanical Trigger: Relative Anterior Spinal Overgrowth (RASO). While the origin may be genetic or neural, the physical execution of the curve follows specific biomechanical laws. The RASO concept: As emphasized by Nikolla (2022), a critical mechanical driver is the Relative Anterior Spinal Overgrowth (RASO). This hypothesis posits that in AIS patients, the anterior column (the vertebral bodies) grows at a faster rate than the posterior elements (the neural arches and ligaments). Mechanical pre-conditioning: Because the posterior structures act as a "string" on a bow, the overgrowing anterior column has no room to expand vertically. To accommodate the extra length, the spine is forced to buckle laterally and rotate axially. This creates the three-dimensional "spiral" effect characteristic of idiopathic curves. The Heuter-Volkmann feedback loop: Once the initial rotation begins, the Heuter-Volkmann Law takes over: asymmetric loading leads to increased pressure on the concave side, which suppresses growth, and decreased pressure on the convex side, which accelerates it. This transforms a functional neural imbalance into a permanent structural bone deformity.

The "Endocrine-Biologic" Theory of Spinal Deformity

As of the early twenty-first century, the clinical conception ofAIS has shifted from that of an isolated spinal deformity to that of an illness based upon a systemic "biologic imbalance". For many decades now, the classification of the disorder as "idiopathic" has implicitly masked a multifaceted endocrinologic and molecular dysregulation. The confluence of the aforementioned factors ultimately produces the fertile "biologic substrate" for a skeletal curvature during a pivotal period of growth.

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Melatonin and Calmodulin Hypothesis

Underlying the neuro-endocrine theory is the endocrine factor melatonin-the pineal gland's endocrine agent that controls circadian rhythms. Its influence, however, extends far beyond the Sleep-wake cycle. Melatonin is a strong antagonist of calmodulin-the ubiquitous calcium-binding protein that, amongst many roles, controls smooth and skeletal muscle contraction.

Normally, the hormonal cascade is: reduced melatonin leads to uninhibited activity of calmodulin; this over-activity stimulates the paraspinal muscles to hypercontracture. These muscular forces create the muscular "tug-of-war" which, over a growth spurt, structurally rotates and wedged the vertebral bodies. This also explains the higher degree of curve progression at night when bone turnover and hormones are both at their peak activity.

Leptin and Energy Homeostasis

A clinically observed trait in some AIS patient populations, predominantly in women, is a lower than average BMI and less than normal subcutaneous fat. Because of this observation, research interest has turned toward the adipocyte-derived hormone leptin. This hormone is the crucial mediator between body fat and the central nervous system that controls linear bone growth.

There appears to be a state of hypothalamic resistance to leptin within the endocrine system of AIS patients. As a result, an over-active sympathetic nervous system is prompted. This has the effect of spurring rapid linear growth of both the spine and limbs; however, there is a simultaneous loss of bone mineralization. The "growth-density disparity" makes bone very brittle and easily deformable under mechanical stress, as will be explained in detail below.

Estrogen and Bone Mineralization (Osteopenia)

The striking disproportionate prevalence of progression in the female population cannot be ignored and directly implicates estrogen signaling pathways. These

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signaling pathways control receptors in the vertebral growth plates, as well as general bone mineralization processes throughout the skeleton.

Many individuals with progressing spinal deformity exhibit systemic osteopenia- a diminished quality to bone mass, making the vertebral bodies less resistant to mechanical deformation. The Heuter-Volkmann Law states that less brittle bone is more vulnerable to unequal force distribution leading to structural wedge deformation of the vertebral body. During a woman's adolescent growth spurt, when there are also altered growth factor-hormonal interactions, there is an opportunity to enter a critical "vulnerable phase" of rapid, uncontrolled growth.

