# Scoliosis Imaging: What Radiologists Should Know[1]

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**LEARNING OBJECTIVES**

*After reading this article and taking the test, the reader will be able to:*

- Summarize the etiology, biomechanics, definition, classification, and measurement of scoliosis.
- Describe the uses of imaging in diagnosing, monitoring, and planning the treatment of scoliosis.
- Identify patients with radiographic findings of scoliosis who should undergo MR imaging or CT.

**TEACHING POINTS**

*See last page*

Scoliosis is defined as a lateral spinal curvature with a Cobb angle of 10° or more. This abnormal curvature may be the result of an underlying congenital or developmental osseous or neurologic abnormality, but in most cases the cause is unknown. Imaging modalities such as radiography, computed tomography (CT), and magnetic resonance (MR) imaging play pivotal roles in the diagnosis, monitoring, and management of scoliosis, with radiography having the primary role and with MR imaging or CT indicated when the presence of an underlying osseous or neurologic cause is suspected. In interpreting the imaging features of scoliosis, it is essential to identify the significance of vertebrae in or near the curved segment (apex, end vertebra, neutral vertebra, stable vertebra), the curve type (primary or secondary, structural or nonstructural), the degree of angulation (measured with the Cobb method), the degree of vertebral rotation (measured with the Nash-Moe method), and the longitudinal extent of spinal involvement (according to the Lenke system). The treatment of idiopathic scoliosis is governed by the severity of the initial curvature and the probability of progression. When planning treatment or follow-up imaging, the biomechanics of curve progression must be considered: In idiopathic scoliosis, progression is most likely during periods of rapid growth, and the optimal follow-up interval in skeletally immature patients may be as short as 4 months. After skeletal maturity is attained, only curves of more than 30° must be monitored for progression.



**Abbreviations:** AP = anteroposterior, CSVL = central sacral vertical line, PA = posteroanterior, 3D = three-dimensional

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## Introduction

Scoliosis is defined as the presence of one or more lateral curves of the vertebral column in the coronal plane, although abnormal curves may affect spinal alignment in all three dimensions (1). Radiography, computed tomography (CT), and magnetic resonance (MR) imaging all can play important roles in evaluating scoliosis and determining its underlying cause (2,3). Although scoliosis is usually (in 80% of cases) idiopathic, various congenital or developmental osseous or neurologic abnormalities may lead to abnormal lateral curvatures of the spine. The selection of the most appropriate imaging modality for a particular examination may be aided by greater familiarity with the imaging manifestations of various causes of scoliosis; furthermore, the image interpretation may be improved by an understanding of the principles underlying the development, progression, and management of scoliosis.

The objectives of this article therefore are to *(a)* describe the biomechanics, classification, nomenclature, and measurement of scoliosis; *(b)* provide specific information about the current uses of radiography, CT, and MR imaging to diagnose idiopathic scoliosis and guide its management; *(c)* help radiologists identify appropriate imaging modalities for evaluating idiopathic and secondary scoliosis; and, finally, *(d)* explain the basic principles of scoliosis management.

## Biomechanics of Scoliosis Progression

To understand the biomechanics of scoliosis progression, it helps to bear in mind the complex three-dimensional (3D) nature of spinal curvature: The lateral scoliotic curvature seen in the coronal plane often is accompanied by perturbations in physiologic spinal alignment in the sagittal and axial planes (1). Scoliosis appears to develop in two stages, namely curve initiation and subsequent progression (4). According to the Hueter-Volkmann law, bone growth in the period of skeletal immaturity is retarded by mechanical compression on the growth plate and accelerated by growth plate tension. Because of the physiologic curvature in the normal thoracic spine, compressive force is delivered on the ventrally located part of the vertebral column, whereas distractive force is delivered on the dorsally located part. The process leading to abnormal spinal curvature is thought to be initiated by the rotation of vertebral bodies in the axial plane, which causes discrepant axial loading between the ventrally and dorsally located portions of the involved vertebrae (5). Over time, the discrepancy manifests as a change in the directionality of spinal curvature; that is, the ventrally located part of the vertebral column becomes the concave side and the dorsally located part becomes the convex side of a lateral curve (5) (Fig 1).

**Teaching Point**

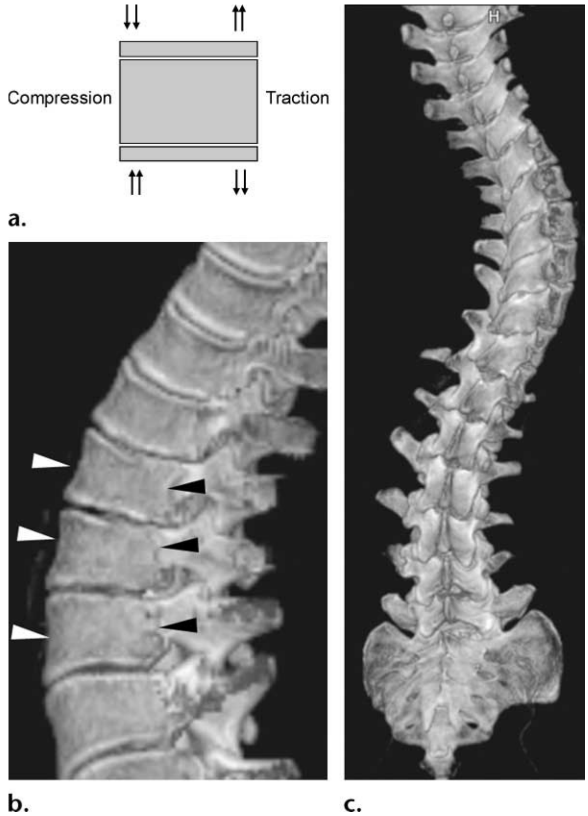



**Figure 1.** Progression of scoliosis. **(a)** Illustration based on the Hueter-Volkmann law shows that compression exerted on the vertebral growth plates at the predetermined concave side of curvature (left side in diagram) causes growth to slow, while traction exerted on the growth plates at the predetermined convex side of curvature (right side in diagram) causes growth to accelerate. **(b)** Magnified volume-rendered CT image obtained in a 16-year-old girl with idiopathic scoliosis shows vertebral wedging caused by discrepant axial loading with resultant difference in growth velocity between the convex and concave sides of spinal curvature: The vertebral height is greater at the convex side (white arrowheads) than at the concave side (black arrowheads). **(c)** Volume-rendered CT image of the whole spine (same patient as in **b**) shows a loss of visibility of the left-sided spinous processes in the scoliotic segment because of rightward vertebral rotation.

**Table 1**
**Etiologic Classification of Scoliosis**

| Main Class and Subtype | Demographic and Clinical Characteristics |
|---|---|
| Idiopathic | |
| Infantile | Occurs in the first 3 years of life; male preponderance; levoscoliosis is more common than dextroscoliosis |
| Juvenile | Occurs at age 4–10 years; female preponderance; dextroscoliosis is more common than levoscoliosis |
| Adolescent | Occurs at age 10–18 years; female preponderance; dextroscoliosis is more common than levoscoliosis |
| Congenital | |
| Osteogenic | Wedge-shaped vertebrae, hemivertebrae, fused vertebrae, unilateral bar |
| Neuropathic | Tethered cord, syringomyelia, Chiari malformation, (myelo)meningocele, diastematomyelia |
| Developmental | |
| Skeletal dysplasia | Achondroplasia |
| Skeletal dysostosis | Neurofibromatosis, osteogenesis imperfecta |
| Neuromuscular | |
| Neuropathic (acquired) | Cerebral palsy, spinocerebellar degeneration, poliomyelitis |
| Myopathic | Muscular dystrophy of various types (eg, Duchenne dystrophy) |
| Tumor-associated | |
| Osseous | Osteoid osteoma, osteoblastoma |
| Extraosseous | Extramedullary (eg, neurofibroma) or intramedullary (eg, astrocytoma) tumor |

After a critical degree of curvature has developed, a vicious mechanical cycle drives the progression of scoliosis (2), which accelerates during periods of rapid spinal growth. Therefore, the effects of both time and 3D structural distortions must be taken into account when considering scoliosis progression and planning appropriate management. One possible effect is that the pedicle and epidural space on the concave side of the curvature may be too narrow to accommodate the pedicle screws that are sometimes used in surgical treatment of scoliosis (6). Foreknowledge about such narrowing is helpful for surgical planning.

## Etiologic Classification

Scoliosis is usually classified as primary (ie, idiopathic) or secondary. Idiopathic scoliosis is further classified according to the patient's age, whereas secondary scoliosis is further classified according to the cause. In this article, we further classify cases of secondary scoliosis as neuromuscular, congenital, developmental, or tumor-associated, using the categories defined by the Scoliosis Research Society in 1969 and modified in 1970 and 1973 (Table 1) (2,7).

Idiopathic scoliosis is the most common type and accounts for 80% of scoliosis cases. Congenital scoliosis, which includes scoliosis caused by structural abnormalities of bone and neural tissues, is the second most common type, accounting for 10% of cases. Neuromuscular, developmental, and tumor-associated scoliosis together constitute the remaining 10% (8). Currently, degenerative scoliosis and traumatic scoliosis are also considered important subcategories by those involved in management of the disease.

