Measurement of Axial Rotation of Vertebrae in Scoliosis

IAN A. F. STOKES, PhD, LLYNDA C. BIGALOW, MS, and MOREY S. MORELAND, MD

The authors report a radiographic method for measuring the axial rotation of vertebrae in degrees and its use in 99 patients with adolescent idiopathic scoliosis. The offset of the pedicle images from the vertebral body center and a "depth" estimate measured radiographically in a population of patients with scoliosis permitted calculation of axial rotation by means of a simple mathematical formula. It was found that measurements of vertebral rotation can be made clinically from single-plane radiographs with a standard deviation of 3.6° (95% confidence limit ±7.1°) based on a study of known rotations of a radiographic phantom, and with a standard deviation of 2.44° (95% confidence limit ±4.8°) based on comparisons with three-dimensional measurements of the orientation of each vertebra derived from low-dose stereo films of a group of patients. Measurements from clinical films are unlikely to be made more accurately than this, because of inherent geometric constraints. [Key words: scoliosis, vertebral rotation, radiographic measurement, pedicle offset, vertebral geometry.

MEASUREMENT OF THE shape of the spine and, in particular, of the orientation of vertebrae, is of special interest in spinal deformities such as scoliosis and in assessing the alignment of the painful lumbar spine and of its intervertebral motion. Measurement of the axial rotation of vertebrae has always been difficult, because conventional radiography cannot produce an intelligible apical view of the vertebrae. Recently, computerized tomography has made this possible, and this technique has been used for the study of the scoliotic spine.[1,2] However, these CT images are still subject to possible distortion if the slice is inclined relative to the plane of the vertebra.

The axial rotation of vertebrae has been assessed from anteroposterior or posteroanterior radiographs by examining the symmetry of the vertebral image. Cobb[7] proposed a method based on the offset of the spinous process from the center of the vertebral body image. Mehta[18] and Nash and Moe[19] demonstrated how the pedicle images provide a better basis for measuring rotation than does the spinous process. This is especially true in scoliosis, in which the neural arch and the spinous process are known to develop asymmetries in severe cases. Errors introduced by asymmetry of vertebrae are therefore minimized by using the pedicles, which are less deformed by this bony remodeling process. Unfortunately, there is an inherent geometric difficulty in assessing axial rotation by these approaches.[5] This problem is illustrated in Figure 1. The apparent offset of the neural arch structures relative to the vertebral body image depends on a number of factors, including the axial rotation of the vertebra as well as the shape of the vertebral body, the distance (perpendicular to x-ray film) between the vertebral body and the neural arch structure, and the inherent symmetry of the bony geometry of the vertebra itself. The first two of these additional factors depend on the anatomic location within the spine, because the shapes of the vertebrae vary quite consideraby between the lumbar and thoracic regions. Coetsier et al[8] and Perdriolle[20] produced nomogram methods by which vertebral axial rotation could be assessed from the amount of pedicle image offset. These methods incorporated typical values of the depth-to-width ratio of the vertebrae. Because such methods are approximate, variable errors might be produced between individuals and also at the different anatomic levels within the spine.

Because of the difficulties in measuring axial rotation from anteroposterior radiographs is a result of the inability to know the depth or anteroposterior distance between geometric features on the vertebrae, it is possible to improve measurement accuracy by making a measurement of this depth dimension from a lateral film. This approach has been used in the technique by biplanar radiography.[3,6,21,23] In these studies, allowance was also made for the magnification, which is inherent in radiographic images due to the diverging beams of x-ray from the point source within the tube. The technique of biplanar radiography involves marking anatomic landmarks on the spine image in two film planes and using a computer program to combine the measurement of the locations of these images into three-dimensional coordinates for the spatial location of these points. When computerized reconstruction techniques are used, one is not restricted to the use of anteroposterior and lateral film pairs, because the more complicated computations involving intermediate planes can be performed relatively easily by a computer.[9,12,13,15] A stereo technique has also been used in this study. The principles of this technique are illustrated in Figure 2.

In this study, width and depth dimensions of the vertebrae T4 through L4 were measured using stereoradiography in a population of patients. Mean values of the dimensions were then used to estimate the axial rotation from the pedicle offset measured from posteroanterior (PA) films. The values of axial rotation obtained in this way were compared with measurements from the stereo, three-dimensional reconstructions of the spine. The technique was further validated by measurements from films of a radiographic phantom in eight different positions.

