Radiographic Evaluation of Scoliosis: *Review*

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OBJECTIVE

Despite enormous advances in cross-sectional imaging over the past few decades, radiography remains the mainstay of diagnosis and evaluation of scoliosis. Knowledge of technical factors, measurement error, and measurement techniques is important in the comparison of serial radiographs and affects surgical decision making. This article focuses on adolescent idiopathic scoliosis as a framework for understanding the general concepts in the radiographic evaluation of the scoliotic spine.

CONCLUSION

The concepts of sagittal and coronal balance are critical to the evaluation of spinal deformity. Sideward-bending views allow the differentiation of structural and nonstructural curves and affect the choice of levels to be included in an operative fusion. Structural curves also are identified by the presence of marked rotation that manifests clinically by the rib hump.

Scoliosis is defined as a lateral curvature of the spine in the coronal plane. The most common causes include idiopathic scoliosis, more common in younger patients and degenerative scoliosis, seen in older patients. Other causes include neuromuscular, congenital, and developmental abnormalities. Scoliosis also may occur secondary to tumor, infection, and trauma. Despite the enormous advances in cross-sectional imaging over the past few decades, radiography remains the mainstay of diagnosis and evaluation of scoliosis. The key advantage of radiography is the ability to image the entire spine in the standing patient while giving the clinician an appreciation of the 3D rotatory nature of the scoliotic deformity. Curvatures, truncal imbalance, and listhesis are often more prominent on standing weightbearing views compared with images of the same patient in a recumbent position. Standing radiographs allow more reliable radiographic measurements that are important in following the magnitude of the spinal deformity over time and ultimately in surgical decision making. The radiographic analysis of curvatures may include sideward-bending views and flexion–extension views. Radiography has the additional advantages of low radiation dose, low cost, and wide availability.

This article will concentrate on what measurements are obtained in the radiographic evaluation of the spine and how these values inform management. Understanding these concepts and their role in surgical decision making assists the radiologist in the interpretation of preoperative and postoperative radiographs as well as cross-sectional imaging. The primary focus will be on adolescent idiopathic scoliosis as a framework for understanding the general concepts in the radiographic evaluation of the scoliotic spine. A limited review of other less common causes of scoliosis will be included.

Technique

Careful attention to technique is critical in scoliosis radiography. Small differences in rotation or magnification and other alterations in patient position can significantly alter spinal curvature measurements [1]. Strict adherence to a standardized technique reduces these errors. The scoliosis radiograph should include the cervical spine superiorly and the pelvis inferiorly. The assessment of sagittal balance makes it particularly important to include the cranium down to both femoral heads on the same radiograph. Determinations of C2 and C7 plumb lines as well as a number of pelvic parameters are frequently measured preoperatively for planning of correction and after surgery [2, 3].

This field of view may be too large for a single projection, particularly when the deformity is significant. Two digital radiographs are "stitched" together to reproduce the scoliosis radiograph. The patient is positioned 72 in (183 cm) from the radiation source with the feet a shoulder width apart and the knees extended. On the lateral images, the patient looks straight ahead with elbows flexed and hands placed over the clavicles [4]. This keeps the upper extremities from being superimposed over the spine on the lateral view. Breast and pelvic shields may be used to reduce the radiation dose. A compensating filter ensures that proper bone density is maintained throughout the spine.

Keywords: deformity, MRI, radiography, scoliosis

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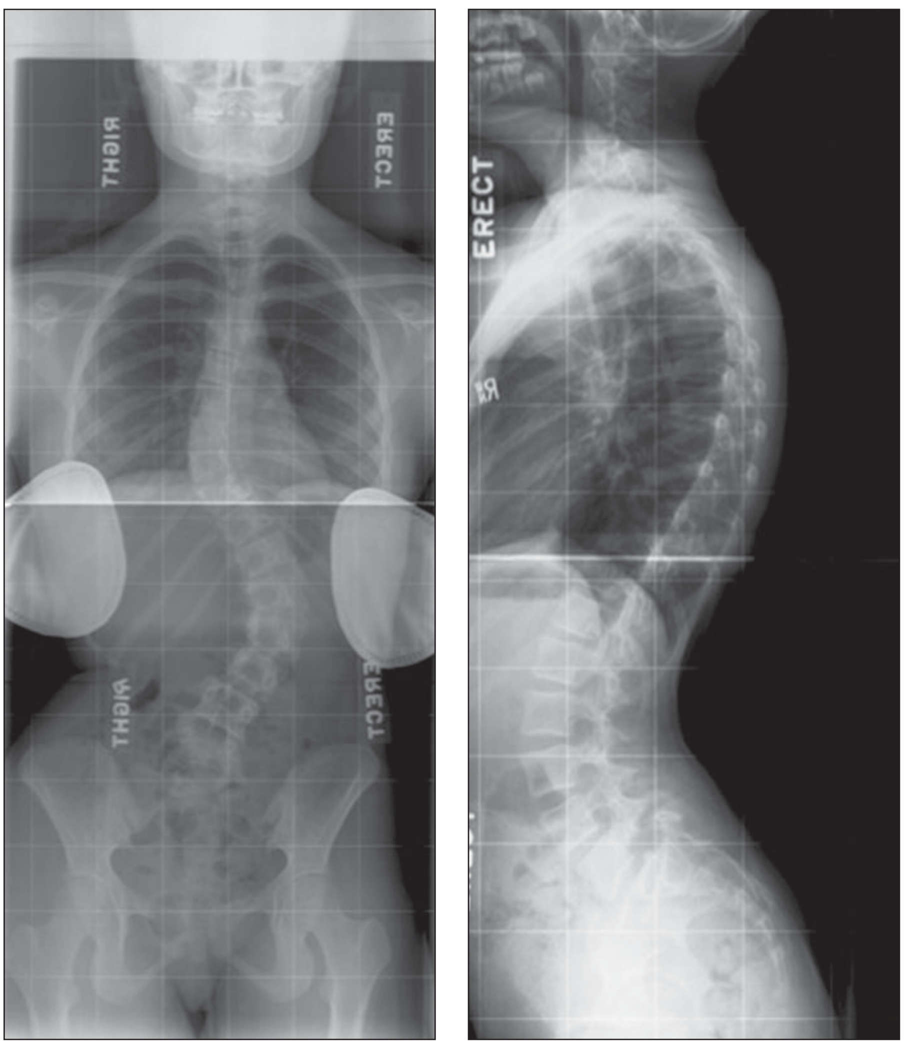
The Anatomy of a Curvature

Some general definitions are helpful in the discussion of spinal deformity. The largest curve in the scoliotic spine is known as the primary or major curvature. A scoliotic deformity may have one or several major curves. Other small curves (if present) are termed secondary or minor curvatures. These minor curves may be fixed, inflexible structural curves or flexible, nonstructural curves. For each curvature, there are terminal and apical vertebrae. The terminal vertebra is the most tilted superior or inferior vertebra included in a curve. The apical vertebra is the most laterally displaced and most horizontally oriented. It also is the most profoundly rotated vertebra and is generally found at the apex of the curve (Fig. 1). Terminal vertebrae are typically the most tilted and are selected to make the largest Cobb angle.

Measuring Curves

The most commonly used and most accurate measurement of spinal curvature is the Cobb angle [5]. It is obtained by measuring the maximal angle from the superior endplate of the superior-end vertebra to the inferior endplate of the inferior-end vertebra. If endplates are difficult to visualize, the borders of the pedicles may be used. The measurements obtained using this method should be precise and reproducible because the magnitude of the curve is a major factor in the clinical decision-making process. The total error in assessing the Cobb angle is approximately 2–7° [6–9]. This error results from variations in both radiograph production and measurement error. Subtle changes in radiograph production, including changes in patient position and posture, caused 2° of standard error in one study [6]. Overall, intraobserver variability is less than interobserver variability. Therefore, the radiologist should measure the Cobb angle on both the current study and the historical comparison studies to avoid introducing the additional interobserver error. Measuring angles using a PACS has been shown to be equivalent to manual measurements on conventional radiographs [10].

When comparing two radiographs, both measured Cobb angles introduce measurement error. A 5° difference in the Cobb angle measured between two radiographs represents a 95% chance that there is a true difference [8]. In adolescent idiopathic scoliosis, an increase of 5° is thought to indicate



A B

Fig. 1—20-year-old woman with adolescent idiopathic scoliosis.
A and **B,** Anteroposterior (**A**) and lateral (**B**) standing radiographs show typical thoracic dextroscoliosis and thoracolumbar levoscoliosis. Thoracolumbar curvature is larger and exhibits more rotation and is therefore major curve in this example. Apical vertebra of this curvature is L1.