## Nomenclature and Measurement

An understanding of the nomenclature and methods of measurement used to describe scoliosis is essential for radiologists who counsel spine experts and guide family physicians, pediatricians, and neurologists who are not specialists in scoliosis. In this section, we address the nomenclature of point vertebrae, define various types of curves and lines, and describe measurement techniques.

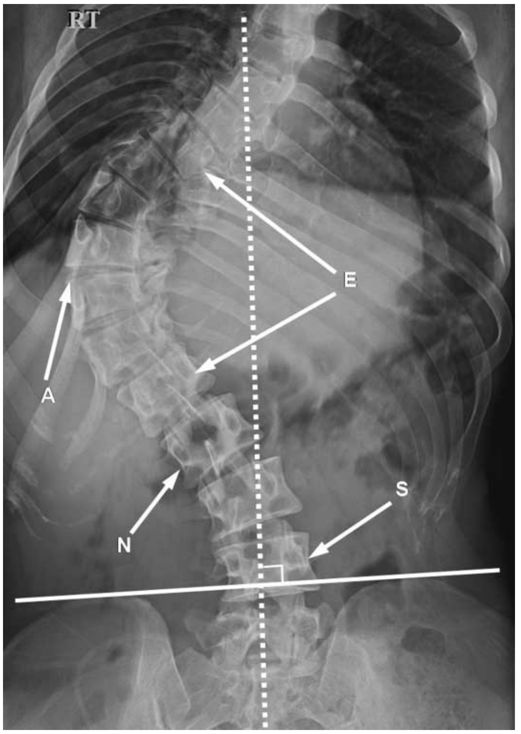



**Figure 2.** Diagram superimposed on a standing AP radiograph from a patient with scoliosis shows the significant components of the abnormal curvature: The end vertebrae *(E)* are those most tilted, and the apex *(A)* is the disk or vertebra deviated farthest from the center of the vertebral column. A neutral vertebra *(N)* is one that is not rotated, and a stable vertebra *(S)* is one that is bisected or nearly bisected by the CSVL (dotted line), which is exactly perpendicular to a tangent drawn across the iliac crests (solid line).

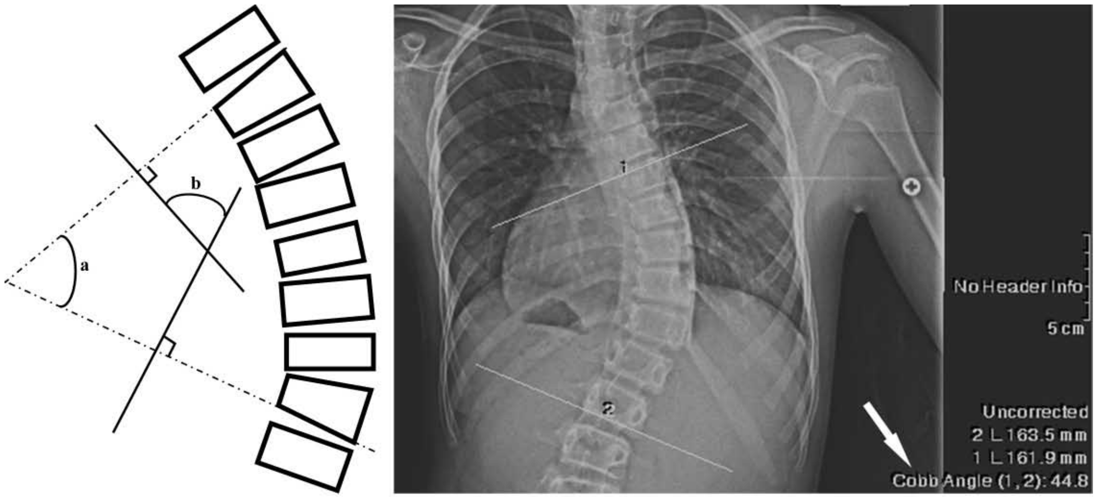
## Identification of the Apex and Significant Vertebrae

Identification of the curve apex and significant vertebrae is crucial for denoting the curve type, selecting the surgical approach and instrumentation system, and determining the optimal level for fusion (9). Surgical strategies are surgeon dependent; thus, a discussion of the clinical implications of individual vertebrae is too expansive a topic to discuss here. Nevertheless, a clear understanding of definitions is mandatory. The apex is the vertebra or disk with the greatest rotation or farthest deviation from the center of the vertebral column. End vertebrae are those with the maximal tilt toward the apex of the curve, and they are used to measure the Cobb angle. Neutral vertebrae are those that show no evidence of rotation on standing frontal (either posteroanterior [PA] or anteroposterior [AP]) radiographs; their pedicles are in the normal, symmetric positions (9). Neutral vertebrae may be at the same levels as end vertebrae, either above (proximal to) or below (distal to) the curve, but are never nearer to the apex than end vertebrae are. Stable vertebrae are the vertebrae farthest cephalad that are bisected or nearly bisected by the central sacral vertical line (CSVL) at a level below the end vertebra of the distal curve (10) (Fig 2). The CSVL is a roughly vertical line that is drawn perpendicular to an imaginary tangential line drawn across the top of the iliac crests on radiographs. It bisects the sacrum.

## Measurement of the Cobb Angle and Its Pitfalls

Measurement of the Cobb angle has limitations in that it is performed by using a two-dimensional radiographic image of a 3D deformity and does not take vertebral rotation into account. In addition, Cobb angle measurement may be inherently difficult (11). However, it is still the main standard for diagnosis, monitoring, therapeutic planning, and epidemiologic analysis of scoliosis.

The Cobb angle of a scoliotic curve is the angle formed by the intersection of two lines, one parallel to the endplate of the superior end vertebra and the other parallel to the endplate of the inferior end vertebra (Fig 3a). The angle may be plotted manually or digitally. Digital Cobb angle measurements obtained by using a software



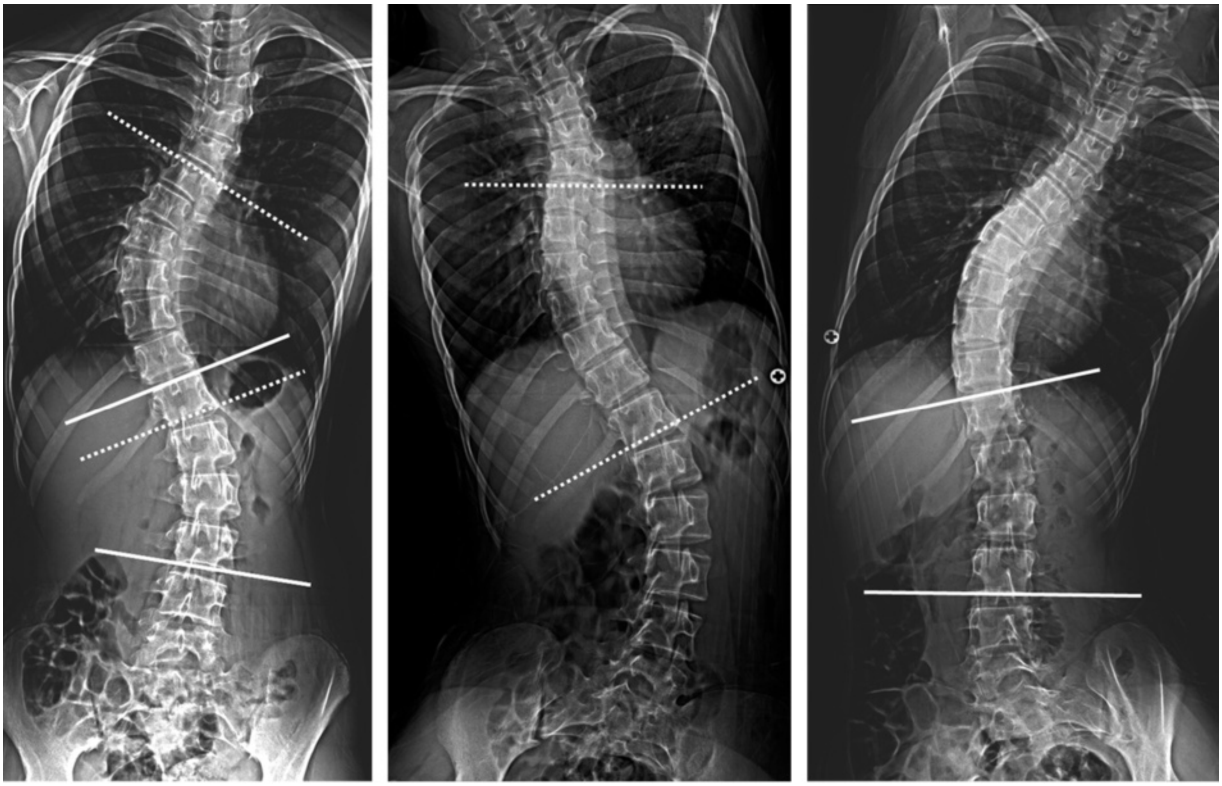

a. b.

