Defining the “Three-Dimensional Sagittal Plane” in Thoracic Adolescent Idiopathic Scoliosis

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Background: Obtaining accurate measurements of scoliosis from two-dimensional (2-D) radiographs can be challenging because of the three-dimensional (3-D) nature of the deformity. Previous studies have shown that the sagittal plane, in particular, is misrepresented on 2-D radiographs because of the influence of axial plane rotation. The purpose of the current study was to define a methodology for measuring the 3-D segmental sagittal alignment of the spine in patients with adolescent idiopathic scoliosis (AIS) and to assess the effect of axial plane rotation on differences between 3-D and 2-D measures of deformity.

Methods: Preoperative and postoperative EOS images of 120 consecutive patients with AIS (primary thoracic curves) treated with segmental thoracic pedicle-screw instrumentation were analyzed in the “3-D sagittal plane.” The technique measured 3-D kyphosis or lordosis in the specific plane of sagittal motion for each spinal motion segment. The kyphosis (+) and lordosis (−) values of the segments from T5 to T12 were summed to give the 3-D measurement of T5-T12 kyphosis. These values were compared with the standard 2-D measurements of T5-T12 kyphosis on lateral radiographs, and a correlation analysis with regard to axial plane rotation of the apex was performed.

Results: The average age (and standard deviation) of the patients was 14 ± 2 years. The mean preoperative Cobb angle on the standard 2-D view was 55° ± 10° and on the 3-D view was 52° ± 9° (p ≤ 0.001). On the 3-D view, the mean preoperative T5-T12 kyphosis was 6° ± 14°, and the kyphosis significantly increased to 26° ± 6° postoperatively (p < 0.001). The T5-T12 kyphosis on the standard 2-D view measured 18° ± 13° preoperatively and 27° ± 6° postoperatively (p < 0.001). The difference between the 2-D and 3-D measurements of T5-T12 kyphosis strongly correlated with apical vertebral rotation (r = 0.85; p < 0.01).

Conclusions: Routine 2-D measurements of thoracic kyphosis erroneously underestimate the preoperative loss of kyphosis in AIS because of errors associated with axial plane rotation, an inherent component of thoracic scoliosis.

Level of Evidence: Diagnostic Level II. See Instructions for Authors for a complete description of levels of evidence.

Disclosures of Potential Conflicts of Interest submitted by authors are always provided with the online version of the article.

Peer review: This article was reviewed by the Editor-in-Chief and one Deputy Editor, and it underwent blinded review by two or more outside experts. The Deputy Editor reviewed each revision of the article, and it underwent a final review by the Editor-in-Chief prior to publication. Final corrections and clarifications occurred during one or more exchanges between the author(s) and copyeditors.

Scoliosis is known to be a complex three-dimensional (3-D) deformation of the spinal column that involves curvature in the coronal plane, which is quantified by the Cobb angle method; rotation in the axial plane, which appears to be greatest at the apex of the curve; and deformity in the sagittal plane, which has been more difficult to fully assess.

One of the major challenges in quantifying not only scoliosis in general but especially kyphosis is the fact that, as scoliosis increases, so does the axial plane rotation. As this occurs, traditional two-dimensional (2-D) radiographs are not able to obtain true coronal and lateral views of each vertebra. The discrepancy is greatest at the apex of the curve,

http://dx.doi.org/10.2106/JBJS.O.00148

J Bone Joint Surg Am. 2015;97:1694-701
where axial plane rotational deformity is typically at a maximum. Du Peloux et al. recognized this and suggested oblique-plane radiographs to obtain coronal and sagittal views of the apex in the coronal and sagittal planes of that vertebra. Hayashi et al. measured the sagittal profile of the thoracic spine from two vertebral levels cephalad to two levels caudal to the thoracic apex (five vertebrae) in the “true” lateral view of those vertebrae. They reported that the sagittal profile measured in that view demonstrated significantly less kyphosis than that observed in the standard lateral view.

Deformity issues in the sagittal plane were noted with the use of Harrington rods, especially with postoperative lumbar spine flatback. Techniques have advanced from multihook to multiscrew systems with greater focus on the coronal, sagittal, and axial planes. Some investigators have suggested that pedicle-screw constructs may reduce thoracic kyphosis. An accurate reporting of a change in kyphosis obviously demands an accurate assessment of the original preoperative sagittal deformity.