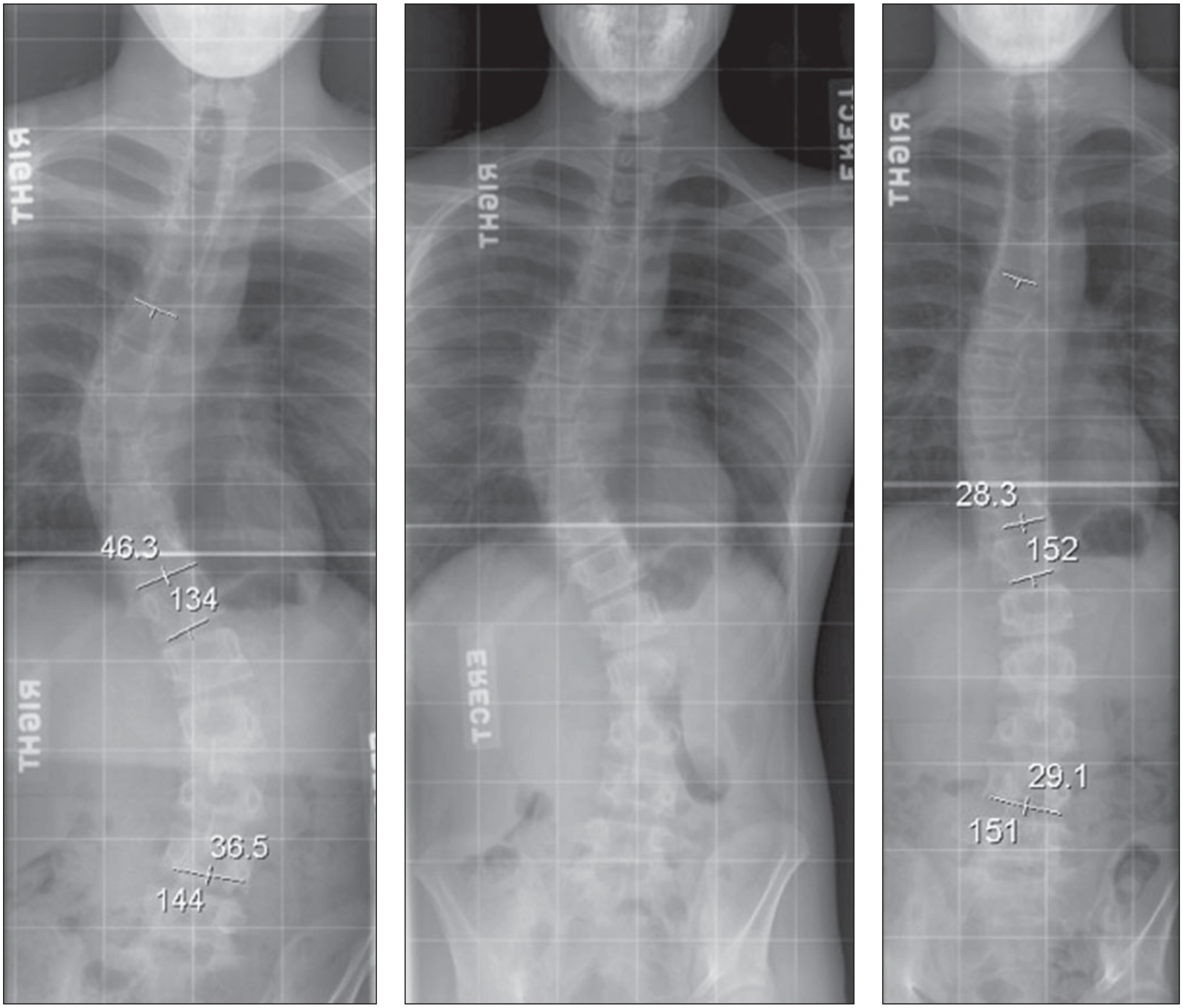
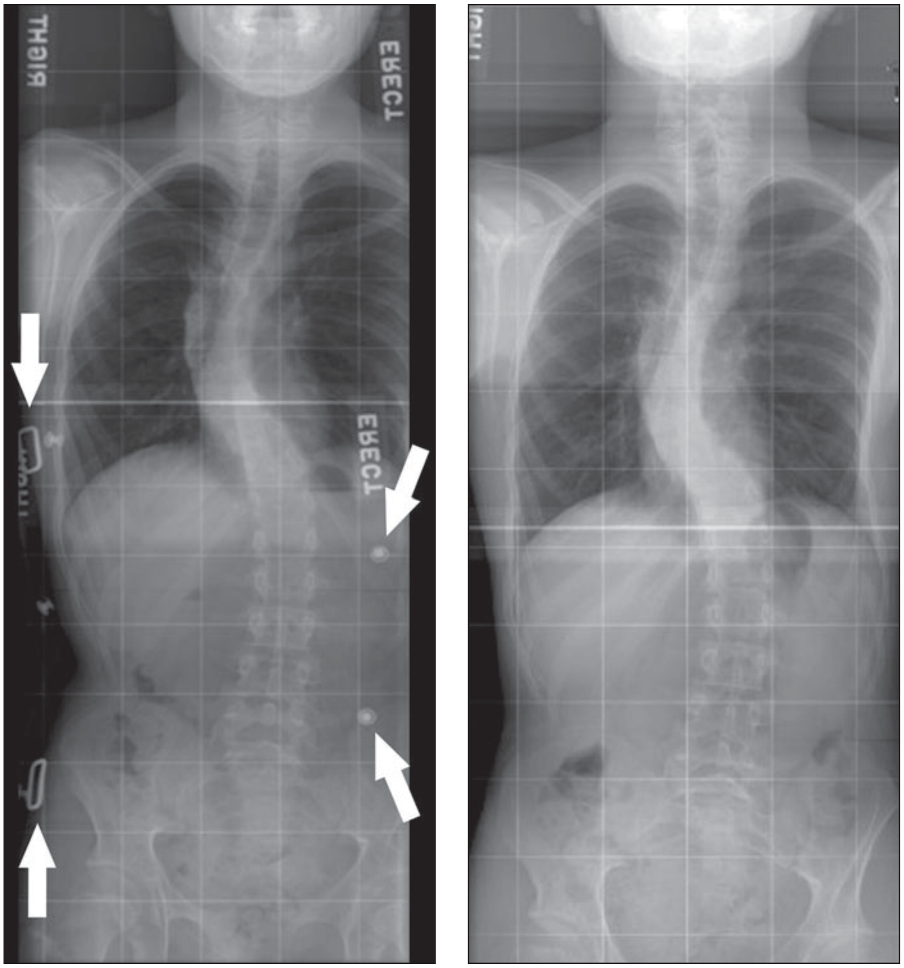


Fig. 2—13-year-old girl with adolescent idiopathic scoliosis.
A–C, Assessment of curve progression should include comparison of current study (**A**) with remote previous study. Over multiple 6-month follow-up examinations (**B**), no significant change was seen, but when compared with study from 2 years previous (**C**), significant increase in deformity has occurred.

that significant curve progression is occurring at a 12-month interval. Cobb angles may also be used to describe kyphotic and lordotic angulation on the lateral view. These measurements are generally reliable and accurate [11]. Exceptions include measuring kyphosis in the upper thoracic spine and measuring Cobb angles in large curvatures because of difficulty in precisely defining the endplates.

Several common pitfalls when comparing radiographs for curve measurements exist. A patient may not show significant curvature progression when the new radiograph is compared only with the most recent previous study. However, significant progression may be detected when comparisons are made with more remote imaging studies; a finding that may alter management (Fig. 2). A second pitfall is the recognition that some of the curvature difference may be due to differences in technique. Is the patient wearing a brace in one study and not the other? The curvature is often exaggerated when the brace is removed (Fig. 3). Is the patient leaning on something or sitting down? It is important to mention the presence of significant technical differences when comparing two studies. In curves of greater magnitude, simply measuring the Cobb angle may not show progression. However, assessing the degree of rotation of the apical vertebra, overall spine balance using a C7 vertical line in relation to the pelvis, or indirect measures such as the distance from the iliac crest to the lower ribs in a degenerative curve are all clinically significant suggestions of a progressive deformity. Finally, it is important to recognize that supine radiographs and cross-



A B

Fig. 3—14-year-old girl with adolescent idiopathic scoliosis.
A and **B**, When comparing these two frontal radiographs in same patient, it is important to note that patient is wearing brace (*arrows*) in one study, which will affect magnitude of curvature.

sectional imaging should not be compared with upright radiographs. Measurement of Cobb angles on cross-sectional images when the spine is not weight bearing will tend to underestimate the degree of deformity.

