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Adolescent Idiopathic Scoliosis: Current Approaches and Treatment Options

Adölesan İdiopatik Skolyoz: Güncel Yaklaşımlar ve Tedavi Seçenekleri

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ABSTRACT

Adolescent idiopathic scoliosis (AIS) is a spinal deformity that emerges during adolescence and may progress over time. Although its exact etiology remains unclear, it is thought to involve a complex interplay of genetic, neurological, and developmental factors. Early diagnosis and regular follow-up are crucial determinants of disease progression and treatment success.
Treatment approaches are tailored based on the degree of curvature and skeletal maturity, ranging from observation to bracing and surgical intervention. Particularly in individuals undergoing growth, consistent and effective use of braces is critical to prevent curve progression. Surgical treatment is preferred in cases with severe curvatures to correct the deformity and halt its advancement.
The many unknowns surrounding the pathogenesis of AIS underscore the importance of continued research in this field. Advances in diagnostic techniques and innovative treatment strategies may offer more effective and lasting solutions. Current literature emphasizes the significance of personalized treatment planning and a multidisciplinary approach. There remains a continuing need for future research in the fields of genetics and biomechanics. Although artificial intelligence has made significant progress, it is not yet sufficiently functional for routine clinical use and requires further development.

Key Words: Adolescent Idiopathic Scoliosis, Management, Diagnosis, Treatment, Classification

ÖZ

Adölesan idiopatik skolyoz (AIS), ergenlik döneminde ortaya çıkan ve ilerleyebilen bir omurga deformitesidir. Etiyolojisi tam olarak aydınlatılamamış olmakla birlikte, genetik, nörolojik ve büyümeye bağlı faktörlerin karmaşık bir etkileşimini içerdiği düşünülmektedir. Erken tanı ve düzenli takip, hastalığın seyrini ve tedavi başarısını doğrudan etkileyen en önemli unsurlardır.
Tedavi yaklaşımları, eğriliğin derecesine ve iskeletsel olgunluğa göre belirlenmekte; gözlem, korse tedavisi ve cerrahi seçenekler arasında bireyselleştirilmiş bir planlama yapılmaktadır. Özellikle büyüme çağında olan bireylerde, eğriliğin ilerlemesini önlemek amacıyla korsenin etkin ve düzenli kullanımı kritik öneme sahiptir. Cerrahi tedavi ise büyük eğriliklerde deformitenin düzeltilmesi ve ilerlemenin durdurulması amacıyla tercih edilmektedir.
Adölesan idiyopatik skolyozun patogenezine dair bilinmeyenlerin fazlalığı, bu alanda yapılacak araştırmaların önemini artırmaktadır. Gelişen tanı yöntemleri ve yenilikçi tedavi yaklaşımlarıyla, daha etkin ve kalıcı çözümlere ulaşmak mümkün olabilir. Güncel literatür, bireyselleştirilmiş tedavi planlarının ve multidisipliner yaklaşımın önemini vurgulamaktadır. Gelecekte genetik ve biyomekanik alanlarında yapılacak çalışmalara duyulan ihtiyaç devam etmektedir. Öte yandan, yapay zekâ önemli bir gelişim göstermiş olsa da mevcut durumda klinik kullanım açısından yeterince işlevsel değildir ve daha da geliştirilmesi gerekmektedir.

Anahtar Sözcükler: Adölesan İdiopatik Skolyoz, Yönetim, Tanı, Tedavi, Sınıflandırma

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Introduction

Scoliosis is a complex spinal deformity characterized by structural abnormalities in all three anatomical planes. Clinically, it is most notably identified by a lateral curvature of the spine in the frontal plane, often accompanied by vertebral rotation along the longitudinal axis. Radiologically, the condition is assessed using the Cobb angle, with a measurement of 10 degrees or more considered diagnostic [1,2].