METHODS

Radiographic Technique

Axial rotations were measured from a 14- by 36-inch PA film. This film was also used as one of a stereo pair of films for three-dimensional measurement. The stereoradiographic technique used a single film plane. The two projections used were PA and a 15° oblique posterior–anterior projection. The arrangement of the radiography equipment relative to the patient is illustrated in Figure 2. A low-dose, air gap technique (similar to that described by Ardran et al[4]) was employed to minimize x-ray exposure. This used a 200-mm air gap between patient and film, no Potter–Bucky grid,

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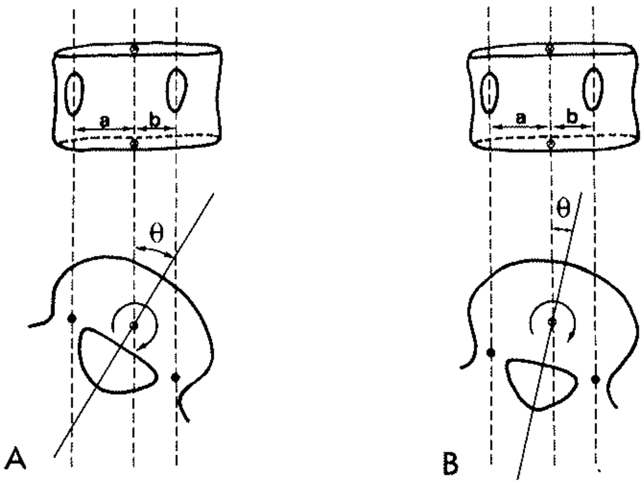

Fig 1. Two identical AP plane images of vertebrae (above) with asymmetric pedicles may correspond to vertebrae rotated by quite different angular amounts. This is because the apparent pedicle offset depends on the shape of the vertebrae, specifically on its sagittal plane depth compared with its coronal plane width.

a distance of 4 m from film to x-ray tube, and Dupont Quanta III screens with Kodak type XK3 film. In the case of larger patients, a Clear Pb (Victoreen Nuclear Associates, NY) graded filter was used to obtain more even exposure of the entire length of the spine. Typical exposures were at 96 kV, 60 mAs, giving a skin entry dose of about 17 mR. The conflicting needs to minimize radiographic exposure yet obtain clear, well-penetrated exposures of the entire length of the spine were considered in the choice of the second projection. Preliminary studies with test exposures of an x-ray phantom and a female cadaver demonstrated that the 15° oblique view provided an adequate compromise between x-ray dose, visibility of the landmarks, and accuracy of the three-dimensional geometric reconstruction of the spine.

After developing the films, we marked anatomic landmarks on the vertebrae with a film-marking pencil (Figure 3). The landmarks used were the centers of the vertebral endplates and the upper and lower margins of each of the pedicle bases. These landmarks were selected because they could be visualized in both the PA and oblique projections over the length of the thoracic and lumbar spine and in the presence of significant scoliotic deformities. Films were then placed on a digitizing tablet (Summagraphic Corp., Fairfield, CT), and the location of each of the landmarks was digitized. The digitizer was on-line to a computer (DEC MINC 11/23) programmed to construct a data file from the digitized coordinates. Subsequently, a direct linear transformation (DLT) program (Marzan[17]) was used to convert the coordinates of the landmarks as seen in the two projections into the three-dimensional spatial coordinates of these points. This program required calibration data from a test object with steel balls embedded in known locations that had previously been radiographed in the same two projections.

Patients

Ninety-nine patients attending a scoliosis clinic were studied. The mean Cobb angle was 19.8°, (range, 4–85°) and the mean age was 14.8 years (range, 8.9–37 years). The male-to-female ratio was 1:5. An x-ray phantom was used in a study of accuracy. This phantom (a human skeleton embedded in a material simulating human tissue) was used because it could be radiographed repeatedly. The radiographic quality of films of the phantom was somewhat inferior to that of the clinical films.

