The Adolescent Spine

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Abstract

Adolescent idiopathic scoliosis (AIS) is the most characteristic disorder of the adolescent spine. It is a three-dimensional (3D) disorder that occurs from 10 years of age and comprises 90% of all idiopathic scolioses. Imaging plays a central role in the diagnosis and follow-up of patients with AIS. Modern imaging offers 3D assessment of scoliosis with less radiation exposure. Imaging helps rule out occult conditions that cause spinal deformity. Various imaging methods are also used to assess skeletal maturity in patients with AIS, thus determining the growth spurt and risk of progression of scoliosis. This article provides a brief overview of the pathophysiology, biomechanics, clinical features, and modern imaging of AIS relevant to radiologists in clinical settings.

Adolescent idiopathic scoliosis (AIS) is a tridimensional disorder of the spine occurring in children from the age of 10 years.1 Infantile and juvenile idiopathic scoliosis are sometimes considered together and called early-onset idiopathic scoliosis. Using this terminology, AIS is also called late-onset idiopathic scoliosis.2

AIS is the most common form of scoliosis with a prevalence of 0.47 to 5.2% in the general population.3 AIS is diagnosed in up to 2 to 4% of adolescents and includes 90% of all idiopathic scoliosis.4

The classification of scoliosis was first established by John Cobb in 1948.5 In 2001, Lawrence Lenke issued a new guideline to help surgeons decide on the best treatment based on curve pattern, with the Cobb angle just one of the findings influencing surgical planning. Because the Lenke classification, requiring supplementary bending lateral views, is used mainly for surgical planning, it is not chosen by radiologists in routine practice.6 Hence its discussion is beyond the scope of this review. This article provides a brief overview of the pathophysiology, biomechanics, clinical features, and modern imaging of AIS relevant to radiologists in clinical settings.

Physiopathology

The pathophysiology of AIS is largely unknown, and, by definition, it cannot be related to a specific pathologic underlying condition. Hence imaging plays a key role in unraveling conditions that can lead to spinal deformity including congenital spinal anomalies, posttraumatic conditions, myopathies, metabolic disorders, and neoplasms.7

Genetic

Several studies have pointed to the role of a genetic factor underlying AIS.8 An increased risk of developing AIS was proven in adolescents whose first-degree family members are affected by AIS with a prevalence up to 6 to 11%.9 In addition, higher AIS match rates were found in homozygote twins than in heterozygote twins.10 At a molecular level, it has been suggested that familial AIS may be linked to the X chromosome, with a dominant inheritance pattern.11 Other genetic loci linked to AIS have been mapped on chromosomes 8, 9, 17, 18, and 19.12–16

Sex

Although the prevalence of mild curvatures is the same in girls and boys, severe curvatures are more common in girls.17 AIS incidence and progression rates are high during the pubertal growth spurt.18 Girls with severe AIS have delayed menarche and faster bone growth between 12 and 16 years of age.19 In addition, girls with AIS are generally taller and with a higher body mass index (BMI) than healthy controls.20 Furthermore, the curve severity of girls with AIS is positively correlated to height corrected by age and arm span.21
Metabolic Factors
Low bone density has been found to be positively associated with AIS. Several endogenous molecules also play a role in the development of AIS. In addition, adolescents with AIS have been found to have high levels of calmodulin and low serum levels of oestrogens and melatonin.22

Overweight or obesity was proven to negatively impact the prognosis of AIS. BMI ≥ 85th percentile was associated with a greater average curve (~ 24 degrees versus 18 degrees), increased risk of having a curve ≥ 40 degrees, and more advanced skeletal maturity at presentation.23

Balioglu et al found vitamin D levels were lower in AIS patients, and levels were negatively correlated with a Cobb angle.24

Biomechanics
The Hueter-Volkmann theory is widely accepted to explain the pathogenesis of scoliosis. According to this theory, the increased pressure on a vertebral epiphyseal growth plate decreases its rate of growth, whereas a relative low pressure has the opposite effect.25 In scoliosis, on the concave side of the curve, increased pressure on the epiphyseal plates leads to decreased rates of growth, whereas on the convex side, the pressure is diminished with a relative overgrowth.26 This pressure imbalance induces a vicious cycle, causing a vertebral wedging during growth, especially in progressive scoliosis curves. Therefore, regardless of the initial cause of scoliosis, mechanical factors increase significantly during periods of rapid adolescent growth when the risk of curve progression is maximal.27

