SPINE Volume 28, Number 7, pp 693–698
©2003, Lippincott Williams & Wilkins, Inc.

Changes in Alignment of the Scoliotic Spine in Response to Lateral Bending

Murray J. Beuerlein, MSc,* Vincent J. Raso MASC,† Douglas L. Hill MBA,†
Marc J. Moreau, MD,* and James K. Mahood, MD*

Study Design. A retrospective cross-sectional review studied the posteroanterior and lateral bending radiographs of 26 preoperative patients with thoracic major adolescent idiopathic scoliosis.

Objective. To characterize the relation of vertebral axial rotation, apparent vertebral wedging, and disc wedging with lateral bending in patients with severe adolescent idiopathic scoliosis.

Summary of Background Data. Lateral bending radiographs are used commonly in surgical planning to assess the flexibility of the spine and to establish the placement of instrumentation. However, their use in the assessment of motion in the axial plane has not been clearly established.

Methods. Data were collected retrospectively from 26 subjects immediately before spinal surgery. All the subjects had adolescent idiopathic scoliosis with right thoracic major curves. Axial rotation, vertebral wedging, and disc wedging were measured from T4 to L4 on left and right supine bending and standing posteroanterior radiographs. The apexes of the major and minor curves, the neutral vertebrae, and the Cobb angles were recorded.

Results. No significant differences in axial rotation were found at the thoracic apex, neutral vertebrae, or lumbar apex in response to lateral bending. Most of the wedging occurs in the disc, and is maximal at the apex of the curve. The total amount of wedging was higher in more severe curves.

Conclusions. Lateral bending does not improve axial rotation in severe scoliosis (scoliosis for which surgical correction is advised). Structural changes including disc and vertebral wedging may be responsible for the lack of rotational correction of the scoliotic spine. Lack of axial flexibility in the thoracic region may hamper surgical attempts to correct the deformities of the trunk. [Key words: coupled movements, lateral bending, rotation, scoliosis] **Spine 2003;28:693–698**

Scoliosis is a three-dimensional spine deformity characterized by lateral deviation and axial rotation of the vertebrae.[1] The axial rotation is primarily responsible for the development of the rib hump that represents the major cosmetic deformity associated with scoliosis, and that may compromise pulmonary function in severe cases.[2] Ideal treatment of the scoliotic deformity addresses not only the frontal plane curvature, but also the rib hump with the underlying causative axial rotation. Current surgical techniques for treating scoliosis significantly reduce the frontal plane deformity, but do not adequately correct axial rotation.[3–6] As a result, the rib hump can persist after the surgery. The reason for this is not fully understood.

Several studies have shown a relation between flexibility of the spine in the frontal plane, as indicated by lateral bending radiographs, and the surgical correction of the frontal plane deformity.[3,7–11] These studies concluded that spinal "flexibility" is the limiting factor in the surgical correction of scoliosis, and that surgery only minimally improves the rotation of the spine. Measurements taken during surgery have found primarily *en bloc* rotation. That is, the whole spine is rotated, as opposed to individual vertebra derotation.[12,13]

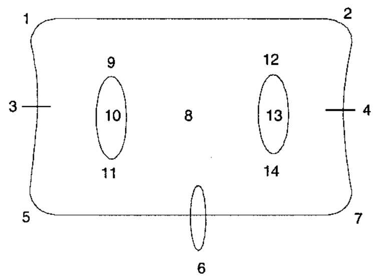
Likewise, flexibility in the axial plane may be the factor limiting correction of the axial deformity and resulting rib hump. Unfortunately, extensive evaluation of scoliotic spine flexibility in the axial planes is not available. Biomechanical studies of the normal human spine have indicated that the lateral curvature and axial rotation are coupled, and that they change in tandem in response to lateral bending.[14] For example, as the spine undergoes lateral bending and curvature, the vertebrae respond by rotating into the curvature, with the severity of rotation related to the extent of curvature. However, whether this coupling mechanism holds true for patients with severe scoliosis requiring surgery has not been established. Furthermore, if the scoliotic spine decouples, could it be a result of structural changes to the spine such as vertebral or disc wedging? The objective of this study was to characterize the relation of vertebral axial rotation, apparent vertebral, and disc wedging to lateral bending in patients with severe adolescent idiopathic scoliosis (AIS).

