Pelvic Evaluation in Thoracolumbar Corrective Spine Surgery: How I Do It

Surgeons and radiologists have traditionally focused on frontal radiographs and the measurement of scoliosis curves as important tools in the management of spinal deformity. It has become evident, however, that the management of spinal deformity should use a multidimensional approach with an increased emphasis on standing lateral radiographs and the sagittal position of the spine. Furthermore, they have come to realize the critical role that the pelvis plays in the maintenance of posture. Failure to recognize pelvic compensation can lead to under-treatment and poor postoperative outcomes.

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Scoliosis is increasingly recognized as an important health concern in the adult population, with prevalence as high as 60% of the elderly population (1,2). In addition to cosmetic concerns, patients with scoliosis can present with substantial pain and disability (2). Historically, surgeons have focused on coronal alignment and planned surgery accordingly to correct scoliotic deformity (3). In this setting, the goal of surgery is to reduce the degree of coronal deformity by using rods held in place by hooks, screws, or a combination of both.

The spine, however, does not function in a single dimension, and while many surgical procedures were able to successfully reduce or alleviate coronal deformity, they neglected or even exacerbated the sagittal deformity, the result of which was persistent pain, limited physical function, and adverse self-image, even in the setting of successful radiologic outcomes in the coronal plane (4,5).

It is apparent that sagittal alignment correlates highly with quality of life scores and that failure to address sagittal alignment, in addition to the coronal deformity, can lead to persistent pain and deformity (3). Specifically, the failure to create the appropriate degree of lumbar lordosis at surgery through osteotomies and/or intervertebral cages can lead to a persistent sagittal imbalance in the postoperative patient. In addition, it is understood that anatomic segments of the spine-pelvic axis act as a continuum and share a degree of interdependence in an effort to maintain a stable posture with a minimum of energy expenditure (6). Surgeons have long understood that changes in biomechanics of one segment of the spine can affect the biomechanics in adjacent segments. The pelvis, in particular, plays an important role in global coronal and sagittal balance, and pelvic morphology and position are important in the biomechanics of the spine (3). Failure to address pelvic positioning and morphology as part of the preoperative strategy can substantially affect postsurgical outcomes; therefore, the pelvis is increasingly scrutinized in presurgical planning.

Imaging of scoliosis is no longer just measuring Cobb angles on roller boards full of “stitched” frontal radiographs using measurement tools on a picture archiving and communication system. The radiologist needs to understand the concepts of coronal and sagittal deformity, should appreciate the role that the pelvis plays in global balance, and be able to recognize compensatory measures on imaging.

In 2011, Dubouset introduced the concept of “cone of economy” (Fig 1) (7). When standing upright, there is minimal energy and maximal comfort when C7 is centered over S1. Normally the spine is straight in the coronal plane, and this position is maintained with minimal effort. In the sagittal plane, C7 is positioned comfortably over S1 as a result of a series of lordotic and kyphotic curves. Malalignment in either plane, through scoliosis or loss of the normal sagittal curves, can disrupt this balance, requiring more energy expenditure to compensate for posture. While the compensated patient may appear balanced at physical examination, the result of this increased energy expenditure to maintain comfortable positioning can be fatigue, pain, and persistent disability (3,7).

The cone of economy theory provides the basic concept for a multidimensional approach to the correction of spinal deformity. While the concepts of sagittal and coronal balance are not novel, the role of the pelvis in balance has been largely neglected. The goal of this article is to familiarize the radiologist with the concepts of coronal and sagittal balance, with an emphasis on pelvic imaging parameters.
available, a full-length 36-inch cassette or combining “stitching” of smaller images can be performed. Stitching using conventional radiography is similar in concept to the digital technique in which images acquired at three different levels are attached to form one larger image. It should be noted, however, that stitching is less optimal and must be done in a controlled environment with close attention to detail (specifically, the patient must not move between acquisitions). Whether a full-length cassette or stitching is used, the radiographs must extend from the level of the skull base through the femoral heads.