The purpose of the present study was to develop a method to measure the sagittal and coronal deformity in the local sagittal and coronal planes of each vertebral motion segment. This 3-D segmental method was compared with the conventional 2-D measurement of coronal and sagittal deformity, with the goal of assessing the correlation of the differences between 2-D and 3-D measurements and apical rotation in the axial plane. Secondarily, the immediate surgical changes in 3-D coronal and sagittal alignment were evaluated by comparing the preoperative with the first standing postoperative measurements in order to define the 3-D changes in coronal and sagittal alignment associated with modern pedicle-screw instrumentation, to make some assessment of whether pedicle-screw usage is associated with an increase or decrease in the thoracic kyphosis.

**Materials and Methods**

This study included one hundred and twenty consecutive patients with adolescent idiopathic scoliosis (AIS) involving a primary thoracic curve, all from a single institution. The average patient age (and standard deviation) was 14 ± 2 years. All patients were scanned by an EOS imaging system (EOS imaging, Paris, France), which simultaneously obtains upright, biplanar radiographic images of the spine (posteroanterior and lateral views). These images were obtained preoperatively and in the early postoperative period (within six weeks of surgery). Two-D and 3-D measurements were made from these biplanar images utilizing sterEOS software (EOS imaging).

**2-D Measurements**

The biplanar images were uploaded into the sterEOS workstation, and the superior and inferior end-plate corners were located. Digital 2-D measurements were reported from the sterEOS software. The standard output of 2-D measurements included coronal measurements (Cobb angle) and sagittal measurements (T1-T12 kyphosis, T4-T12 kyphosis, L1-S1 lordosis, L1-L5 lordosis, pelvic...
tilt, pelvic incidence, and sacral slope). Additionally, T5-T12 kyphosis was calculated, as this has been a common value reported in the literature.

### 3-D Reconstruction

Using sterEOS software, a single trained operator created vertebral surface models from biplanar images of each spine. For each vertebra, twenty-eight handle points (eighteen of which can be moved independently) were used to morph a generic 3-D vertebra of the appropriate vertebral level to match the landmarks visible on each of the biplanar images, resulting in a 3-D model of the spine in full (Fig. 1). The accuracy of radiographic measurements made in this fashion has previously been compared with measurements made with the use of computed tomography (CT) and shown to be within an average of 1.6\(^\circ\) (maximum, 3.9\(^\circ\)) for the Cobb angle, 1\(^\circ\) (maximum, 4.9\(^\circ\)) for sagittal kyphosis, and 1.9\(^\circ\) (maximum, 5.8\(^\circ\)) for axial rotation.

### Reference Frames

The reference frames used in this study were defined in accordance with the Scoliosis Research Society Working Group on 3-D terminology of spinal deformity. Using a standard right-handed axis convention, axes were defined as follows: x axis, anterior; y axis, left; and z axis, superior. The global spinal reference frame used was the standard anatomic gravity-based axis system, with axes defined as follows: Z axis, the upward direction in the EOS scanner; Y axis, the vector from the right hip socket to the left hip socket projected onto the Z plane; and X axis, the cross product of the Y and Z axes.

### Measurements in the 3-D Sagittal View and in the 3-D Coronal View

The local kyphosis of each vertebra and each disc was defined as the angle between vectors normal to the bounding end plates when projected into the

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**TABLE I Comparison of Curve Magnitude by View**

<table>
<thead>
<tr>
<th>Measurement Method</th>
<th>Standard 2-D View(^\ast) (deg)</th>
<th>True 3-D View(^\ast) (deg)</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobb angle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preop.</td>
<td>55 ± 10</td>
<td>52 ± 9</td>
<td>≤0.001</td>
</tr>
<tr>
<td>Postop.</td>
<td>10 ± 6</td>
<td>11 ± 6</td>
<td>≤0.001</td>
</tr>
<tr>
<td>Thoracic kyphosis</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preop.</td>
<td>18 ± 13</td>
<td>6 ± 14</td>
<td>≤0.001</td>
</tr>
<tr>
<td>Postop.</td>
<td>27 ± 6</td>
<td>26 ± 6</td>
<td>≤0.001</td>
</tr>
</tbody>
</table>

\(^\ast\)The values are given as the mean and the standard deviation.
local sagittal (xz) plane. Similarly, the local coronal Cobb angle of each vertebra and disc was defined as the angle between vectors normal to the bounding end plates when projected into the local coronal (yz) plane. Local vertebral kyphosis measurements from T5 to T12 and local disc kyphosis measurements from T5-T6 to T11-T12 were summed to obtain a 3-D measurement of T5-T12 kyphosis (Fig. 4).