In adolescent idiopathic scoliosis, the primary clinical utility of the Cobb angle is in determining the risk of curve progression. The Cobb angle otherwise has limited prognostic value. It does not correlate with the degree of morbidity or pain. The degree of reduction of the Cobb angle does not correlate with patient satisfaction in postoperative outcome surveys [12–15]. In fact, complete correction, decompensation, or imbalance in patients with neuromuscular scoliosis in whom overcorrection has been reported, results in increased risk of instrumentation failure.

Sagittal and Coronal Balance

The concept of truncal balance is critical in the evaluation of spinal deformity. In the setting of adolescent idiopathic scoliosis, the primary goals of surgery are to stabilize the spine and prevent further progression of deformity. This goal is achieved by surgical fusion across the spinal deformity. Additional goals include alleviating the patient's symptoms and reducing cosmetic deformity. These goals are best achieved by restoring sagittal and coronal balance.

Sagittal balance describes the relationship of the head relative to the pelvis in the sagittal plane. It is measured on a standing lateral view by dropping a plumb line from the center of the C7 vertebral body vertically downward and assessing the distance of this line from the posterior aspect of the S1 vertebral body (Fig. 4). In healthy patients with neutral sagittal balance, this plumb line intersects this sacral landmark [15]. Positive sagittal balance is present if the plumb line is greater than 2 cm anterior to the posterior aspect of the S1 vertebral body. Similarly, negative sagittal balance is described with the plumb line is 2 cm posterior to the sacral landmark. Coronal balance is measured on an upright anteroposterior view. A plumb line is dropped vertically from the center of the C7 vertebral body. This usually intersects with the central sacral vertical line (Fig. 5). Positive and negative coronal balance are present when this plumb is line is greater than 2 cm to the right and left, respectively.

Patients with positive sagittal balance commonly present with back pain, likely to be fatigue pain because the truncal muscles, hips, knees, and thighs are under continual strain to keep the patient's head in line with the shoulders and hips and over the feet. Patients with positive sagittal balance may be described as having a "flat-back" deformity with loss of normal lumbar lordosis and resultant forward-tilting posture. These patients unknowingly will flex their hips and knees to maintain a more erect posture, and this must be accounted for during positioning for lateral radiographs. Restoration of sagittal balance improves the success rate of scoliosis surgery. Schwab et al. [16], compared preoperative radiographic parameters and postoperative outcomes. They found that patients presenting with loss of normal lumbar lordosis and positive sagittal balance showed the most benefit from surgery. Glassman et al. [17] presented an outcome study involving 298 patients before adult scoliosis surgery. Clinical outcome did not correlate with curve magnitude, apical rotation, or the number of major curves. The key radiographic abnormality that resulted in significant improvement in pain, function, and self image was found to be sagittal balance. The authors concluded

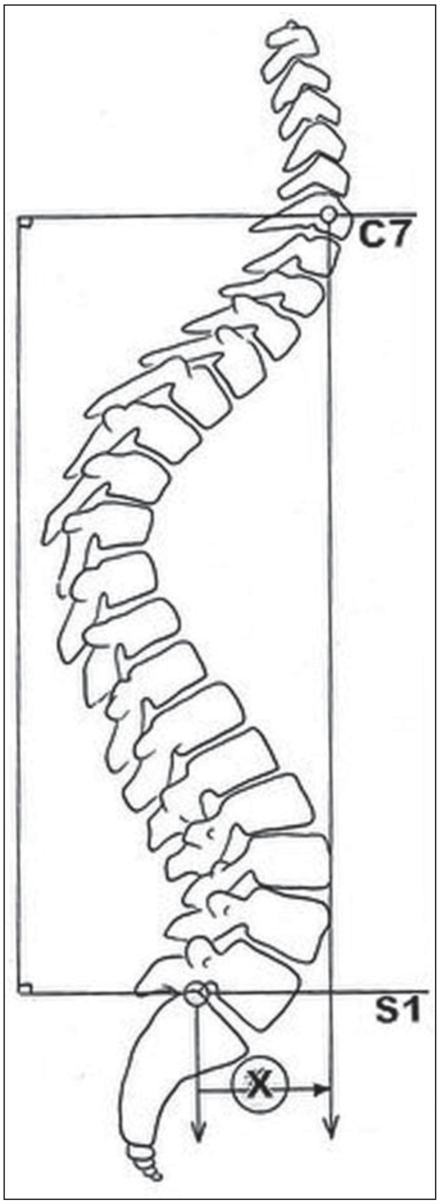


Fig. 4—Drawing shows sagittal balance, measured as distance between C7 plumb line and posterosuperior aspect of S1 vertebral body. Positive or negative sagittal balance is described when plumb line is anterior and posterior to this sacral landmark, respectively.

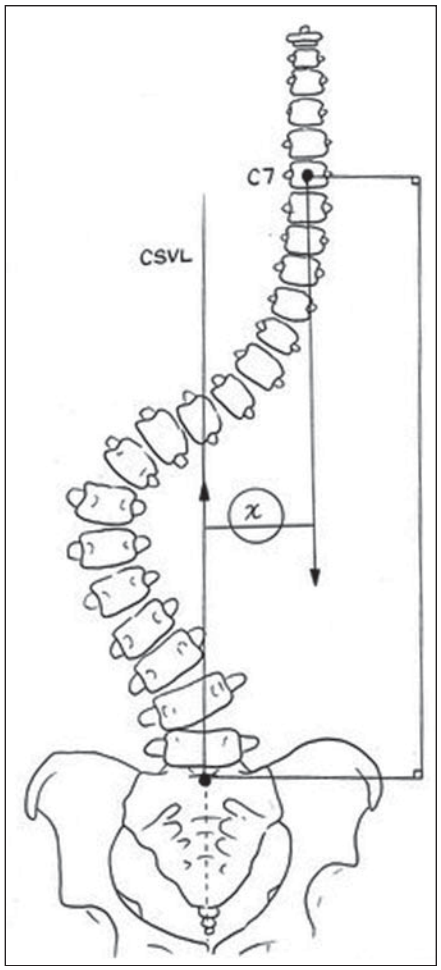


Fig. 5—Drawing shows coronal balance, measured as distance between C7 plumb line and central sacral vertical line (CSVL). Positive and negative coronal balance is described when plumb line is to right or left of this sacral landmark, respectively.

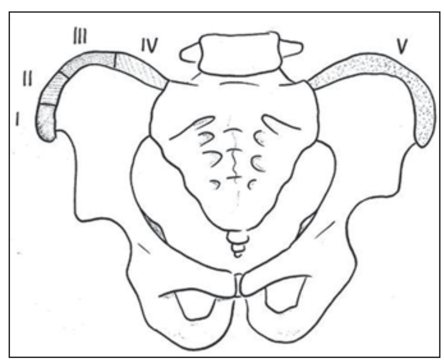


Fig. 6—Drawing shows Risser grading. Skeletal maturity is estimated on scoliosis radiographs by assessment of degree of ossification of iliac crest hypophysis.

that restoration of sagittal balance should be a primary goal of spinal deformity surgery. In a related study, the magnitude of sagittal imbalance correlated with the degree of functional impairment preoperatively [18].

Coronal balance is another key factor in patient satisfaction. The restoration of coronal balance reduces several cosmetic deformities including having one shoulder higher than the other. Several measurements of shoulder asymmetry have been described [19], but assessment of the clavicle angle is the most reliable. The clavicle angle is formed by the intersection of a tangential line connecting the superior aspect of the bilateral distal clavicles to a line parallel to the floor. Kuklo et al. [20] suggest that the clavicle angle can be used to determine whether the proximal thoracic curve (T1–T3) needs to be included in the fusion in adolescent idiopathic scoliosis. If the patient has a clavicle angle that is neutral or shows elevation of the right shoulder, correction of a major thoracic dextroscoliosis results in symmetric shoulder position. In contradistinction, surgical correction of a thoracic dextroscoliosis exacerbates the position of an already elevated left shoulder. Surgical fusion of the proximal thoracic curve in this subset of patients can prevent this. This same study found that normal postoperative shoulder balance correlated with successful patient postoperative assessments.