Adolescent idiopathic scoliosis is a structural spinal deformity of unknown etiology that arises between the ages of 10 and skeletal maturity. Its prevalence in the general population is estimated to be between 2% and 4%. AIS is defined by a lateral spinal curvature of at least 10° in the coronal plane, accompanied by vertebral rotation. It represents the most common form of idiopathic scoliosis, accounting for approximately 80% of all cases. AIS is more frequently observed in females, and curve progression is influenced by factors such as sex, growth potential, and initial curve magnitude [1,3].

Although AIS is often asymptomatic, progressive deformities can lead to postural abnormalities, pain, and, in severe cases, respiratory dysfunction. The Cobb angle remains the most widely used radiographic method for diagnosis. Treatment options include observation, bracing, and surgical intervention, depending on the severity and progression of the curve [2,3].

Pathophysiology

The pathophysiology of AIS is multifactorial and has not yet been fully elucidated. However, research suggests that genetic, neurological, hormonal, biomechanical, and growth-related factors may contribute to its development [2,3].

- **Genetic Factors**

AIS is known to exhibit familial transmission. Studies have shown an increased prevalence of scoliosis among first-degree relatives of affected individuals. Recent genome-wide association studies (GWAS) have identified multiple single nucleotide polymorphisms (SNPs), particularly in the LBX1, GPR126, and CHL1 genes, which appear to be strongly associated with scoliosis susceptibility [4]. Additionally, the BNC2 variant rs10738445 has been shown to correlate with both disease onset and curve progression [Ikegawa 2024]. A recent study also demonstrated that specific SNP profiles may help predict the outcome of brace treatment, suggesting a role for genetic screening in personalized management approaches for AIS [5].

- **Growth Rate and Asymmetric Spinal Development**

AIS typically begins during adolescence, a period marked by rapid growth. Structural imbalances occurring during this growth spurt may result in asymmetric vertebral development, which can contribute to the onset or progression of the scoliotic curve [6,7].

- **Neurological and Proprioceptive Mechanisms**

Some studies have reported impairments in balance, proprioception, and postural control in individuals with AIS. These findings suggest that dysfunctions originating in the central nervous system may play a role in the pathogenesis of scoliosis [8].

- **Hormonal Factors**

Melatonin deficiency and abnormalities in melatonin receptors have been proposed as potential contributors to scoliosis development. Additionally, hormones such as growth hormone and estrogen are known to influence spinal growth and development [9].

- **Biomechanical Influences**

Vertebral rotation and asymmetric loading are key factors in curve progression. Uneven mechanical stress on the spine over time may lead to structural deformation [10]. Recent biomechanical modeling studies have also emphasized the importance of growth modulation forces and intervertebral disc elasticity in curve dynamics, suggesting that minor structural asymmetries during peak growth periods can amplify progression through altered load distribution [4].

Clinical Manifestations

AIS typically has an insidious onset and remains asymptomatic in its early stages. Consequently, many cases are identified through school-based screening programs or when parents observe asymmetries in their child's posture [2,3,11]. The clinical manifestations of AIS vary depending on the degree and location of the spinal curvature.

The most notable signs are visible asymmetries in body alignment. Shoulder asymmetry, where one shoulder appears higher than the other, is a common early finding. Due to vertebral rotation, one scapula may become more prominent than the other. Asymmetry in the waistline specifically in the paraspinal muscle contour is another common observation. Additionally, deviation of the torso from the midline, referred to as trunk shift, is often present, particularly in more severe curves [6-8].

A widely utilized clinical assessment tool is the Adam’s forward bending test, which is particularly helpful for detecting rotational deformities. During this test, when the patient bends forward, a noticeable rib prominence or costal hump may appear on one side of the back, indicating axial rotation of the vertebrae [8].

Although AIS is usually painless, back or lumbar pain may occasionally occur in cases involving large curves or rapid progression. The presence of pain warrants further evaluation to rule out underlying pathologies such as spinal tumors or infections [7].

Postural alterations are also among the characteristic features of AIS. These may include imbalance during forward bending, asymmetrical pelvic alignment, visible lateral trunk curvature, and in advanced cases gait disturbances [1].