The longitudinal growth of the vertebral bodies by endochondral ossification in AIS patients is excessive and faster than in age-matched controls. In addition, in patients with AIS, the anterior thoracic spine is longer than the posterior, a phenomenon known as relative anterior spinal overgrowth, as demonstrated by several anatomical and magnetic resonance imaging (MRI) studies.28–32

The anteroposterior length discrepancy is thought to be a consequence of both anterior and posterior column hypodevelopment associated with a secondary increased anterior intervertebral disk height.28 Asynchronous growth of the spinal cord and vertebral bodies has also been proposed to favor AIS.11

Clinical Presentation
Patients with AIS are typically referred because of an asymmetry identified by the patient or a physician, or by a screening program, chest radiographs, or other imaging studies.33 Adolescents with a severe thoracic curvature with a Cobb angle can present lung disease.34 Patients with idiopathic scoliosis may also have an obstructive lung disease. In a retrospective study of 176 patients with idiopathic scoliosis and a Cobb angle ≥ 40 degrees, 39% had obstructive lung disease.35

Radiographs should not be a part of the first-line clinical assessment of patients with AIS. Clinical evaluation should select patients for whom imaging is appropriate.22

A sociometer is used with patient in the Adam’s forward bend test for the screening and quantification of trunk deformities.36 The sociometer measures the angle of trunk rotation (ATR) in the upper thoracic, midthoracic, thoraco-lumbar, or lumbar region. The sociometer is now available as an app on a smartphone.37

The cutoffs at which radiography should be performed vary from 5 to 7 degrees of trunk rotation using the sociometer.38 The sociometer measurement is not reliable to predict the Cobb angle. As a rule of thumb, patients with a 7-degree angle of ATR have a Cobb angle of ~ 20 degrees. A lower cutoff set at 5 degrees of trunk rotation should be used in patients with a BMI higher than the 85th percentile. Radiographs should be performed in any adolescent with a readily apparent deformity of the chest or spine on physical examination.38

Imaging of Adolescent Idiopathic Scoliosis
Radiographs
Three-dimensional (3D) imaging of the spine with a low radiation dose is increasingly available worldwide.39 Digital radiography reduces radiation exposure, as well as the cumulative radiation dose during follow-up.40 Initial radiographic examination for scoliosis should include standing posteroanterior (PA) and lateral views of the spine down to the sacrum.41 Radiographs of the spine in the supine position underestimate the severity of the curvature because the effect of gravity is not present. The presence of a gastric air-fluid level confirms that the radiographs was performed with the patient in the upright position. Leg length discrepancy (if present) should be corrected by placing a shim under the shorter limb. Alternatively, radiographs can be taken in a sitting position to neutralize the effect of member imbalance.42

The balance of the spine in the sagittal plane is assessed in the lateral view. Patients with AIS often have reduced thoracic kyphosis compared with normal patients.43 Increased thoracic kyphosis is uncommon in AIS, and other underlying diseases should be excluded. Lateral views may not be performed during follow-up, if baseline radiographs reveal only normal scoliosis findings (e.g., dextroconvex thoracic kyphosis in the typical range and lumbar lordosis) (Fig. 1). The lateral views should be carefully assessed to rule out a spondylolysis that is more common in patient with AIS than in the rest of the population.44

Lateral bending radiographs are not required for diagnosis but may be mandatory for planning surgery. Long film cassettes may not be available in all facilities. In modern machines, the tube and detector move automatically, take different views in four different planes, adjusting the dose for the body part, and combine the images into a single view of the entire spine, the so-called stitching. If a long film detector or modern machine is not available, patients should be referred to a facility where long film cassettes are available to avoid suboptimal radiographs and high radiation exposure.
It is mandatory to start the radiographic assessment counting the number of thoracic or lumbar vertebrae on the lateral radiographs. An abnormal count is found in up to 10% of patients with AIS. Radiographs should also be assessed preliminarily to exclude findings suggestive of congenital or neuromuscular scoliosis. These include soft tissue abnormalities, wedged vertebrae, or hemivertebrae suggestive of congenital scoliosis, vertebral bone abnormalities suggestive of a bone tumor, increased distance between pedicles suggestive of a spinal cord tumor, syringomyelia, diastematomyelia or spinal dysraphism, or an increased thoracic kyphosis.