Three-dimensional (Stereo) Measurement of Axial Rotation

Projection of the vertebral landmarks onto an auxiliary plane (inclined to the horizontal) was used to measure axial rotation. This plane was defined as being perpendicular to the axis of the vertebral body (the line joining the endplate center landmarks). Axial rotation was defined by the angle between the line joining the pedicle center projections in this plane and the line representing the frontal plane in this projection (Figure 4). This method eliminates the effects of lateral tilt and flexion from the measurement.[10]

Two-dimensional (PA film) Measurement of Axial Rotation

The locations in the frontal plane (PA film) of the pedicles in relation to the vertebral body axis (the line joining the endplate centers) were expressed as a symmetry ratio (Figure 5). This ratio was then multiplied by a width-to-depth ratio to give the tangent of the rotation angle. The theoretic basis for this method is shown in Figure 6.

The width-to-depth ratios of each vertebra in the region T4 to L4 were determined experimentally by measurement in the group of 99 patients with adolescent idiopathic scoliosis seen in the scoliosis clinic. The width measurement (distance between pedicle centers)

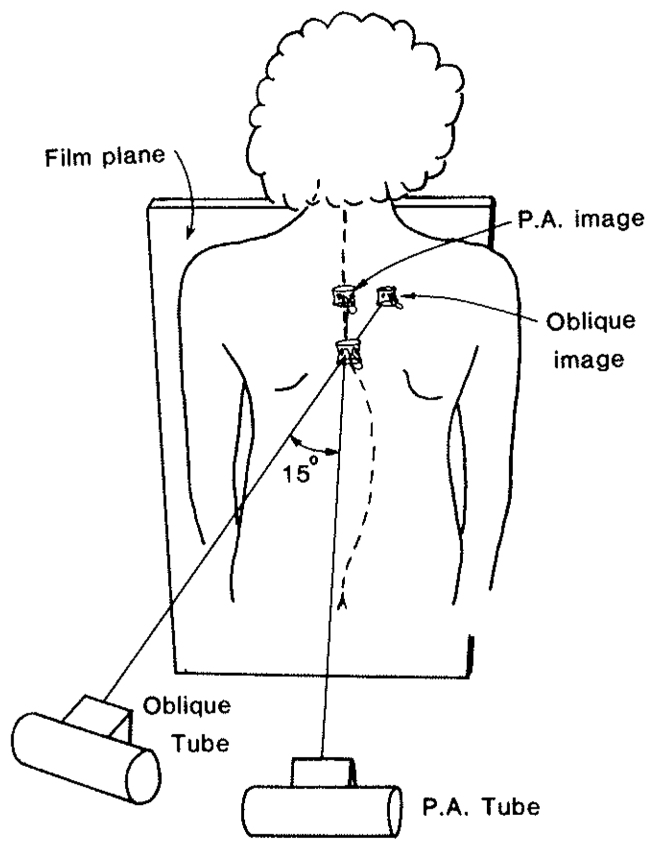

Fig 2. Method of stereoradiography of the spine. Two radiographs (on separate films) were made using the PA tube and the oblique tube. Positions of landmarks on the two images of the vertebrae were digitized for subsequent computer analysis. The system was calibrated and positions of the images on the film planes used to locate the landmark positions in space. Geometrically, landmark positions can be found at the intersection (or closest approach) of lines joining the image points to the respective x-ray sources.