**Figure 3.** **(a)** Diagram demonstrates measurement of the Cobb angle. First, tangents (dashed-dotted lines) are drawn along the superior endplate of the superior end vertebra and the inferior endplate of the inferior end vertebra. If the endplates are not reliably visualized, the borders of the pedicles are used instead. The Cobb angle is defined either as the angle between the tangential lines (angle *a*) or the angle between two lines drawn perpendicular (solid lines) to the tangents (angle *b*). When correctly measured, the two angles are identical. **(b)** Screen capture from a picture archiving and communication system workstation shows the use of interactive software to calculate the Cobb angle (arrow) from two tangents drawn on a spinal radiograph.

program at the workstation of a picture archiving and communication system were reported to be comparable to manual measurements on radiographs, a finding suggestive of equal reliability of the two measurement methods (12) (Fig 3b).

When incorporating measurement of the Cobb angle into routine clinical assessments of curvature, especially in monitoring for progression, the following caveats should be kept in mind. First, a diurnal variation of 5° has been observed in Cobb angle measurements of the same curve over the course of a single day, with an angular increase occurring in the afternoon (13). Second, because of the vertebral rotation associated with scoliosis, it may be difficult to position the patient so as to obtain an accurate frontal view, and the actual Cobb angle might be 20% greater than that plotted on radiographs (14). It is particularly important that the patient's position at follow-up imaging be consistent with that at initial radiography. Third, surgeons have reported that a Cobb angle decrease due to prone positioning and anesthesia during surgery sometimes is followed by a postoperative rebound effect, with a loss of correction when the patient returns to the standing position (15). Fourth, a total error of 2°–7° in Cobb angle assessment has been reported to result from variations in radiographic acquisitions and measurement error (8). Because measurement error is lower when end vertebrae are consistently defined, the same endpoints should be used at follow-up as at the initial curve assessment (2,8,16,17). Fifth, intraobserver variation by 5°–10° in Cobb angle measurement has been reported, and the interobserver variation is even greater (11,16). When radiographs obtained at two different time points were compared to assess curve progression, a measured difference of 10° in the Cobb angle had a 95% chance of representing a true difference, according to an article by Carman et al (17).

Despite these caveats, for practical purposes curve progression is measured in increments of 5°, the smallest angular difference that can be measured accurately (2). A progressive curve that requires management is defined by a Cobb angle increase of 5° or more between consecutive radiographic examinations (18).



a. b. c.

**Figure 4.** Structural and nonstructural curves in a 14-year-old girl with scoliosis. **(a)** Neutral standing AP radiograph shows dextroscoliosis at the upper thoracic level (spinal segment between the dotted lines; Cobb angle, 58.8°) and levoscoliosis at the thoracolumbar level (spinal segment between the solid lines; Cobb angle, 32.6°). **(b)** Rightward-bending view shows a Cobb angle of 32° (>25°) for the right-sided curve at the upper thoracic level, a finding indicative of a structural curve. **(c)** Leftward-bending view shows a Cobb angle of 15° (<25°) for the left-sided curve at the thoracolumbar level, a finding indicative of a nonstructural curve.

## Identification of Primary and Secondary Curves

Major curves, also called primary curves, are the largest abnormal curves in the scoliotic spine and the first to develop. Minor curves, also called secondary curves, are smaller and are considered to develop afterward, to compensate for the perturbation of balance that accompanies the progression of major curves by repositioning the head and trunk over the pelvis to maintain balance (8). These terms are generally used in daily clinical practice as well as in the classification systems devised by various investigators to describe types of scoliotic curves. The terms *major curve* and *minor curve* are sometimes used as synonyms for *structural curve* and *nonstructural curve*, respectively, although the definitions of these entities do not correspond exactly.

Teaching Point

Because of vertebral morphologic changes (eg, wedging and rotation), a structural curve is not correctable with ipsilateral bending. By contrast, no vertebral morphologic changes take place in a nonstructural curve, which is a mild compensatory curve enabling sagittal and coronal truncal balance; therefore, it is correctable with ipsilateral bending. A nonstructural curve does not usually progress. However, a nonstructural curve may progress to a structural curve if ligament shortening results from growth retardation on the concave side of curvature (8).

Differentiation between structural and nonstructural curves is important when selecting the appropriate level for fusion. Although some sources express reservations about the best method for determining whether a curve is structural or nonstructural (19,20), a structural curve may be reliably defined as one with a Cobb angle

a. b.

**Figure 5.** Measurement of coronal and sagittal alignment of vertebrae on neutral standing radiographs obtained in an 11-year-old girl. **(a)** AP radiograph shows a distance (arrow) of 1.8 cm between a plumb line (dotted line) drawn downward from the center of the C7 vertebral body (*), parallel to the lateral edge of the radiograph, and the CSVL (solid line). This distance is less than that defining a coronal imbalance (≥2 cm). **(b)** Left lateral radiograph shows that the shortest distance (arrow) between the plumb line (dotted line) and the posterosuperior aspect of the S1 vertebral body (arrowhead) is 1.7 cm, less than that defining a sagittal imbalance. * = C7 vertebra.

of 25° or more on ipsilateral side-bending radiographic views (21) (Fig 4).

## Assessment of Vertebral Alignment and Balance

The CSVL drawn on radiographs serves as a reference for identifying stable vertebrae (10), evaluating coronal balance (8), and determining the curve type, irrespective of the classification system applied (King or Lenke) (10,21,22).

The plumb line is a vertical line drawn downward from the center of the C7 vertebral body, parallel to the lateral edges of the radiograph. It is used to evaluate coronal balance on standing frontal radiographs and sagittal balance on standing lateral radiographs. Coronal balance is evaluated by measuring the distance between the CSVL and the plumb line, and sagittal balance is evaluated by measuring the distance between the posterosuperior aspect of the S1 vertebral body and the plumb line. For both coronal and sagittal measurements, balance is considered abnormal if the distance is greater than 2 cm (Fig 5). For measurements of coronal balance, a plumb line located to the right of the CSVL is considered to reflect positive coronal balance, whereas a plumb line located to the left of the CSVL is considered to reflect negative coronal balance. For measurements of sagittal balance, a plumb line that is anterior to the posterosuperior aspect of the S1 body is considered to reflect positive sagittal balance, whereas a plumb line that is posterior to the posterosuperior aspect of the S1 body is considered to represent negative sagittal balance (8).

## Measurement of Vertebral Rotation

The advent of modern instrumentation systems led to a marked increase in the importance of measuring vertebral rotation in the scoliotic spine (15,23). The shortcomings of the Cobb angle for describing vertebral rotation are partly overcome by the so-called Nash-Moe method, in which the pedicle location on frontal radiographs is used as an indicator of the extent of vertebral rotation. With the Nash-Moe method, the half vertebra on

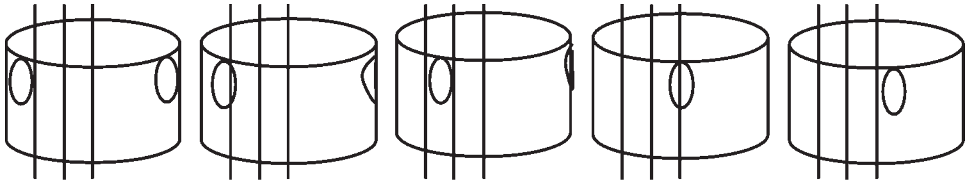



**Figure 6.** Diagrams show the grading of vertebral rotation according to the Nash-Moe method: *A,* neutral position (no rotation); *B,* grade 1; *C,* grade 2; *D,* grade 3; and *E,* grade 4. In frontal views showing a lateral spinal curve, each of the involved vertebrae is bisected by an imaginary line, and the half vertebra on the side of convexity is then segmented into outer, second, and inner or midline thirds (vertical lines in *A–E*). Rotation is quantified on the basis of the location of the convex-side pedicle in one of these segments and the visibility of the concave-side pedicle, which gradually disappears as rotation progresses. Both pedicles normally are seen within the outer thirds of the two halves of a vertebra (small, vertically oriented ovals in *A*).

the convex side of curvature is divided into three segments, and rotation is quantified on the basis of the pedicle location in regard to the segments (24) (Fig 6).

## Idiopathic Scoliosis

Idiopathic scoliosis is diagnosed by excluding congenital and other causes of scoliosis. The presence of a lateral curve with a Cobb angle of 10° or more is an essential criterion for a diagnosis of scoliosis. A curve with a Cobb angle of less than 10° is asymptomatic and does not progress; this state is known as spinal asymmetry, not scoliosis (15).

### Classification according to Patient Age

Although there is some debate about the topic, occurrences of idiopathic scoliosis in skeletally immature patients are traditionally categorized on the basis of age and characteristic clinical features as infantile (age 0–3 years), juvenile (age 4–10 years), or adolescent (age 11–18 years) (Table 1). Infantile idiopathic scoliosis is a structural malformation that affects boys more commonly than girls (male-to-female ratio, 3.5:1). Most cases of infantile idiopathic scoliosis develop within the 1st year of life and involve a leftward-trending curvature (levoscoliosis) (25). Adolescent idiopathic scoliosis is preponderant in girls (male-to-female ratio, 4:1) and involves a structural curvature that is usually rightward trending (dextroscoliosis) (18).