The majority of radiographs in patients with scoliosis will be stored and viewed on one of the many commercially available picture archiving and communication systems. Many of them provide measurement tools for the calculation of distance and angles, allowing the radiologists and surgeons to perform relevant measurements at the time of interpretation. Other robust, spine-dedicated software programs are available from third-party vendors.

This article emphasizes parameters obtained from standing radiographs. Radiography has the advantage of being readily available, inexpensive, and fast while exposing the patient to relatively little ionizing radiation compared with standard computed tomographic (CT) technique. Perhaps most importantly, radiographs are obtained with the patient in standing position, providing a view of the anatomy in upright, weight-bearing position. The limitations of radiography include relatively poor spatial resolution and the inability to visualize the spine in three dimensions, limiting evaluation of axial rotation and other abnormal axial morphology (8).

Scoliosis is a complex three-dimensional deformity, and therefore the ability to evaluate the spine in three
dimensions is useful in the evaluation of the deformity and planning of surgery. CT provides excellent spatial resolution of the bone structures, and modern scanners allow for volumetric acquisition with the ability to reconstruct in multiple planes. This comes at the expense of increased cost and radiation exposure relative to radiography. Recent advances have substantially decreased radiation exposure relative to standard technique and this is particularly appealing in the pediatric population (9,10). Low-dose digital stereoradiography is a technique that uses biplanar x-ray technique to create three-dimensional images of the spine with lower radiation exposure than is traditionally seen with standing frontal and lateral radiography (8,11). The machinery required to obtain these images is costly relative to traditional radiography and is therefore seen predominately in a few facilities that do a large volume of scoliosis imaging.

Finally, magnetic resonance (MR) imaging can play a role in the work up of scoliosis. Limitations of MR imaging in the work up of scoliosis include cost, MR imaging contraindications, and artifacts created by any hardware. While upright MR imaging is available, the majority of MR imaging is performed with the patient in supine position. Advantages of MR imaging include excellent spatial resolution of soft-tissue structures, with an important role in the evaluation of the spinal canal and intradural structures in the adult population, and the detection of any associated neural axis anomalies in patients with idiopathic scoliosis (10).

The Concept of Coronal Balance and Important Radiologic Parameters

Humans are most comfortable in a neutral, midline posture in the upright position (ie, not leaning to the left or right). Coronal spinal deformity (scoliosis), abnormal pelvic tilt, and even leg length discrepancy can affect the neutral position, causing the individual to lean to the left or right. For example, severe dextroscoliosis will cause a shift of the more cranial neural axis to the left. In this setting, the patient will attempt to compensate by tilting the pelvis to the right to restore neutral midline positioning.

The unintended consequences of this compensation are both cosmetic and physiologic. From a cosmetic standpoint, these patients can present with a rib hump and shoulder asymmetry. From a physiologic standpoint, these patients must expend additional energy to return to and maintain neutral balance. Compensating patients, whether they have had surgery or not, often present with poor self-image and often complain of pain and fatigue (3).

Coronal balance plays an important role in the multidimensional approach to deformity surgery and, if not sufficiently addressed, persistent deformity, pain, and fatigue can result in what is perceived to be a failed surgery. As a result, it is important that the radiologist, surgeon, and other treating physician understand the concepts of coronal balance and compensation. The most important measurements in the interpretation of coronal balance from the standpoint of the spine (exclusive of the pelvis at this point) are coronal plane decompensation and Cobb angles.

Coronal Plane Decompensation

Coronal plane decompensation is the most useful tool in assessment of coronal balance, and an assessment of coronal positioning should be mentioned in the interpretation of all full frontal, standing radiographs (Fig 2). In neutral position, the midpoint of the inferior endplate of C7 is directly superior to the midpoint of the superior endplate of S1. The coronal plane decompensation is calculated first by drawing a plumb line (which is a line drawn perpendicular to the floor) from the inferior midpoint of C7. The central sacral vertical line is then identified. The central sacral vertical line is a plumb line that passes through the midpoint
of the superior endplate of the sacrum (12). Coronal plane decompensation is the horizontal difference between these two lines. Coronal plane decompensation is described as being “right” or “left” depending if the shift is to the patient’s right or left. Coronal plane decompensation is most often the result of scoliosis but can result from any abnormality (eg, a leg length discrepancy) that shifts the C7 plumb line to the right or left of the central sacral vertical line. Patients with coronal plane decompensation greater than 4 cm have been shown to report poor function and increased pain relative to those with less than 4 cm of coronal plane decompensation (5).