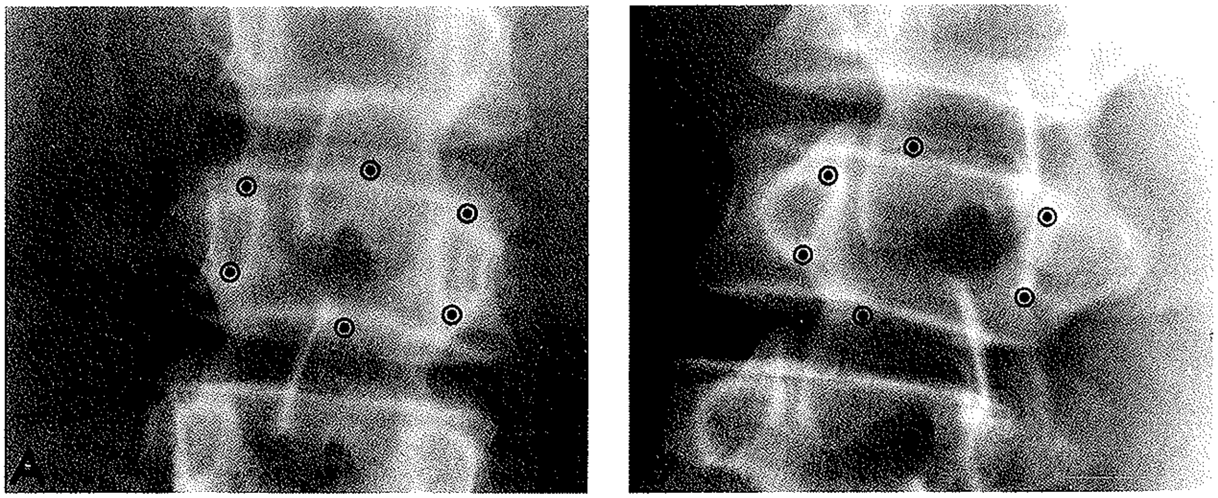

Fig 3. Positions of landmarks on the endplate centers and at the bases of the pedicles in the (A) PA and (B) oblique projections. Three-dimensional locations of these landmarks were computed after digitizing the landmark position in the stereo pair of films.

and the depth measurement (perpendicular distances from the line joining the endplate centers to the midpoint between pedicles) were calculated from the stereo reconstructions of the landmark positions. These measurements were then used to calculate the width-to-depth ratio for each vertebra in each patient. After it was established statistically that these ratios were different by anatomic level but not dependent on size of the patient (measured by the spine length), mean values of the ratio for each vertebral level were found. These values are given in Table 1.

The accuracy of the two-dimensional technique was studied by comparing the two-dimensional with the three-dimensional measurements of the patients and by means of a series of measurements of vertebral rotations taken from the the vertebrae of the x-ray phantom. This phantom was mounted on a rotating platform and accurately rotated in 7.5° increments from a neutral position, then radiographed in each position. Two observers made independent measurements of these films. In addition, a theoretic assessment of probable errors in measurement of rotation, based on probable errors in measuring the locations of pedicles and vertebral body centers, was made.

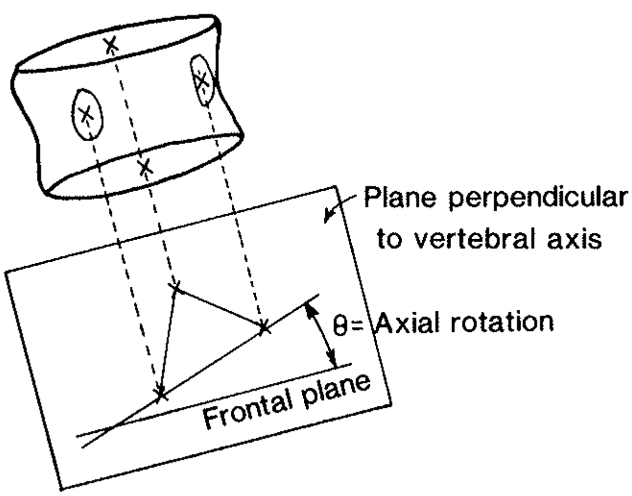

Fig 4. Three-dimensional method of measuring axial rotation of vertebrae. The measurement was made in a plane perpendicular to the axis of the vertebra centrum to eliminate effects of distortion due to lateral tilting or flexion of the vertebra.

RESULTS OF VALIDATION OF METHOD

In 99 patients with adolescent idiopathic scoliosis, the axial rotation of each of 12 vertebra was calculated by the three-dimensional method and by the two-dimensional method. In each case, the