Scoliosis is defined as curvature of the spine in the coronal plan. It is typically accompanied by a variable degree of rotation of the spinal column. The typical curvature of AIS is a right convex thoracic and left convex lumbar double curve. However, other curve configurations can occur. The direction of the curve (right or left) is defined by its convexity. The position of the curve is determined by the vertebra that deviates most from the center line and with the highest degree of rotation.

The Cobb angle is the reference method for assessing scoliosis. It is obtained by intersecting a line parallel to the upper end plate of the most tilted cephalad vertebra with a line parallel to the lower end plate of the most tilted caudal vertebra. By convention, a Cobb angle > 10 degrees can be defined as a scoliosis. Curves with a Cobb angle ≤ 10 degrees are within the normal limits of spinal asymmetry and have no long-term clinical significance. The direction (right or left) of a scoliotic curve is defined by the side of the curve convexity. The location of the scoliosis is defined by the apical vertebra.

The Cobb angle has some limitations because it captures a 3D deformity in a bidimensional plane. Moreover, the Cobb angle is not directly related to the severity of scoliosis. Finally, inter- and intraobserver variation in the measurement of the Cobb angle can approach 5 degrees. The Cobb method is also used to determine the degree of lordosis or kyphosis on the lateral view. Thoracic kyphosis is normally measured between the upper end plate of T3 and the lower end plate of T12. Likewise, lumbar lordosis is measured between the upper end plate of L1 and the lower end plate of L5. Normal thoracic kyphosis is between 21 and 42 degrees, and normal lumbar lordosis is between 31 and 50 degrees. These values do not change with age, sex, height, or BMI.

Severe scoliosis is often associated with thoracic lordosis and straightening of the lumbar lordosis. Rotation is maximal at the apical vertebra. One or more of the vertebrae above or below the apical vertebra may also be rotated. In general, the vertebral body rotates anteriorly to the direction of convexity. However, computed tomography (CT) studies have shown that this general rule can be broken and that some rotation can also be found in patients without scoliosis. Rotation of the vertebral body is a common finding in scoliosis even if some moderate curves show no rotation. Nash and Moe
described a method for estimating rotation, from mild to severe, that should be sufficient for clinical purposes.\textsuperscript{52}

The pedicles of a nonrotated vertebra are positioned symmetrically, tangential to the edges of the vertebral body. The anterior aspect of the vertebral body usually rotates toward the convex side of the curve. Conversely, the pedicles at the convexity of the curve move away from the edge of the vertebral body and toward the midline. The pedicle on the concave side becomes less visible. The rotation can be estimated by assessing the pedicle position relative to the vertebral body (assessment of the pedicle on the convex side of the curve).

The distance between the edge of the vertebra and the midline of the vertebral body is divided into thirds. If the pedicle is located in the lateral third, the rotation is designated as 1\textsuperscript{+}, in the middle third as 2\textsuperscript{+}, and in the medial third or in the midline as 3\textsuperscript{+}. Any rotation beyond the midline is classified as 4\textsuperscript{+}. As a rule of thumb, the percentage displacement of the pedicle corresponds to the degree of rotation of the body.

For example, 50\% pedicle displacement (pedicle on the midline, or 3\textsuperscript{+}) corresponds to a rotation of 50 degrees.\textsuperscript{52} On PA views, the degree of rotation of each vertebral body can also be assessed more precisely with the Stokes or Perdriolle methods or using Raimondi’s template.\textsuperscript{53} The coronal and sagittal balance are measured in relation to a plumb line drawn down from the center of the C2 vertebral body.

In the frontal view, the distance between the plumb line and the central sacral vertebral line (CSVL) is used to assess the static imbalance of the spine on the coronal plane. The CSVL bisects the sacrum and is drawn perpendicular to a tangent connecting the iliac crests. In normal subjects, CSVL falls within 2 cm of the vertical plumb line. In the lateral view, the plumb line should be within 2 cm from the sacral prominence (defined as the anterior margin of the first sacral vertebra).\textsuperscript{54}

The rib-vertebral angle (RVA) is determined on a frontal radiograph, at the level of the apex vertebra. It is the angle formed by the intersection of a line drawn along the center (midpoint) of the head and neck of each rib and a vertical line drawn perpendicular to the upper or lower end plates of the vertebra.\textsuperscript{7} The RVA is usually smaller on the convex side of the curve. The RVA predicts the brace treatment outcome in Risser grade 0 and premenarchal girls with AIS.\textsuperscript{55}

Skeletal Maturity

Skeletal maturity is assessed in patients with AIS to determine the risk of progression. The Risser classification is a visual grading of the degree to which the iliac apophysis is ossified and fused. The classification is used to assess the degree of maturity of the skeleton on PA radiographs of the spine. Ossification of the iliac apophysis proceeds gradually from anterolateral to posteromedial along the iliac crest.