In the normal spine, axial rotation is coupled with sideward-bending. In severe scoliosis, bending and axial rotation are often decoupled [21] because of structural changes, such as wedging of vertebrae and intervertebral disks, that occur over time. This structural deformity in the axial plane is not corrected by scoliosis surgery. This has important clinical implications. Cosmetic deformities such as a rib hump caused by axial rotation may persist after correction of the scoliosis and may be addressed with a concomitant thoracoplasty, wherein the prominent rib segments are surgically resected.

Structural Versus Nonstructural Curves

The major (largest) curve in the patient with adolescent idiopathic scoliosis is often accompanied by vertebral axial rotation and will not completely correct with side-bending views and is thus, by definition, the structural curve. Other curvatures may be inflexible, structural curves or flexible, nonstructural curves that are present to maintain truncal balance. For example, a lumbar levoscoliosis may be present to compensate for the major thoracic dextroscoliosis and keep the head above the pelvis. Over time, a nonstructural curve may become structural because of shortening of ligaments, muscle atrophy, and osseous changes that occur with the spine in a prolonged position. In general, the surgeon attempts to minimize the number of fused motion segments. Shorter fusions maintain maximal range of motion and decrease the risk of nonunion. Recognition of a nonstructural curve can allow a shorter fusion. If the structural curve is straightened, the nonstructural curve will correct spontaneously.

The most common method for determining whether a curve is structural is the evaluation of sideward-bending views. Sideward-bending views are obtained upright with the patient leaning maximally to one side or the other. Some authors advocate traction methods or bending over a fulcrum to assess curve flexibility [22, 23]. Klepps et al. [24] noted that sideward-bending views were more effective in showing flexibility in the proximal thoracic and lumbar curves, whereas fulcrum-bending views were more effective in showing flexibility in main thoracic curvatures. All methods fell short compared with the correction found after surgery in this study.

Regardless of the method of obtaining the views, the Cobb angle of the curvature is assessed on each bending view and compared with neutral position. A curve that has significant flexibility will straighten when the patient bends toward the curve. For example, a nonstructural lumbar levoscoliosis will straighten when the patient bends to the left. The radiographic definition of a structural curve is one that does not reduce to less than 25° on bending views. A nonstructural curve is one that will reduce on bending views, supine position, or after surgical correction of the primary curve.

Adolescent Idiopathic Scoliosis

Adolescent idiopathic scoliosis is a structural lateral curvature of the spine evident in otherwise healthy patients between the ages of 10 and 18 years. The diagnosis is confirmed when a 10° lateral curvature is present on a frontal upright radiograph. Curves smaller that this are within normal variation, tend to be asymptomatic, and are less likely to progress. Taking these factors into account, deformities of a magnitude less than 10° are best termed curvatures rather than scoliosis, which implies a disease state. As the name suggests, adolescent idiopathic scoliosis is a diagnosis of exclusion after careful clinical history, physical examination, and radiographic analysis. It is a common disorder affecting 2–4% of this age cohort [25]. Although small curves are equally common in both genders, larger curves are 10 times more common in females. The prevalence of larger curves measuring greater than 40° is 0.1% of the adolescent population [26].

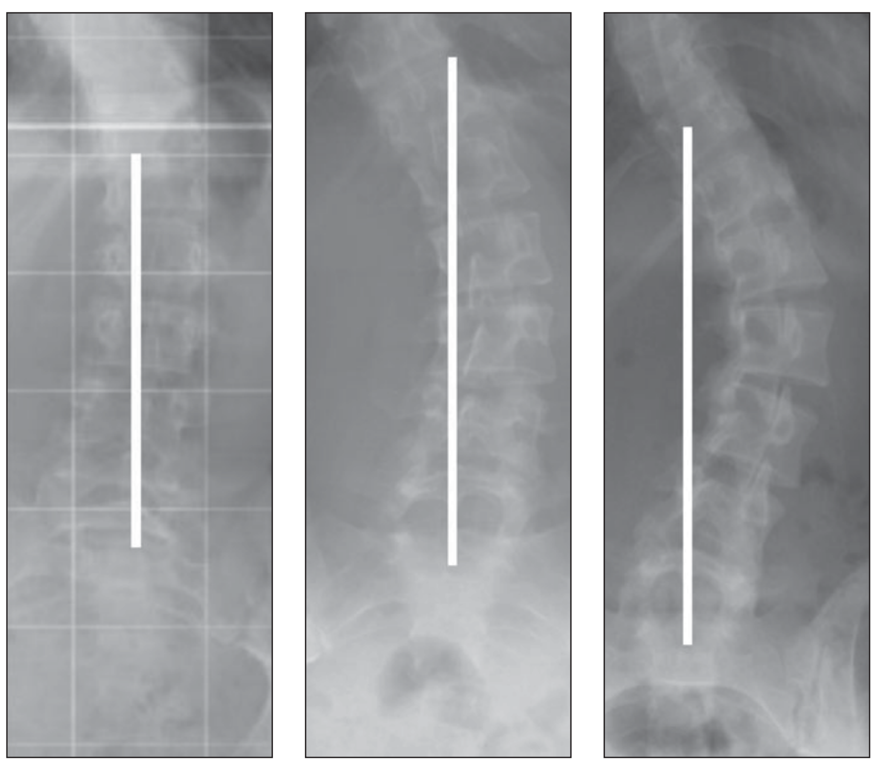
The natural history of adolescent idiopathic scoliosis is usually uncomplicated in patients with a small or moderate degree of deformity. Most patients with curvatures under 50° tend to have the same incidence of back pain and mortality as is found in the general population [27]. Patients with curves with a magnitude greater than 50° have been found to experience a greater prevalence of back pain. Thoracic curvatures greater than 100° affect lung function, and these patients had an increased mortality rate compared with the general population [27].

The risk of curve progression depends on the magnitude of the curvature and the skeletal maturity. In one study of 727 patients with adolescent idiopathic scoliosis and curves measuring between 5° and 29°, the main determinants of curve progression were the magnitude of the curve, skeletal maturity, and patient's menarchal status [28]. Skeletal maturity is most commonly determined by looking at the presence and degree of ossification of the iliac crest apophysis [29]. In Risser stage 0, the apophysis is not present. In Risser stages I, II, III, and IV, the apophysis covers 25%, 50%, 75%, and 100% of the iliac wing, respectively (Fig. 6). Stage V is the adult pelvis. Risser staging is commonly used but less accurate in the determination of skeletal maturity than the use of hand radiographs [30]. Spinal curvatures in skeletally immature patients with nonossified iliac apophysis have been found to progress in 65% with curves between 20° and 30° and in nearly all patients with a curvature greater than 30° [31].

Small curvatures seldom progress in an adult. In contrast, thoracic curves that measure greater than 30° tend to progress. One study with 40 years of follow-up found an average of 10° of progression in patients with a 30–50° curve and 30° of progression in patients with a thoracic curve greater than 50° [32]. Therefore, patients with a more severe curvature should undergo continued radiographic evaluation. This slow rate of curve progression in the adult patient offers a unique imaging archiving challenge in the digital age. Images may be stored for only 7–10 years. A surgeon may be more likely to operate in a minimally symptomatic 40-year-old patient with a 60° dextroscoliosis if that curve has significantly progressed over the past 20 years and less likely to operate in a stable, unchanging deformity. Comparison with recent radiographs is unlikely to show a change in these slowly progressive curvatures. It may be beneficial for patients to keep a copy of the original imaging in these circumstances.

Treatment of adolescent idiopathic scoliosis is varied and includes observation, bracing, and surgery. The choice of treatment is based on the degree of morbidity, patient factors, surgeon preference, and the risk of curve progression over time. Bracing has limited effectiveness and is generally recommended for curves between 25° and 40° only in skeletally immature patients. Bracing has been shown to successfully prevent curve progression in 75% in this patient population [33]. A radiograph showing 50% reduction of the Cobb angle when the patient is wearing a brace correlates with a successful outcome [34]. It should be noted that good outcomes also occur with smaller or minimal reduction of curvatures when the patient is wearing a brace. Surgery is generally the preferred option for a skeletally immature patient with a progressing 40° scoliosis or a skeletally mature patient with a painful or progressive curve greater than 45°. Skeletally immature patients continue to grow anteriorly after a posterior fusion. This may result in a rotational deformity, often with a stable Cobb angle, known as the "crankshaft" phenomenon [35]. Clinically, this often manifests as an increased rib hump in the postsurgical patient. The surgeon may include an anterior fusion in these patients to prevent this occurrence.