With regard to juvenile idiopathic scoliosis, the age range is arbitrary; when patients are dichotomized around a cutoff of 6 years of age, the disease features in those aged 3–6 years resemble infantile idiopathic scoliosis, whereas the disease features in those aged 6–10 years more closely resemble adolescent idiopathic scoliosis. Hence, it seems rational to consider early juvenile idiopathic scoliosis identical to infantile idiopathic scoliosis that is diagnosed late (25). Furthermore, the use of MR imaging to evaluate scoliosis resulted in an increase in the number of preadolescent patients in whom an underlying cause of scoliosis was identified, findings that prompted questions regarding the merits of the diagnostic category of juvenile idiopathic scoliosis (2) (Fig 7). Hence, there is increasing acceptance for classifying idiopathic scoliosis of the immature spine as either early- or late-onset (2). The cutoff usually used to divide these two types of scoliosis is the age of 5 years, because of the higher risk of cardiopulmonary complications in children who develop large curves before this age (2,7).

Cases of scoliosis progression after skeletal maturity are subdivided into two categories: adult idiopathic scoliosis and degenerative scoliosis. The former denotes a deformity that commences before skeletal maturity, worsens through degenerative progression, and becomes symptomatic between the ages of 20 and 50 years (2). The latter denotes a de novo deformity that occurs in the absence of a preexisting idiopathic curvature and is associated with degenerative change and a consequent collapse of sagittal and coronal balance (26).

a. b.

**Figure 7.** Secondary scoliosis due to bone hemangiomas in a 7-year-old boy with mild back pain. **(a)** Standing AP radiograph shows an extended region of thoracic levoscoliosis, a characteristic appearance of juvenile idiopathic scoliosis. Because of back pain, the patient was referred for further evaluation with MR imaging. **(b)** Coronal T2-weighted (repetition time msec/echo time msec, 3000/95) MR image shows fatty infiltrative lesions that proved to be aggressive hemangiomas in the T10 and T11 vertebrae (arrows). The osseous lesions were believed to be the cause of scoliosis.

## Determining the Probability of Progression and the Appropriate Follow-up Interval

Biomechanical curve progression parallels spinal growth. Hence, irrespective of type, scoliosis progresses only during growth and ceases when skeletal maturity is reached, provided that the final curvature is not severe. The rates of spine-related symptoms and mortality among patients who have a curve with a Cobb angle of less than 50° are similar to those among patients without scoliosis; by contrast, patients who have a curve with a Cobb angle of more than 50° have higher rates of back pain and mortality associated with cardiopulmonary complications (27).

The progression of idiopathic scoliosis after skeletal maturity depends on the severity of curvature. If the Cobb angle is less than 30° after the cessation of skeletal growth, the scoliotic curve tends not to progress, regardless of the pattern of curvature. Curves with a Cobb angle of 30°–50° at skeletal maturity progress 10°–15° per year during a normal lifetime, whereas curves with a Cobb angle of 50°–75° at skeletal maturity progress at a rate of 1° per year (28).

The frequency of curve progression differs according to the cause and type of scoliosis. Congenital scoliosis progresses in 75% of cases. Among patients with idiopathic scoliosis, progression is most common in the juvenile group (70%–95% of patients) (25). Most cases of infantile idiopathic scoliosis are self-limited. Adolescent idiopathic scoliosis also progresses less often than juvenile idiopathic scoliosis and congenital scoliosis. Only 5% of adolescent patients with idiopathic scoliosis experience curve progression beyond a Cobb angle of 30° (28).

**Teaching Point**

The factors that have the greatest effect on the probability of progression of adolescent idiopathic scoliosis are spinal growth velocity and magnitude of the curve at initial presentation (28). Because growth velocity is the main factor that affects curve progression, accurate estimation of the time of the spinal growth spurt is important for managing scoliosis. The following parameters are associated with curve progression: growth velocity (height increase) of more than 2 cm per year; chronologic age of 9–13 years; bone age of 9–14 years; iliac ossification of Risser grade 0 or 1; and, in girls, premenarchal status. The growth spurt usually occurs one-half to 2 years before menarche; after menarche, there is a lower probability of progression (28,29). Another useful indicator is closure of the triradiate cartilage of the acetabulum, which usually occurs before Risser grade 0 is achieved, during the period of maximal spinal growth (15).

To estimate the stage of skeletal maturity, the ossification center of the iliac crest is usually assessed radiographically by using the Risser index. Grades 0 through 5 describe the extent of apophyseal ossification, which commences laterally and extends medially (Fig 8). Complete excursion of the ossified apophysis takes approximately 1 year, and fusion of the ossification center to the iliac crest takes another 2 years (2). Risser grade 4, which signifies complete excursion of the ossified apophysis of the iliac crest, has been considered to denote the completion of spinal growth and cessation of curve progression in girls (30). However, the use of Risser grade 4 as an indicator of arrested progression has been criticized (31). Furthermore, grading of skeletal maturity according to the Risser index is far less reliable in boys, in whom ossification starts at a later age than it does in girls; in boys, growth cannot be considered complete until Risser grade 5 ossification is achieved.

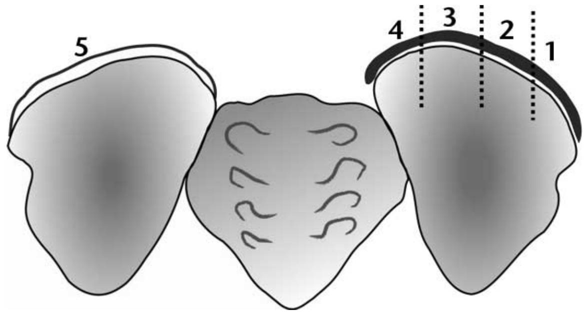



**Figure 8.** Diagram shows the anatomic appearances that correspond to grades of visible skeletal maturity as defined by the Risser index: grade 1, ossification of the lateral 25% of the iliac apophysis; grade 2, ossification of the lateral 50%; grade 3, ossification of the lateral 75% of the apophysis; grade 4, complete excursion of the ossified apophysis before fusion; and grade 5, complete fusion of the iliac apophysis. Risser index grade 0 (no visible ossification of the iliac apophysis) is not shown.

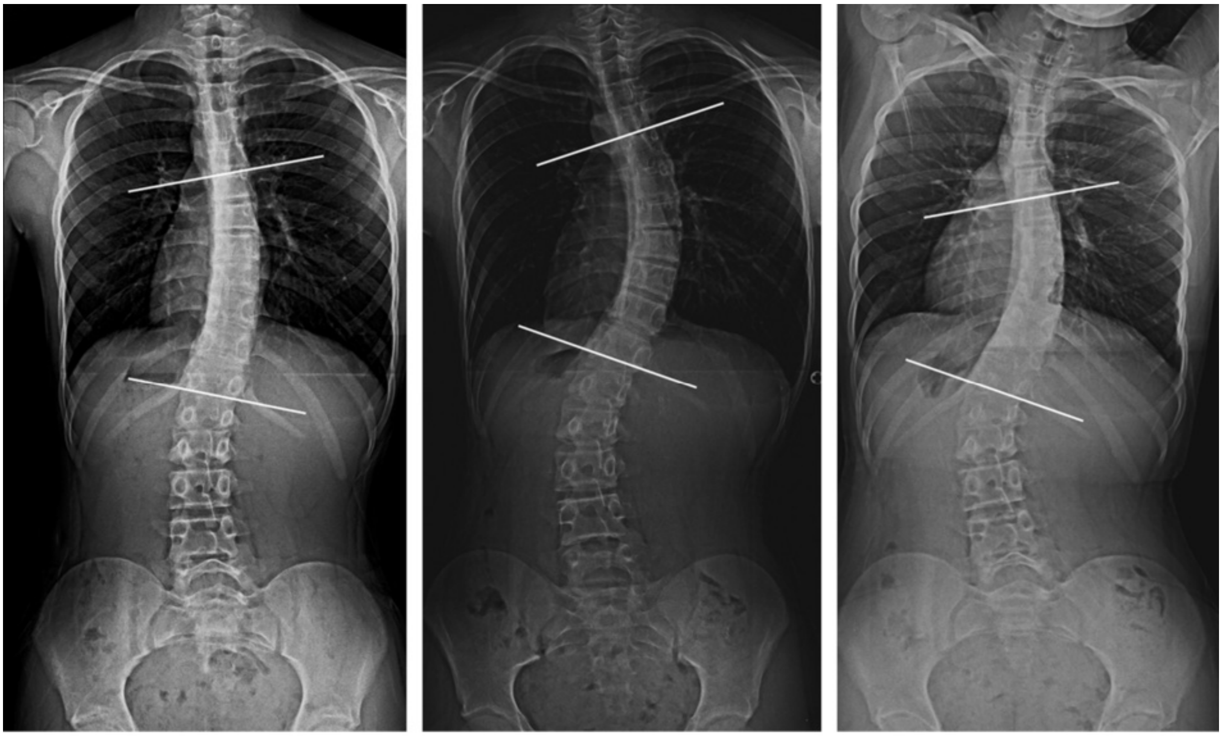
In addition to skeletal maturity, other prognosticators of curve progression include age at initial presentation, curve magnitude, and curve pattern, with earlier onset, more pronounced angulation, and primary thoracic (instead of lumbar) location of curvature being associated with a higher probability of progression.