The Risser grades of ossification are described as follows\textsuperscript{77}: 0, none; 1, up to 25\%; 2, 26 to 50\%; 3, 51 to 75\%; 4, > 76\%; and 5, complete osseous fusion of the apophysis.

Because Risser grade 1 usually occurs after maximum height velocity, it should not be used as the sole indicator of skeletal maturity.\textsuperscript{56} Other methods of assessing skeletal maturity on radiographs that can be used include the Tanner and Whitehouse method, the Sanders method, the Sauvegrain method, and the olecranon method.\textsuperscript{57}

The method of Tanner and Whitehouse is based on the radiographic appearance of the secondary ossification centers of the distal radius, ulna, and small bones of the hand.\textsuperscript{58} The Sanders assessment of skeletal maturity assesses the radiographic appearance of the hand bones in eight stages.\textsuperscript{57} The maximum height velocity occurs at Sanders stage 3. To use the Sanders method, the PA view of the spine can be performed with the hands opened placed at the side of the shoulders. Assessment of the triradiate cartilage (maximum height velocity occurs in women with open triradiate cartilage before reaching Risser 1).\textsuperscript{57}

In the Sauvegrain method, the appearance of four different ossification centers of the elbow (lateral condyle, trochlea, olecranon apophysis, and proximal radial epiphysis) is assessed on a 27-point scale that is then plotted on a graph.\textsuperscript{59} In the olecranon method, only the olecranon apophysis is assessed. The olecranon apophysis goes through five radiologic stages at 6-month intervals: appearance of two ossification nuclei, crescent ossification center, rectangular ossification center, onset of fusion, and complete fusion.\textsuperscript{60} The appearance of the rectangular ossification center corresponds to the closure of the triradial cartilage. The progressive ossification of the olecranon accurately describes the acceleration of spine growth, and it ends at the time of the deceleration of the craniocaudal growth of the spine (\textsuperscript{Fig. 2}).\textsuperscript{5}

Ultrasonography

New ultrasound (US) 3D probes equipped with a position sensor and an advanced postprocessing software offer a valuable opportunity to reformat images in multiplanar planes to reduce the dose in case of the need for ongoing follow-up.\textsuperscript{61} This nonirradiating technique may be considered in the future, especially for patient needing a long follow-up with a high cumulative dose.

Computed Tomography

CT is a valuable tool for the diagnosis and treatment planning of patients with severe AIS. It allows a multiplanar evaluation of the deformity of the spine including length and rotation, and it also provides information on lung volume and chest wall deformities. The capability of visualizing a 3D reconstruction of the spine is advantageous for preoperative planning, especially in the case of respiratory involvement due to the magnitude of the scoliosis.

Several unique measurements based on CT have been described. Ilharreborde et al\textsuperscript{62} presented the spinal penetration index to measure the space occupied by the spine in the thorax that correlates with an increase in thoracic lordosis. Gollogly et al\textsuperscript{63} described the thoracic distortion index that measures the cross-sectional area of the thorax and compares it with normal children of the same age. This index is closely correlated with the severity of respiratory impairment.
CT can also be used to measure the vital capacity of children and is then a useful tool for assessing changes in lung volume after treatment. Smith et al\textsuperscript{55} showed that during the 12-month follow-up, average lung volume increased by 257 mL after chest expansion.

CT can create and print a plastic model of the spine for research or planning purposes before complex corrective surgery or resections are performed. In recent years, rapid prototyping technology has improved dramatically, simplifying the process of obtaining these 3D models.