Although rare, severe thoracic curves can result in thoracic cage deformities. Such deformities may compromise pulmonary function and lead to restrictive lung disease, manifesting as dyspnea or other respiratory complaints [1,12].

Diagnosis

The diagnosis of AIS is established through a comprehensive clinical assessment and radiological evaluation. This diagnostic process begins with the exclusion of secondary causes of scoliosis and includes objective quantification of spinal curvature [13].

A detailed medical history is essential and should include questions regarding a family history of scoliosis, rapid growth during adolescence, and the presence of pain which is uncommon in idiopathic cases and may indicate an underlying pathology. Additionally, the occurrence of neurological symptoms necessitates further investigation to exclude other neurological disorders [1,2,13].

Physical examination plays a vital role and typically involves the Adam’s forward bending test, which may reveal a rib hump suggestive of vertebral rotation. Other clinical signs include asymmetry in the shoulders, waist, and pelvis, as well as scapular prominence and trunk imbalance. A neurological examination assessing reflexes, motor strength, and sensory function should also be performed [1-3].

Radiological assessment plays a crucial role in confirming the diagnosis. Posteroanterior and lateral spinal radiographs are used to identify the location, magnitude, and rotational aspect of the spinal curvature. The Cobb angle is the gold standard measurement, and a curvature of 10 degrees or more is diagnostic of scoliosis. The Risser sign is also assessed to determine skeletal maturity and to estimate the likelihood of curve progression. In cases where there is pain, neurological signs, or atypical curvature, magnetic resonance imaging (MRI) is recommended to rule out any underlying spinal cord abnormalities [13].

School-based screening programs have proven effective in the early identification of AIS, particularly in girls aged 10 to 14 years, and are widely implemented in several countries to ensure timely diagnosis and intervention [14,15].

Disease Progression (Prognosis)

The course of AIS is influenced by several factors, including the initial Cobb angle, patient age, sex, and skeletal maturity. In cases diagnosed early and followed regularly, the curvature may remain stable or progress slowly. However, some patients are at risk for rapid curve progression [10,11,16].

Factors Associated with Curve Progression:

- Higher Cobb angle at diagnosis (especially >30°)

- Lower Risser stage (indicating less skeletal maturity)
- Female sex
- Period of rapid linear growth
- Positive family history of scoliosis [17]

In general, curves less than 30° tend not to cause significant problems in adulthood, whereas curves exceeding 50° have a greater likelihood of progression and may be associated with functional limitations. Untreated severe curves can lead to chronic back pain, restrictive pulmonary function, and reduced quality of life in the long term [16,17].

AIS Classification

The classification of Adolescent Idiopathic Scoliosis (AIS) is essential for its diagnosis, follow-up, and treatment planning. Over the years, several classification systems have been developed. Among them, the most widely used today are the King-Moe and Lenke classifications [1,2,18]

King-Moe Classification

This system is particularly useful for the surgical planning of thoracic curves. However, it does not take sagittal plane deformities into account, which is a significant limitation. The King-Moe classification includes five types:

- **Type 1:** Thoracic and lumbar curves are both present; the lumbar curve is larger.
- **Type 2:** Thoracic and lumbar curves are both present; the thoracic curve is larger.
- **Type 3:** The primary curve is thoracic; the lumbar curve corrects on bending radiographs.
- **Type 4:** A long thoracic curve on the right side is present.
- **Type 5:** Double thoracic curves are present [1,2].

Lenke Classification

Developed to overcome the limitations of the King-Moe system, the Lenke classification considers both coronal and sagittal plane deformities and provides more comprehensive data for surgical planning. It consists of three main components: curve type, lumbar modifier, and sagittal thoracic modifier (Table 1) [18].