The optimal follow-up interval is based on the individual case, with consideration given to the probability of progression and the likely effect of progression on the treatment plan (2). It is generally recommended that patients with idiopathic scoliosis be monitored every 4–12 months, depending on their age and growth rate (Fig 9). After the cessation of spinal growth, only curves with a Cobb angle greater than 30° should be monitored for progression. Follow-up imaging usually is performed every 5 years, although the follow-up interval depends on the patient's symptoms and the severity of the curvature (28).

## Lenke Classification of Curve Types

Two main classification systems are used for the anatomic and morphologic description of curves in adolescent idiopathic scoliosis: one devised by King and colleagues (10), and another devised by Lenke et al (21). Both systems are used to guide surgical treatment, with the Lenke system being more widely used for the following reasons: *(a)* it includes not only thoracic curves but also thoracolumbar and lumbar curves, *(b)* it describes sagittal curves, which are neglected by the King classification system, and *(c)* it allows higher rates of interobserver and intraobserver agreement than are achievable with the King system (32). From a practical standpoint, a strict interpretation of every radiograph on the basis of the Lenke system seems unnecessary. However, an understanding of this classification system may help improve both the comprehension and the interpretation of radiographic features of scoliosis.

The Lenke classification includes three components: *(a)* curve type, *(b)* lumbar modifier, and *(c)* thoracic sagittal modifier. To describe curve types, Lenke and colleagues divide the spine into three regions: proximal thoracic (with the apex between T1 and T3), main thoracic (with the apex between T3 and T12), and thoracolumbar to lumbar (with the apex between T12 and L4). One of the main purposes of this classification system is to guide decision making about the length of vertebral column to be included in surgery (33). The more specific focus is on the main debate of scoliosis surgery, that is, whether to include minor curves in the level of fusion. Curves are distinguished according to whether they are at the proximal thoracic, main thoracic, or thoracolumbar-to-lumbar level and are major, minor and structural, or minor and nonstructural. (Major curves are always structural, but not all structural curves are major curves.) Thus, six curve types are identified in the Lenke system (Table 2). Next, a lumbar spine modifier (A, B, or C) is assigned on the basis of the position of the lumbar curve apex vertebra in relation to the CSVL. If the CSVL lies between the pedicles, the lumbar



a. b. c.

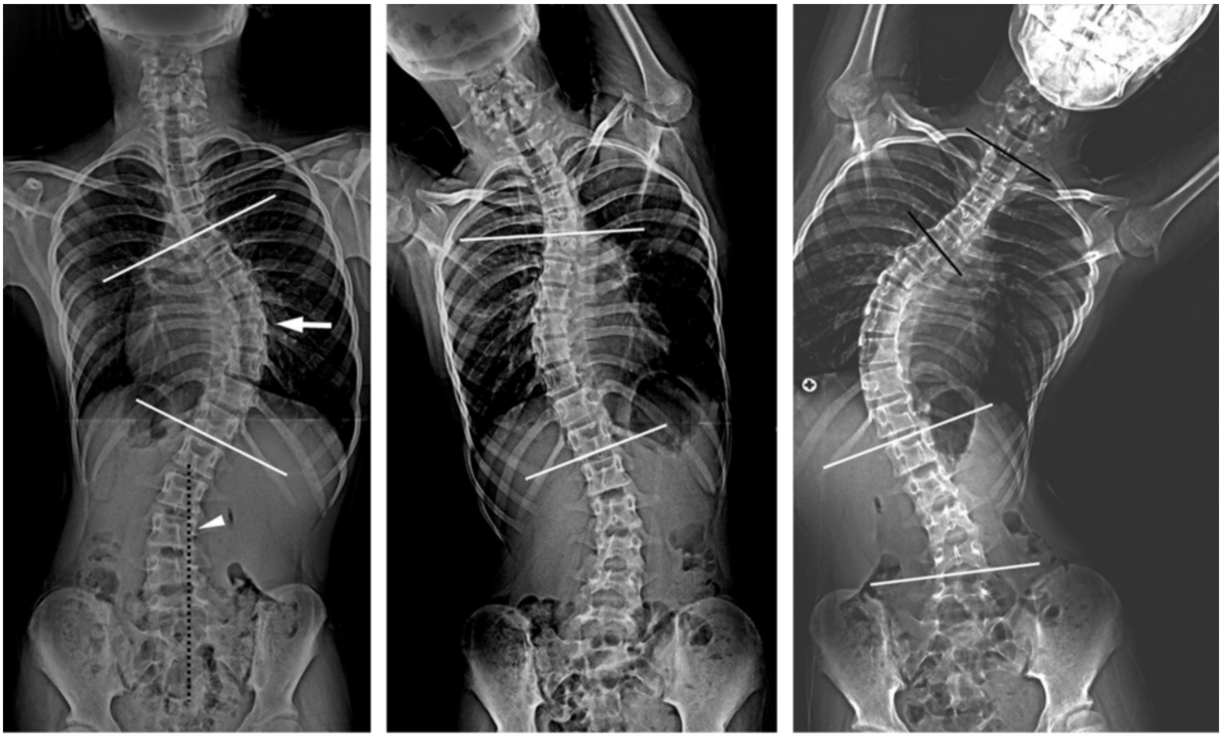
**Figure 9.** Radiographic monitoring of curve progression in an 11-year-old girl with idiopathic scoliosis. White lines drawn across the end vertebrae at levels T6 and T12 are tangents used to measure the Cobb angles. **(a)** PA radiograph obtained with the patient in neutral position reveals a rightward curvature of the thoracic spine with a Cobb angle of 24°, just shy of the 25° threshold that defines a structural curve. The curve straightened on a leftward-bending radiograph. **(b)** PA radiograph obtained 1 year later with the patient in neutral position shows progression of the thoracic curve to a Cobb angle of 49°. **(c)** PA radiograph obtained at the same time as **b** but with the patient bending rightward shows progression with a Cobb angle of 33°, a finding indicative of a structural curve.

**Table 2**
**Definition of Curve Types according to the Lenke Classification System**

| Numeric Designation of Curve Type | Spinal Location and Structural or Nonstructural Nature of Curve | | | Description of Curve Type |
|---|---|---|---|---|
| | Proximal Thoracic | Main Thoracic | Thoracolumbar/Lumbar | |
| 1 | Nonstructural | Structural* | Nonstructural | Main thoracic |
| 2 | Structural | Structural* | Nonstructural | Double thoracic |
| 3 | Nonstructural | Structural* | Structural | Double major |
| 4 | Structural | Structural* | Structural* | Triple major |
| 5 | Nonstructural | Nonstructural | Structural* | Thoracolumbar/lumbar |
| 6 | Nonstructural | Structural | Structural* | Thoracolumbar/lumbar—main thoracic |

*Denotes a major curve.

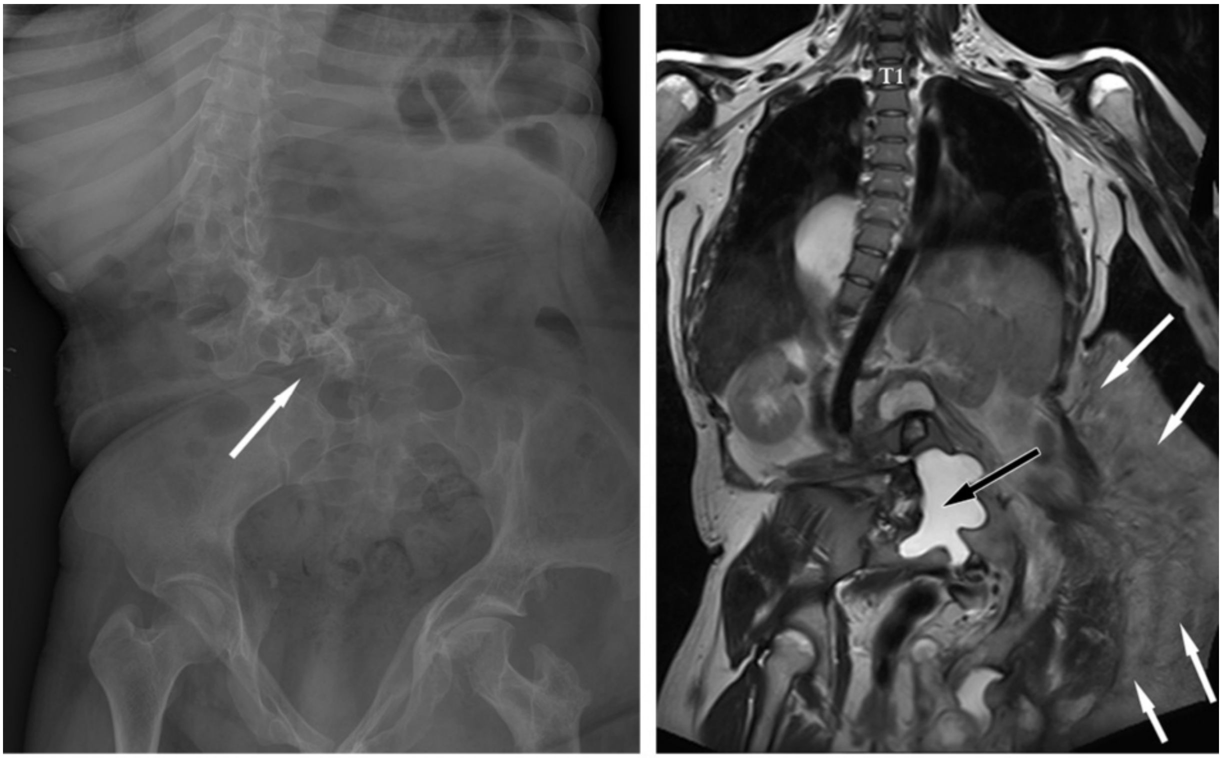
**Figure 10.** Lenke classification of curve pattern in a 12-year-old girl with adolescent idiopathic scoliosis. **(a)** PA radiograph shows a large right main thoracic curve with its apex (arrow) at the level of the T8-9 disk and its end vertebrae at T5 (upper white line) and T12 (lower white line). The CSVL (dotted line) touches the pedicle (arrowhead) of the apical vertebral body of a second, lumbar curve. The main thoracic curve, because it had the largest Cobb angle, was denoted as the major curve. **(b)** Rightward-bending AP radiograph shows a nonstraightening main thoracic curve (segment between the straight white lines) with a Cobb angle of more than 25°, a finding denoting a structural curve. **(c)** Leftward-bending AP radiograph shows that the Cobb angles of the proximal thoracic (spinal segment between the black lines) and lumbar (spinal segment between the white lines) curves do not exceed 25°. These two minor curves are nonstructural. **(d)** Lateral standing radiograph depicts a normal sagittal profile of the thoracic spine, with Cobb angles of 10°–40° between vertebral levels T5 and T12 (white lines). Based on the combined findings in **a–d**, the Lenke type was 1BN. **(e)** Standing PA radiograph shows that only the structural curve (vertebral levels T5 through T12) was included in fusion.