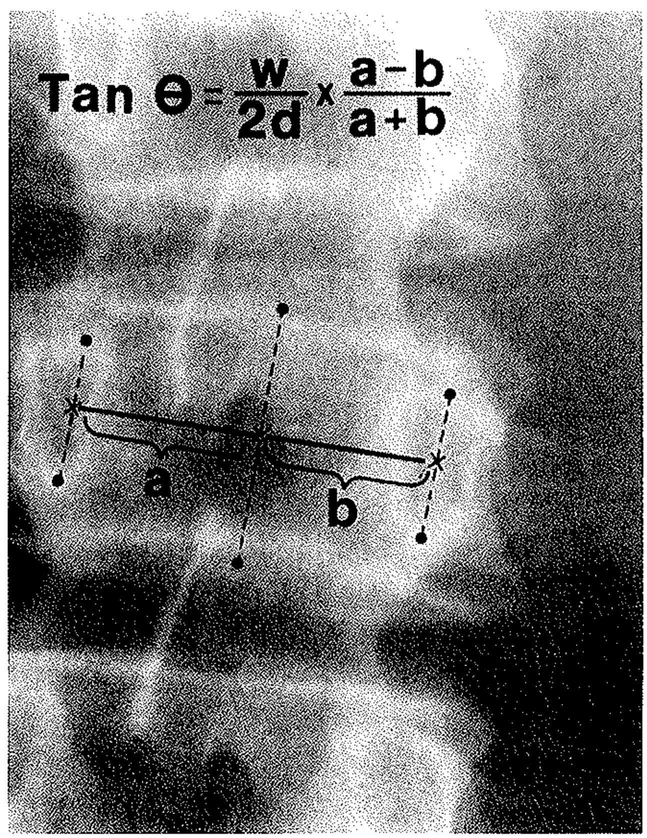

Fig 5. Method of measurement of axial rotation of vertebrae from a single PA film by the pedicle offset method. Because the ratio of measurements is used, the measure is independent of radiographic magnification. The method relies on the width-to-depth ratio. Expeimentally determined values are given in Table 1.

Table 1. Values of the Width-to-depth Ratio Measured from Stereo Radiographs of a Population of Patients in the Scoliosis Clinic

Vertebra	*Width-to-depth Ratio*	*95% confidence interval*
T4	1.5	1.27-1.72
T5	1.375	1.17-1.57
T6	1.16	1.07-1.25
T7	1.04	0.91-1.16
T8	0.92	0.85-0.95
T9	0.95	0.85-0.95
T10	0.95	0.85-1.0
T11	0.96	0.90-1.0
T12	1.00	0.90-1.05
L1	0.97	0.90-1.03
L2	0.92	0.85-1.0
L3	1.04	0.95-1.13
L4	1.25	1.08-1.42

Values given are mean values from this population.
The 95% confidence interval was typically ±10% of the mean values given.

difference between the two measures was calculated. A histogram giving the distribution of these differences is shown in Figure 7. The mean difference was not significantly different from zero, but the standard deviation was 2.44°. The differences might result from random errors in measuring the oblique films (the measurements from PA films were common to both techniques) or to individual variations in the width-to-depth ratio of the shapes of vertebrae (Table 1).

$$\tan\theta = \frac{(a'-b')/2}{d}$$

but $$\frac{a'-b'}{a'+b'} = \frac{a-b}{a+b} = \frac{a'-b'}{w}$$

so $$\tan\theta = \left(\frac{a-b}{a+b}\right)\times\frac{w}{2d}$$

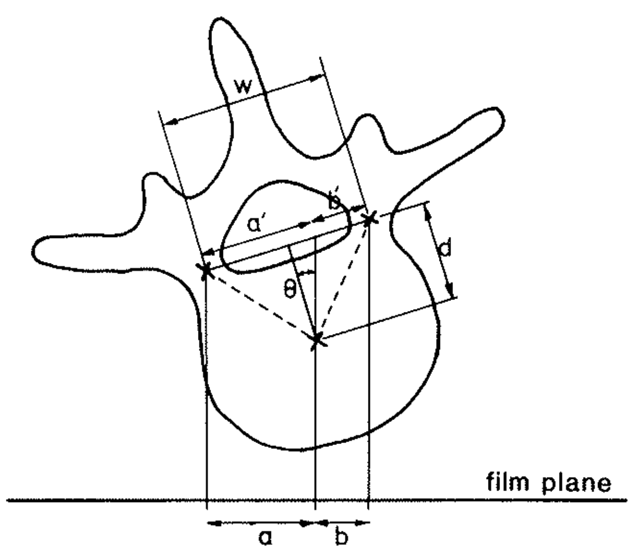

Fig 6. Geometric basis for measurement of the axial rotation (θ) of a vertebra from the pedicle offset ratio on a film plane. Increasing values of the angle (θ) increase the difference between a and b, but the actual value of the tangent of (θ) depends on the shape of the vertebrae (specifically, the distance between the pedicles [w] to the depth dimension [d]). The shape varies between individuals and by anatomic level.