Mesenchymal Stem Cells (MSCs) and the Cellualar blueprint

At a basic, cellular level, the deformity in the skeletal structure is believed to be attributable to intrinsic abnormalities in the cellular blueprint of mesenchymal stem cells-precursors that ultimately differentiate into osteoblasts. When in culture, mesenchymal stem cells taken from AIS patients have demonstrated impaired osteogenic potential due to inherent molecular defects, particularly in Wnt/-catenin signaling.

The inherent deficiency in this fundamental cell blueprint results in an imbalanced production of osteoblasts versus osteoclasts between the concave and convex sides of the spine; thereby effectively creating a "living lever" that, when influenced by biochemical markers, self-accelerates its own curvature.

Connective tissue and Ligamentous laxity

The mechanical stability of the spine is in part a function of the intrinsic structure of the ligaments surrounding and attaching the vertebral column. A change in the normal ratio of Type I to Type III collagen, often identified in the ligaments and intervertebral discs of AIS patients, can result in a state of widespread laxity. This laxity does not allow the ligaments to provide optimal tension around the axial core, leading to spine instability under normal spinal column pressure.

This examination of various system markers and endocrine mechanisms supports the theory that adolescent idiopathic scoliosis is a multifactorial illness. A patient

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is predisposed to the deformity by a combination of genetically acquired traits and acquired endocrinologic milieu. What is readily seen physically in a person with AIS is a structural problem stemming from very basic, fundamental biologic deficiencies in skeletal and hormone development. Future therapeutic advancements and treatments will undoubtedly be aimed at manipulating these systemic markers, rather than only trying to straighten the spine with brute force alone. Early detection of one or more of these markers would hopefully allow for interventions before the physical deformation of the spine becomes too great to correct.

Comprehensive Biomechanical Classification and Curve Morphologies

For decades, spinal deformity assessment focused on the King classification, which primarily looked at the frontal plane. However, as our understanding improved, it became clear that Adolescent Idiopathic Scoliosis is a complex, three-dimensional issue. The Lenke classification, introduced in 2001, changed how we plan surgeries. It is now the "gold standard" because it carefully considers the primary curve, the compensatory curves, and the patient's sagittal profile. This creates a multi-planar roadmap for intervention.

The Six Lenke Curve Types. The system divides deformities into six distinct types based on whether specific spinal regions are "structural" (rigid) or "non-structural" (flexible). This distinction is crucial for identifying which levels of the spine need fusion. Type 1: Main Thoracic (MT). This is the most common pattern. The primary deformity is in the thoracic spine, while the upper thoracic and lumbar regions remain flexible enough to balance themselves after correcting the main curve. Type 2: Double Thoracic (DT). In this pattern, both the proximal thoracic (PT) and main thoracic (MT) curves are structural. Clinically, this often shows as a shoulder height difference, where the shoulder on the concave side of the main curve is elevated. This requires including both regions in the surgical plan. Type 3: Double Major (DM). Both the thoracic and thoracolumbar/lumbar

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curves are structural and often similar in size. Both need direct surgical stabilization for a balanced spine. Type 4: Triple Major (TM). This is the most complex shape, where structural changes happen in three distinct areas: the proximal thoracic, main thoracic, and lumbar spine. Type 5: Thoracolumbar/Lumbar (TL/L). The main deformity is in the lower back (junctional or lumbar area), while the thoracic spine remains non-structural. Type 6: Thoracolumbar/Lumbar-Main Thoracic (TL/L-MT). The lumbar curve is the primary deformity and is at least 10 degrees larger than the thoracic curve. In this type, both areas are structural.

The Lumbar Modifier. To improve the assessment of the lower spine, the Center Sacral Vertical Line (CSVL) is used to analyze the relationship between the lumbar spine and the pelvic center: Modifier A: The CSVL runs between the pedicles of the apical lumbar vertebra. Modifier B: The CSVL touches the inner edge of the apical pedicle on the concave side. Modifier C: The CSVL falls fully to the inner side of the apical lumbar vertebra. A "C" modifier indicates a significant lateral shift of the lumbar spine, which is important for planning pelvic and trunk stability.