a. b. c.

d. e.

**Figure 11.** Short-segment scoliosis in a 27-year-old woman with a previous diagnosis of type 1 neurofibromatosis. **(a)** AP radiograph of the thoracolumbosacral spine shows a severe curvature that affects a short spinal segment (arrow), a characteristic radiographic feature of dystrophic type 1 neurofibromatosis. **(b)** Coronal T2-weighted (3100/110) MR image reveals dural ectasia at the sacral level (black arrow). The huge infiltrative mass in the left trunk and thigh (white arrows) was found to be a plexiform neurofibroma at surgery.




a. b.

modifier "A" is assigned; if the CSVL touches a pedicle, the lumbar modifier "B" is assigned; and if the CSVL lies medial to a pedicle, the lumbar modifier "C" is assigned. Finally, a thoracic sagittal modifier (–, N, or +) is specified on the basis of the sagittal alignment of the thoracic vertebrae at levels T5 through T12, as follows: *(a)* When the angle of sagittal kyphosis is less than 10°, the modifier "–" is assigned; *(b)* when the angle of kyphosis is 10°–40°, the modifier "N" is assigned; and *(c)* when the angle of kyphosis is greater than 40°, the modifier "+" is assigned. The angle of kyphosis is measured by using the Cobb method. To define a curve on the basis of the Lenke classification system, standing frontal, standing lateral, and rightward- and leftward-bending radiographic views should be obtained (21) (Fig 10).

## Use of Cross-sectional Imaging Modalities

### When to Use CT and MR Imaging

The main purpose of performing CT or MR imaging in a patient with scoliosis is to identify an underlying cause. In addition, the cross-sectional imaging modalities are useful for guiding surgical treatment and evaluating postoperative complications. Radiography is the method of choice for the initial diagnostic imaging evaluation; it is sufficient to exclude most congenital and developmental osseous anomalies, which account for most cases of scoliosis with an underlying pathologic origin. It is noteworthy that congenital and developmental osseous causes tend to produce curvatures that affect a relatively short segment of the spine on radiographs. Neurofibromatosis with dystrophic curvature, although it is uncommon, also may produce a short-segment curve (34) (Fig 11). In cases with a complex osseous deformity, radiography alone is inadequate and the use of CT is mandatory, especially when surgery is planned. MR imaging is used with increasing frequency to evaluate patients with an unusual curve pattern or alarming clinical manifestations (Tables 3, 4).

**Table 3**
**Main Indications for Further Imaging in Patients with Radiographic Findings of Scoliosis**

| |
|---|
| Congenital osseous abnormality (fusion and segmentation anomaly) |
| Congenital neuropathic abnormality (Arnold-Chiari malformation, tethered cord, dysraphism-related abnormality) |
| Dysplasia (neurofibromatosis, osteogenesis imperfecta, Marfan syndrome) |
| Pain suggestive of bone tumor, infection, or intervertebral disk herniation |
| Neurologic deterioration with abnormality at electroneurography or evoked electromyography |
| Preoperative evaluation of osseous abnormality |
| Presumed postoperative complication |
| Idiopathic curvature of spine with specific clinical or radiographic features listed in Table 4 |

**Table 4**
**Indications for MR Imaging in a Patient with Presumed Idiopathic Scoliosis**

| |
|---|
| Clinical features |
| Age <10 years |
| Signs of neurologic deterioration |
| Rapid progression |
| Foot deformity |
| Back pain, neck pain, headache |
| Radiographic features |
| Curve type commonly associated with neuropathy (left thoracic, double thoracic, triple major, short-segment, or long right thoracic curve; severe curvature after skeletal maturity) |
| Wide spinal canal, thin pedicle, wide neural foramina, or other features suggestive of a nonosseous lesion |

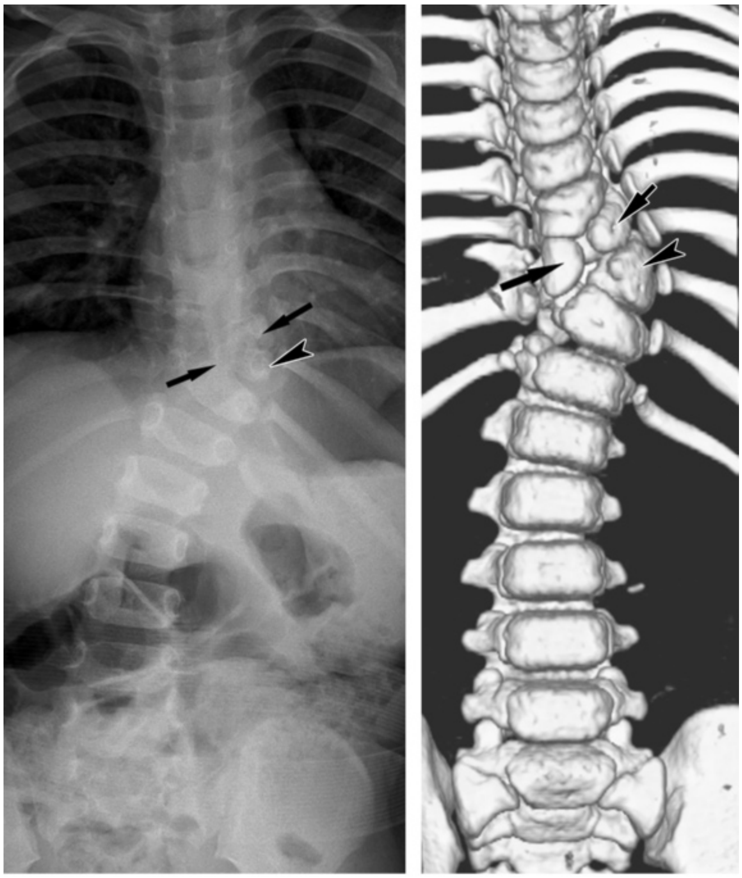
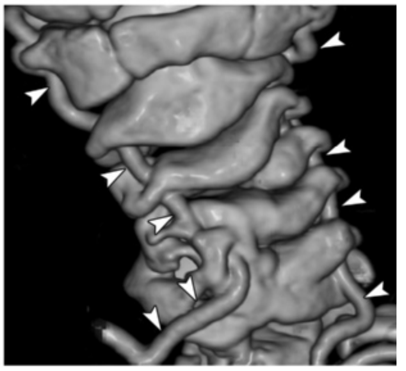

a. b.

**Figure 12.** Short-segment scoliosis due to congenital fusion and segmentation anomaly. Radiography alone is inadequate and CT is mandatory when evaluating complex osseous abnormalities, especially when surgery is planned. PA radiograph **(a)** and volume-rendered thin-section multidetector CT image **(b)** obtained in an 18-month-old girl show a unilateral left hemivertebra (arrowhead) at the thoracolumbar junction and adjacent bilateral hemivertebrae (arrows), features best depicted on the CT image.

Multidetector CT with 3D image reconstruction allows the visualization of complex osseous abnormalities of congenital scoliosis (Fig 12). CT can be especially helpful when planning the surgical excision of hemivertebrae because it may depict unexpected osseous anomalies that were not clearly depicted at initial radiography (35). Preoperative CT angiography is also useful for determining whether coexistent anomalous vascular conditions are present (36) (Fig 13).

