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Adolescent Idiopathic Scoliosis: A comprehensive review

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ABSTRACT
Adolescent idiopathic scoliosis (AIS) is a three-dimensional spinal deformity that affects youngsters between the ages of 11 and 18. The authors conducted a review of the accessible literature to offer an overview and updates on current management choices for spine surgeons.
While smaller thoracic and thoracolumbar curves can be handled conservatively with monitoring or bracing, bigger or quickly expanding curves may require corrective surgery. The authors discuss the unusual characteristics to look for in patients who may require additional MRI study during diagnosis and explain the essential concepts of surgical management of AIS.
Patients with AIS can be extremely successfully handled using a mix of conservative and surgical approaches. Such children had great long-term outcomes.
Keywords: adolescent idiopathic, scoliosis; pediatric; spine; deformity

1. Aetiology of Idiopathic Scoliosis

The exact etiology of idiopathic scoliosis is unknown. A variety of hypotheses and concepts have been proposed, with etiologies involving genetics, the central nervous system, biomechanics, metabolic pathways, skeletal spinal growth, bone metabolism, and others**[1]*(Figure 1).***

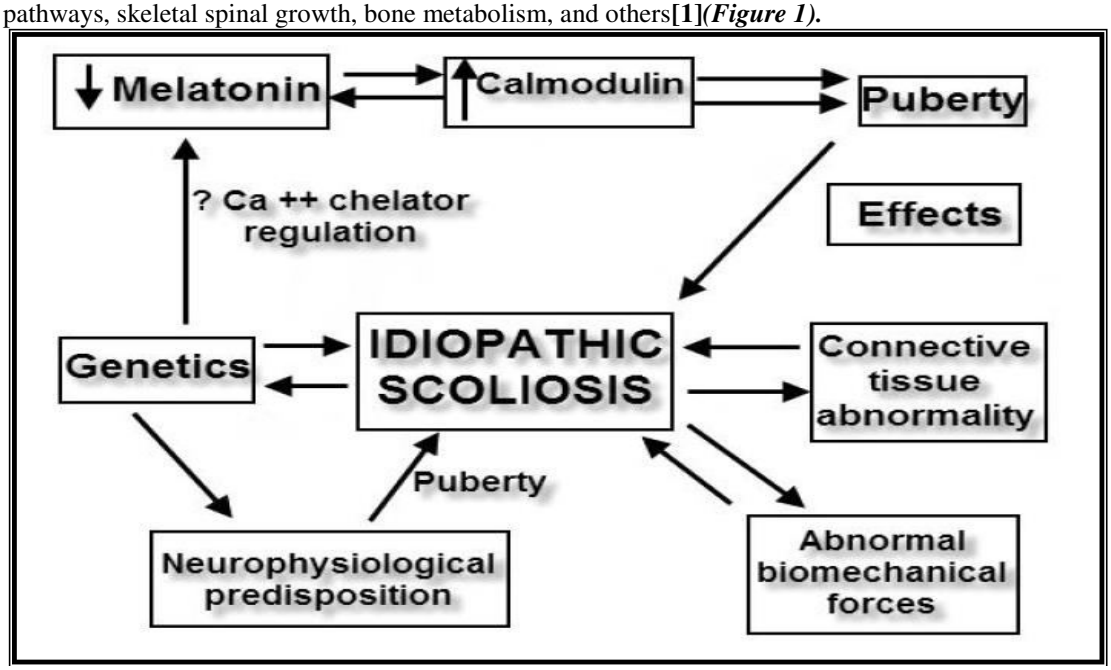

Figure (1): Possible inter-relationships of various factors that have been shown to have possible role in the pathogenesis of idiopathic scoliosis**.[2]**

The genetic Factors:

AIS has been shown to have a genetic component, with a meta-analysis revealing concordance for AIS in 36% of dizygotic twins and 73% of monozygotic twins. **[3]** Large pedigree studies have demonstrated different methods of inheritance, including autosomal dominance, maternal factors, multiple gene inheritance, X-linked dominance, and multifactorial inheritance**[4]**.

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One large pedigree study of 101 families, including 778 individuals, found that severe forms of AIS could be attributed to an autosomal dominant major gene diallele model with incomplete sex-dependent penetrance**[5]**

Genome-wide association studies (GWASs) examine a genome-wide set ofgenetic variants in individuals to determine if any variant is associated with a trait Several loci have been detected by linkage analysis. IS related zones are spotted in 6q, 10q and 18q, 17p11.2, 19p13.3, 8q11, Xq23–26.1, 9q31.3–q34.3, 5q13–q14 and 3q11–q13, 9q31.2-q34.2, 17q25.3-qtel chromosomes**.[6]**

Tissue deficiencies:

Competing theories propose that the primary pathology of scoliosis is centered in each part of the structural tissues of the spine (bone, muscle, ligaments and intervertebral disc).

Cheung and colleagues 2006 suggested that scoliosis may be related to osteopenia. They found that the mineraldensity of the vertebrae is lower in girls with scoliosis, compared to matched control subjects.**[5,6]**

Vertebral growth abnormality theories:

Studies of the growth mechanism of the anterior and posterior aspects of the vertebral elements suggest a different mechanism in each (endochondral growth anteriorly and intramembranous growth posteriorly).**[7]**

Villemure and other investigators 2002 had postulated that the etiology of scoliosis is related to altered growth primarily in the sagittal plane with the development of relative thoracic lordosis. If the condition is severe enough, the spine **[8]**rotates laterally to maintain global sagittal balance. The increased length of the anterior spine is effectively shortened by rotation or buckling of the apical segment laterally. This theory accounts for all three planes of deformity.**[9]**

Central nervous system theories:

The etiopathogenesis of AIS has also been tied to several functional and morphological abnormalities of the central nervous system (Fig. 38). Derangements in neurophysiological functions have been found in patients with AIS, including abnormal somatosensory-evoked potentials, static and dynamic postural instability, abnormal proprioceptive function, and vestibular and visuo-oculomotor dysfunction**[10]**.