Table1: Lenke Classification

Type	Proximal Thoracic	Main Thoracic	Thoracolumbar / Lumbar	Description
1	Non-structural	Structural (major)	Non-structural	Main thoracic
2	Structural	Structural (major)	Non-structural	Double thoracic
3	Non-structural	Structural (major)	Structural	Double major
4	Structural	Structural (major)	Structural (major)	Triple major
5	Non-structural	Non-structural	Structural (major)	Thoracolumbar /lumbar
6	Non-structural	Structural	Structural (major)	Thoracolumbar /lumbar-main thoracic

Curve Types

- **Major curve:** The curve with the largest Cobb angle and is structural.
- **Minor curves:** Considered structural if Cobb angle is >25° on bending radiographs, or if proximal thoracic (T2–T5) or thoracic (T10–L2) kyphosis exceeds 20°.

Lumbar Modifier (L):

Determined by the relationship between the Central Sacral Vertical Line (CSVL) and the apex of the lumbar curve:

- Type A: CSVL passes between the pedicles of the apical vertebra.
- Type B: CSVL touches the apical vertebra.
- Type C: CSVL is completely medial to the apical vertebra.

Sagittal Thoracic Modifier (S):

Based on the kyphotic angle between T5–T12:

- \- (Hypokyphosis): Less than 10°
- N (Normokyphosis): Between 10° and 40°
- \+ (Hyperkyphosis): More than 40°

As a result, a scoliosis curve is defined using the Lenke system as “Type – Lumbar Modifier – Sagittal Modifier” [1,2,18].

Treatment

The treatment of AIS should be individualized according to the degree of spinal curvature, the patient's chronological and skeletal age, and the estimated risk of curve progression.

Observation is primarily recommended for patients with a Cobb angle between 10° and 20°, particularly when there is considerable remaining growth potential. These individuals are typically followed up every 4 to 6 months with clinical and radiographic evaluations. This approach is suitable for those at low risk of progression, and scoliosis-specific exercise programs such as the Schroth method may be incorporated as adjunctive therapy [15,19,20].

Bracing, or orthotic management, is generally indicated in patients who present with Cobb angles between 20° and 40° and are still skeletally immature. The primary objective is to halt or slow the progression of the spinal curvature. Commonly used braces include the Boston, Milwaukee, Charleston, and Providence braces, with recommended daily use ranging from 16 to 23 hours. Patient compliance is crucial, as adherence directly impacts treatment efficacy. (Figure1). Recent advancements have led to the increasing availability of personalized braces produced using 3D printing Technologies [14,15].

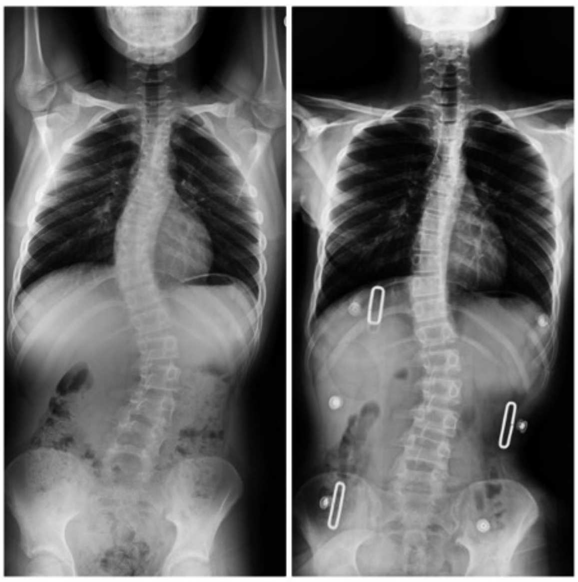

Figure 1: Bracing and exercise therapy are applied for curvatures with a Cobb angle between 20 and 40 degrees.

Recent advancements in bracing technology have led to the development of sensor-integrated brace systems, which aim to improve compliance and treatment outcomes in adolescents with idiopathic scoliosis. These systems utilize embedded sensors to monitor brace wear time and pressure distribution, providing real-time feedback to both patients and clinicians. Studies have shown that such technology significantly enhances adherence to bracing protocols and allows for more personalized treatment strategies [21] Despite their promising potential, sensor-integrated braces are not yet widely adopted in clinical practice, indicating the need for broader awareness and long-term outcome evaluations.