Methods

Vertebral axial rotation relative to the frontal plane (global reference), vertebral wedging, and disc wedging data were collected retrospectively from 26 subjects (1 boy and 25 girls) immediately before spinal surgery. Their age at surgery was 15 ± 3.5 years. All the subjects had advanced AIS with right thoracic major curves. Rotation and wedging were measured from T4 to L4 at every level on the left and right supine bending and standing posteroanterior radiographs. As shown in Figure 1, 14 points were marked on each vertebra and digitized into a computer by a single observer to provide four quantitative measures of rotation[15–18] (also J. Koreska, personal communication, 1988). These methods rely on the apparent position of

From the *University of Alberta, Edmonton, and the †Capital Health Authority, Glenrose Site, Edmonton, Alberta Canada.
Acknowledgment date: December 10, 2001. First revision date: March 29, 2002.
Acceptance date: August 30, 2002.
Device status/drug statement: The submitted manuscript does not contain information about medical devices or drugs.
Conflict of interest: No funds were received in support of this work. No benefits in any form have been or will be received from a commercial party related directly or indirectly to the subject of this article.
Address reprint requests to Doug L Hill, MBA, Glenrose Rehabilitation Hospital, 10230 111 Avenue, Edmonton, Alberta, Canada T5G 0B7.

Copyright © Lippincott Williams & Wilkins. Unauthorized reproduction of this article is prohibited.



1,2,5,7:	Corners of vertebra body
3,4:	Lateral margins
6:	Intersection of spinous process on inferior endplate
8:	Center of vertebral body
9,12:	Top of pedicles
11,14:	Bottom of pedicles
10,13:	Center of pedicles

Figure 1. Diagram of the points marked on each vertebra and digitized from T4 to L4.

the spinous process or the pedicles relative to the vertebral body edges and have been found accurate with a mean error of 3°.[17,19] The apexes of the major and minor curves, the neutral vertebrae, and the Cobb angles were recorded. Paired, two-tailed Student *t* tests were used to detect significant changes in vertebral axial rotation between posteroanterior, left, and right bending radiographs. To minimize variability, a standard radiograph tube distance was used, and the same instructions were given to all the patients by the same radiograph technician.

Wedging was determined by assessing the endplate angulations: points 1 and 2 for the upper endplate and points 5 and 7 for the lower endplate (Figure 1). Wedging was calculated for the vertebra as the angle formed by the intersection of lines through the upper (points 1 and 2) and lower (points 5 and 7) endplates. Disc wedging was calculated as the angle formed by the intersection of lines through the lower endplate of the superior vertebra and the upper endplate of the immediate inferior vertebra. For example, the wedging of the disc between T4 and T5 would use the angle formed by the intersection of lines through the lower endplate (points 5 and 7) of T4 and the upper endplate (points 1 and 2) of T5. The amount of wedging seen on a radiograph depends on the orientation of the spine as dictated by the amount of axial rotation. Derotation of the spine during surgery may change the perceived wedging. To minimize radiation exposure, the subjects did not have repeated radiographs at the same axial rotation.

The distribution of wedging between the disc and the vertebra was assessed in both standing and supine bending. Vertebra wedging should not change during bending with all the changes occurring in the disc (bony changes cannot occur because of active motion alone). To determine whether curve magnitude affected the amount and distribution of wedging, only the lumbar curves were analyzed. The subjects were divided into two subgroups representing small curves (Cobb angle, <30°) and large curves (Cobb angle, ≥30°) and compared using an unpaired Student *t* test, with a P of 0.05 considered significant. There was not an adequate range of thoracic curve sizes (all were uniformly large) that could be used to determine the effect of curve size.

Results

The four measures of axial rotation were well correlated (average correlation coefficient, 0.85), so one method (Stokes) was used for the analysis. The Stokes method was chosen because it relies on the position of the pedicles rather than the spinous processes because the former are more consistently visible on radiographs in the thoracic spine.

The patients in this study all had advanced scoliosis that required surgical treatment. The Cobb angle (Table 1) measured on preoperative posteroanterior radiographs averaged 62° (range, 40–82°) in the thoracic spine. The apex of the thoracic curve was at T9 on the average, whereas the lumbar curve centered at approximately L2–L3.