Caution must be exercised when placing screws in the pedicles at the upper thoracic level, especially on the concave side of curvature, because the pedicles are extremely narrow; the spi-

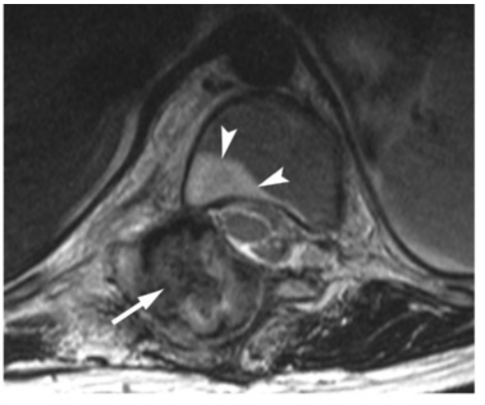
a.



b.

**Figure 13.** Short-segment scoliosis due to congenital fusion and segmentation anomaly. **(a)** AP radiograph obtained in a 5-year-old girl with Klippel-Feil syndrome shows a severe spinal malformation (arrow) at the level of the cervicothoracic junction. **(b)** Volume-rendered thin-section multidetector CT angiographic image shows the location of vertebral arteries (arrowheads), critical structures that must be avoided during surgery.

a.



b.

**Figure 14.** Painful scoliosis due to osteoblastoma in a 13-year-old girl. **(a)** AP radiograph depicts levoscoliosis of the thoracolumbar spine with an osseous mass (arrow) to the right of the costovertebral junction at vertebral levels T11 through T12. **(b)** Axial T2-weighted (4500/110) MR image demonstrates the origin of the mass (arrow) from the posterior element of the 11th thoracic vertebra. Note the bone marrow edema (arrowheads), a characteristic feature of osteoblastoma. The diagnosis was confirmed at surgery.

nal cord also is vulnerable at this level because of the narrow epidural space (37). Preoperative CT in this context has been recommended because of the high probability of the presence of a narrow pedicle (38,39). Postoperative CT is recommended for patients with a new neurologic deficit after pedicle screw placement.

Most of the underlying causes of scoliosis are osseous or neuropathic. Radiography and CT are generally used to detect osseous causes, sometimes in conjunction with MR imaging (Fig 14).

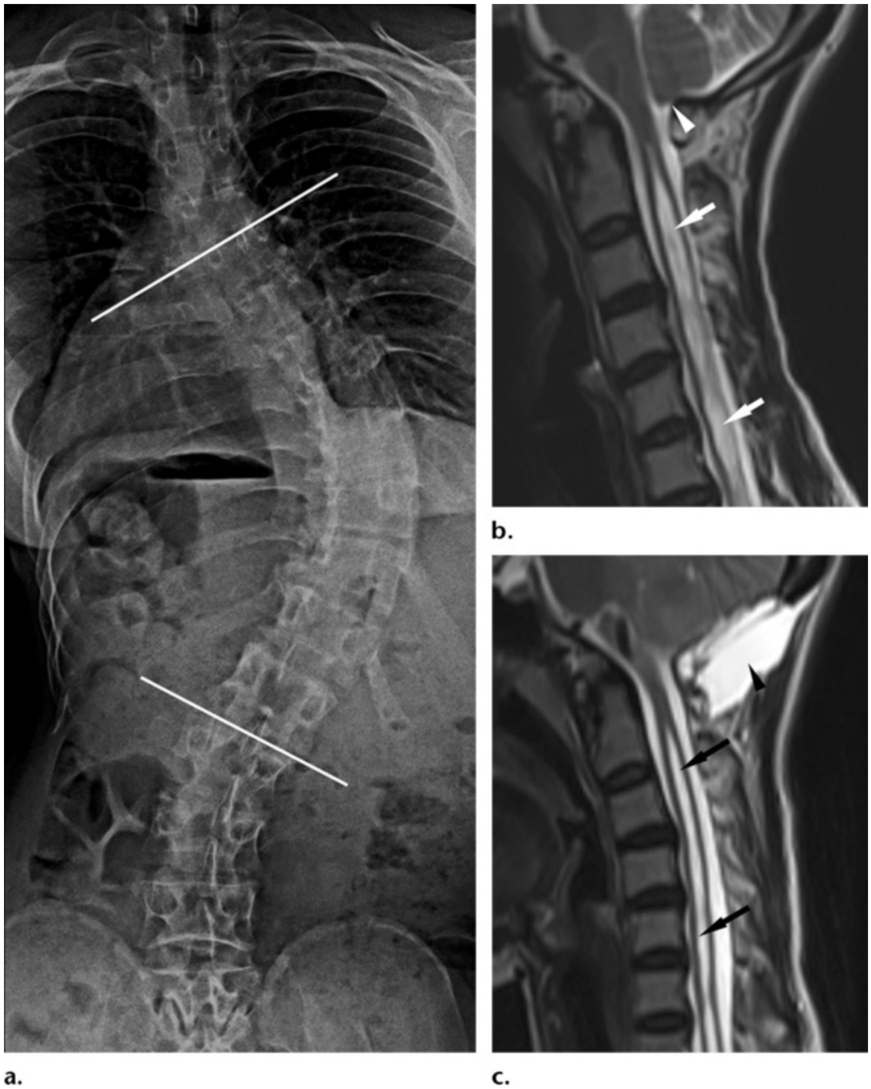


**Figure 15.** Incidentally detected scoliosis and Arnold-Chiari malformation in a 26-year-old woman with a neurologic deficit. **(a)** PA radiograph shows dextroscoliosis of the thoracolumbar spine (segment between the lines) with a Cobb angle of 61°. Because this type of curvature is associated with a high risk of progression despite skeletal maturity, surgical correction was considered necessary. **(b)** Preoperative sagittal T2-weighted (3000/100) MR image of the cervical spine depicts prominent syringomyelia (arrows). Note the vaguely beaklike appearance of the cerebellar tonsil, which extends beyond the margin of the foramen magnum (arrowhead). Given these findings, decompression of the posterior cranial fossa was needed before surgical correction of the curve. **(c)** Postoperative sagittal T2-weighted (3000/100) MR image shows a fluid collection (arrowhead) and decreased syringomyelia (arrows).

MR imaging is mandatory if a neuropathic cause is suspected. The use of MR imaging for the evaluation of scoliosis is guided by the following principles: *(a)* Scoliosis with neurologic deterioration denotes the possibility of an underlying cause; *(b)* intramedullary lesions such as syringomyelia or tumors may occur in association with scoliosis without producing neurologic signs; and *(c)* genuine idiopathic scoliosis is not accompanied by significant spinal pain (2,40). To identify the underlying cause of these three conditions, especially when the cause is a radiographically occult intramedullary lesion, MR imaging is the only tool that enables early detection and appropriate early treatment. Asymptomatic neurologic conditions that result in scoliosis with a late onset (even after skeletal maturity) include Arnold-Chiari malformation (Fig 15), tumors, and various other entities that cause syringomyelia. In conclusion, the exclusion of a clinically occult neurologic cause is the only plausible indication for preoperative MR imaging in patients with apparent idiopathic scoliosis.

## Use of MR Imaging in Presumed Idiopathic Scoliosis

With the increasing use of MR imaging in recent decades, scoliosis specialists have become aware that apparent idiopathic scoliosis may have an

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underlying cause. The typical curve in adolescent idiopathic scoliosis is a thoracic curve with right-sided convexity, with or without a compensatory lumbar curve with left-sided convexity. The use of MR imaging appears to be generally accepted for the evaluation of an unusual pattern of curvature that is commonly associated with neuropathy or a curve with an early onset, unusually rapid progression, and neurologic deterioration at follow-up (2) (Table 4). The problem is that indolent neurologic abnormalities such as syringomyelia and tethered cord syndrome may coexist with a curve pattern that is typical of adolescent idiopathic scoliosis. However, the prevalence of central nervous system abnormalities among patients with presumed adolescent idiopathic scoliosis has been reported to be only 2%–4% (8,41–43). In one prospective study, only seven (2%) of 327 patients with adolescent idiopathic scoliosis and without a neurologic deficit at physical examination were found to have a neurologic abnormality, and none of these abnormalities required treatment before surgical correction of scoliosis (41). For example, subtle syrinx and insignificant Arnold-Chiari malformation without a significant neurologic deficit are not generally treated (8). The rate of positive findings of neurologic abnormality would be predictably low if all patients with adolescent idiopathic scoliosis underwent screening with MR imaging. For these reasons, the routine use of MR imaging for neurologic screening of this group of patients is controversial.

Nevertheless, there are two plausible reasons for performing such screening: First, the treatment of an underlying neurologic lesion could help alleviate progressive neurologic deterioration and lead to improvement or stabilization of scoliosis. Second, surgery performed to correct scoliosis in the presence of an underlying neurologic disorder that has not been identified and treated could result in new or additional neurologic deficits (44,45). The results of a prospective study performed by Inoue and colleagues (46), albeit inconclusive, provide some support for these arguments: A neurologic abnormality was found at MR imaging in 44 (18%) of 250 patients with presumed adolescent idiopathic scoliosis, and the neurologic abnormality in 12 of those 44 patients was considered to require treatment before surgical correction of scoliosis.