Cobb Angles
The Cobb angle (Fig 3) is a well-established technique for measuring scoliotic curvature. The curve is calculated by identifying the vertebral bodies at the superior and inferior margins of the curve (also known as the terminal vertebral bodies) (12). The terminal vertebral bodies are the cranial and caudal vertebral bodies with the greatest degree of tilt. Once identified, a line is drawn along the superior endplate of the most cranial terminal vertebral body, and another line is drawn along the inferior endplate of the caudal terminal vertebral body. The resultant angle is the Cobb angle. In the adolescent population, progressive scoliosis with a Cobb angle between 25° and 45° will be managed conservatively, while Cobb angle greater than 50° is typically treated surgically (13).

The Concept of Sagittal Balance and Important Radiologic Parameters
The principles of sagittal balance are similar to those of coronal balance: Humans are most comfortable in a neutral standing position and will expend effort to maintain this position when acted upon by internal deformity or outside forces. For example, loss of lumbar lordosis can cause the patient to lean forward (increased or “positive” sagittal balance). As a re-

Figure 4: Sagittal balance. (a) Image shows neutral sagittal balance in which the plumb line (yellow line) from the midpoint of the inferior endplate of C7 (red dot) passes through the posterior superior corner of S1 (black dot). (b) Image shows 4.5 cm of positive sagittal balance calculated as the distance between the plumb line from the midpoint of the inferior endplate of C7 (yellow line) and the plumb line through the posteriorterior corner of S1 (green line). SVA = sagittal vertical alignment.

Figure 5: Standing frontal radiograph in a 70-year-old man demonstrates pelvic obliquity, which is calculated as the angle between a line connecting the most superior margins of the iliac wings (pelvic coronal reference line) and a horizontal reference line (line parallel to the floor). There is substantial pelvic obliquity to the right (7°) but only minimal coronal plane decompensation from midline (red line shows coronal plane decompensation). Findings are consistent with pelvic compensation to correct coronal plane decompensation.
result, the subject will expend additional energy attempting to compensate for the imbalance, including retroversion of the pelvis and flexion of the knees. Glassman et al and others have shown that sagittal balance is the single most important and consistent radiologic predictor of clinical outcomes as determined by self-assessment surveys including the Scoliosis Research Society (SRS)-22 questionnaire, Short Form 12-item survey, and Oswestry Disability Index profiles (14,15). This applies to nonoperated deformities, as well as to patients with persistent deformity after surgery (16). The presence of sagittal imbalance is more likely to predict persistent disability and pain than the size of the curve, location of the curve, or the presence of coronal plane decompensation (5,14). The end result after surgery can be markedly impaired health status measures (manifested as persistent pain, limited function, and poor self-image) if this imbalance is not properly addressed. Relevant radiologic parameters in the understanding of sagittal balance include spinal vertical alignment, thoracic kyphosis, and lumbar lordosis.

Spinal Vertical Alignment
Spinal vertical alignment (Fig 4) is measured as the distance between a plumb line through the midpoint of the inferior endplate of C7 and a plumb line through the posterosuperior corner of S1. In neutral position, the plumb line of C7 will intersect with the posterosuperior corner of S1. The mean spinal vertical alignment in asymptomatic adults is 0.5 cm ± 2.5 (standard deviation) and increases with normal aging (17,18). In 2012, the SRS published the SRS-Schwab Classification as a guideline for the interpretation and treatment of adult deformity. By using this classification system, a spinal vertical alignment of less than 4 cm is graded as “0” or “non-pathological” sagittal alignment, that 4 cm to 9.5 cm is graded as “+” or “moderate” deformity, and that greater than 9.5 cm is graded as “++” or “marked” deformity (17–19).