The deformity in the frontal plane responds to lateral bending (Table 1). Significant differences ($P < 0.05$) were found between the Cobb angles measured for the posteroanterior and right bending radiographs on the thoracic curve, and between posteroanterior and left bending positions on the lumbar curve.

Axial rotation did not respond to lateral bending. A move from standing to lying did not appear to change axial rotation. The measured differences were within the measurement error of vertebra rotation (±3°).[9,20] The comparative axial rotation for posteroanterior and for left and right bending radiographs is displayed in Figure 2. The severity of vertebral rotation was maximal at T9, which corresponded to the apex of the thoracic curve. As compared with the thoracic spine, the lumbar spine had relatively little vertebral rotation. No significant differences ($P > 0.05$) in vertebral rotation were found at the thoracic apex, the neutral vertebrae, or the lumbar apex in response to lateral bending (Table 2).

The typical curve has T6 and T12 as the end vertebrae and T9 as the apex. The end vertebrae do not change

Table 1. Cobb Angles

	Posterior–Anterior		Left Bending		Right Bending		Left Bending—Paired Difference from PA (°) Mean (SD)	Right Bending—Paired Difference from PA (°) Mean (SD)
Curve Type	Mean (SD)	Min–Max	Mean (SD)	Min–Max	Mean (SD)	Min–Max		
Thoracic (right)	62° (11°)	40–82°	59° (13°)	45–82°	33° (16°)*	10–75°	6 (18)	29 (12)
Lumbar (left)	35° (14°)	12–60°	17° (9°)*	0–34°	39° (13°)	19–60°	24 (19)	−5 (10)

* Denotes a statistically significant difference from the PA value ($P < 0.05$).

Copyright © Lippincott Williams & Wilkins. Unauthorized reproduction of this article is prohibited.

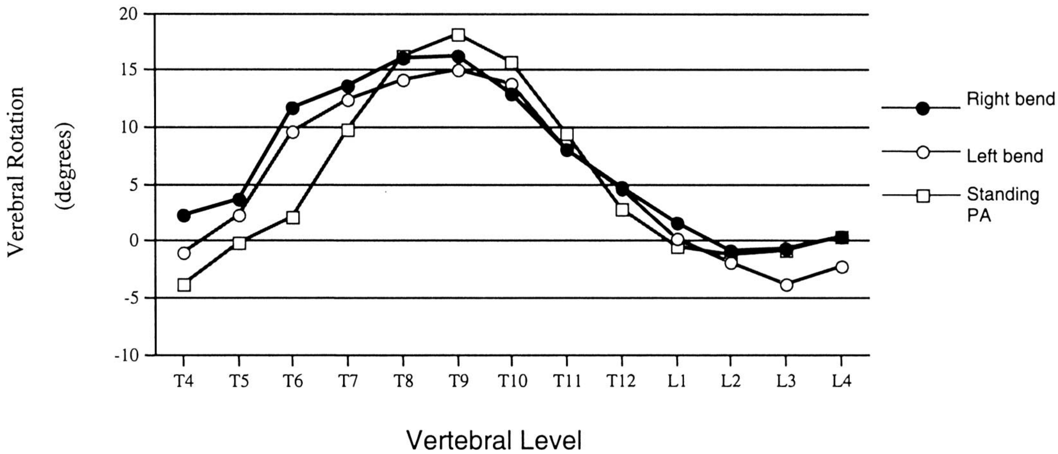


Figure 2. Average amount of axial rotation (n = 26) at each vertebral level for left bending, right bending, and posteroanterior radiographs.

with bending (Figure 3). Most (75%) of the correction of the thoracic curve during right bending appears to come superiorly to the curve apex (T6–T9), as compared with the region of the curve inferior to the apex (T9–T12). The lumbar curve decreased in magnitude during left bending.

Most of the wedging occurred in the disc, especially in the lumbar region (Figure 4). In the thoracic spine, the disc accounted for 64% of the vertebra–disc unit (a vertebra and the immediate inferior disc) wedging, whereas in the lumbar spine, the disc accounted for 78% of the wedging (Table 3). Maximum wedging of both the disc and vertebra occurred at the apex of the curve and was insignificant at the neutral bodies. Left and right bending has negligible effects on vertebrae wedging (~1°). Disc wedging changes considerably on lateral bending, especially at the lumbar apex for left bending (9°) and at the thoracic apex for right bending (−4°) (Figure 5).