The goals of surgery include restoration of truncal balance; a stable, pain-free spinal fusion; and improved cosmesis, including rib hump, shoulder, and hip symmetry [36].



A B C

Fig. 7—Lenke classification of adolescent idiopathic scoliosis: lumbar modifier. Lumbar **A–C,** Modifiers A, B, and C are given when sacral central vertical line lies between pedicles (**A**), at level of pedicles (**B**), and outside pedicles (**C**), respectively.

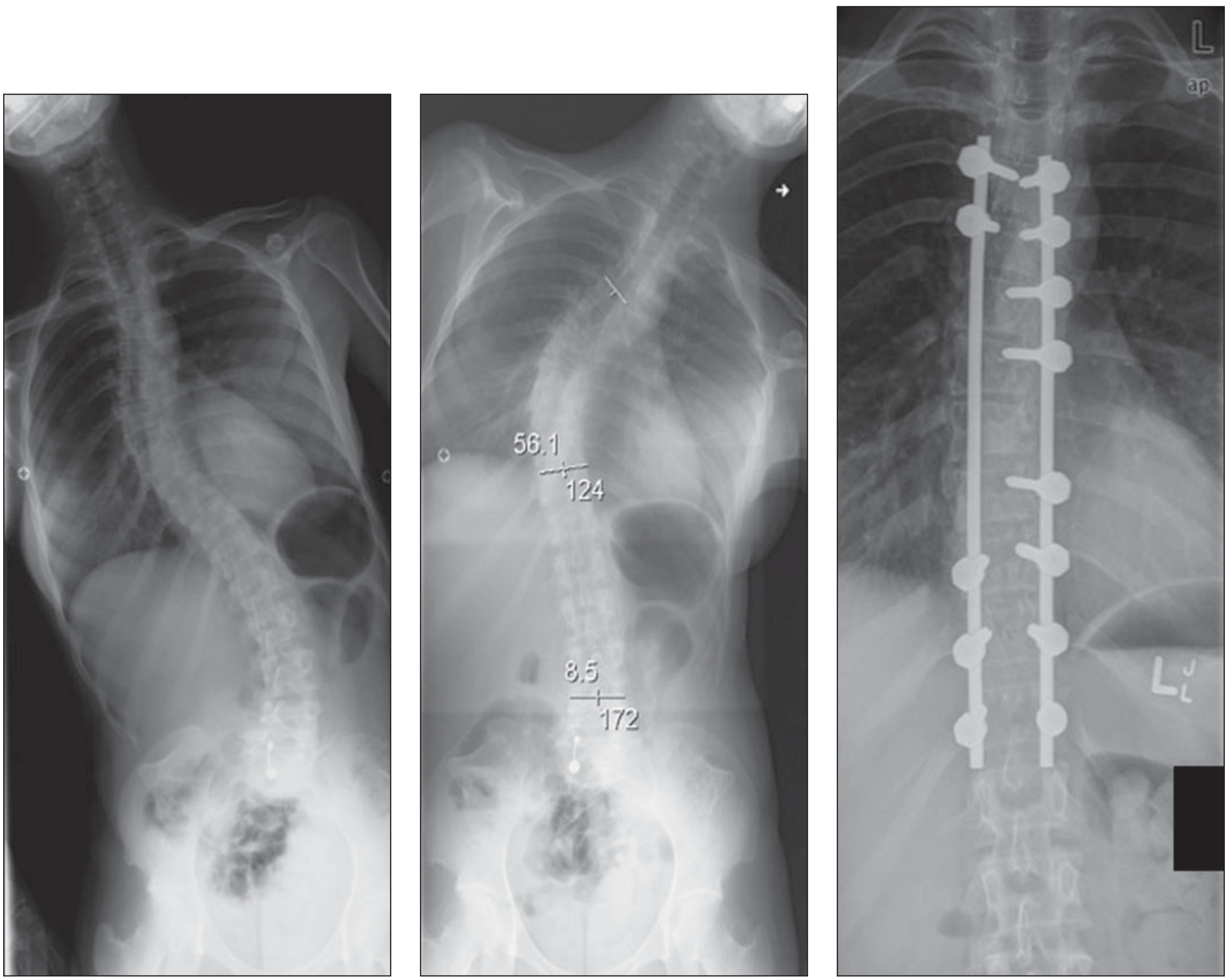
While doing so, the surgeon attempts to spare as many motion segments as possible. The goal is not necessarily to completely straighten the spine. In fact, the degree of deformity correction does not correlate with clinical outcome [37]. Overcorrection of curves may lead to truncal imbalance [38, 39] or asymmetry of the shoulders. Surgery has a 5% major complication rate including a rate of neurologic sequelae of approximately 0.2% [40].

Classification of Scoliosis

The Lenke classification for adolescent idiopathic scoliosis is based on the upright anteroposterior, lateral, and sideward-bending radiographs [41]. It is designed to help the surgeon decide which vertebral levels should be included in an operative fusion. On the frontal radiograph, three measurements are obtained: the proximal thoracic (apex between T1 and T3), main thoracic (apex between T3 and T12) and thoracolumbar/lumbar curve (apex between T12 and L4). The major curve is the region with the largest Cobb measurement. The other curves are termed minor curves. On the lateral radiograph, thoracic kyphosis and lumbar lordosis are measured.

The major curve is always included in the operative fusion. The purpose of the side-bending views is to determine whether the minor curves should be included in the fusion. On the side-bending views, if the lesser curve reduces to less than 25° Cobb angle measurement, it is a nonstructural curve. If it remains greater than 25°, it is a structural curve. On the basis of which curves are structural or nonstructural, six types of curves are constructed (Table 1).

Two modifiers are added to this classification system. The lumbar modifier is determined by assessing the relationship