Patients with AIS have been found to have differences in brain volume ratios and indices via functional MRI, with abnormalities coinciding with functional areas involved in motor control and vestibular and somatosensory systems **[11]**. Studies have also shown that the vestibular apparatus, including semicircular canal abnormalities, may be linked to the etiopathogenesis of AIS, or may alternatively be a compensatory response to in the development of AIS. This could possibly explain the abnormal somatosensory function and poor balance control that may be present in patients with AIS **[12]**

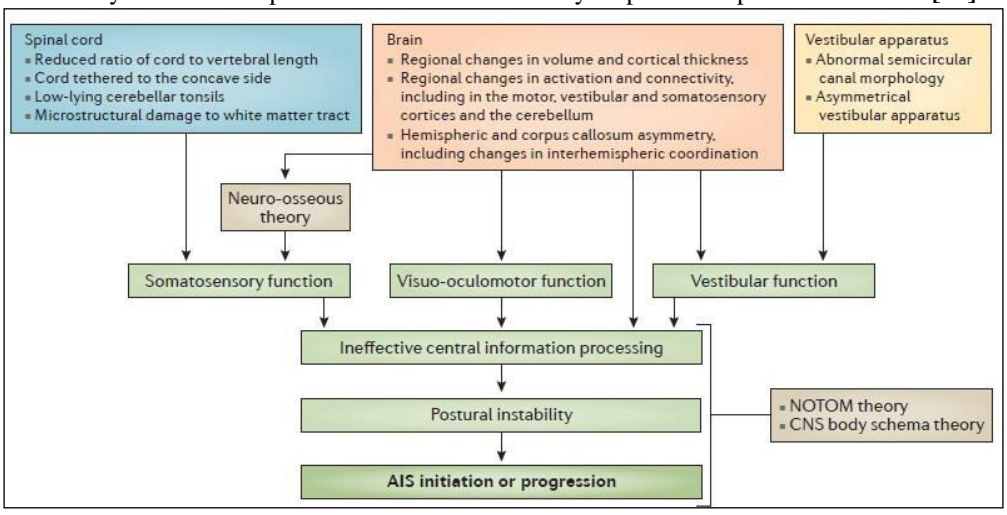

Figure (2): Summary of the morphological changes in the central nervous system involved in AIS**[5]**

Pineal body dysfunction and melatonin deficiency theory:

Pineal body dysfunction and melatonin deficiency may be related to scoliosis. This theory is based on research involving pinealectomy in chickens. The procedure was found to result in high incidence of severe scoliosis, therefore post-pinealectomy melatonin deficiency presumably led to scoliosis in chickens.**[13]**

Dubousset and Machida 2018 found lower-than-normal melatonin concentration in the serum of patients with progressive scoliosis compared to the serum of those with stable curve and concluded that a simple lack of melatonin is not the cause, but rather that melatonin may act as a preventive measure

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against progression of the curve because melatonin receptors are located in the brain stem and spinal cord dorsal gray matter, areas associated with postural control**[13]**.

2. Clinical Evaluation

History:

The spinal deformity: One of the most common is shoulder height asymmetry, in which one shoulder appears higher than the other. A shift of the body to the right or the left can occur especially when there is a single curve in the thoracic or the lumbar spine without a second curve to help balance the patient. This is often seen as some waistline asymmetry in which one hip appears to be higher than the other and may result in one leg appearing taller than the other. A prominence on the back or a rib hump secondary to the rotational aspect of the scoliosis is the most visible sign of scoliosis**[14].**

Pain: Low back pain is not uncommon; pain is often reported as discomfort of a mild fatigue variety. However, a study by Ramirez et al.**[15]** looked at 2442 patients with AIS and noted that 23% (560 patients) had back pain at the time of presentation and 9% had back pain during the period of observation. Furthermore, these authors found an association between back pain, an age > 15 years, skeletal maturity (Risser grade ≥ 2) and postmenarchal stage**[14,15]**

***Neurological symptoms*:** should be absent.Adolescent idiopathic scoliosis generally does not result in severe or radiating pain orneurological symptoms such as weakness, sensorychanges and balance or gait disturbances. If these symptoms occur, further meticulous evaluation and MRI examination are necessary to exclude other pathologies.**[16]**

***The family history*:**

Scoliosis occurs three times more frequently in a child whose parent is similarly affected and seven times more frequently if a sibling has been treated for scoliosis. **[14]**

Physical examination

Objective:

General examination:

The height of the patient while standing and sitting and the arm span shouldbe measured and recorded; these measurements are compared with later ones to determine changes in the patient's total heightand whether any changeis caused by growth of the lower extremities or by an increase or a decrease in the height of the trunk**[14]**.