Table 2. Vertebral Rotation

Location	Posterior–Anterior Mean (SD)	Left Bending Mean (SD)	Right Bending Mean (SD)
Thoracic apex	18° (8°)	15° (10°)	16° (6°)
Neutral vertebra	3° (9°)	5° (9°)	5° (7°)
Lumbar apex	−1° (7°)	−2° (8°)	−1° (8°)

The total amount of wedging was greater in the more severe lumbar curves. The lumbar curves larger than 30° had significantly more total wedging than those smaller than 30° ($P < 0.05$), but the distribution of wedging between the vertebra and the disc was similar (Table 4).

Discussion

In this study, the vertebra motion was measured relative to the radiograph (global reference). A local reference would have provided only an offset. The deformity in the frontal plane responds to lateral bending. The thoracic curve improved an average of 47% (from 62° to 33°) in response to bending to the right, and the lumbar curve improved by 51% (from 35° to 17°) on bending to the left. Axial rotation did not respond to lateral bending. No significant differences in vertebral rotation were found at the thoracic apex, the neutral vertebrae, or the lumbar apex in response to lateral bending. Most of the

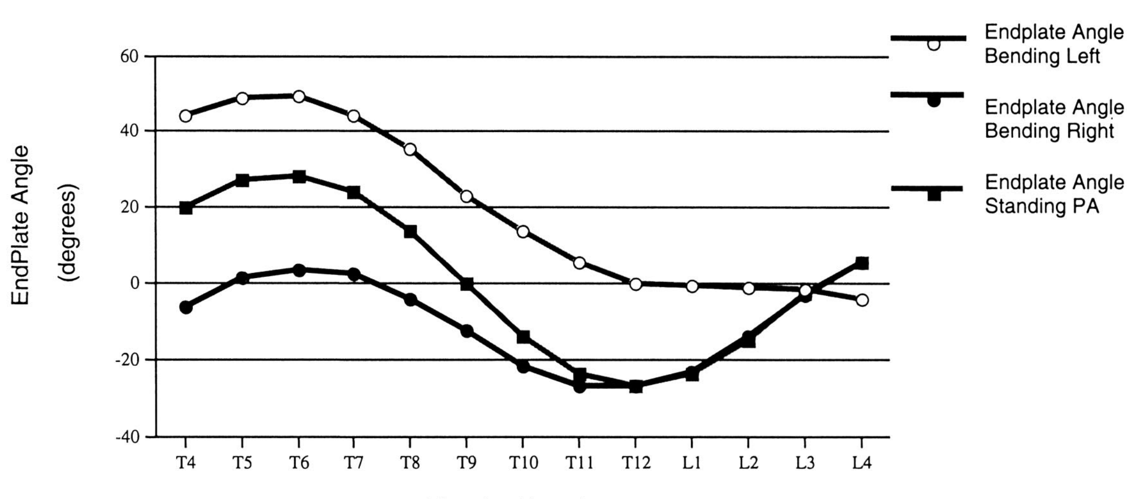


Figure 3. Superior endplate angles from T4 to L4 for posteroanterior and left and right bending (n = 26).

Copyright © Lippincott Williams & Wilkins. Unauthorized reproduction of this article is prohibited.

