Maintenance of Derotation in Adolescent Idiopathic Scoliosis: a Novel Technique Measuring Postoperative Vertebral Rotation by Pedicle Screw Position

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Abstract *Background:* Current methods of measuring vertebral rotation by plain radiographs rely on anatomic landmarks that are not present in the postoperative spine or require advanced imaging. Furthermore, there are few studies on the incidence of crankshaft with modern pedicle instrumentation. *Questions/Purposes:* We sought to (1) describe and validate a method of vertebral rotation measurement using plain radiographs and (2) measure postoperative rotation in a series of patients treated for adolescent idiopathic scoliosis. *Methods:* Patients with adolescent idiopathic scoliosis treated with surgery over a 6-year period were reviewed. Patients with computed tomography (CT) scans and radiographs within 60 days of another were included. Vertebral rotation was calculated by radiographic measurements and measured directly by CT scan. As an internal control, patients with two apical pedicle screws on all radiographs were analyzed. Rotation was measured for all patients with at least 1 year of radiographic follow-up. *Results:* Three thousand five hundred fifty-two instrumented spinal levels in 308 consecutive patients were reviewed. Ten patients with 93 screws were analyzed by CT and radiographs. The average discrepancy between computed tomography (CT) and radiographs was $3.3 \pm 1.9^\circ$, with 81.7% (76/93) within 5° . Intra- and inter-rater reliabilities for measured

axial rotation were excellent (intra-class correlation coefficient (ICC)=0.879 and 0.900, respectively). One hundred twenty-eight patients were eligible with an average follow-up of 2.3 ± 1.2 years; 84.8% (151/178) had screw(s) visible on all images at the major curve apex. The average postsurgical rotation was $3.5 \pm 2.9^\circ$; 19.2% (29/151) were measured to have a rotation over 5° , and 4.0% (6/151) demonstrated a rotation over 10° . Only 4.6% (7/151) of patients demonstrated a postoperative Cobb angle change over 10° . *Conclusions:* Most major curves have apical pedicle screw instrumentation that can be followed by radiographs alone to measure rotation. Vertebral rotation measurement requires only plain radiographs and is a more sensitive determination for subtle postoperative crankshaft than change in Cobb angle.

Keywords pedicle screw · crankshaft · adolescent idiopathic scoliosis · Cobb angle · deformity · progression · complications · rotation

Introduction

Pedicle screw instrumentation has profoundly changed the surgeon's ability to correct rotational deformity. While the existing literature seems to suggest that pedicle screws provide sufficient stability to prevent derotation and the crankshaft phenomenon [9, 34, 37, 38], there have been reports suggesting that pedicle screws alone may not be enough to control rotation [21]. The crankshaft phenomenon describes continued growth of the anterior column despite posterior fusion, resulting in a predominantly rotational deformity [15]. In the largest series available, vertebral rotation was corrected from 28° to 16° [13]. All the above studies, however, have been unable to accurately measure apical vertebral rotation given the obfuscation of radiographic landmarks postoperatively. The net result has been an

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inability to make a strong statement regarding pedicle screws and their ability to control rotation [26].

Several measurements of axial rotation have been described. The first description by Cobb used location of the spinous process with relation to the lateral borders [11]; this was later supplanted by the Nash-Moe system [31], measuring the medial displacement of the convex pedicle overlying the vertebral body. The Perdriolle “torsionmeter” method further refined these techniques to calculate rotation by pedicle displacement relative to the lateral vertebral borders. Additional methods using additional oblique radiographs [36], fluoroscopy [28], CT scans [1, 20, 23], or magnetic resonance imaging (MRI) studies [6] incur both additional cost and/or radiation. For example, one method [20] demonstrated the accuracy of CT measurements by selecting adolescent volunteers to undergo CT scans of the entire spine at 11 positions of tilt in the frontal plane, and then at 5 different positions of tilt. This methodology would now seem unethical, as CT scans are now thought to contribute to as many as 1.5% to 2% of all adult cancers [7]. Other methods utilize various anatomic landmarks and calculated relationships within the vertebra [2, 4, 6, 8, 12, 14, 19, 22, 28, 30–32, 35, 40], but these techniques [24] including the Nash-Moe are limited by the fact that the important landmarks are obscured after surgery by pedicle screws and other hardware [25]. Only one method [39] to our knowledge uses pedicle screw orientation to estimate rotation. This method requires two pedicle screws with visualized ends at the level of interest and assumes a uniform pedicle screw length. Based on our literature review and the observed limitations of existing techniques, the present study had two principal goals: (1) to create a simple and reproducible methodology of measuring axial rotation using routine AP and lateral radiographs and (2) to apply this methodology to measure the ability of pedicle screws to maintain derotation of the apical vertebra.