Any clue of possible cause e.g. high arched palate (Marfan's syndrome), deformed ear (congenital scoliosis),café au lait patches (neurofibromatosis), joint hyperflexibilty (Ehlers-Danlos syndrome) and midline dimples or hairy patches(spinal dysraphism)**[16].**

Assesment of puberty: Puberty lasts 2 years and begins at a bone age of 11 in girls and 13 in boys. This stage is characterized by an "*acceleration phase*" of rapid growth lasting 2 years and is followed by a steady reduction of growth for 3 years,known as the "*deceleration phase*." The skeletal maturation of the patient must be followed to evaluate the risk of AIS progression during the acceleration phase; the younger the child, the higher the risk for progression of a scoliotic curve.**[17]** Bone age, Tanner classification, stages of puberty,standing and sitting height, arm span, and weight should all be considered when evaluating patients.**[18]**

Grading is performed using Tanner system (breast and pubic hair development in girls) and (genitalia and pubic hair in boys)

Stage 1: There is no true pubic hair, although there may be a fine velus over the pubes similar to that over other parts of the abdomen.

Stage 2: Sparse growth oflightly pigmented hair is usually straight or only slightly curled. This usually begins at either side of the base of the penis. Stage 3: The hair spreads over the pubic symphysis and is considerably darker and coarser and usually more curled.

Stage 4: The hair is now adult in character but covers an area considerably smaller than in most adults. There is no spread to the medial surface of the thighs.

Stage 5: The hair is distributed in an inverse triangle as in the female. It has spread to the medial surface of the thighs but not up the linea alba or elsewhere above the base of the triangle.**[19]**

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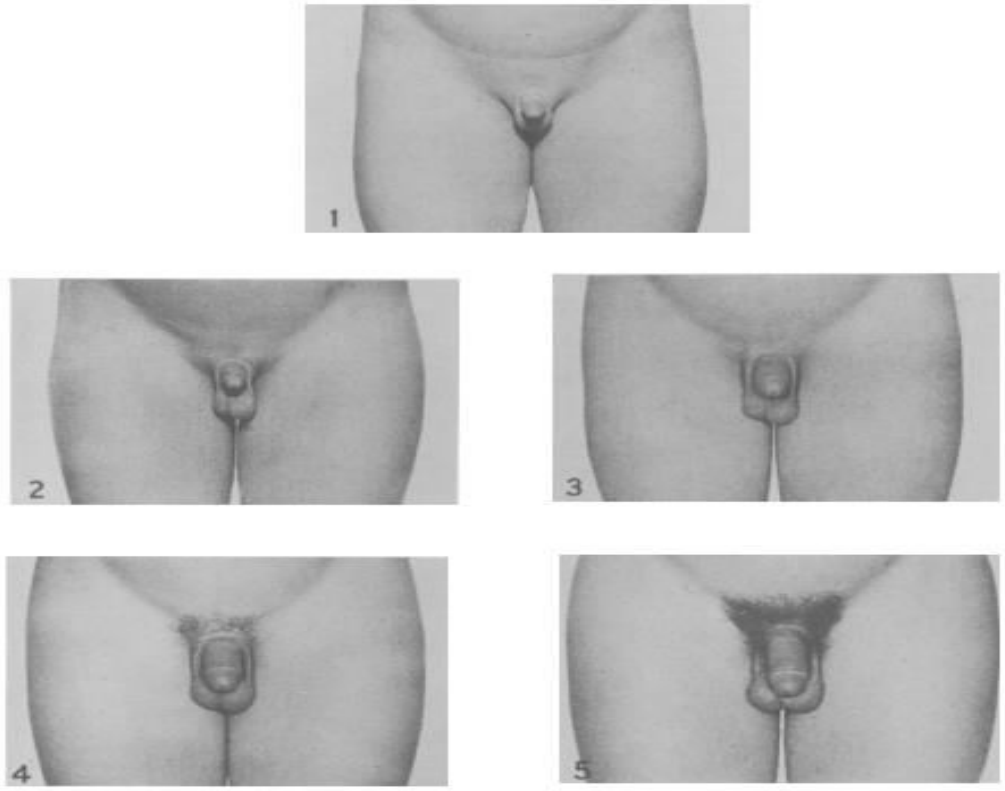