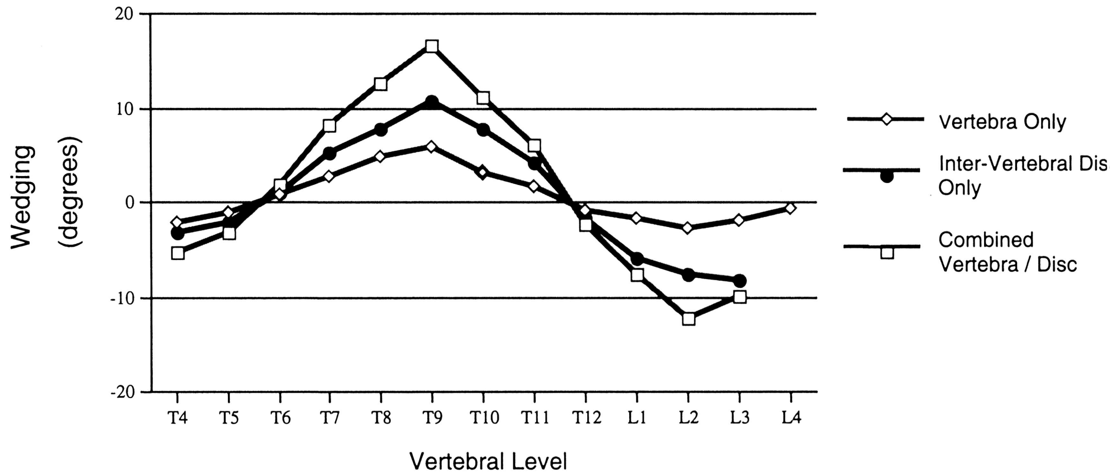


Figure 4. Wedge angles for the vertebra, disc, and vertebra–disc unit for the posteroanterior view (n = 26).

wedging occurred in the disc, especially in the lumbar region. The lumbar curves larger than 30° had more total wedging than those smaller than 30°, but the distribution of the wedging between the vertebra and the disc was similar. The apical vertebral rotation method has a 95% confidence limit of ±4.8° when used to measure patients with scoliosis.[21]

One observer selected all the landmarks to remove interobserver errors. The relative smoothness of Figures 2 and 3, in which no sharp discontinuities between vertebra levels would be expected, suggests that there are no gross errors.

The patients in this study all had severe scoliosis (Cobb angle, ≥40°) that required surgical treatment. The curves had structural changes including vertebral wedging. Despite these structural changes, the curves remained flexible in the frontal plane. The spine's response to lateral bending resulted in a correction of approximately 50%, as observed also by several other authors: Upadhyay *et al*[2] (51%), Cheung and Luk[7] (47%), and Vedantam *et al*[11] (58%). Cheung and Luk[7] also described the use of the fulcrum bending technique, which results in a better correction than supine bending (59% *vs* 47%) for the same patients with adolescent idiopathic scoliosis and major thoracic curves.

Preoperative bending radiographs commonly are used to assess flexibility of the spine in the frontal plane, and to establish the placement of the instrumentation.[8] In studies comparing the correction in the frontal plane in response to bending with the postoperative correction, the two are well correlated. However, surgical correction is consistently greater.[3,7,11] This may result from the soft tissue release during the surgical procedure that allows for improved correction. Lateral bending may not show

Table 3. Distribution of Wedging in the Scoliotic Spine Measured on Standing PA Radiographs

	Thoracic Apex		Neutral Vertebra		Lumbar Apex	
	Degrees	% Total	Degrees	% Total	Degrees	% Total
Vertebra	6.0°	36%	−0.7°	30%	−2.7°	22%
Disc	10.7°	64%	−1.6°	70%	−9.5°	78%
Total (disc/vertebra unit)	16.7°		−2.3°		−12.2°	

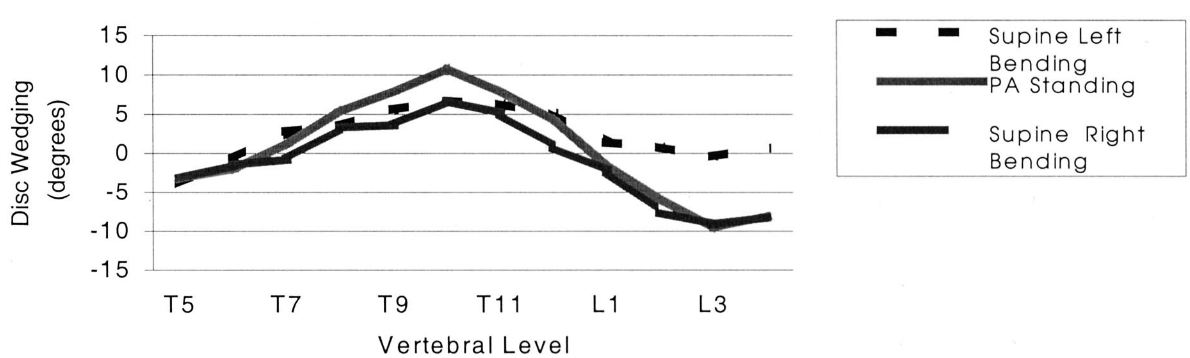


Figure 5. Disc wedging because of lateral bending (n = 26).