For the 3-D coronal view, each local coronal vertebral angulation and the angulation of the corresponding disc immediately inferior to that vertebra were calculated. In the same manner, local vertebral and disc coronal Cobb measurements were summed between bounding vertebrae to obtain a 3-D measurement of the coronal curve magnitude. For example, for a curve between T4 and T11, T4 to T11 vertebral measurements and T4-T5 to T10-T11 disc measurements would be summed to get the 3-D coronal curve magnitude.

### TABLE II Local Sagittal Angle Between Each Pair of Vertebrae and Axial Vertebral Rotation*

<table>
<thead>
<tr>
<th></th>
<th>T5-T6</th>
<th>T6-T7</th>
<th>T7-T8</th>
<th>T8-T9</th>
<th>T9-T10</th>
<th>T10-T11</th>
<th>T11-T12</th>
<th>Regional T5-T12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preop. (*')</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard 2-D view</td>
<td>3.5 ± 1.9</td>
<td>4.1 ± 1.9</td>
<td>4.0 ± 2.3</td>
<td>3.0 ± 1.8</td>
<td>3.9 ± 1.9</td>
<td>3.4 ± 2.1</td>
<td>3.6 ± 1.8</td>
<td>18 ± 13</td>
</tr>
<tr>
<td>True 3-D view</td>
<td>3.6 ± 2.1</td>
<td>4.3 ± 2.1</td>
<td>3.5 ± 2.5</td>
<td>1.6 ± 2.1</td>
<td>2.2 ± 1.9</td>
<td>2.1 ± 2.1</td>
<td>3.1 ± 2.1</td>
<td>6 ± 14</td>
</tr>
<tr>
<td>Difference between views</td>
<td>-0.2 ± 0.5</td>
<td>-0.2 ± 0.7</td>
<td>0.6 ± 1.0</td>
<td>1.4 ± 1.2</td>
<td>1.7 ± 1.6</td>
<td>1.3 ± 1.4</td>
<td>0.4 ± 1.1</td>
<td>11 ± 7</td>
</tr>
<tr>
<td>Axial rotation</td>
<td>3.9 ± 5.4</td>
<td>0.2 ± 6.1</td>
<td>-7.2 ± 7.2</td>
<td>-11.7 ± 6.6</td>
<td>-14.1 ± 7.7</td>
<td>-13.6 ± 8.7</td>
<td>-9.7 ± 9.6</td>
<td>NA</td>
</tr>
<tr>
<td>Postop. (*)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard 2-D view</td>
<td>4.1 ± 1.8</td>
<td>4.3 ± 1.9</td>
<td>4.5 ± 1.9</td>
<td>3.6 ± 1.9</td>
<td>3.9 ± 1.9</td>
<td>2.8 ± 1.8</td>
<td>4.7 ± 1.7</td>
<td>27 ± 6</td>
</tr>
<tr>
<td>True 3-D view</td>
<td>4.2 ± 1.8</td>
<td>4.3 ± 1.8</td>
<td>4.3 ± 1.9</td>
<td>3.4 ± 1.9</td>
<td>3.8 ± 1.9</td>
<td>2.7 ± 1.8</td>
<td>4.6 ± 1.6</td>
<td>26 ± 6</td>
</tr>
<tr>
<td>Difference between views</td>
<td>0.0 ± 0.2</td>
<td>0.0 ± 0.3</td>
<td>0.1 ± 0.4</td>
<td>0.2 ± 0.3</td>
<td>0.2 ± 0.4</td>
<td>0.2 ± 0.3</td>
<td>0.1 ± 0.2</td>
<td>0.8 ± 1</td>
</tr>
<tr>
<td>Axial rotation</td>
<td>0.6 ± 5.1</td>
<td>-0.7 ± 5.2</td>
<td>-3.7 ± 5.7</td>
<td>-4.4 ± 5.3</td>
<td>-4.3 ± 5.7</td>
<td>-4.6 ± 6.2</td>
<td>-2.4 ± 6.1</td>
<td>NA</td>
</tr>
</tbody>
</table>

*Values are given as the mean and the standard deviation. NA = not applicable.

### Apical Vertebral Rotation
Apical vertebral rotation was defined as the angle between projections of the x axis of the apical vertebra and the X axis of the global spinal reference frame onto the XY plane of the global spinal reference frame. Clockwise rotation was defined as positive.