Fig. (3): Stages of development of the penis and scrotum.**[19]**

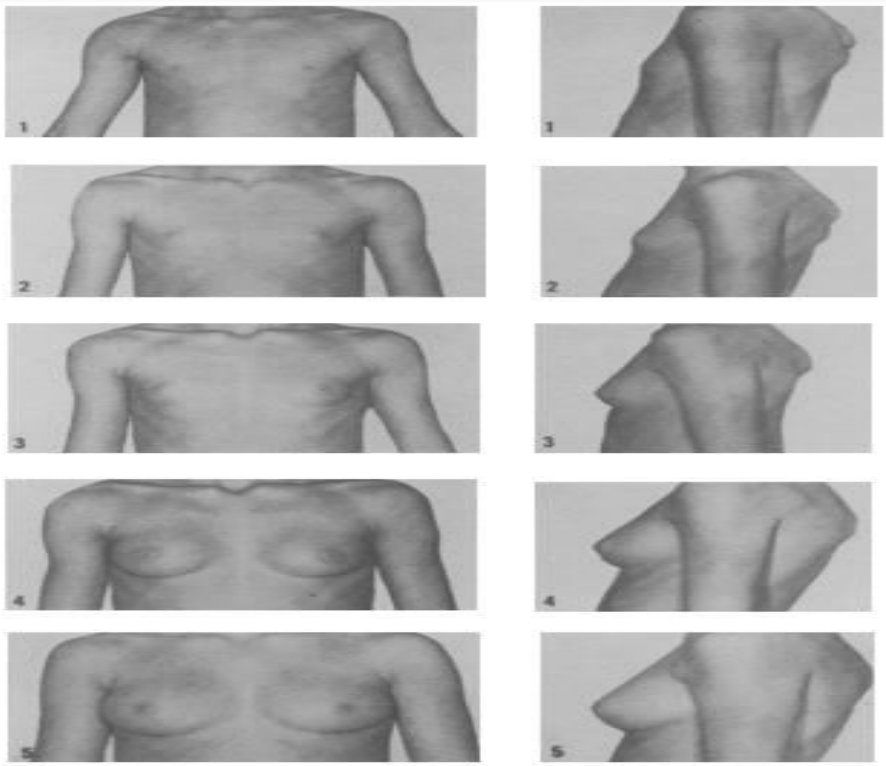

Fig. (4): Stages of breast development**[19]**

Stage 1: The infantile stage persists from the immediate postnatal period until the onset of puberty.

Stage 2: This is the bud stage, during which the breast and papilla are elevated as a small mound, and the diameter of the areola is increased. The development of this appearance is the first indication of pubertal development of the breast.

Stage 3: The breast and areola are further enlarged and present an appearance rather like that of a small adult mammary gland with a continuous rounded contour.

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Stage 4: The areola and papilla are further enlarged and form a secondary mound projecting above the corpus of the breast.

Stage 5: This is the typical adult stage with a 188 smooth rounded contour, the secondary mound present in stage 4 having disappeared**.[19]**

Lower limb examination: assessment of leg lengths (Limb-length discrepancy) may result in pelvic tilt, which can induce a "compenstory scoliosis." Conventional teaching recommends absolute limb measurement from the anterior superior iliac spine (ASIS) to the medial malleolus or from the ASIS to the lateral border of the sole of the foot just below the fibula, hip deformity or contracture and foot deformity(spinal dysraphism) **[16]**

Local Examination:

The spine should be examined carefully from posteriorly and from the sides, and the characteristics of the deformity should be recorded.

Determine whether the shoulders and hips are level and check for waist asymmetry or a flank crease.

Spinal coronal balance is assessed by a plumb line which, dropped from the base of the neck, should bisect the natal cleft and the offset measured with a ruler.

In the *Adams forward-bend test*, the bend should exhibit a smooth "spinal rhythm." In having a child perform the Adams forward-bend test, the examiner should note any curvature of the spine or rib prominence on the side of the convexity of a spinal curve.This is best done by standing directly behind the child and looking in a straight line from the gluteal cleft of the buttocks to the neck.**[16]**The scoliometer is an excellent screening device that can be used in conjunction with the Adams forward-bend test to evaluate truncal rotation (Fig. 5). The device when placed at different spinous processes can quantify rotation of the trunk. An angle of less than 7 degrees is considered within the limits of normal.**[16]**

Fig (5)(1) Standing clinical photograph; note the rib prominence and scapular elevation. **(2)** Adams forward-bend test showing a prominent rib hump on the right. **(3)** Measurement with a scoliometer shows a 17-degree angle**[9]**.

Palpate the whole spine, noting the shape of the curve and the level of the apical vertebra, and repeat when prone to assess for tenderness,

Neurological examination:

Assessment of all reflexes including the planter response and clonus are important objective tests and should always be performed. Asymmetric abdominal reflexes may indicate a cervical syrinx and this may be the only abnormal finding in these patients**[14]**.

Radiological Evaluation

Roentgenographic Evaluation:

Standing examination:

Both posteroanterior and lateral views are taken. These radiographs should include the iliac crest distally and most of the cervical spine proximally, which generally require 14 x 36 inch cassettes**[20]** as shown in **figure 6**.

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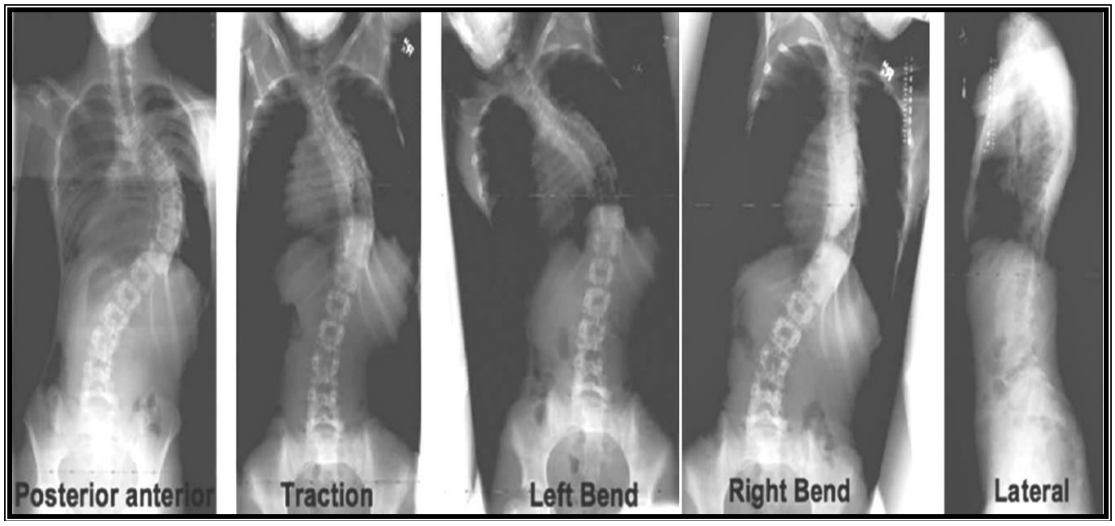

Figure (6): PA and Lateral radiograph (Lt) of a RT thoracic scoliosis (Rt), LT bending view (LT) and RT bending view (RT) , Note the decrease in curve degree in the Rt bending view which is the direction of the convexity **[21]**.