Copyright © Lippincott Williams & Wilkins. Unauthorized reproduction of this article is prohibited.

Table 4. Distribution of Wedging in the Disc and Vertebra at the Lumbar Apex Comparing Large and Small Curves

	Curve <30° (n = 10)		Curve ≥30° (n = 16)	
	Degrees	% Total	Degrees	% Total
Vertebra	−1.6	24%	−3.4	22%
Disc	−5.2	76%	−12.0	78%
Total (disc/vertebra unit)	−6.8		−15.4	

the true flexibility of the spine, and better surgical systems may provide more correction.

Despite the mobility of the spine in the frontal plane, the axial rotation of the spine does not change in response to lateral bending (Figure 6). In a comparison of right bending and posteroanterior (PA) views, the correlation r^2 is 0.88 (right bend = 0.76 × PA + 3.7), and in a comparison of left bending and posteroanterior views, the correlation r^2 is 0.83 (left bend = 0.96 × PA − 0.3). The kinematics of the normal spine are such that the motions in the frontal and axial planes are coupled because of the geometric arrangement of the motion segments.[14] Axial rotation occurs into the concavity of the curve as a lateral curve is introduced into the spine in response to bending. However, in the scoliotic spine, bending and rotation appear to be decoupled. It appears that the coupling is intact during the formation of the curve because the amount of axial rotation is correlated with the severity of the deformity in the frontal plane and is maximum near the curve apex.[20,22] However, as the curve "matures" and structural changes such as wedging develop, the kinematics change, resulting in the decoupling. This process leaves the vertebrae "fixed" in axial rotation and renders the vertebrae unresponsive to attempts to improve the axial deformity. This is in agreement with Matsumoto *et al*,[9] who found that rotational stiffness is related to the severity of the curve in the frontal plane. These authors found that curves measuring larger than 40° showed no improvement in vertebral rotation despite improvement in Cobb angle in response to axial traction. In contrast, less severe curves measuring smaller than 40° showed decreased axial rotation in association with decreased Cobb angles in response to axial traction.

Current surgical techniques such as the Cotrel–Dubousset system attempt to derotate the spine, but postoperative studies have consistently shown little or no correction of the deformity in the axial plane.[4,5,23,24] Similarly, correction of the axial deformity with other systems has been equally disappointing. Recent studies have shown minimal or no correction of the axial rotation with the Colorado system,[25,26] Drummond–Wisconsin instrumentation,[3,6] Texas Scottish Right Hospital instrumentation,[3] sublaminar wires,[24] and Harrington instrumentation.[3,6,27] Considering the lack of flexibility exhibited by the severely scoliotic spine in the axial plane, as described in this report, the lack of surgical correction is not surprising. It appears that by the time these patients are treated surgically, the structural changes to the spine and surrounding tissues make correction of the axial deformity difficult. As a result, the rib hump deformity often is only minimally corrected.[27] The correction of the vertebral rotation achieved with surgery likely is aided by soft tissue release during the operative procedure.

Vertebral and disc wedging was studied in these patients to help explain the decoupling of axial rotation and lateral curvature of the spine. Approximately one third of the wedging at the thoracic apex and one fourth of the wedging at the lumbar apex are present within the vertebra. For larger curves, the magnitude of wedging is