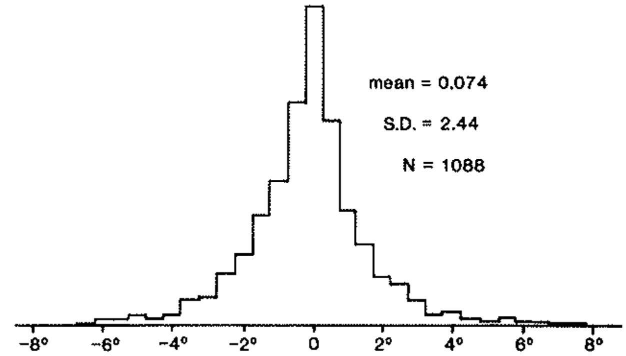

Fig 7. Histogram of differences between rotation of vertebrae measured by three-dimensional and two-dimensional methods. The histogram shows results of the two-dimensional methods. The histogram shows results from 1,088 measurements of rotation of 12 vertebrae in each of 99 patients.

Measurements from the phantom radiographed in each of seven 7.5° increments of rotation from a neutral position were made using the two-dimensional technique. The measurements in each position were corrected by subtracting the amount of rotation of the corresponding vertebra in the neutral position. This rotation offset was measured as the mean difference of the measured rotations of that vertebra from the actual rotation in each of the eight positions.

The corrected measurements are summarized in Table 2. Two observers made independent measurements. All marks made on the films by the first observer were erased before measurements were made by the second observer. The radiographs were made on 14 × 17-inch films, so normally all of the vertebrae from T4 to L4 (13 vertebrae) were visible. In five cases, part of a vertebra was not visible at the film edge or because of collimation errors, leaving 99 measurements of vertebral rotation by each observer. The overall standard deviation of these measurements from the actual rotation was 3.2° for observer 1 and 4.1° for observer 2. This gave an overall standard deviation of 3.6° for 198 observations. The maximum error by observer 1 was 7.7° and by observer 2 10.2°. Observer 2 was less experienced at the film-marking technique. Measurements of small rotations were slightly more accurate than measurements of large rotations.

Theoretic analysis showed that it would be difficult to improve upon the accuracy we found for measurement of axial rotation

Table 2. Rotation Measurements Using the Two-dimensional Method

Actual rotation		*Mean (SD) of measured rotation*		*Maximum error*	
°	*N*	*Observer 1*	*Observer 2*	*Observer 1*	*Observer 2*
22.5	13	24.7 (4.3)	19.8 (5.3)	−7.7	−9.9
15.0	13	17.6 (2.4)	16.4 (4.6)	5.8	10.2
7.5	13	6.4 (2.6)	4.7 (3.4)	−5.0	−7.8
0	12	0.8 (1.3)	0.7 (2.5)	2.3	4.4
−7.5	11	−7.2 (2.0)	−4.6 (2.9)	−3.0	8.0
−15.0	13	−16.6 (2.7)	−15.7 (3.9)	−6.5	−8.1
−22.5	12	−25.0 (3.3)	−21.3 (2.3)	−7.7	5.3
−30.0	12	−30.9 (2.9)	−29.3 (3.9)	−5.9	−6.0

The phantom was rotated accurately in 7.5° increments from a neutral position. Rotation of the 13 vertebrae T4-L4 was measured. The mean and standard deviation of the 12 measurements in each position are given along with the maximum errors for each of two observers. In five cases, a vertebra was not measureable because of technical problems (collimation or film positioning). All measurements are in degrees.

from x-ray films. The results of a theoretic analysis of measurement accuracy are shown in Table 3. The apparent amount of axial rotation was calculated for a vertebra actually not rotated from the x-ray film, assuming small errors in identifying the pedicle images. In this example, it was assumed that the true distance between pedicle centers was 26 mm and that the width-to-depth ratio was 1.0. An error of 1 mm in identifying a pedicle would give an apparent rotation of approximately 2.2°. An error of 1 mm in identifying the axis of the centrum (from the endplate images) resulted in an apparent rotation of 4.4°.