Patients and Methods

IRB approval was obtained prior to the initiation of this study. Patients who underwent spinal fusion at age 10–18 from July 2007 to July 2013 at our institution were reviewed. Inclusion criteria for the study were diagnosis of androgen insensitivity syndrome (AIS), age 10–18 at the time of surgery, availability of digital preoperative bending posterioranterior (PA) radiographs, as well as pre- and post-operative PA (or AP) and lateral radiographs of the entire spine. All radiographs were with the patient standing upright. Patients were excluded for a diagnosis other than AIS or if the requisite digital imaging was unavailable.

All radiologic studies were performed and digitized at our institution and with standard 36-in plate, calibrated with a 2.5-cm magnification marker placed on the patient’s neck. Three hundred eight patients from the study period had appropriate radiographs for review. Twelve patients were identified to have postoperative CT scans with hardware present in the spine; pedicle screws were visible in ten of these patients. Nine of these patients had appropriate

radiographs performed within 2 weeks of the CT scan, and an additional patient had a CT scan within 60 days of radiographs. These ten patients were all included in our analysis.

All radiographs were assessed for adequacy using original Lenke criteria [27]; C7 to S1 vertebra were completely visible, and pelvic obliquity was corrected to less than 2 cm when present due to limb-length discrepancy. All of the images evaluated in the study underwent standard plate radiography.

To ensure a proper orthogonal view, all radiographs were assessed on both views for adequacy. Orthogonal accuracy has previously been expressed as a comparative distance of ASIS to SI distance on either side [33]; however, this was not available for all patients. Instead, the distance from the S1 spinous process was measured to the most lateral aspect of the sciatic notch (S1–SN) as seen in Fig. 1. To control for rotation, the PA radiograph was deemed adequate if the side-to-side difference of S1–SN was less than 10 mm. On the lateral view, we could not find precedent to assess adequacy. We therefore defined acceptable alignment was by the distance in measurement between the most superior aspects of the acetabula in the sagittal plane; a radiograph was deemed acceptable if this distance was less than 10 mm as seen in Fig. 2. If the latest follow-up radiograph was deemed inadequate, penultimate radiographs were used, and so on.

Radiographic Measurement of Rotation

All radiographs were measured using PACS (IDS7™, Sectra Corporation, Linköping, Sweden). All levels were included if visualization of the screw tip was possible and not obscured by overlying hardware (e.g., rods in most cases, and infrequently a cross-connector). The horizontal displacement (medial to lateral) from the center of the rod was then measured. For reference, the rod width was measured adjacent to the screw measured. Measurements from PA radiographs are illustrated in Figs. 3 and 4.

On the lateral radiograph, the posterior to anterior length of the screw was measured from the center of the rod, parallel to the floor. Since hardware visualization was more difficult on the lateral radiograph, multiple landmarks on the instrumentation were used to confirm laterality of the rod (e.g., absence of pedicle screws, presence of hooks or wires,

Fig. 1. Assessment for adequacy on the PA radiograph using S1 spinous process to sciatic notch distance.

Fig. 2. Assessment for adequacy on the lateral radiograph using the PA difference between the most superior aspects of the acetabula.

Fig. 3. PA radiograph demonstrating displacement of screw tips and rod widths, as well as hook identification. NV signifies that the screw tip was not visible.