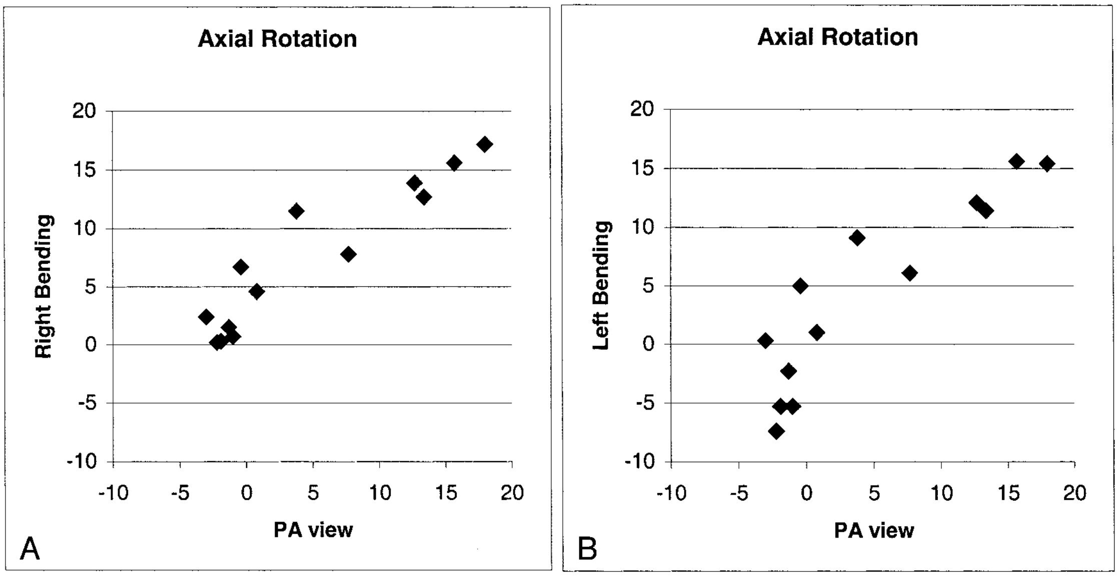


Figure 6. Axial rotation response to lateral bending for vertebrae levels T4–L4 (n = 26).

Copyright © Lippincott Williams & Wilkins. Unauthorized reproduction of this article is prohibited.

greater, but the proportion of wedging in the vertebra and disc is similar. Other authors also have shown significant vertebral and disc wedging in patients with progressive AIS. Similar to the current results, Stokes and Aronsson[21] found that wedging of the vertebrae and disc were maximal at the apex of the deformity, and that in the thoracic region, there is more wedging in the disc than in the vertebra. However, in contrast to the current study, they found that in a group composed of both thoracolumbar and lumbar curves, the wedging was greater in the vertebrae than in the disc. The reason for this difference is hard to determine. It may be explained by the relatively small sample size (n = 9) in their group of thoracolumbar and lumbar curves. Alternatively, it may relate to the fact that their subjects in this group had primary thoracolumbar and lumbar curves, whereas the current patients all had major thoracic curves with a secondary lumbar curve.

It is possible that the structural changes in the vertebra itself are responsible for the loss of axial plane mobility. However, other changes to the vertebra not measured in this study, such as distortion of the posterior elements, may lead to the loss of axial plane mobility. Further study to clarify the source of the rigidity is warranted.

■ Conclusions

Frontal plane deformity corrects in response to lateral bending, but axial rotation does not. Severe scoliosis results in decoupling of axial rotation and lateral bending. Wedging occurs mostly in the intervertebral disc, but up to 22% occurs in the vertebra. Wedging is positively correlated with curve severity. Lateral bending does not improve vertebral rotation in the scoliotic spine. The lack of axial flexibility in the thoracic region may hamper surgical attempts to correct vertebral rotation and the resulting rib hump.

■ Key Points

- A retrospective radiographic study on preoperative AIS subjects was performed to characterize the relationship of vertebral axial rotation and apparent vertebral and disc wedging with lateral bending.
- Supine bending does not improve axial rotation in severe scoliosis.
- Lack of axial flexibility in the thoracic region may hamper surgical attempts to correct the deformities of the trunk.

Acknowledgment

The authors thank the MSI Foundation for its generous financial support.