Thoracic Kyphosis
Thoracic kyphosis is the Cobb angle created by drawing a line across the superior endplate of T2 and the inferior endplate of T12 (3). It is often difficult to visualize the superior endplate of T2 on lateral views, and the superior endplate of T3 is often used in lieu of T2. The normal thoracic kyphosis is between 30° and 40° in men aged 50–80 years old and increases with normal aging. Average thoracic kyphosis is closer
to 40° in women older than 50 years of age (20).

**Lumbar Lordosis**

The lumbar lordosis is the Cobb angle resulting from intersecting lines drawn across the superior endplate of T12 and S1 (3). The average lumbar lordosis in adults is 33.2° ± 12.1 and increases with aging (21). Decreased lumbar lordosis is correlated with pain and loss of function (22). Flatback deformity is a term applied to patients with severe loss of both lumbar lordosis and thoracic kyphosis, effectively giving the spine a flat appearance on lateral views.

The spine and pelvis effectively act as a continuum in the maintenance of neutral coronal and sagittal balance. Abnormal positioning or biomechanics seen in one segment inherently affect the adjacent segment. For example, changes in the position or biomechanics of the lumbar spine can produce changes in both the position of the pelvis and the thoracic spine secondary to compensatory mechanisms.

The pelvis plays a critical role in spine-pelvic alignment, yet recent studies have shown that the position of the pelvis has long been neglected in the work up of scoliosis patients (3). Failure to evaluate the pelvic parameters in deformity surgery can result in postoperative misalignment and subsequent treatment failure. The pelvis has increasingly been shown to play an important role in upright sitting and standing postures, and as a result presurgical planning now requires evaluation of pelvic parameters. The relevant parameters include pelvic obliquity, pelvic incidence, pelvic tilt, sacral slope, and the T1 pelvic angle.

**Pelvic Obliquity**

Pelvic obliquity (Fig 5) refers to the position of the pelvis relative to a line drawn parallel to the floor. Pelvic obliquity is calculated as the angle between the pelvic coronal reference line and a horizontal reference line (a line drawn parallel to the floor) (3). The pelvic coronal reference line can be identified in a number of ways, most commonly as a line connecting the two iliac crests. Pelvic obliquity plays an important role in the coronal correction strategy. As stated previously, humans are most comfortable in neutral alignment (little or no coronal plane decompensation), and the pelvis can serve as a compensatory mechanism when there is substantial right or left coronal plane decompensation resulting from scoliosis. Tilting of the pelvis to the right or left in the coronal plane can substantially affect coronal plane decompensation by moving the C7 plumb line toward midline. While pelvic obliquity can serve as an indicator of compensation in a patient with scoliosis, it can also signify the presence of other important underlying physiologic abnormalities, such as leg length discrepancy, that should be sought out and addressed, if present. Ideally, correction of the coronal deformity should reduce the need for compensation, thereby correcting the pelvic obliquity.

**Pelvic Incidence**

The pelvic incidence is the angle created by intersecting lines drawn from the midpoint of the femoral heads to the midpoint of the superior endplate of the sacrum and a line perpendicular to the superior endplate of the sacrum as measured on lateral images (5,17). This parameter describes the morphology or shape of the pelvis. It is fixed and does not change with posture or positioning (6). The pelvic incidence is a value that stays nearly constant throughout life, except for a slight change at puberty.

The pelvic incidence (Figs 6, 7) is perhaps most important for its relationship to the lumbar lordosis. Ideally, the lumbar lordosis is within 9° of the pel-
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Radiology: Volume 278: Number 3—March 2016 • radiology.rsna.org

vic incidence such that lumbar lordosis equals pelvic incidence \( \pm 9° \) (17–20). By using the SRS-Schwab Classification, pelvic incidence-lumbar lordosis of less than 10° is graded as "0" or "non-pathologic," that of 10°–20° is graded as "+" or "moderate" deformity, and that greater than 20° is graded as "++" or "marked" deformity (17–20). Pelvic incidence effectively describes the natural shape of a patient’s sacrum and, from this, provides a baseline reference for the calculation of the optimal degree of lumbar lordosis to be introduced at surgery. Surgeons can increase lordosis by taking away height posteriorly in the lumbar spine (such as through Smith Peterson or pedicle subtraction osteotomy) or by adding height anteriorly (with interbody cages).