Fig. 4. Enlarged PA radiograph at T12, demonstrating a three-digit precision of rod measurement and horizontal displacement of the screw as measured from the center of the set screw.

or amount of rod extending from one end of the construct). The laterality and screw length could be measured in nearly all cases; in two levels, the pedicle screw overlap was essentially complete, and the screws could not be discerned from one another. The rod width was then measured at the nearest available level for reference. Although the radiographs were pre-calibrated, this step was seen as necessary once we observed that there was a small but noticeable difference in rod width on the two radiographs. Measurements from lateral radiographs are illustrated in Figs. 5 and 6.

PA measurements were corrected using the width of the rod at the level being measured, where δ is the correction factor for magnification differences.

$$\delta = L_{\text{rod, lateral}} / L_{\text{rod, PA}}$$

The visible horizontal length of the screw visible on PA (corrected for rod width) and lateral images were then related using the trigonometric relationship described below to calculate axial rotation.

$$\theta = \tan^{-1}(L_{\text{lateral}} / (\delta \times L_{\text{PA}}))$$

Axial rotation was recorded as the medial angle formed by the screw body and horizontal. Figure 7 displays the trigonometric relationship of apparent displacement of the screw tip from the rod for the two radiographic views.

Fig. 5. Lateral radiograph demonstrating displacement of screw tips and rod widths, and identification of left and right rods by instrumentation pattern. This radiograph represents the only lateral radiograph in which the paired screws could not be distinguished from one another.

Fig. 6. Enlarged lateral radiograph of T12, demonstrating screw displacement and rod width measurement.

Validation of Radiographic Measurement

For validation purposes, all patients were reviewed for availability of a CT scan performed within 60 days of postsurgical radiographs. Screw level on axial imaging was confirmed using triangulation with sagittal and coronal reformatted images. Axial rotation was measured by a line drawn parallel to the body of the screw and subtended with a line parallel to the floor. This direct measurement is shown in Fig. 8.

θ was calculated for each pedicle screw by three blinded raters. Each rater rated each screw twice, at least 1 week apart, with patients placed in random order; each rater did not know which CT scan corresponded to the measured radiographs. Intra-rater reliability was calculated using test-retest methodology. Inter-rater reliability was calculated by comparing the three raters' mean θ calculated for each pedicle screw.

Fig. 7. CT scan illustrating the geometric relationship of PA and lateral screw displacement measurements. Vantage points from orthogonal radiographs are illustrated.

Measurement of Apical Rotation

The same set of patients was reviewed for rotation at the apical vertebrae (AVR) at a minimum 1-year follow-up. Axial rotation of pedicle screw instrumentation at the apex of the major curve was measured on postoperative and latest standing radiographs. Rotation was averaged between the left and right pedicle screws (if both present and visible).

Curve apex of the major curve was determined from preoperative radiographs. A screw was included if the tip was measurable and distinguishable on PA and lateral

Fig. 8. CT scan of T12 vertebra. A line drawn along the body of the screw measures 70° with the horizontal.

radiographs on postoperative and standing radiographs. As a measure of internal control, patients with two measurable apical screws were analyzed separately. For the purposes of this, we study defined crankshaft as AVR more than 5° [32].

Statistical Methods

Microsoft Excel 2010 (Microsoft Corp., Redmond, WA, USA) was used for data management and all trigonometric calculations. Intra- and inter-rater reliabilities were calculated using the intra-class correlation coefficient (ICC 2.1) with absolute agreement in SPSS 19.0 (SPSS Inc., Chicago, IL, USA).

Results

Out of 3552 instrumented spinal levels visible by radiographs, 95 total spinal levels were visible on all radiographs with corresponding CT scans with 190 pedicles visualized (Fig. 9). There were 93 visible pedicle screws at these levels (48 left-sided and 43 right-sided), 38 non-visible screws, 12 hooks, 8 wires, and no instrumentation at 36 levels; two screws were offset from the rod and could not be measured with this technique, and two inner set screws were disengaged from the pedicle screw (the reason CT scan was obtained for this patient).

The average difference between axial rotation measured on CT and radiographs was $3.3 \pm 1.9^\circ$; 81.7% (76/93) of all pedicle screws measured on radiographs were within 5° of the measured value on CT scan (Fig. 10). Intra-observer reliability for the three raters was excellent (ICC=0.879; range, 0.777–0.995). Inter-observer reliability was also excellent (ICC=0.900).