Surgical intervention is typically reserved for patients with progressive curves exceeding 40–45° Cobb angle. The goals of surgery are to prevent further deformity, restore spinal alignment, and improve physical appearance. The most frequently employed surgical procedure is posterior spinal fusion with instrumentation (Figure2). In select cases, anterior or combined anterior-posterior approaches may be warranted. Although surgical outcomes have improved due to advances in minimally invasive techniques and intraoperative navigation systems, potential complications such as infection, bleeding, implant displacement, and pseudoarthrosis remain concerns [19,20,22].

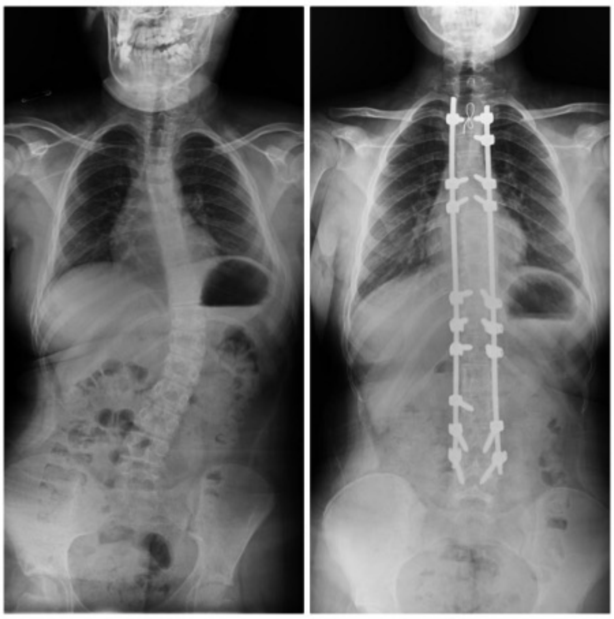

Figure 2: Surgical procedures are applied for curvatures with a Cobb angle greater than 40 degrees.

Vertebral body tethering (VBT) has emerged as a relatively novel, growth-modulating technique for the treatment of AIS, particularly in skeletally immature patients. The procedure involves the thoracoscopic or mini-open placement of screws along the convex side of the scoliotic curve, which are then connected with a flexible tether that applies compressive force, gradually correcting the curvature through asymmetric growth. The primary advantages of VBT include the preservation of spinal motion, avoidance of spinal fusion, and reduced surgical morbidity compared to traditional posterior spinal fusion [23,24].

Recent meta-analyses have reported promising short- to mid-term outcomes, with a mean Cobb angle correction of approximately 25–30 degrees and notable improvements in trunk balance and patient satisfaction [24]. However, the technique is not without risks. The most frequently reported complication is tether breakage, occurring in up to 21–23% of cases, potentially necessitating revision surgery [25]. Moreover, newer studies exploring posterior VBT approaches suggest that while comparable correction can be achieved, complication rates may be higher due to surgical learning curves and hardware challenges [26].

Despite these challenges, VBT remains a promising option for selected AIS patients, particularly those with flexible curves and remaining growth potential. Nevertheless, long-term data, standardized surgical protocols, and robust comparative trials with fusion techniques are still needed to establish its definitive role in scoliosis management [27].

Artificial intelligence (AI) has become increasingly prevalent in many fields of medicine, including orthopedics and spinal surgery. Although the current application of AI in Adolescent Idiopathic Scoliosis (AIS) remains limited, it offers promising potential for the future. Recent studies highlight the use of deep learning techniques, particularly convolutional neural networks (CNNs), for the analysis of scoliosis radiographs. These systems can automatically measure Cobb angles, evaluate coronal deformities, and even perform complex tasks such as Lenke classification. Additionally, AI models have shown the capability to predict curve progression and, in some cases, provide treatment recommendations. Nevertheless, the integration of AI into clinical practice still faces numerous uncertainties and ethical challenges. To ensure the safe and effective use of AI in diagnosis, decision-making, and treatment, further high-quality, multicenter studies are essential. Moreover, emerging technologies like robotic-assisted surgery offer promising alternatives for selected patients [28,29].