Supine examination: Supine films are used to evaluate flexibility with bending or traction**[16].**

Flexibility views: Spinal flexibility is a decisive biomechanical parameter for the planning of (AIS) surgery. It provides information regarding, among other things, the extent of structural curves, the vertebral levels to be instrumented, and the surgical approach**[22]**.

3. Classification of AIS

The purposes of a scoliosis classification system are first to allow a systematic and reproducible way of describing various types of curves, and second to guide treatment. The first scoliosis classification system was described by Cobb; the first system to classify and guide treatment was the King classification. The interobserver and interobserver reliability of the King classification was found to have poor-to-fair validity, reliability, and reproducibility

King Classification:

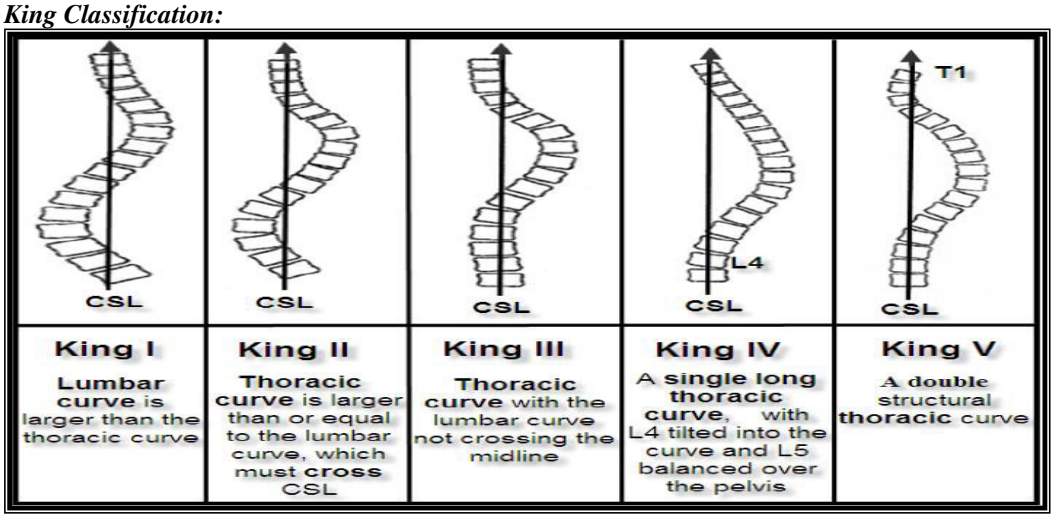

Figure (7): King Classification of thoracic Curve Patterns**[23].**

Type I: The type I and II curves are the most frequently confused because they are both S-shaped double curves. The type I curve should be recognized easily because the lumbar curve is larger than the thoracic curve. Occasionally, the thoracic and lumbar curves are nearly equal in magnitude, but the lumbar curve is less flexible on side-bending. Clinically, the lumbar rotational prominence is larger than the thoracic.

Type II: This curve has stimulated more discussion and created more confusion than any of the other curve patterns. It is a combined thoracic and lumbar curve pattern. On radiographs, the thoracic curve is larger than, or equal to the lumbar curve. By definition, the lumbar curve must cross the center sacral line. On supine side-bending radiographs, the lumbar curve is more flexible than the thoracic curve. On clinical examination, the thoracic rotational prominence is larger than the lumbar**[24]**.

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Type III: This is a pure thoracic curve. The lumbar curve does not cross the midline and is very flexible on side-bending radiographs. On clinical examination, the thoracic prominence should be much more apparent than the lumbar prominence, which is frequently nonexistent.
Type IV: This type is also a single thoracic scoliosis. It is a long thoracic curve with L5 balanced over the pelvis and L4 tilted into the curve
Type V: It is a double structural thoracic curve. On radiographs the first thoracic vertebra is tilted into the concavity of the upper curve, which is structural on side-bending radiographs. On clinical examination there is frequently elevation of the left shoulder. On forward-bending examination, there is an upper left thoracic prominence and a lower right thoracic prominence**[23].**

***Lenke Classification*[25].**

The Lenke classification system of AIS was developed in 2001 to provide a comprehensive and reliable means to categorize and guide treatment.

Description of curve types:

Type 1: main thoracic (MT) is the only structural curve while the others (proximal thoracic and lumbar or thoracolumbar) are non-structural.
Type 2: 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 non-structural.
Type 3: 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.
Type 4: triple major curve pattern when the MT is the major curve but all three curves are structural.
Type 5: the TL or L curve is the major and only structural curve, with the PT and\or MT curves being minor and nonstructural.
Type 6: the TL or L curve is the major curve measuring at least 5° more than the MT which is the minor but structural curve.
Structural curves were defined as those that fail to correct to <25° as measured on side bending radiographs and/or that have a segmental kyphosis of >20°, such as for the PT curve (T2 through T5 kyphosis) or thoracolumbar curve (T10 through L2 kyphosis). The treatment recommendations of the system state that major and structural minor curves are included in the instrumentation and fusion and the nonstructural minor curves are excluded**[25]**.
The Lenke lumbar modifiers A, B, and C are defined according to the relationship between the CSVL and the pedicle of the apical lumbar vertebra: modifier A, CSVL between the pedicles; modifier B, CSVL through the pedicle; modifier C, CSVL lateral to the pedicle**[26]**.
In Lenke type 1 or 2A curves in which the lumbar curve does not cross the midline, the most cephalad vertebra that is merely touched by the CSVL not the vertebra that is bisected by the CSVL (ie,SV) is selected as the LIV.
Correction techniques are similar for type 1B curve patterns; however, it is recommended to keep a slight bit of residual tilt to the LIV to accommodate the slight lumbar apical translation seen in a B modifier lumbar curve pattern.
The type 1C curve pattern is, at times, highly controversial. Even though the TL/L region completely deviates from the CSVL at the apex, the TL/L curve side bends less than 25 and lacks a true junctional kyphosis. Thus, a selective thoracic fusion is recommended. Selective thoracic fusions for a type 1C curve pattern are important to maximize lumbar spine motion and can be accomplished successfully with thorough evaluation and appropriate operative techniques, including under correction of the MT curve to allow harmonious balance with the unfused lumbar spine below**[26]**.
In a study aimed at evaluation of the Lenke classification system to assess whether the classification recommendations actually changed treatment algorithms. The study evaluated the adherence to the Lenke classification's recommendation of only fusing the major structural or minor structural curves.
It was found that the Lenke 1, 2, and 5-type curves significantly decreased in the number of "Rule-breakers" after the guidelines of the Lenke classification were introduced, to only fuse the structural curves. Defining the structural and nonstructural nature of the curves in each type was probably valuable in aiding surgical decision-making.
The Lenke type curves, in which the structural nature of the curves may be confusing or open to interpretation (3, 4, 6), either did not reduce the number of "Rule-breakers" before and after the introduction of guidelines or remained similar. These curve types were the three least common ones, together making up 13% of the total cases**[27]**.

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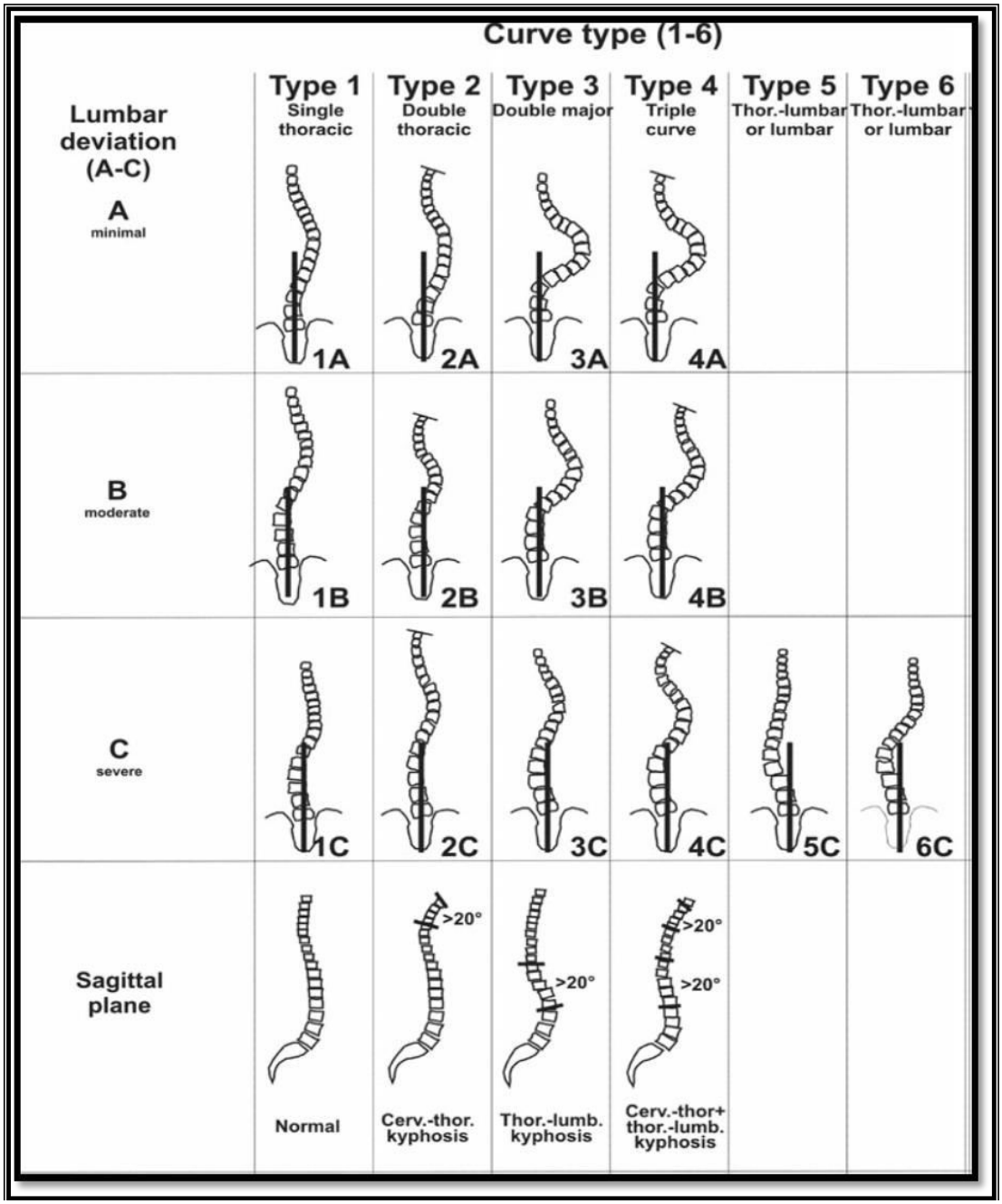