DISCUSSION

The measurement technique based on pedicle offset has been proposed previously. Based on our comparison of it with three-dimensional measurements, and because we based the method on geometric principles and measurements of actual vertebra dimensions in a population of patients with scoliosis, we propose that it can be applied clinically. Measurement of axial rotation of vertebrae has always been a challenge and remains difficult with the modern techniques of tomography because of the difficulty of angling the slice relative to the vertebral plane.[1,2] The use of the pedicle offset method described here, along with the geometric analysis of the relationship of pedicle offset to axial rotation, provides a method that can work well even without a lateral film to provide a depth measurement of the vertebrae. The biplanar technique described by Brown et al[6] was highly accurate when tested with a model spine. When used with a cadaver spine specimen, errors in identifying points were approximately ±1 mm. A typical distance between pedicles was given as 21 mm. If one of these points were located inaccurately in the AP direction with an error of 1 mm, then there would be an apparent rotation of $\text{Tan}^{-1}(1/21)$, or about 2.7°. Thus the biplanar technique and the technique we describe have similar accuracy, but at the expense of an additional lateral x-ray exposure and a more complex marking and measuring procedure in the case of the biplanar technique. It appears that the errors introduced by measuring the "depth" dimension of the vertebrae may be similar to those obtained by assuming a fixed value, as we have done for this method. There was a nearly constant ratio between the width and depth of vertebrae, both between individuals and within the various anatomic levels of the same individual. Therefore, the measurements we have given should be widely applicable.

The data from this study suggest that the pedicle offset measured from a midpoint of the vertebrae (provided by the line joining the endplate centers) provides a better basis for measurement than a method using deviation of the pedicle from the outer margins of the centrum in the radiographic image. This is because the latter type of measurement incorporates a further variable of vertebrae shape, because the cross-sections of centra vary between individuals and considerably by anatomic level.

There was no correlation in our sample of patients between the width-to-depth ratio of vertebrae and the size of the patients' spine (measured by spine length). This was true despite evidence that the width (between pedicles) and the depth (from pedicles to vertebra centrum axis) grow at different rates. Knutsson[14] showed that there is a smooth linear increase in dimensions of the centrum up to skeletal maturity, while the dimensions of the neural canal grow rapidly during infancy, with little further growth after the age of 10 years.[14,16,22,24] However, these published data are for the interpedicular dimension of the neural canal, which is smaller than the distance between pedicle image centers we use. This dimension may grow more closely in proportion to that of the vertebral centrum dimensions. Eisenstein[11] found, in a South African population, that there were differences in sizes of lumbar vertebrae between white and black people and that these exceeded the differences between men and women. However, the shapes calculated as the ratios of dimensions given do not show differences that would significantly affect the accuracy of the measurements of axial rotation. It therefore appears that the width-to-depth ratios shown in Table 1 are adequately close to the actual ratios in adults and in patients with adolescent idiopthic scoliosis. We recommend, however, that these ratios not be used for children younger than 10 years of age.

Table 3. Error Analysis

Error (mm)	a	b	Calculated rotation (°)
0	13	13	0
1	12	13	−2.3
1	14	13	2.1
2	11	13	−4.8
2	15	13	4.1
3	10	13	−7.4
3	16	13	5.9

For a typical vertebra with a width-to-depth ratio of 1.0 and an interpediculate width of 26 mm. The dimensions a and b are the distances assumed to have been measured from pedicle images to the vertebral axis. (It is assumed that the correct distance in each case was 13 mm.) If these distances are used to calculate axial rotation by the two-dimensional method (Fig. 5), the angles shown in the fourth column are obtained.

CONCLUSIONS

The accuracy of measurements of axial rotation from coronal plane radiographs has been in doubt, because of uncertainties about the effects of variable vertebral geometry. We studied a population of patients with adolescent idiopathic scoliosis to measure vertebral shape by stereoradiography and to validate a pedicle offset method for measuring axial rotation of vertebrae.

Our method for measuring axial rotation was found to have a standard deviation of 3.6° in the study of rotation of an x-ray phantom and a standard deviation of 2.44° in comparison with a stereo radiographic method.

A theoretic analysis of effects of measurement errors indicates that measurements of axial rotation are sensitive to errors in measurement of pedicle images. This accuracy is unlikely to be improved upon.

We propose that this method should be adopted for clinical estimation of vertebral rotation in patients with adolescent idiopathic scoliosis.

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LETTERS

To the Editor:

This is a report on an error in the published description of a method of measuring axial rotation of vertebrae, reported by Stokes et al.[5] In Table 1 of that paper, values of average "width-to-depth" ratios of thoracic and lumbar vertebra were given. The numbers listed were w/2d, but they were reported in the caption of Table 1 as "width-to-depth ratios," implying w/d. Thus the values reported were exactly half of the values that should have been given. Although this error did not enter into the validation experiments reported in that paper, nor into subsequent use of this method by the authors, they would mislead readers as to the published method. The corrected version of these values are given in Table 1.