References

1. Robin G. *The Aetiology of Idiopathic Scoliosis*. Boca Raton, FL: CRC Press, 1990.
2. Upadhyay SS, Mullaji AB, Luk KD, et al. Relation of spinal and thoracic cage deformities and the flexibilities with altered pulmonary functions in adolescent idiopathic scoliosis. *Spine* 1995;20:2415–20.
3. Aronsson DD, Stokes IAF, Ronchetti PJ, et al. Surgical correction of vertebral axial rotation in adolescent idiopathic scoliosis: Prediction by lateral bending films. *J Spinal Disord* 1996;9:214–9.
4. Gray JM, Smith BW, Ashley RK, et al. Derotational analysis of Cotrel–Dubousset instrumentation in idiopathic scoliosis. *Spine* 1991;16:S391–3.
5. Krismer M, Bauer R, Sterzinger W. Scoliosis correction by Cotrel–Dubousset instrumentation: The effect of derotation and three-dimensional correction. *Spine* 1992;17(8 Suppl):S263–9.
6. Stokes IA, Ronchetti PJ, Aronsson DD. Changes in shape of the adolescent idiopathic scoliosis curve after surgical correction. *Spine* 1994;19:1032–7, discussion 1037–8.
7. Cheung KMC, Luk KDK. Prediction of correction of scoliosis with use of the fulcrum bending radiograph. *J Bone Joint Surg* [Am] 1997;79:1144–50.
8. Margulies JY, Floman Y, Robin GC, et al. An algorithm for selection of instrumentation levels in scoliosis. *Eur Spine J* 1998;7:88–94.
9. Matsumoto T, Kitahara H, Minami S, et al. Flexibility in the scoliotic spine: Three-dimensional analysis. *J Spinal Disord* 1997;10:125–31.
10. Vaughan JJ, Winter RB, Lonstein JE. Comparison of the use of supine bending and traction radiographs in the selection of the fusion area in adolescent idiopathic scoliosis. *Spine* 1996;21:2469–73.
11. Vedantam R, Lenke LG, Bridwell KH, et al. Comparison of push-prone and lateral-bending radiographs for predicting postoperative coronal alignment in thoracolumbar and lumbar scoliotic curves. *Spine* 2000;25:76–81.
12. Labelle H, Dansereau J, Bellefleur C, et al. Comparison between preoperative and postoperative three-dimensional reconstructions of idiopathic scoliosis with the Cotrel–Dubousset procedure. *Spine* 1995;20:2487–92.
13. Labelle H, Dansereau J, Bellefleur C, et al. Peroperative three-dimensional correction of idiopathic scoliosis with the Cotrel–Dubousset procedure. *Spine* 1995;20:1406–9.
14. Veldhuizen AG, Scholten PJ. Kinematics of the scoliotic spine as related to the normal spine. *Spine* 1987;12:852–8.
15. Bunnell WP. Vertebral rotation: Simple method of measurement in routine radiographs. *Orthop Trans* 1985;9:114.
16. Drerup B. Principles of measurement of vertebral rotation from frontal projections of the pedicles. *J Biomech* 1984;17:923–35.
17. Russell GG, Raso VJ, Hill D, et al. A comparison of four computerized methods for measuring vertebral rotation. *Spine* 1990;15:24–7.
18. Stokes IAF, Bigalow LC, Moreland MS. Measurement of axial rotation of vertebrae in scoliosis. *Spine* 1986;11:213–8.
19. Stokes IAF. Report on an error in the published description of a method of measuring axial rotation of vertebrae, reported by Stoke et al. *Spine* 1991;16:599–600.
20. Stokes IAF, Bigalow LC, Moreland MS. Three-dimensional spinal curvature in idiopathic scoliosis. *J Orthop Res* 1987;5:102–13.
21. Stokes IAF, Aronsson DD. Disc and vertebral wedging in patients with progressive scoliosis. *J Spinal Disord* 2001;14:317–22.
22. Stokes IAF, Armstrong JG, Moreland MS. Spinal deformity and back surface asymmetry in idiopathic scoliosis. *J Orthop Res* 1988;6:129–37.
23. Lenke LG, Bridwell KH, Baldus C, et al. Analysis of pulmonary function and axis rotation in adolescent and young adult idiopathic scoliosis patients treated with Cotrel–Dubousset instrumentation. *J Spinal Disord* 1992;5:16–25.
24. Wood KB, Olsewski JM, Schendel MJ, et al. Rotational changes of the vertebral pelvic axis after sublaminar instrumentation in adolescent idiopathic scoliosis. *Spine* 1997;22:51–7.
25. Delorme S, Labelle H, Aubin CE, et al. Intraoperative comparison of two instrumentation techniques for the correction of adolescent idiopathic scoliosis: Rod rotation and translation. *Spine* 1999;24:2011–7.
26. Ecker ML, Betz RR, Trent PS, et al. Computer tomography evaluation of Cotrel–Dubousset instrumentation in idiopathic scoliosis. *Spine* 1988;13:1141–4.
27. Weatherley CR, Draycott V, O'Brien JF, et al. The rib deformity in adolescent idiopathic scoliosis: A prospective study to evaluate changes after Harrington distraction and posterior fusion. *J Bone Joint Surg* [Br] 1987;69:179–82.

Copyright © Lippincott Williams & Wilkins. Unauthorized reproduction of this article is prohibited.