Figure (8): Curve types according to Lenke classification **[28]**

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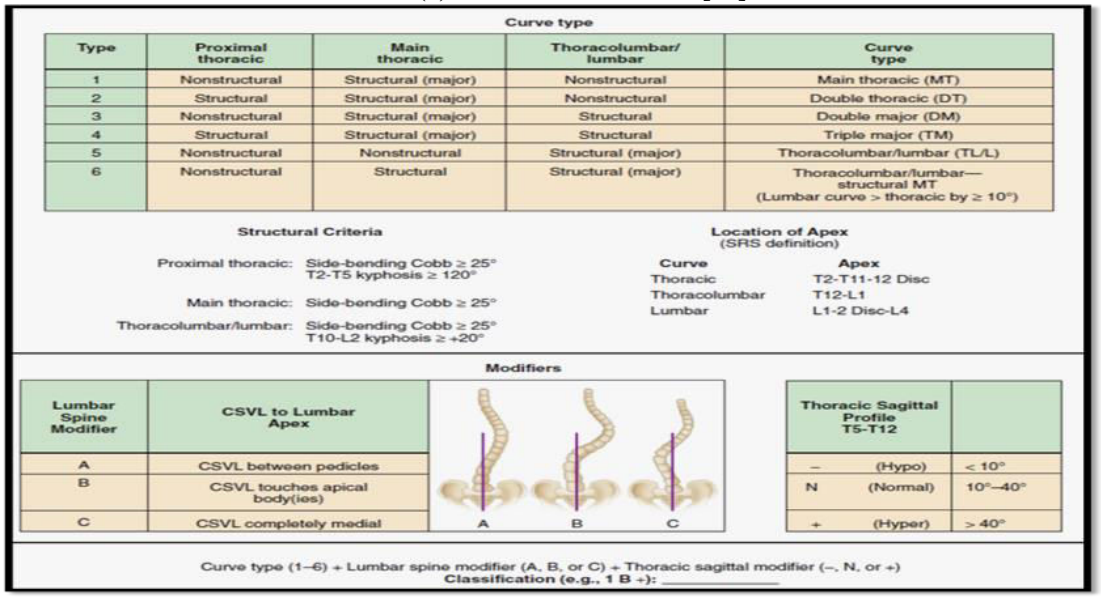
Table (1): Lenke Classification [25].



Curve type

Type	Proximal thoracic	Main thoracic	Thoracolumbar/ lumbar	Curve type
1	Nonstructural	Structural (major)	Nonstructural	Main thoracic (MT)
2	Structural	Structural (major)	Nonstructural	Double thoracic (DT)
3	Nonstructural	Structural (major)	Structural	Double major (DM)
4	Structural	Structural (major)	Structural	Triple major (TM)
5	Nonstructural	Nonstructural	Structural (major)	Thoracolumbar/lumbar (TL/L)
6	Nonstructural	Structural	Structural (major)	Thoracolumbar/lumbar—structural MT (Lumbar curve > thoracic by ≥ 10°)

Structural Criteria

Proximal thoracic: Side-bending Cobb ≥ 25°, T2-T5 kyphosis ≥ 120°

Main thoracic: Side-bending Cobb ≥ 25°

Thoracolumbar/lumbar: Side-bending Cobb ≥ 25°, T10-L2 kyphosis ≥ +20°

Location of Apex (SRS definition)

Curve	Apex
Thoracic	T2-T11-12 Disc
Thoracolumbar	T12-L1
Lumbar	L1-2 Disc-L4

Modifiers

Lumbar Spine Modifier	CSVL to Lumbar Apex
A	CSVL between pedicles
B	CSVL touches apical body(ies)
C	CSVL completely medial

Thoracic Sagittal Profile T5-T12		
–	(Hypo)	< 10°
N	(Normal)	10°–40°
+	(Hyper)	> 40°

Curve type (1–6) + Lumbar spine modifier (A, B, or C) + Thoracic sagittal modifier (–, N, or +)
Classification (e.g., 1 B +): _____

4. Surgical Treatment

The relative indications for surgery in patients with AIS are curves > 45°–50° or rapidly progressing curves. The goals of surgery are to correct the deformity and stabilize the spinal curve, typically with instrumentation, while accounting for overall spinal balance. Posterior pedicle screw and rod fixation techniques represent the mainstay of approaches, with anterior approaches reserved for some thoracolumbar curves or anterior releases reserved for severe deformities. Anterior spinal fusion is typically indicated for skeletally immature patients to arrest vertebral growth and prevent a crankshaft deformity, reduce the number of vertebral bodies included in the fusion construct, and increase flexibility for the correction of rigid curves**[29]**.

For either the anterior or posterior approach, all levels to be included in the fusion are typically exposed. For anterior approaches, discectomies are performed at the intended fusion levels. For posterior approaches, the ligamentum flavum can be resected to allow for greater correction of curves, with or without discectomies, depending on the extent and type of correction required.

For anterior approaches, a thoracic surgeon provides exposure to the anterior chest. From this approach, cortical screws and interbody constructs can be placed. Care must be taken to measure the length of the vertebral cortex in order not to penetrate the contralateral side with the screw. Furthermore, the interbody grafts or cages should be typically placed on the concave side of the scoliosis to facilitate curve reduction **[30]**.