In conclusion, no clear consensus has been reached on the use of MR imaging for neurologic screening of patients with presumed idiopathic scoliosis with a typical curve pattern and without pain or a neurologic deficit. Many investigators, including those in the two studies described here, have presented negative opinions. Nevertheless, there is no doubt that MR imaging should be recommended in the presence of a neurologic deficit or the other specific indications described earlier (2).

## Basic Principles of Treatment

The treatment plan, although somewhat dependent on the surgeon, is governed by curve severity, the likelihood of curve progression over time, and the patient's perception of the deformity and symptoms (2, 8). Observation, bracing, and surgery are treatment options. Although all options are available for the treatment of adolescent idiopathic scoliosis, bracing has no role in adult idiopathic scoliosis (skeletally mature patients) (18). Surgery is the only option for congenital scoliosis and other forms of scoliosis with known underlying causes, when intervention is necessary (8,15).

### Observation

Regular observation is maintained if a patient with adolescent idiopathic scoliosis has a curvature with a Cobb angle of less than 20° or a skeletally mature patient has a curvature with a Cobb angle of less than 30° at presentation. Patients are followed up at 4- to 12-month intervals (18,28).

### Bracing

The aim of bracing is to avoid surgery. Bracing is considered for curves with a Cobb angle of 20°–45° in patients with adolescent idiopathic scoliosis. For curves of 20°–30°, bracing is commenced only when progression of 5° or more occurs between consecutive visits. However, when a patient is evidently skeletally immature (Risser grade 2 or lower) and presents with a 30°–45° curve, bracing is commenced at the first visit (18).

### Surgery

The primary goal of surgery in idiopathic scoliosis is to prevent curve progression by achieving solid bone fusion of the involved vertebral segments. The secondary goals are curve correction, trunk balance restoration, and sagittal contour preservation, while leaving as many mobile segments in the lumbosacral spine as possible (2). In nonidiopathic scoliosis, the goals of surgery depend on the underlying cause. In the presence of degenerative scoliosis, the goal is primarily spinal decompression and truncal balance correction, whereas in neuromuscular scoliosis it is curve correction. The objectives of curve correction in neuromuscular scoliosis are to restore seating balance, to ease wheelchair use, to control pain, and to support the trunk so as to reinforce respiratory function (8).

For idiopathic scoliosis, surgery is indicated in skeletally immature patients with a Cobb angle of 45° or more at presentation. Surgery is recommended also for patients with curve progression despite the use of a brace and for those who cannot tolerate the use of a brace (18,28). In addition, for skeletally mature patients, surgery is recommended for curves with a Cobb angle of 45° or more, given that curve progression is accompanied by pain (8). Progressive congenital scoliosis, in which the involved spinal segment is usually too short or too inflexible to respond well to bracing, is also treated surgically (15).

The phrases *anterior approach* and *posterior approach* are commonly seen in surgical reports. The posterior approach involves fusion performed from the posterior aspect of the spine by using bone grafts and posterior instrumentation (hooks and wires, or more commonly now, transpedicular screws and rods). The anterior approach denotes total disk excision with anterior instrumentation, which allows a more substantial correction with fewer fused segments than is characteristic of posterior instrumentation with fusion. When the anterior approach is used, the surgeon must exercise caution to avoid overcorrection of the curvature and resultant trunk imbalance.

To optimize treatment outcomes, surgeons make every effort to spare mobile segments of the lower lumbar region when performing fusion so as to minimize the loss of lumbar lordosis and avoid postoperative low back pain. Low back pain occurs in most patients who undergo fusion beyond the L3 level (2).

## Summary

Scoliosis is defined as a lateral spinal curvature with a Cobb angle of 10° or more. The Cobb angle is measured between the superior endplate of the proximal end vertebra and the inferior endplate of the distal end vertebra. An increase in the Cobb angle by 5° or more per year indicates progression of scoliosis. On the basis of the Hueter-Volkmann law, it is hypothesized that scoliosis is initiated by vertebral rotation in the axial plane, which produces asymmetric forces of compression and traction on the convex and concave sides of spinal curvature.

The identification of the curve apex, end vertebrae, neutral vertebrae, and stable vertebrae is important when interpreting the radiographic features of scoliosis. The ability to accurately differentiate between major (larger) and minor (smaller) curves and structural and nonstructural curves is likewise important for identifying the type of curvature and guiding surgical treatment. However, it should be borne in mind that minor curves may begin as nonstructural curves and progress to structural curves.

With regard to etiologic classification, idiopathic scoliosis is the most common type (80% of cases), followed by congenital scoliosis (10% of cases). Idiopathic scoliosis is diagnosed after underlying causes are excluded and is generally further classified according to patient age and disease characteristics as infantile (age 0–3 years), juvenile (age 4–10 years), or adolescent (age 11–18 years). Adult-type idiopathic scoliosis is defined as idiopathic scoliosis that is detected after skeletal maturity has been achieved. Juvenile scoliosis and congenital scoliosis are considered to represent progressive forms of disease, whereas infantile and adolescent scoliosis are not generally progressive. The spinal growth rate affects curve progression, which peaks before skeletal maturity is achieved, and the growth spurt is the main prognostic indicator of progression, although scoliosis may progress even after skeletal maturity. On the Risser index, which describes skeletal maturity as the extent of excursion of the ossification center of the iliac crest, grade 0 (no ossification center) and grade 1 (ossification center at the outer fourth of the iliac crest) are notable prognosticators of curve progression. Follow-up at intervals of 4–12 months is generally considered optimal for monitoring curve progression.

The Lenke classification system, because of its great reliability and comprehensiveness, is the system most widely used to describe curve types. The structural or nonstructural nature of curves should be assessed on the basis of ipsilateral side-bending views, especially when surgery is contemplated. The radiographic definition of a structural curve is one with a Cobb angle of 25° or more on ipsilateral side-bending views.

Both MR imaging and CT can be recommended for the detection of underlying causes of scoliosis. CT is also used to guide preoperative planning. The use of MR imaging in presumed idiopathic scoliosis is warranted in the presence of reasonable indications.

Treatment options are observation, bracing, and surgery. Bracing is not beneficial after skeletal maturity. Surgery is recommended for juvenile idiopathic scoliosis and congenital scoliosis. The recommended treatment for adolescent and adult idiopathic scoliosis is observation (follow-up at 4- to 12-month intervals) when the Cobb angle is less than 20° in adolescent idiopathic scoliosis and less than 30° in adult idiopathic scoliosis; bracing when the Cobb angle is 20°–45° in adolescent idiopathic scoliosis; and surgery when the Cobb angle is greater than 45° in both adolescent and adult idiopathic scoliosis.

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# Scoliosis Imaging: What Radiologists Should Know

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**Page 1824 (Figure on page 1824)**
Scoliosis appears to develop in two stages, namely curve initiation and subsequent progression (4). According to the Hueter-Volkmann law, bone growth in the period of skeletal immaturity is retarded by mechanical compression on the growth plate and accelerated by growth plate tension. Because of the physiologic curvature in the normal thoracic spine, compressive force is delivered on the ventrally located part of the vertebral column, whereas distractive force is delivered on the dorsally located part. The process leading to abnormal spinal curvature is thought to be initiated by the rotation of vertebral bodies in the axial plane, which causes discrepant axial loading between the ventrally and dorsally located portions of the involved vertebrae (5). Over time, the discrepancy manifests as a change in the directionality of spinal curvature; that is, the ventrally located part of the vertebral column becomes the concave side and the dorsally located part becomes the convex side of a lateral curve (5) (Fig 1).

**Page 1828**
Because of vertebral morphologic changes (eg, wedging and rotation), a structural curve is not correctable with ipsilateral bending. By contrast, no vertebral morphologic changes take place in a nonstructural curve, which is a mild compensatory curve enabling sagittal and coronal truncal balance; therefore, it is correctable with ipsilateral bending. A nonstructural curve does not usually progress. However, a nonstructural curve may progress to a structural curve if ligament shortening results from growth retardation on the concave side of curvature (8).

**Page 1831**
The factors that have the greatest effect on the probability of progression of adolescent idiopathic scoliosis are spinal growth velocity and magnitude of the curve at initial presentation (28).

**Page 1839 (Table on page 1836)**
The typical curve in adolescent idiopathic scoliosis is a thoracic curve with right-sided convexity, with or without a compensatory lumbar curve with left-sided convexity. The use of MR imaging appears to be generally accepted for the evaluation of an unusual pattern of curvature that is commonly associated with neuropathy or a curve with an early onset, unusually rapid progression, and neurologic deterioration at follow-up (2) (Table 4).

**Page 1841**
The recommended treatment for adolescent and adult idiopathic scoliosis is observation (follow-up at 4- to 12-month intervals) when the Cobb angle is less than 20° in adolescent idiopathic scoliosis and less than 30° in adult idiopathic scoliosis; bracing when the Cobb angle is 20°–45° in adolescent idiopathic scoliosis; and surgery when the Cobb angle is greater than 45° in both adolescent and adult idiopathic scoliosis.