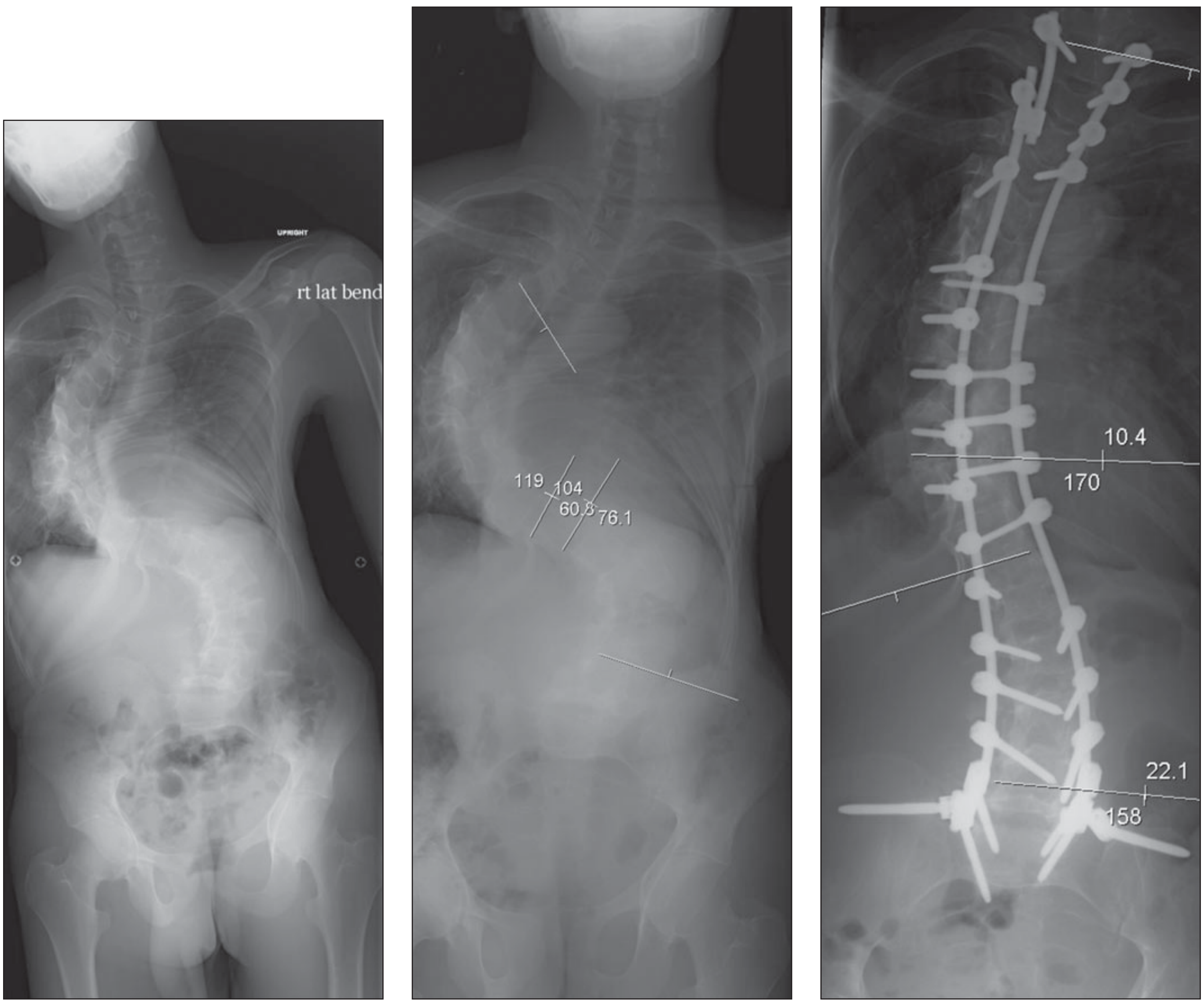


A B C

Fig. 8—15-year-old girl with adolescent idiopathic scoliosis.
A–C, Side-bending radiographs show thoracic curve is largest curve and therefore structural curve. On leftward-bending views, proximal thoracic and lumbar curves reduce to below 25° and are therefore nonstructural. Only structural curve is included in operative fusion.

of the central sacral vertebral line (CSVL) to the apical vertebrae of the lumbar spine (Fig. 7). This central sacral vertebral line lies between the pedicles in lumbar modifier “A,” intersects the pedicle in modifier “B,” and is medial to the pedicles in modifier “C.” The second modifier is based on the degree of thoracic kyphosis. A “–” modifier is given in the case of a kyphotic angle less than 10°. An “N” modifier indicates a 10–40° kyphosis between T5 and T12. A “+” modifier indicates a thoracic kyphosis or greater than 40°. The lumbar modifier is important in that it guides the surgeon as to when a selective thoracic fusion may be performed. The thoracic modifier will identify those patients who have profound thoracic hypokyphosis and would benefit from restoration of thoracic kyphosis to improve their thoracic anteroposterior dimension and thus chest capacity.

This classification system can be illustrated with two examples. The thoracic dextroscoliosis is the largest curvature and therefore by definition the major curve (Fig. 8). A proximal thoracic levoscoliosis and lumbar levoscoliosis are present. These minor curves straighten to less than 10° on leftward-bending views. They meet the criterion for nonstructural curves and do not need to be included in the fusion. This is classified as a Lenke type 1 curve. Postoperative views show spontaneous reduction of the minor curves after surgical fusion of the thoracic dextroscoliosis. The largest curvature is again a thoracic dextroscoliosis in the second example (Fig. 9). However, in this case the proximal thoracic levoscoliosis and lumbar levoscoliosis do not reduce on leftward-bending views. All three curvatures are structural and must be included in the fusion. This is a Lenke type 4 curve.



A B C

Fig. 9—Side-bending views in 18-year-old woman with adolescent idiopathic scoliosis.
A–C, On bending views, proximal thoracic curve, main thoracic curve, and lumbar curves do not straighten. All three curves are structural and included in surgical fusion.

TABLE 1: Lenke Classification of Adolescent Idiopathic Scoliosis

Curve Type	Proximal Thoracic	Main Thoracic	Thoracolumbar/Lumbar	Description
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

Note—Bold denotes major curve.

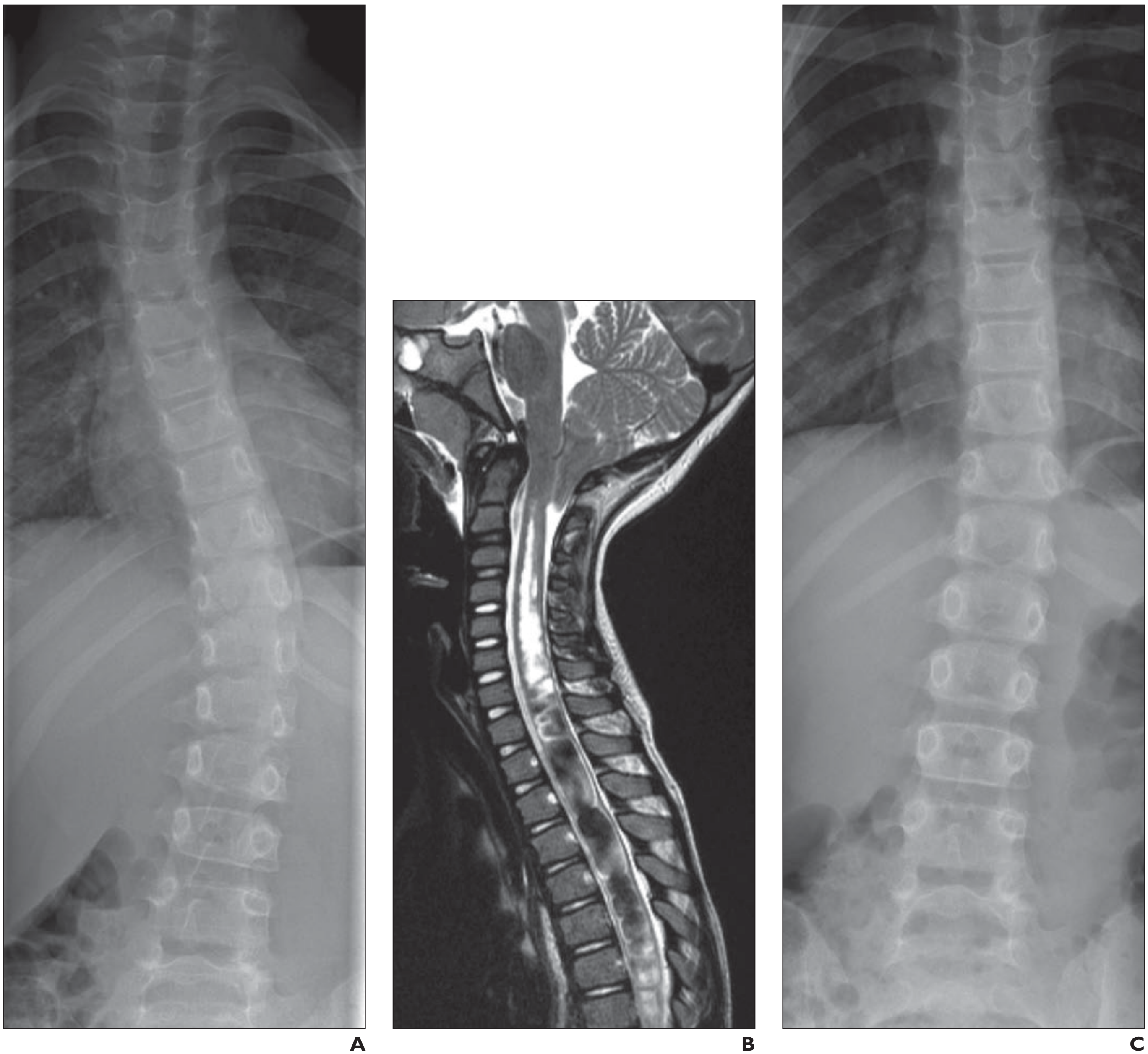


Fig. 10—10-year-old boy with scoliosis due to Chiari 1 malformation and syrinx.
A–C, Initial frontal radiograph (**A**) shows left thoracolumbar curvature as major curve. Age of presentation, sex, leftward curvature, and lack of apical rotation are atypical for adolescent idiopathic scoliosis. MR image (**B**) shows peglike cerebellar tonsils and large syrinx. Significant improvement of spinal deformity occurs after neurosurgical decompression (**C**).

From a practical standpoint, it is not necessary for the radiologist to classify these curves, but an understanding of the classification system is helpful in understanding and evaluating these standing films in the preoperative and postoperative period.

This classification system is not the only factor in determining which levels should be operated on. Skeletal maturity, coronal–sagittal balance, shoulder alignment, and patient factors also weigh in the surgical decision making. In the original description of this classification system, inter- and intraobserver agreement was very good [42]. The curves in these studies were evaluated with premeasured Cobb angles. When Cobb angles are measured at the time of curve classification, inter- and intraobserver agreement is fair, with kappa values of 0.5–0.6 [43].

When Is MRI Indicated?