Following development and validation of the measurement system described above, we identified the preoperative apical vertebra of the major curve in all 308 patients. Postoperatively, a measurable pedicle screw was present at the apical vertebra in 90.3% (272/308) of patients.

Of the 308 patients, 178 patients had appropriate radiographic images with an average follow-up of 2.3 ± 1.2 years; 84.8% (151/178) had at least one pedicle screw with a visible tip on all images at the major curve apex. The average postoperative AVR was $3.5 \pm 2.9^\circ$; 19.2% (29/151) were measured to have a rotation over 5° , and 4.0% (6/151)

Fig. 9. Instrumentation type for 95 pedicles visible on both CT and radiograph.

Fig. 10. Measurement discrepancy between CT and radiograph measurement.

demonstrated a rotation over 10° . As a measure of internal control, patients with two pedicle screws visible at the apex were analyzed separately. Fifty-six patients demonstrated two visible and measurable screws at the curve apex on all radiographs; the average rotation difference between screws was $1.5 \pm 1.4^\circ$.

Postoperative Cobb angle change was measured on immediate and latest postoperative follow-up radiographs for the 151 patients with derotation values. There were seven patients (4.6%) with change in Cobb angle over 10° , the previously defined value for crankshaft [9] (Fig. 11). There is a moderately positive correlation (0.38) between Cobb angle and rotation changes; a 10° of Cobb angle change was equivalent to 3.2° change in rotation. A case example illustrates this process. A 12-year-old girl with AIS and Lenke 2A curve underwent PSF from T2 to L2. Despite pedicle screw fixation at several levels, postoperative rotation was measured to be 16° at 2.7-year follow-up (Fig. 12). Subsequent revision was performed to derotate and extend the fusion to L3 (Fig. 13).

Discussion

We describe a simple method to accurately measure axial rotation of pedicle screws in the postoperative spine,

Fig. 11. Measurement of Cobb angle change versus loss of rotation.

Fig. 12. Initial (*left*) and postoperative (*right*) radiographs of a 12-year-old girl with AIS treated with PSF T2-L2. Despite surgery, her AVR was 16° at 2.7-year follow-up.

validated by comparison with measurements by CT scan, with good/excellent inter- and intra-observer reliabilities. Unlike previous methods, it does not require additional imaging with CT, MRI, or oblique radiographs, and it does not make assumptions about screw length or rod width. Future methodology may automate this process to create a computerized algorithm for the calculation of rotation.

The method described makes several assumptions about the geometric orientation of imaging studies. The lateral and PA radiographs are assumed to be perfectly orthogonal views of one another. Newer linear scanning radiograph imaging systems [18] (EOS® Imaging, Cambridge, MA, USA) may prove more useful in this regard for future studies. This provides biplanar imaging in which the two orthogonal views are taken simultaneously. Imaging modalities involving a rotating platform [17] or synchronous image acquisition technique [5] have been described; however, neither is practical for our clinical setting.

Several computer algorithms [3, 16, 40] have been created and studied for the purpose of axial rotation measurement in preoperative planning; however, we were unable to find a methodology which was validated in vertebrae with pre-existing implants.

This method has several important strengths. It provides a simple, accurate, and reproducible method to measure postoperative vertebral rotation. It addresses an important deficiency in current techniques and provides an additional tool to assess maintenance or loss of rotational correction postoperatively; this is particularly valuable as spinal instrumentation, pedicle screws in particular, obscure radiographic markers of rotation in the spine. A similar technique [39] describes vertebral body rotation, however, requires bilateral instrumentation and assumes an identical screw length. Another method [29] utilizes the separation between rods on a lateral radiograph to estimate rotation.

Weaknesses of this technique are that it does not measure axial rotation of the vertebral bodies directly but rather measures rotation of the instrumentation; hence, it cannot be used for preoperative planning or to estimate correction. In addition to the geometric assumptions detailed in the previous paragraph, we assume a uniform rod-to-pedicle distance. Our radiographic measurements were within 5° in the majority of patients (82%). Since a definition of

Fig. 13. Subsequent revision was performed with additional derotation and extension to L3.

crankshaft is a 5° rotation postoperatively, some of our final estimate crankshaft may be due to measurement error.