The Sagittal Thoracic Modifier. This modifier looks at the thoracic kyphosis between T5 and T12, which is essential for keeping the patient balanced from the side: as of Hypokyphosis (less than 10°). This "flat back" profile is common in AIS and is often seen with lower lung capacity. Normal kyphosis (10°–40°) and Hyperkyphosis (greater than 40°).

Biomechanics of Deformity: The Mechanics of the "Buckle"

To understand curve morphology, we must analyze the biomechanical forces at play. Current research, particularly from ca14, highlights several key factors driving the scoliosis "vicious cycle":

Relative Anterior Spinal Overgrowth (RASO). In AIS, the front part of the vertebral body grows faster than the back elements. In the tight space of the adolescent torso, the spine cannot grow straight and instead has to "buckle"

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sideways and rotate to fit the extra length. This explains why many patients show a true lordosis at the curve's peak, even though the visible "rib hump" might suggest otherwise.

Rotational Instability and the Hueter-Volkmann Law:Once there is a slight deviation from the vertical axis, gravity and muscle pull create uneven weight distribution. The Hueter-Volkmann Law states that added pressure on the concave side of the curve stops bone growth, while less pressure on the convex side boosts it. This mechanical feedback turns a flexible curve into a rigid, structural deformity with wedged vertebrae.

Three-Dimensional Global Balance: Vertebroloists see the deformity as a loss of an energy-efficient vertical position. The body tries to counter the primary curve by forming counter-curves in areas like the neck or lower back to keep the head over the pelvis. The Lenke system is vital because it helps clinicians tell apart the "true" structural problem from the body's compensatory efforts to maintain overall balance.

Overall the Lenke classification is more than just a list; it serves as a clinical guide. It shows which segments should be fused and which should be left intact to keep mobility. The aim of modern surgery has shifted from simply "straightening" the spine in a flat plane to executing a true three-dimensional derotation. This method returns the vertebrae to their natural position and restores a healthy sagittal profile. This process often refers to "re-kyphosing" the thoracic spine to improve long-term respiratory and spinal health.

Diagnostics and Predictors of Progression

The diagnostic approach for Adolescent Idiopathic Scoliosis is a clinical and radiographic process to define the magnitude and, crucially, to forecast future evolution of the deformity. As scoliosis is a dynamic condition, the information gained from the initial clinical assessment and x-rays needs to be placed into the context of skeletal maturity.

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Gold standards for clinical and radiographic assessment. Cobb Angle (1948): this remains the worldwide 'gold standard' measurement for curve magnitude. This angle is measured in a standing AP radiograph; end vertebrae for the curve (the superior and inferior vertebrae which form the limit of the curvature, angle between them is 90 deg), then lines are drawn parallel to the superior and inferior endplates. A curve Cobb of 10 deg is considered scoliotic. Risser scale (1958): To assess skeletal maturity. It measures the ossification of the iliac apophysis on a grade 0 to 5, stage 0-2 having a higher probability of curve progression, as the spine has more remaining growth. Stages 4 and 5 usually indicate a near or fully developed spine. This scale is essential to assess the 'window of opportunity' for brace treatment.

Prognostic markers for curve progression. A significant 50-year natural history study from the University of Iowa by Stuart Weinstein has identified the variables which dictate treatment decisions. From this study the three main predictors of progression are known to be: 1. Magnitude of curve, a curve that presents at the first visit as greater than 20deg will progress more likely than those curves which present with a lower Cobb measurement; 2. Skeletal maturity; patients who have not yet achieved a Risser stage of 3-5 (i.e. Stages 0, 1, or 2) are a risk for progression, because they still have the potential to grow significantly more. The remaining growth will increase the curve magnitude like a fuel to drive the process; 3. Premenarchal state in females. If a female is pre-menarchal, this has been identified as a risk factor for progression, because the rapid growth spurt is often associated with menarche.