Adolescent idiopathic scoliosis is a designation that applies once other causes of scoliosis have been clinically and radiologically excluded. Adolescent idiopathic scoliosis is by far the most common cause of spinal curvature in the teenage patient. There is a long differential diagnosis for the causes of spinal deformity (Appendix 1). Most of these different causes of scoliosis are easily distinguished from adolescent idiopathic scoliosis by age of presentation, clinical history, radiographic appearance, and physical examination. In addition, many of the other causes of deformity present with spinal curvatures very different from those of adolescent idiopathic scoliosis. However, some presentations can imitate adolescent idiopathic scoliosis. The prevalence of CNS abnormalities in patients with presumed adolescent idiopathic scoliosis is between 2% and 4% in most series [44–46].

The typical curve pattern in adolescent idiopathic scoliosis is usually a right convex thoracic curve plus or minus an additional leftward lumbar curve. An atypical curve pattern, such as a thoracic levoscoliosis, may occur in adolescent idiopathic scoliosis but increases the likelihood of an underlying disorder, particularly when it is observed in a male. Other atypical curve patterns requiring further investigation include a short segment curve (less than six segments), decreased vertebral rotation, rapid progression, and kyphosis near the apex of the curve (Fig. 10). Aside from the curve pattern, other findings on the scoliosis radiograph may elicit further investigation. An underlying tumor or infection may present with osseous destruction or sclerosis (Fig. 11). Widening of an intervertebral foramen or thickening of the paraspinal line are additional clues for a mass lesion. Occasionally, however, pathology such as a tethered cord or syrinx may mimic the typical thoracic dextroscoliosis of adolescent idiopathic scoliosis. In these cases, it is controversial as to when MRI is needed. The positive rate for screening all patients is low; however, the risk associated with missing one of these neurologic diagnoses and proceeding with surgery is extreme.

Many authors contend that routine MRI examinations are not necessary in the absence of neurologic findings when there are typical radiographic findings. Pain is a common symptom of adolescent idiopathic scoliosis, occurring in as many as 32% of patients in one series, although it is rarely disabling [47]. Imaging studies are seldom positive when pain

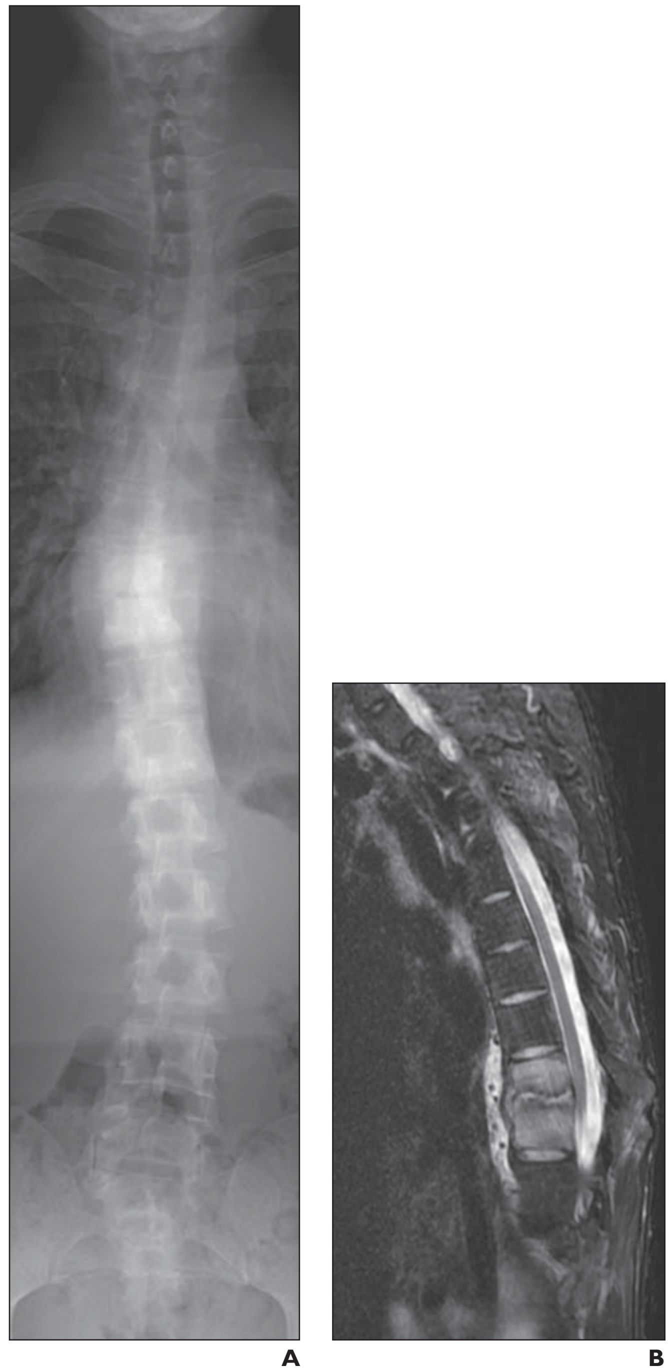


Fig. 11—40-year-old man with scoliosis secondary to infection.
A, Frontal radiograph shows thoracic dextroscoliosis. T9 and T10 vertebrae at apex of curve show prominent sclerosis and endplate irregularity.
B, Sagittal fat-saturated T2-weighted image confirms presence of osteomyelitis–discitis at this level.

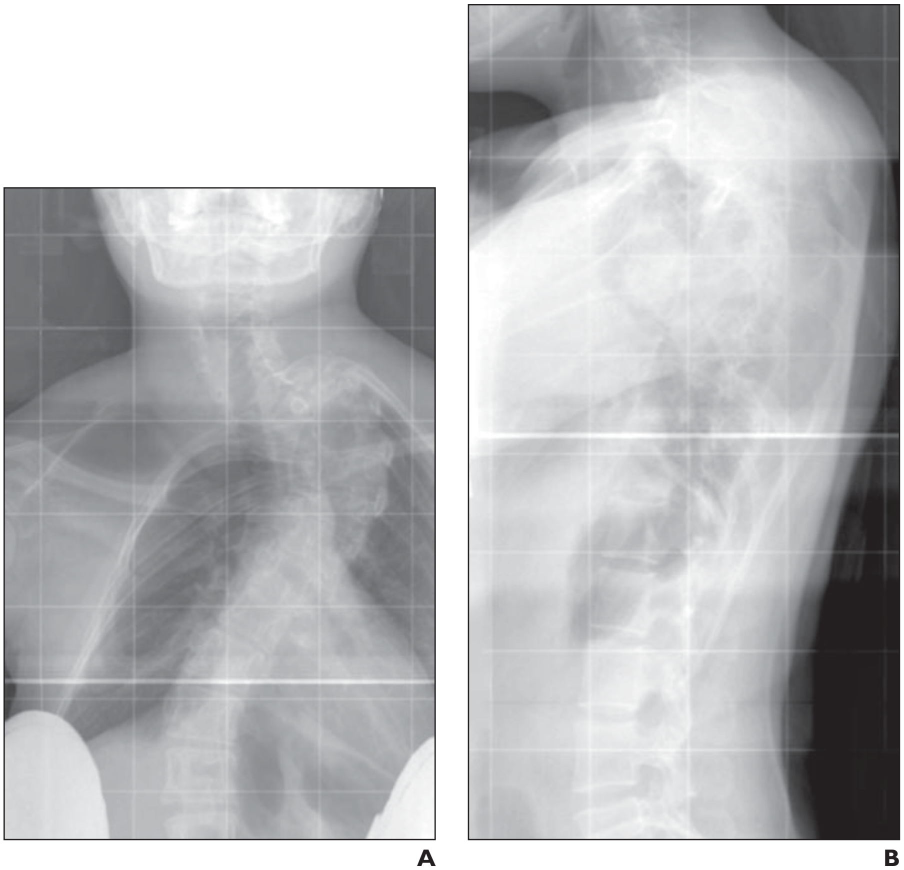


Fig. 12—23-year-old woman with neurofibromatosis.
A and **B**, Frontal (**A**) and lateral (**B**) radiographs shows characteristic short-segment kyphoscoliosis, found in patients with neurofibromatosis.

is the only complaint in patients with a normal neurologic examination and typical curvature. In a prospective series of 1,280 patients with adolescent idiopathic scoliosis, no patients presenting with only pain had positive MRI findings [46]. Significant MRI abnormalities are rare in patients with a normal neurologic examination. In a prospective study, 327 patients with adolescent idiopathic scoliosis and a normal neurologic examination underwent preoperative MRI of the spine. Seven patients (2%) were found to have an abnormality, most commonly an Arnold-Chiari malformation. No patient required neurosurgical intervention before deformity correction [44]. It should be noted that sometimes treatment of a Chiari I malformation can result in spontaneous reduction of scoliosis without the need for surgical deformity correction. A second study found that 44 (18%) of 250 consecutive patients referred for possible adolescent idiopathic scoliosis had an abnormality on MRI, but only 12 (5%) required surgery before deformity correction [48]. Most patients with abnormal findings on MRI, such as small syrinx or a small Chiari malformation, were not treated in the absence of neurologic symptoms.