There is considerable debate in the literature regarding single versus dual rod placement, with dual rod constructs resulting in increased stiffness in torsion and flexion-extension loading**[31]**. In a recent retrospective study, Nambiar et al**.[32]**.analyzed patients undergoing an anterior approach for the correction of AIS. In that multicenter study, patients received either single or dual rod instrumentation via an anterior approach. The authors found no significant differences in postoperative radiographic measurements and functional outcomes between the groups.

With recent advances, video-assisted thoracoscopic surgery (VATS) has been employed for anterior approaches. Reviews of the procedure advocate its use based on superior cosmesis as compared to that obtained with standard approaches and less surgical trauma. However, in addition to increasing operative time, adequate anterior release and curve correction cannot be achieved through the limited VATS corridor**[33]**.

Growth modulation via anterior surgery using internal implants has also been investigated as an alternative surgical option. Vertebral body stapling was developed using the Hueter-Volkmann principle to anchor the convexity of a curve and allow for correction by differential growth along the concavity. However, the indications for vertebral body stapling were quite narrow, encompassing curves ideally between 25° and 34° in magnitude**[34].** Ultimately, research based on the staple led to further advances, and current investigations into a vertebral body tether are ongoing**[35]**.

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Currently, the most commonly adopted surgical approach is posterior spinal fusion with or without multiple Ponte osteotomies with derotation techniques to provide correction. Pedicle screw instrumentation is used to stabilize the correction, and arthrodesis is augmented with biologics per surgeon preference.

5. Nonsurgical Treatment

The primary nonsurgical treatment for AIS is bracing, whose goal is to obviate the need for surgery by limiting curve progression. Many scoliotic curves in AIS that are < 20° can be observed and followed with serial radiographs or clinical examinations at 6-month intervals until skeletal maturity. If the curve is between 25° and 40° in a skeletally immature patient with a Risser Grade 0–1, most would agree that bracing is indicated**[36].** While the goal of bracing is to deter further progression of the curve, bracing will not result in curve regression. Two types of braces are used for treating AIS: a thoracolumbosacral orthosis (TLSO) and a cervicothoracolumbosacral orthosis (CTLSO). The former brace type includes the Wilmington, Boston, Lyon, Cheneau, Rigo-Cheneau, Malaga, and SPoRT orthoses. The latter type brace, such as the Milwaukee brace, is typically used for thoracic scoliosis with an apex above T-8, and a TLSO is employed for thoracic scoliosis with an apex at or below T-8**[37]**. Though opinions in the literature vary, most authors recommend that braces be worn at least 16–20 hours per day with bracing treatment protocols lasting anywhere from 2 to 4 years or until skeletal maturity**.[38]** Standing radiographs are usually taken at 6-month intervals to assess bracing efficacy or curve progression.

The literature varies on the efficacy of bracing in AIS. Some authors report that Boston bracing is effective in girls with 25°–35° curves**[39].** One Swedish study with a 16-year follow-up concluded that braced patients had no curve progression and that unbraced patients had 6° of curve progression**[40]**. Conversely, a large meta-analysis by Dolan and Weinstein **[41]** revealed no significant difference in surgical rates between braced and unbraced patients.

Ideal candidates for bracing are young, have scoliotic curves between 25° and 40°, are in acceleration growth phases, with a Risser Grade 0–1 and the goal of delaying surgery to maintain spinal and chest growth **[29]**.

The most recent and definitive bracing trial was the Bracing in Adolescent Idiopathic Scoliosis Trial (BrAIST), the results of which were published in 2013**[42]**. The BrAIST was a multicenter prospective controlled trial comparing bracing to observation in patients with AIS. It included a randomized cohort and preference cohort. The population comprised patients 10–15 years old with Risser Grades 0, 1, or 2, a Cobb angle of 20°–40° for the largest curve, and no prior treatment for their scoliosis. The bracing group received a rigid TLSO, which was prescribed to be worn 18 hours/day. The trial was stopped early given the efficacy of bracing, which significantly decreased the progression of high-risk curves and was associated with a greater likelihood of reaching skeletal maturity with a major curve < 50°, as compared with observation alone. Furthermore, the likelihood of a successful outcome correlated with the average hours of daily brace wear**[42].**

There were important limitations to the study, however. It was not a true randomized controlled design. Treatment preferences limited enrollment in the randomized trial; as a result, the authors added observational patient preference groups, with 116 patients receiving randomly assigned care and 126 receiving patient-directed care, meaning that 71% of this group chose the bracing treatment. Additionally, not all of the patients wore braces for 18 hours/day, and 27% stopped using the brace altogether. Furthermore, the association between the duration of brace wear and better outcomes may have been skewed because patients with curves that were likely to progress may have been less inclined to wear the brace. In particular, these curves would be relatively stiff and would resist the corrective measures of bracing. Moreover, the end point of the trial was not curve progression but only curve magnitude and the need for surgery.

There is a need for further research on bracing, and newer studies are analyzing prognostic factors for bracing efficacy. Ogilvie et al. have looked at various genetic markers in AIS as a predictive measure of bracing efficacy**.[43]**Using a 30-marker genetic panel, the authors predicted which patients had curves that were likely to be brace resistant**.[43]** Despite initial promising data, recent reviews have demonstrated that methods for predicting curve progression and bracing efficacy are not reliable and cannot be recommended as diagnostic criteria**.[44]**

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