### Surgical Technique
Briefly, the surgical correction involved apical Ponte osteotomies, segmental uniplanar pedicle-screw fixation, 5.5-mm-diameter 200-ksi (1379-MPa) stainless steel rods, differential rod contouring, concave thoracic distraction, and segmental axial plane manipulation relative to the neutral vertebra.

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**Fig. 3**
The local reference frame representing each thoracic and lumbar vertebra and inferior disc segment. Visualizing each in the sagittal plane of the individual segments provides a clear representation of the sagittal shape/deformity. (Reproduced with permission of San Diego Pediatric Orthopedics.)
The mean preoperative 2-D Cobb angle was 55° ± 10° (range, 40° to 103°) (Table I), and the mean preoperative 2-D thoracic kyphosis (T5-T12) was 18° ± 13° (range, −12° to 49°) (Fig. 5). After surgery, the mean 2-D Cobb angle decreased to 10° ± 6° (range, 0° to 26°) (p < 0.001), and the mean postoperative 2-D thoracic kyphosis (T5-T12) was 27° ± 6° (range, 15° to 45°) (p < 0.001).

Measurements in the 3-D Coronal and Sagittal Views

The mean preoperative summed local Cobb angle in the 3-D coronal view was 52° ± 9° (range, 32° to 96°) (Table I). The mean preoperative summed local thoracic kyphosis in the 3-D sagittal view was 6° ± 14° (range, −24° to 40°) (Fig. 5). After surgery, the mean 3-D coronal Cobb angle decreased to 11° ± 6° (range, 0° to 25°) (p < 0.001). The mean postoperative T5-T12 kyphosis in the 3-D sagittal view significantly increased to 26° ± 6° (range, 14° to 44°) (p < 0.001).

Apical Vertebral Rotation

The mean preoperative apical vertebral rotation in the main thoracic curve was −14° ± 9° (range, −31° to 18°). After surgery, the mean apical vertebral rotation was −5° ± 6° (range, −20° to 11°). The absolute value of apical vertebral rotation after surgery was significantly smaller than that before surgery (p < 0.01).

Difference Between the Standard 2-D Method and the 3-D View Method

Before surgery, the mean difference in coronal Cobb angle between the standard 2-D and the summed 3-D views was 2° ± 3° (range, −8° to 12°). The mean difference in thoracic kyphosis between the 2-D and 3-D views was 11° ± 7° (range, −1° to 40°). After surgery, the mean difference in Cobb angle between these measurement techniques was −1° ± 3° (range, −15° to 10°), and the mean difference in thoracic kyphosis measurements was 1° ± 1° (range, −2° to 5°). The segmental sagittal angles between each pair of vertebra from T5-T12 as measured in the standard 2-D and the 3-D views are shown in Table II.

Difference Between 2-D and 3-D Measurements of Thoracic Kyphosis as a Function of Apical Vertebral Rotation

A strong correlation was found for the difference between the 2-D and 3-D measurements of thoracic kyphosis and the absolute apical vertebral rotation (r = 0.85; p < 0.01) (Fig. 6). The difference between the standard 2-D and the segmental 3-D measurements became greater when the absolute value of apical rotation increased.
Discussion

AIS is a 3-D deformity associated with lateral deviation in the coronal plane, thoracic hypokyphosis in the sagittal plane, and rotation in the axial plane\(^1\). Deformities in these three planes form the complex linked deformity. The extent to which the apical vertebra is rotated from the coronal plane has been measured in the past by the Perdriolle protractor\(^2\) or the method of Nash and Moe\(^3\). Although these two measurement methods have been widely accepted, they may have limitation of accuracy for quantifying rotation of consecutive vertebrae because of manual measurement. An EOS imaging system enables measurement of consecutive vertebral rotation more accurately because it uses computer measurements and registration of as many as twenty-eight anatomic points corresponding to anatomic landmarks. The accuracy of the sterEOS software measurements has been validated with the use of radiographs and 3-D CT as the gold standard, and compared with these modalities, sterEOS measurements have been found to correlate best in the coronal and sagittal planes, with a maximum error of <6° in the axial plane\(^4\).