Atypical curves on radiographs may predict an abnormality on MRI. In one retrospective study of 30 patients with possible adolescent idiopathic scoliosis and preoperative MRI, six of the seven cases with an underlying syrinx presented with a left convex or thoracolumbar curve [49]. Schwend et al. [50] reviewed 95 patients with possible adolescent idiopathic scoliosis who were referred for MRI. Fourteen of these studies showed intraspinal abnormalities, including 12 cases of syrinx (most secondary to an Arnold-Chiari malformation) and one patient with astrocytoma. Four of these patients required neurosurgical intervention. A left thoracic curve, the presence of a neurologic abnormality, and presentation before the age of 11 years were significantly associated with a positive MRI examination. In the prospective study by Davids et al. [46], 274 of 1,280 patients underwent MRI. Of 58 patients with an abnormal radiograph but no neurologic symptoms, six had abnormal findings on MRI. Loss of apical segment lordosis was found to be the most specific predictor of an intraspinal abnormality. The highest yield was for patients with abnormal neurologic findings and an atypical curve pattern. Thirteen of 53 cases referred for abnormal radiographs and positive neurology had positive MRI studies.

Spondylolysis at L5 is common in patients with adolescent idiopathic scoliosis because of increased biomechanical forces at this level. Identification of this finding on radiographs may alter management because the surgeon may choose to extend the posterior fusion to the pelvis to include the area of spondylolysis. If there is concern regarding spondylolysis in the lower lumbar spine, a thin-section CT study is the most accurate confirmatory test.

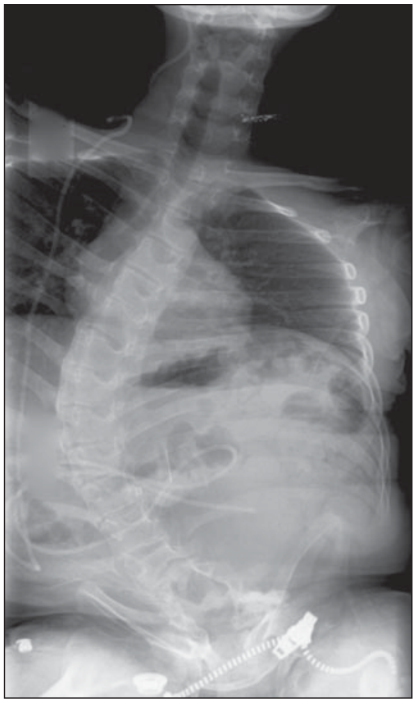


Fig 13—25-year-old man with neuromuscular scoliosis secondary to spinal dysraphism. Radiograph shows characteristic long-segment C-shaped curve involves entire lumbar and thoracic spine. Lower lumbar spinal dysraphism is present as is ventriculoperitoneal shunt. Note pelvic obliquity with left iliac crest higher than right.

Degenerative Scoliosis

Degenerative lumbar scoliosis is a common cause of back pain in the elderly patient. Greater than 50% of elderly women showed curves of greater than 10% in some referral centers [51]. The initial event in these patients is asymmetric degenerative change of the disks or facet joints. These changes result in asymmetric biomechanical forces that result in additional asymmetric disk space collapse and eventual lateral listhesis and segmental rotator listhesis between lumbar segments. This degenerative cascade culminates in a deformity seen in the coronal, sagittal, and transverse planes.

Degenerative scoliosis tends to occur in the lumbar spine and is often associated with hypolordosis, lumbar flat-back, and coronal plane decompensation, although any number of curve patterns may occur. Rotatory listhesis is common, often in the coronal plane. Patients with degenerative scoliosis often present with pain and disability, which are often associated with either radicular pain due to foraminal or far lateral root compression or claudication symptoms due to central, foraminal, or subarticular spinal stenosis [17, 18]. Degenerative scoliosis represents a complex heterogeneous group of disorders. The surgical treatment choices are numerous and beyond the scope of this article. The goals of surgical treatment are primarily neural decompression and correction of truncal balance.

Neurofibromatosis

Neurofibromatosis is a genetic disorder involving both neuroectodermal and mesenchymal elements. Spinal deformity is the most common skeletal abnormality and occurs in approximately one fourth of patients. Any number of different curve patterns may occur. These are best classified as nondystrophic and dystrophic curves [52]. Nondystrophic curvatures appear similar to those found in adolescent idiopathic scoliosis but tend to occur early and progress more quickly [53]. They are treated more aggressively because they tend to be stiffer and have a higher rate of pseudarthrosis [54].

A dystrophic curvature tends to be a short segment, have a large degree of apical rotation, and is often associated with kyphosis [55]. The phenotype for neurofibromatosis is variable, and patients may first present with a spinal deformity without a diagnosis of neurofibromatosis. The radiologist may be the first to suggest the diagnosis in this setting of the classic curve pattern—a short-segment kyphoscoliosis of the upper thoracic spine (Fig. 12). The main differential diagnosis for this radiographic curve pattern is a failure of segmentation. The presence of widening neural foramen, thinned pedicles, and posterior vertebral body scalloping further supports a diagnosis of neurofibromatosis. These curvatures tend to progress quickly, and many authors recommend early surgery [56]. Severe cervical kyphosis is another common abnormality and is highly suggestive of this diagnosis [57]. It is often visualized on the radiograph but overshadowed by the more salient thoracic curvature abnormality. The surgical changes most commonly occur as a postoperative phenomenon.

Neuromuscular Scoliosis

Spinal deformity may occur because of a variety of disorders involving the CNS, peripheral nervous system, a primary muscle abnormality, or a combination of these disorders. The spinal deformity pattern, natural history, and treatment of these heterogeneous disorders are similar. Spinal deformity occurs in the majority of cases when a disorder of the nervous system or muscles manifests in the growing patient. Although the cause of scoliosis in these patients is incompletely understood, most authors consider asymmetric muscular tone, including spasticity and paralysis, to be an important factor [58].

The goals of treatment are significantly different in this patient population than in adolescent idiopathic scoliosis. Halting progression of the curve is important in this population, and the magnitude of scoliosis continues to increase in adulthood. Respiratory compromise in neuromuscular disorders can be further compromised by a superimposed spinal deformity with reports of improvement after surgical fusion [59]. The concept of seating balance is another consideration in treatment. The curve correction may be performed to allow easier seating balance, use of a wheel chair, pain control, and trunk support to facilitate respiratory function. Ideally, the patient should be able to sit in a wheelchair without using the arms as a support.

A long C-shaped curvature is usually the presenting deformity in the patient with neuromuscular scoliosis (Fig. 13). The presence of pelvic obliquity is important in radiographic evaluation. When present, this obliquity increases the risk of skin breakdown and ischial ulcers. Sitting obliquity is measured as an angle between a line tangential to the iliac crests and one parallel to the floor [60]. The operative fusion will often need to include the pelvis in this circumstance. In some cases, visualized kyphosis is actually secondary to rotation of the apical vertebra. For example, if the apical vertebra is rotated 90°, the lateral curvature has the appearance of a kyphosis relative to the trunk. Deformity correction is more challenging in this patient population. An increased incidence of infection, neurologic complications, and pseudarthrosis has been reported [61].

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APPENDIX 1: Causes of Scoliosis

- Idiopathic
  - Adolescent, juvenile, infantile
- Degenerative neuromuscular
  - Neuropathic
    - Spina bifida, cerebral palsy
  - Musculopathic
    - Muscular dystrophy
- Congenital
  - Anomalous formation
    - Hemivertebra, wedge vertebra
    - Failure of segmentation
    - Unilateral bar or vertebral fusion
  - Neurogenic
    - Chiari malformation, syrinx, tethered cord, diastematomyelia
- Developmental
  - Skeletal dysplasias
    - Achondroplasia, mucopolysaccharidoses
  - Skeletal dysostoses
    - Neurofibromatosis, osteogenesis imperfecta, Marfan, Ehlers-Danlos
- Secondary
  - Tumors, infection, trauma

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