Pelvic Tilt

The pelvic tilt is the angle created between a line drawn from the midpoint of the femoral heads to the center of the superior endplate of the sacrum and a vertical plumb line through midpoint of femoral heads (Fig 8) (3,17,18). Pelvic tilt is dependent on the position of the patient. As humans progressively lose lumbar lordosis with age or degenerative disk disease, there is a steady increase in the spinal vertical alignment. Patients instinctively will seek to restore neutral sagittal balance and can achieve this through a combination of pushing the pelvis posteriorly ("retroversion") and with flexion the knees (3,17,18). Compensatory pelvic retroversion requires additional work and energy expenditure.
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and the presence of pelvic retroversion in the postoperative patient is correlated with poor clinical outcomes (3,17).

As a general rule, the ideal pelvic tilt is greater than 10° and less than 20°. Pelvic tilt greater than 20° indicates compensatory pelvic retroversion. Studies have shown that as the spinal vertical alignment increases there is a compensatory increase in pelvic tilt (Fig 9). A study by Schwab et al (18) showed that for a negative, neutral (0–5 cm), and positive (> 5 cm) spinal vertical alignment, the average pelvic tilt is 10°, 16°, and 21°, respectively. By using the SRS-Schwab Classification, a pelvic tilt of less than 20° is graded as “0” or “non-pathologic,” a pelvic tilt of 20°–30° is graded as “+” or “moderate” deformity, and pelvic tilt of greater than 30° is graded as “++” or “marked” deformity (17–20).

Sacral Slope

The sacral slope, like pelvic tilt, is indicative of pelvic position and can be used to identify pelvic retroversion (Fig 10). The sacral slope is defined as the angle between a line drawn parallel to the superior endplate of S1 and a horizontal reference line or line drawn parallel to the floor. Sacral slope plus pelvic tilt equals pelvic incidence, and therefore changes to sacral slope are inversely proportional to changes in the pelvic tilt (3). While sacral slope and pelvic tilt are complimentary measurements, the pelvic tilt is more often used in treatment planning.

T1 Pelvic Angle

Pelvic tilt and spinal vertical alignment are essential to a basic understanding of a patient’s sagittal balance and compensatory mechanisms used by the patient to maintain neutral balance. The T1 pelvic angle (Fig 11) is a newer measurement technique that takes into consideration the combined effect of both increased sagittal balance and pelvic retroversion (23,24). The T1 pelvic angle is calculated as the angle between a line drawn from the midpoint of the femoral heads to the midpoint of the superior endplate of S1 and a line drawn from the midpoint of the femoral heads to the center of the T1 vertebral body. The T1 pelvic angle effectively incorporates both the spinal vertical alignment and pelvic tilt measurements and has been shown to correlate strongly with clinical outcomes (23,24). According to Ryan et al, the goal of surgery should be a T1 pelvic angle of around 10°. Patients with T1 pelvic angle greater than 20° are considered to have severe deformity (23).

Bringing It All Together

A thorough understanding of scoliosis imaging is one way in which the radiologist can add value to what has traditionally been seen as a mundane imaging modality. Simply stating that there is “S-shaped scoliosis” or providing simple Cobb angle measurements on the frontal view is no longer sufficient because surgeons view deformity as a three-dimensional process. The radiologist should understand the basic concepts of sagittal and coronal balance, understand and be able to calculate the basic metrics relevant to deformity surgery, and be able to synthesize these data to form a relevant and practical overview for each individual that will help the surgeon determine the ap-
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appropriately course of treatment (Table). In particular, it is imperative that the radiologist understands the role of the pelvis in compensation and accurately recognizes when there is pelvic compensation. Failure to do so may lead to an underestimation of the degree of sagittal and/or coronal deformity and subsequently lead to more conservative treatment than may be required.