An important difference between radiographs and CT scans is the plane of weightbearing, which may have an effect on rotation that has not been discussed. While CT scans have been used in the literature as the gold standard to measure rotation [1, 20, 23], their limitations regarding pedicle screw placement and orientation have been noted [10]. Perhaps more importantly for this method, the rib hump is not accounted for. Since the PA measurement calculates screw displacement from the horizontal, the CT scan was measured in relation to the floor to mirror this measurement. This may be more an issue in preoperative patients before deformity correction; however, the postoperative residual rib hump may still alter the perceived rotation with relation to the floor. The difference between rotation measured by CT and radiographic techniques at the seven pedicles visible at the preoperative curve apex was $3.1 \pm 2.0^\circ$, less than the overall difference measured, suggesting that this effect is minimal.

While the ability of pedicle screws to resist derotation and crankshaft has not been clearly defined, the existing literature suggests that screws alone may be enough to prevent rotation of the spine. Tao and colleagues examined a consecutive series of 67 patients who underwent fusion for AIS into three groups based on fixation method. They found no incidence of crankshaft in the group instrumented with pedicle screws while there were seven cases of crankshaft when a hybrid construct of screws and hooks was used. The use of pedicle screws resulted in a significantly better maintenance of rotational correction. Despite these findings, the authors were using plain films to estimate vertebral rotation using the Pedroille method which is difficult to utilize in postoperative radiographs. In a small series of 18 patients, Burton [9] described only one case of crankshaft but were limited in their postoperative measurements to RVAD change $>10^\circ$, change in Cobb angle $>10^\circ$, and distal adding-on. They were unable to measure vertebral rotation as we have described here. A study of seven patients with juvenile idiopathic scoliosis [34] found 2/7 with some evidence of apical vertebral rotation but their ability to measure this was, again, hindered by the hardware in postoperative radiographs. Finally, Suk [37] reported no incidence of crankshaft in a series of 35 patients treated with pedicle screw fixation.

All of the above studies, however, are limited by the methods available to measure rotation in the postoperative spine. Using the method we describe above, we found a significant number of patients (19%) had a rotation greater than 5° at the apical vertebra, meeting the criteria for crankshaft phenomenon. Six patients (4%) had a rotation greater than 10° at the apical vertebrae. These data suggest that the incidence of apical vertebral rotation in an all pedicle screw construct is higher than previously described.

The above results, however, must be interpreted with some caution. Because this is a new method developed to measure rotation, we are the first to quantitate the amount of AVR observed after posterior fusion. It is certainly possible that our method is very sensitive to any rotation and the

previously described cutoff of 5°, obtained using the Pedroille method, might be too low to be of clinical significance. Indeed, our incidence of crankshaft when defined by axial rotation over 5° (19.2%) was times higher than a Cobb angle change of 10° (4.6%).

We believe this to be the most comprehensive and sensitive study to estimate the incidence of crankshaft phenomenon with modern instrumentation. The long-term clinical significance of mild postoperative rotation is unknown, and further clinical studies using this method would prove beneficial. Rotation may be a much more sensitive measurement for loss of postoperative derotation. The previously defined value of 5° may be too sensitive, as it resulted in a fourfold incidence of postoperative crankshaft when compared with a Cobb angle change of 10°.

Disclosures

Conflict of Interest: Benjamin T. Bjerke, MD, MS, Zoe B. Cheung, MS, Grant D. Shifflett, MD, Sravisht Iyer, MD, and Peter D. Fabricant, MD, MPH have declared that they have no conflict of interest. Han Jo Kim, MD reports personal fees from Medtronic, Biomet, and K2M and others from Depuy and Stryker, outside the work.

Human/Animal Rights: All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2008 (5).

Informed Consent: Informed consent was waived from all patients for being included in the study.

Required Author Forms Disclosure forms provided by the authors are available with the online version of this article.

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