The error came to light as a result of a recent paper by Russell et al,[4] who compared the performance of four methods of calculating vertebral axial rotation from AP or PA x-ray projections of vertebrae. It was reported that the Stokes et al.[5] method was the least accurate of four methods. Mr. James Raso kindly provided the original data used in the Russell et al[4] comparison. This was used to determine whether the error in the tabulated values was the cause of the poor accuracy of the Stokes et al[5] method. The corrected w/d ratios were incorporated for this method, and the axial rotation values were calculated. It was found that the corrected values overestimated the true axial rotation by 20% (thoracic vertebra) and 22% (lumbar vertebra). In addition, there was a significant intercept term of −4.54° for the lumbar vertebra, indicating that this vertebra was slightly rotated in the "zero" position. The three other methods were also found to give a similar rotational offset. Despite the correction of the width-to-depth ratios, the Stokes et al[5] method was still found to be the least accurate according to the Russell et al[4] data.

The Stokes et al[5] method had originally been validated by the use of nine thoracic and four lumbar vertebrae in an imbedded human skeleton (x-ray phantom). This phantom was radiographed in eight accurately indexed rotated positions. Russell et al[4] used a similar methodology for comparing the four methods, but they used only two isolated vertebrae. Stokes et al,[5] to eliminate these systematic offsets, allowed for initial rotations of the vertebrae by subtracting the nominal zero position values from all the rotated position measurements. The x-ray phantom films were therefore used to repeat the Russell et al[4] comparison with a greater number of vertebrae. The films of the rotated phantom were marked and digitized according to the methods of Drerup[2] and Monji and Koreska,[3] as was done by Russell et al.[4] The fourth method[1] compared by Russell et al[4] uses the image of the base of the spinous process to determine rotation. Since this process was not visible in many of the films of the x-ray phantom, this method could not be evaluated. The results (Table 2) showed that the three methods tested had different systematic and random error components. The Stokes et al[5] method had the least systematic error (as indicated by the slope of the regression) but a greater random error component (based on r^2) than the other two methods.

The Stokes et al[5] method is not limited to small rotation angles, as stated by Russell et al.[4] With the correct w/d ratios, the problem noted by Russell et al[4] to occur at about 26° when either a or b becomes negative, would not occur until a rotation of about 44°. This reflects only the pedicle image passing through the midline of the vertebral body image and should simply be acknowledged by assigning a negative value to the corresponding measurement, a or b.

Table 1. Corrected Values of Width-to-Depth Ratios*

Vertebra	w/d	95% Confidence Interval
T4	3.00	2.54-3.44
T5	2.75	2.34-3.14
T6	2.32	2.14-2.50
T7	2.08	1.82-2.32
T8	1.84	1.70-1.90
T9	1.90	1.70-1.90
T10	1.90	1.70-2.00
T11	1.92	1.80-2.00
T12	2.00	1.80-2.10
L1	1.94	1.80-2.06
L2	1.84	1.70-2.00
L3	2.08	1.90-2.26
L4	2.50	2.16-2.84

*Where the width-to-depth ratio equals w/d in the equation $\tan(\Theta) = \{(a - b)/(a + b)\} \times w/2d$.

Table 2. Regression Statistics: Measurements of 13 Vertebrae of X-ray

Method	*Slope of Regression*	r^2
Drerup[2]	0.83	0.910
Monji and Koreska[3]	1.23	0.944
Stokes et al[5]	1.06	0.875

All three methods re-evaluated here are similar in that they use the position of pedicle images relative to vertebral body landmarks. The Stokes et al[5] method uses the center of the vertebral body as a reference, whereas the other methods studied use the margins (edges) of the vertebral body. In principle, the vertebral center should be preferable to the margins because it should be more constant with rotation of the vertebra. However, it may be that the greater precision of measuring from the clearly defined lateral margins of the vertebrae outweighs the possibly greater accuracy expected with the use of the body center.

It seems that Russell et al[4] may have used too small a number of vertebrae in their comparative study. By repeating their study with a larger number of representative vertebrae, and taking into account initial rotational offsets of the vertebrae, it was found that the three methods tested have differing systematic and random error components. The decision as to which measurement method to use to measure vertebral axial rotation should be based on which source of error one wishes to minimize.

I apologize for unintentionally misleading readers of our original method, and I thank Russell et al[4] for drawing attention to the error in our published report and for publishing their provocative comparative study.

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Shinomiya et al conclude