On the frontal radiographs the radiologist should be able to identify the individual scoliosis curves, describe the affected levels, and provide accurate Cobb angle measurements. More importantly, the radiologist should be able to recognize and measure coronal plane decompensation and recognize if the patient is attempting to compensate for any clinically important coronal plane decompensation evidenced by pelvic obliquity.

On the lateral radiographs it is not sufficient to simply recognize an increase or decrease in thoracic kyphosis or lumbar lordosis. The radiologist should understand the concept of interdependence between segments of the spine-pelvis axis and appreciate the compensatory capability of the pelvis. Standing lateral radiographs should include a description of any substantial positive sagittal balance (> 4 cm) and, if present, recognition of any compensatory pelvic retroversion (pelvic tilt > 20°). Patients with positive sagittal balance and pelvic retroversion have been shown to have poor outcomes if not addressed during surgery, and therefore it is imperative that this be recognized in the planning stages.

Standing lateral radiographs provide important information to the calculation of the optimal degree of lumbar lordosis to be introduced at the time of surgery. The normal lumbar lordosis is within 10° of pelvic incidence, and it is important to recognize when the patient would benefit from increased lordosis introduced through osteotomies, cages, or both. As a result, a greater than 10° difference between lumbar lordosis and pelvic incidence should be mentioned in the report. Likewise, a pelvic tilt of greater than 20° suggests that there is compensatory pelvic retroversion, and this should also be indicated in the report.

Finally, it should be noted that the emphasis of this review is on the interdependence of the pelvis and the thoracolumbar spine. Recently, and not surprisingly, studies have shown that the positioning of the cervical spine can play an important role in sagittal balance. Specifically, patients with substantial cervical sagittal deformity can compensate with pelvic retroversion, thoracic hypokyphosis, and lumbar hyperlordosis (25). A detailed discussion of cervical coronal and sagittal parameters is beyond the scope of this review article but remains an important consideration in the assessment of global balance.

### Summary

In the interpretation of scoliosis imaging, the radiologist should:

1. Measure Cobb angles on the frontal view.
2. Determine if there is any coronal plane decompensation and, if so, how much. Is there compensatory pelvic obliquity that may cause the reader to underestimate the true amount of coronal plane decompensation?
3. Determine if there is clinically important (> 4 cm) positive sagittal balance. Is the patient compensating for this with pelvic retroversion (pelvic tilt > 20°)?
4. Determine if there is lumbar lordosis within 10° of pelvic incidence. Is there room to introduce more lumbar lordosis at surgery?

### Overview of Spinopelvic Parameters

<table>
<thead>
<tr>
<th>Deformity</th>
<th>Normal</th>
<th>According to SRS-Schwab Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spinal vertical alignment</td>
<td>± 2.5 cm in asymptomatic adults</td>
<td>&lt;4 cm: non-pathologic 4–9.5 cm: moderate deformity &gt;9.5 cm: marked deformity</td>
</tr>
<tr>
<td>Pelvic incidence</td>
<td>Normally within 10° of lumbar lordosis</td>
<td>&lt;10°: non-pathologic 10°–20°: moderate deformity &gt;20°: marked deformity</td>
</tr>
<tr>
<td>Pelvic tilt</td>
<td>Normally between 10° and 20°</td>
<td>&lt;20°: non-pathologic 20°–30°: moderate deformity &gt;30°: marked deformity</td>
</tr>
<tr>
<td>T1 pelvic angle</td>
<td>Approximately 10°</td>
<td>Severe deformity greater than 20°</td>
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Disclosures of Conflicts of Interest: R.D.M. disclosed no relevant relationships. R.M.R., disclosed no relevant relationships. J.J., Activities related to the present article: disclosed no relevant relationships. Activities not related to the present article: reports grant and personal fees from Nuvasive. Other relationships: disclosed no relevant relationships.

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