Finally, although physical therapy alone has limited efficacy in reducing curve magnitude, it plays a supportive role in improving muscular symmetry, posture, and overall quality of life. Scoliosis-specific exercise protocols, especially the Schroth method, are often utilized as complementary to bracing therapy [9,13,19].

Complications

The management of AIS may be accompanied by various complications, which can arise either from the disease itself or as a result of treatment interventions. Understanding these potential complications is essential for optimal clinical decision-making and patient counseling [30].

Treatment-Related Complications

Bracing, a conservative treatment method widely used in skeletally immature patients, is generally safe but not without side effects. Common issues include skin irritation due to prolonged contact and friction, as well as psychosocial impacts such as reduced self-esteem and negative body image, particularly during adolescence when physical appearance plays a critical role in psychological development.

Surgical correction, although effective in halting curve progression and improving spinal alignment, carries a number of inherent risks. These may include:

- Infection, either superficial or deep, requiring antibiotic therapy or surgical debridement;
- Intraoperative or postoperative bleeding, which may necessitate transfusion;
- Implant-related complications, such as loosening or breakage of rods and screws;

• Neurological injury, including spinal cord damage, though this remains a rare occurrence;

• Pseudoarthrosis, or failed spinal fusion, potentially requiring revision surgery;

• Reduced spinal mobility, particularly in long fusions, which may impact the patient's ability to perform activities that require spinal flexibility [13,30,31].

Disease-Related Complications

In the absence of appropriate treatment or in progressive cases, AIS may lead to several long-term complications. One of the most prominent is cosmetic deformity, which manifests as asymmetry of the shoulders and waist, and a noticeable postural imbalance [31].

Chronic pain, particularly in the lumbar or thoracic regions, is more commonly reported in adults with a history of untreated or severe scoliosis during adolescence [27,30].

Another important consideration is respiratory dysfunction. Thoracic scoliosis can compromise lung development and reduce total lung volume, potentially resulting in restrictive pulmonary impairment.

Finally, the psychosocial burden of AIS must not be underestimated. Adolescents are particularly vulnerable to the psychological effects of body image disturbance and social comparison, which can lead to reduced self-confidence and emotional distress [30,32].

Impact on Quality of Life

Adolescent idiopathic scoliosis (AIS) is a complex condition that extends beyond structural spinal deformity, affecting physical, psychological, and social domains of health. As curve severity increases, quality of life often declines proportionally. Moderate to severe curves may lead to persistent back or lumbar pain, reduced mobility, and decreased participation in physical activities. Thoracic deformities can impair pulmonary function, limiting exercise capacity and daily functioning [30-32].

Visible spinal deformities during adolescence can negatively affect body image and self-esteem, contributing to emotional vulnerability. Orthotic bracing, commonly used in conservative treatment, may exacerbate these concerns, leading to social withdrawal and reduced peer interaction. Chronic pain and post-surgical recovery may impair concentration, resulting in decreased academic performance. Prolonged school absence due to hospitalization can further disrupt education and emotional well-being [30-32].

Assessment of Quality of Life

Several validated instruments are available for evaluating quality of life in AIS patients. These include:

• The Scoliosis Research Society-22 questionnaire (SRS-22), which assesses domains such as pain, self-image, and function;

• The Pediatric Outcomes Data Collection Instrument (PODCI), designed to measure physical and psychosocial function in children;

• And the Short Form-36 Health Survey (SF-36), a general health assessment tool widely used across various conditions [31].

Conclusion

In the management of AIS, a multidisciplinary approach, patient adherence, and psychosocial support are essential components. Comprehensive treatment strategies aimed at enhancing quality of life are increasingly emphasized. Future research focusing on genetic and biomarker-based predictors may pave the way for personalized treatment protocols, enabling a holistic approach that encompasses the physical, psychological, and social dimensions of scoliosis.

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