Evidence based treatment management. The treatment decision of AIS patients is very hierarchically arranged based upon evidence:

Conservative modification: Exercises and Braces. These treatments have been shown to maintain the existing curve and stop surgical progression, and have the effect of biological containment of the curve in low to moderate risk cases: Physiotherapy Scoliosis-Specific Exercises (PSSE); these were promoted in

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various papers such as Kaelin, 2020 and those based on SOSORT consensus guidelines (Negrini), to be used for curves below 20deg, involving self-correction, breathing exercises and posture training. Rigid bracing (BrAIST study): for curves greater than 20deg and up to 45deg, brace treatment has been proven by the BrAIST study to significantly reduce the likelihood of surgery by 72% over 2 years if more than 13 hours per day were worn. Braces have progressed beyond that initial study, with modern brace concepts, such as the Lyon, and PASB (Progressive Action Scoliosis Brace), designed by Del Prete et al. (2024), using 3-dimensional modeling. These modern concepts create forces in 3-dimensions but with improved comfort and patient compliance than those described in BrAIST.

Surgical correction. When a curve exceeds a Cobb magnitude of between 45-50deg, the curve will continue to progress to adulthood, at which point medical and physiological problems will arise, due to both lung and degenerative complications. It is at this point when surgical reconstruction of the deformity will be considered. Lenke classification; surgeons use the 6 types of this classification, in order to ascertain what levels should be fused and what levels should remain mobile. Modern fusion methods: Jain et al. (2023) describe how surgery has moved on drastically from Harrington rod techniques which were two dimensional; all pedicle screw constructs now allow 3D straightening of the spine with vertebral derotation, so the spine is straight in the frontal, sagittal and transverse planes. Correction of complex failures, pseudoarthrosis, and flat back;Lawrence Lenke states that modern fusion methods now permit re-fusions for failures of prior surgery, and correction of congenital and acquired deformities of a magnitude which were previously uncorrectable. Neuromonitoring combined with high density instrumentation make complex procedures less likely to fail or cause neurological damage.

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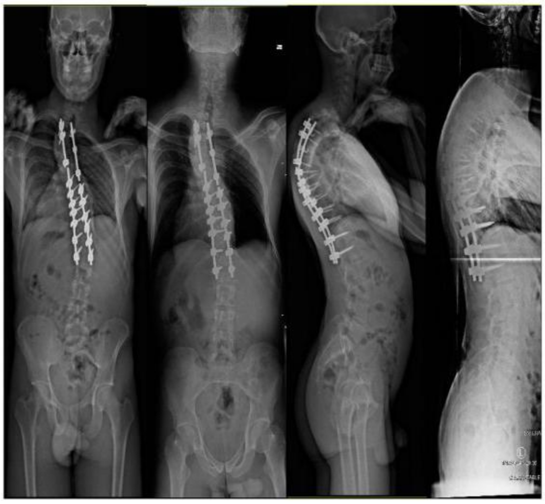

Figure 1 25-year-old male who previously underwent a posterior spinal instrumented fusion (PSIF) for T2-L1 at the age of 17 years presented with progressive back pain in the setting of bilateral rod fractures from T6 to T8. Preoperative anterio-posterior (AP) standing full-body radiographs demonstrated an 82° proximal thoracic and 65° main thoracic curve. Supine images showed the proximal and main thoracic curves decreasing to 77° and 48°, respectively. Preoperative lateral standing full-body radiographs demonstrated 88° of thoracic hyperkyphosis, 78° of hyperlordosis, and a small pelvic incidence of 48°.

Psychosocial Context and Lifetime Outcomes

Treating a case of Adolescent Idiopathic Scoliosis involves much more than simply straightening a curve in the back. Since it is diagnosed during the adolescent period, a time of identity and integration into society, psychosocial considerations are at least as significant as the physical deformity. The current focus of research is on HRQoL, assessing the impact of diagnosis and treatment on the patient's lifetime quality of life.