Viewing the deformed spine from a vantage other than a simple projection on the posteroanterior or lateral planes is not a new concept. Deacon et al. made radiographs of eleven articulated skeletons with idiopathic scoliosis at 10° intervals of rotation through the complete range of 180°. They found the presence of lordosis in the sagittal profile of the thoracic spine in the “true” lateral view, even though it seemed kyphotic in the standard lateral view. However, it is technically difficult to...
obtain a true lateral radiograph for patients by using conventional radiographic devices because actual apical vertebral rotation is unknown. In the present study, reconstructed models from images obtained by an EOS imaging system enabled accurate measurement of the sagittal profile of the spine in the sagittal plane of the apical vertebra. Furthermore, it became possible to measure not only the sagittal profile near the apical vertebra but also that of each vertebral segment. Local sagittal angles of each pair of vertebrae were measured by projecting the sagittal profile into the local reference frame of each motion segment (Figs. 2 and 3). These local segmental angles were then summed within regions to represent regional thoracic sagittal alignment in order to match what has been traditionally measured in 2-D imaging. There was a significant overrepresentation (by 11° ± 7°) of the thoracic T5-T12 kyphosis on standard 2-D imaging compared with the 3-D assessment of kyphosis in the preoperative curves. When there is rotation of the vertebrae out of the global sagittal plane, as occurs with scoliosis, the sagittal profile evaluated by the standard lateral view is unreliable and often results in a false sense of thoracic kyphosis (Fig. 4).

De Jonge et al. measured thoracic kyphosis of 306 patients with AIS using standard 2-D lateral radiographs. They reported that 28% of the patients had thoracic kyphosis of <10°. However, Dickson et al. reported that 75% of their study’s seventy patients with AIS had a lordotic thoracic spine when measured in a true lateral projection of the apex. Hayashi et al. found that the periaxial thoracic kyphosis measured in the lateral view of the apex was significantly smaller than that measured in 2-D views. They reported that the thoracic spine was even lordotic in many cases and falsely appeared to be kyphotic in the standard lateral 2-D projection. Hayashi et al. concluded that the true sagittal profile of the thoracic spine was overestimated by an average of 10° when measured on the standard lateral 2-D radiograph. These reports indicated that standard lateral radiographic measures cannot reliably reveal preoperative kyphosis of patients with AIS.

Our data correspond to these previous results. In our study, 28% of the patients had thoracic kyphosis of <10° in the standard 2-D view (Fig. 5). This percentage corresponded with the findings of de Jonge et al. However, in our 3-D assessment of thoracic kyphosis, 58% of the patients had thoracic kyphosis of <10° (Fig. 5). The T5-T12 sagittal profile of the thoracic spine using 2-D measurements was overestimated by an average of 11° compared with the summed 3-D method. Therefore, it may be unreasonable to compare preoperative kyphosis and postoperative kyphosis measured using a 2-D method because rotational deformity is typically substantially different between preoperative and postoperative evaluations, particularly in the recent era of thoracic pedicle-screw usage and axial derotation maneuvers. Our proposed method of measurement helps to identify the true segmental and regional sagittal alignment of the scoliotic spine. The 3-D reconstruction of the scoliotic spine can be manipulated digitally to produce a “pure” sagittal image of the spine. This segmentally accurate view gives a much different impression of the sagittal deformity (Fig. 4).

An understanding of the relationship within each pair of vertebrae is important not only in elucidating the true deformity, but also in refining the surgical techniques utilized during deformity correction. The segmental pedicle fixation technique enables surgeons to control each vertebra more powerfully for achieving ideal correction. Furthermore, surgeons can more precisely evaluate the correction achieved after surgery. In this sense, measurement with the 3-D, segmental local vertebral approach can be a useful, surgeon-oriented method for evaluating the deformity of scoliosis as well as the correction associated with surgical treatment. In our study population, treated with the use of posterior release and instrumentation methods, the 3-D analysis showed a substantial correction of deformity in the coronal plane (a decrease in the Cobb angle from 52° ± 9° to 11° ± 6°), in the sagittal plane (an increase in T5-T12 kyphosis from 6° ± 14° to 26° ± 6°), and in the axial plane (a decrease in apical rotation from −14° ± 9° to −5° ± 6°).

In conclusion, the 3-D analysis demonstrated that patients with thoracic AIS had considerable thoracic hypokyphosis before surgery. The sagittal profile of the thoracic spine was overestimated by an average of 11° using the standard 2-D method compared with the segmental 3-D method. An increase in apical vertebral rotation resulted in a greater difference between these methods of measurement, particularly in sagittal plane measurements. Thus, patients with larger curves and more rotation had the greatest degree of underestimation of sagittal plane deformity. However, posterior surgical techniques with special attention to all three planes of deformity allowed for a high degree of correction not only of the coronal deformity but also of the sagittal and axial plane deformities.
References