**Magnetic Resonance Imaging**

MRI of the spine may be indicated in patients with AIS when a tumor, an infection, or a nervous system pathology is suspected.\textsuperscript{7} It can be performed in patients with a left-sided thoracic curve (unless they have dextrocardia) and curves with rapid progression, although these indications are controversial.\textsuperscript{7}

In a population of 286 patients with AIS, neural axis abnormalities on MRI were found in 24 patients (6.3%). In most of these patients, only an isolated syrinx was detected and no neurosurgery was required. Only three patients with Arnold-Chiari or Arnold-Chiari syrinx were deemed eligible for neurosurgery. The abnormal MRI findings were significantly more frequent in boys than in girls, and they were associated with increased thoracic kyphosis.\textsuperscript{64}

**EOS**

The EOS system is a radiographic system that allows high-quality whole-body X-rays to be taken while standing or sitting, with a much lower dose than conventional radiographs. The key technical element of the EOS system is the multiwire chamber, for which Georges Charpak received the Nobel Prize in 1992. The high efficiency of photon capture in the Charpak chamber allows the X-ray beam to have significantly lower milliampere (mA) values compared with conventional radiography systems, resulting in high-quality diagnostic images at extremely low doses.\textsuperscript{65,66}

Another important technical element of EOS imaging is the very thin collimated X-ray beam, whose result is nearly parallel. In addition, conventional X-ray systems use a cone-shaped X-ray beam that exposes the patient to a higher dose and causes the well-known magnification artifacts. The highly collimated parallel X-ray beam of the EOS system allows the radiologist to reduce the dose and to achieve only limited deformations of the images without significant magnification. Therefore, EOS imaging is particularly suitable for obtaining a 3D reconstruction of the spine.\textsuperscript{65,67}

The EOS imaging system consists of two X-ray tubes and two Charpak chambers that move synchronously on the vertical axis and allow simultaneous acquisition of frontal and lateral images of the whole body. The possibility of obtaining images of the whole body and in a natural standing position makes the EOS system an excellent tool for examining pathologies of the spine, lower extremities, and pelvis in children and adults.\textsuperscript{67,68} EOS images undergo advanced postprocessing using SterEOS software that enables the semiautomated calculation of the spatial location (\textsuperscript{Fig. 3}).\textsuperscript{65,66,68}

SterEOS postprocessing is able to automatically obtain scalar, vector, or angular measurements of the singular vertebral body, pelvis, and lower extremities in two and three dimensions (\textsuperscript{Fig. 4}).\textsuperscript{53}

**Radiation Protection Facts**

Patients with AIS are exposed to an average of \~25 radiographic examinations of their spine during their follow-up. This radiation exposure was associated with an increased risk of developing breast cancer.\textsuperscript{69} Presciutti et al\textsuperscript{70} and Pace et al,\textsuperscript{71} in two independent studies, compared the radiation...
exposure for AIS among surgical, brace (conservative), and observational (control) cohorts. The average dose of radiation on annual follow-up in the group of children who underwent surgery was 1.400 mrad (14 mSv). In the group of children treated conservatively, radiation was 700 mrad (7 mSv) per year. In the control group, it was 400 mrad (4 mSv) per year. In the group of surgically treated adolescents, 78% of the radiation exposure of their patients was due to intraoperative fluoroscopy.

CT significantly increases radiation exposure in children. The actual amount of radiation varies depending on the type of scanner, the length of the spine imaged, the number of acquisitions obtained, and the settings of the device (kilovolts, milliamperes, pitch, number of tubes, use of iterative reconstruction, etc.). As an example, in the same region, the average radiation of a thorax radiograph is 0.02 mSv, thoracic spine radiograph is 0.07 mSv, and CT of the thorax is 7 mSv.72

In a phantom study, the calculated effective dose for EOS was 2.6 ± 0.5 (μSv) with microdose and 67.5 ± 23.3 (μSv) for standard digital radiography.73

Conclusion
Modern imaging allows a 3D assessment of scoliosis in patients with AIS. Imaging reveals occult conditions that cause deformities of the spine. Various imaging techniques are also used to assess the skeletal maturity of patients with AIS to determine the risk of growth spurts and progression of scoliosis. Modern postprocessing enables radiologists to obtain scalar, vector, or angular measurements automatically of the singular vertebral body, pelvis, and lower extremities in two and three dimensions.

Conflict of Interest
None declared.
Fig. 4  Same patient as in Figs. 1 and 3 at 15 years of age. The EOS explores the so-called third dimension of the spine, representing each vertebral body as a vector in an axial cartesian plane (scale: 10 = 93.4 mm). The femoral heads are represented as a circle at each side. The anteroposterior location of the vertebrae can be visualized with the vertical axis as a reference. The horizontal axis is the coronal plane. The apical vertebral bodies are identified by the yellow points.

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