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Effects of treatment on adolescents' self-esteem: The works of Motyer et al (2022) and Tones et al have highlighted the profound effect the condition can have on the adolescent. For example The "Presurgical period" and anxiety: Motyer et al emphasized that before undergoing spinal surgery the adolescent undergoes "body dysmorphia"-they perceive the curve as far worse than it is clinically. Combined with the fear of surgical risks and protracted rehabilitation, it can induce a social withdrawal disorder, and anxiety related problems. The stigma of bracing: Although it has proven effective, bracing is socially distressing, as Tones et al showed patients feel like "other people" due to the need for 18-23 hours of use of rigid orthosis per day. Patients are embarrassed by the visible curve beneath their clothes, and the potential drop in self-esteem increases non-compliance and thus progression.

Long term physiological and mortality outcomes: Despite the problems in the adolescence, outcomes for patients treated for AIS are generally very good in the long term. Natural history and mortality: Weinstein at the University of Iowa's longitudinal 50 year study on the lifetime outcomes of patients diagnosed with scoliosis revealed that patients treated for AIS do not have increased mortality. Pulmonary function: Although severe un-treated curve (greater than 100 degrees) causes restrictive lung disease and cor pulmonale, patients whose curves are reduced to below 50 degrees have normal lung function throughout their life. Disability and mortality: with regards to chronic disability, it appears that patients treated for AIS have slightly higher incidences of back pain than the healthy control population, however no correlation with serious neurological defects or paralysis is apparent given the curve is managed before reaching a critical size.

Social integration in to adulthood: It is the social and physical transition into an adult that is the ultimate aim. Weinstein found that most women treated forAIS had normal pregnancies and deliveries, and that most patients lead active, professional lives. This transition relies upon adequate emotional support during

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the adolescent treatment phase, because if this is received the psychological resilience developed during this phase, can carry through into adult life.
By considering scores such as the SRS-22 (Scoliosis Research Society) questionnaire quality of life scores, (which measure pain, function, mental health and self-image,) doctors can consider the "person" as well as the "spine".

Conclusion

Over the past decade, a true paradigm shift has been established in the management of Adolescent Idiopathic Scoliosis (AIS) from reactive correction of existing physical deformities to a preventative and systematically addressed system driven by biological and biomechanical intervention. It has been clearly shown, as it is synthesized in this review, that AIS is no longer just an anomaly of the mechanically abnormal spinal axis; rather, it is a multi-system disease, where a "biological window of vulnerability" allows for ultimately three-dimensional collapse of spinal symmetry.
Successful modern treatment hinges on identifying the disease at its onset. With a clearer understanding of systemic biological markers such as disordered melatonin-calmodulin axis signaling and leptin mediated energy homeostasis, the "idiopathic" nature of AIS has been uncovered and is being defined as the failure of the systemic endocrine/molecular state to account for the mechanical feedback loop associated with rapid pubertal skeletal growth which is governed by the Hueter-Volkmann Law, leading to lasting wedging of the vertebrae and rotational deformation.
Use of the Lenke classification has brought accuracy and precision to the management of scoliosis. Unlike that in prior days of only two-dimensional evaluation of physical curve, the Lenke classification addresses every curve in all three dimensions as well as considering sagittal deformity. All treatment of AIS today seeks not only to straighten the spine by the use of rigid bracing (in sufficient dose to act as a barrier to progression) or through sophisticated three-

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dimensional spinal instrumentation and correction (e.g., instrumentation designed to allow 3-D derotation), but also to retain as much range of motion, physiological kyphosis, and long term respiratory health as possible.

Today, the cutting edge of treatment of AIS is primarily biological. Future management is moving towards and is becoming reality based on new research in controlling skeletal growth by pharmaceutical manipulation of molecular signals on mesenchymal stem cell development in the spine at the cellular level. Combination of sophisticated imaging technologies with individual genetic analyses for personalized management has created the potential for the spine to reach skeletal maturity without being unbalanced. This will benefit both the physiological stability and psychological wellbeing of each patient entering adulthood.

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