Placement of pedicle screws in thoracic idiopathic scoliosis: a magnetic resonance imaging analysis of screw placement relative to structures at risk

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Abstract In posterior pedicle screw instrumentation of thoracic idiopathic scoliosis, screw malposition might cause significant morbidity in terms of possible pleural, spinal cord, and aorta injury. Preoperative axial magnetic resonance images (MRI) in 12 consecutive patients with right thoracic adolescent scoliosis, all with King type 3 curves, were analyzed in order to evaluate the relationship between the inserted pedicle screw position to pleura, spinal cord, aorta. Axial vertebral images for each thoracic level were scanned and the simulation of pedicle screw insertion was performed using a digital measurement programme. The angular contact value for each parameter regarding the pleura and spinal cord was measured on both sides of the curve. The aorta-vertebral distance was also measured. Aorta-vertebral distance was found to be decreasing gradually from the cephalad to the caudad with the shortest distance being measured at T12 with a mean of 1.2 mm. Concave-sided screws on T5–T9 and convex-sided screws on T2–T3 had the greatest risk to spinal cord injury. Pleural injury is most likely on T4–T9 segments by the convex side screws. T4–T8 screws on the concave side and T11–T12 screws on the convex side may pose risk to the aorta. This MRI-based study demonstrated that in pedicle instrumentation of thoracic levels, every segment deserves special consideration, where computer scanning

might be mandatory in immature spine and in patients with severe deformity.

Keywords Pedicle screw · Thoracic spine · Pleura · Spinal cord · Aorta

Introduction

Pedicle screw fixation has numerous advantages over other methods of spinal fixation but has the potential for serious complications [5, 13, 23]. Small pedicle width, altered pedicle morphology, and shift of the surrounding structures by rotation causes a consistently smaller safe zone in terms of pleural, spinal cord, and vascular injury in thoracic pedicle fixation of pediatric idiopathic scoliosis [25, 30].

The objective of the present study was to determine the relationship between the inserted pedicle screw to the pleura, spinal cord, aorta in patients with right thoracic idiopathic scoliosis and to analyze the safe angular value of screw insertion using magnetic resonance imaging.

Materials and methods

A retrospective review of twelve idiopathic scoliotic patients who had a magnetic resonance image (MRI) examination of the thoracic spine with right-sided thoracic curve was performed. All curves were classified as type III, according to the system of King et al.

The coronal and sagittal Cobb angles of the thoracic curves were measured using the posteroanterior and lateral radiographs. Apical vertebral rotation of each curve was also measured from the MR images using the Aaro–Dahlborn method [1].

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MRI was performed with a 1.5 T MR scanner (Philips Gyroscan Intera Master, Eindhoven, Netherlands) with a 30 mT/m maximum gradient strength and a 150 mT/m per millisecond slew rate using a synergy spine coil. The patients were placed in the supine position. Sagittal and axial T1 and T2 weighted images were obtained in which acquisition volumes adapted to the individual spinal curvature. A saturation pulse with a thickness of 100 mm was used to reduce respiration and motion artifacts. The imaging parameters for turbo spin echo T2 weighted imaging were TR/TE: 3500/120; matrix: 304×512 ; scan duration: 2 min 58 s and for T1 weighted imaging were TR/TE: 400/11; matrix: 288×512 ; scan duration: 3 min, with a slice thickness: 4 mm and gap: 1 mm.

The axial vertebral images for each thoracic level were scanned to a computer workstation. A digital measurement programme (Canvas 9.0) was used for analyzing the anatomic position of the thoracic pedicles relative to the spinal cord medially and pleural cavity laterally on each side of the curve. A simulation of pedicle screw insertion was performed with an appropriate screw length and diameter (4.0×25 mm) for each vertebra. The screw was introduced from the ideal entry point as described by Suk et al. [21], along the pedicular axis for each pedicle on the concave and convex sides of the curve. The presumed pedicle entry point of the upper thoracic spine is at the junction of superior margin of the transverse process and lateral aspect to midportion of facet joint and that of the lower thoracic spine is at the junction of the bisected transverse process and lateral margin of the facet joint. Then, regarding the entry point as a pivot point, the following measurements were performed (Fig. 1):

1. Screw image on each pedicle was moved medially, until the shaft or the tip of the screw contacted the spinal cord.
2. The same procedure was repeated in the lateral side for pleural contact.

The angular contact value for each parameter regarding the convex and concave sides of the curve was measured and recorded (Fig. 1).

The distance from the vertebral body to the outer wall of the aorta closest to the vertebral body was also measured between T4 and T12 [15].

Statistical analysis was performed using SPSS (version 13.0; Chicago, IL). Means were compared using the Student's *t* test between the convex and concave side for each vertebral level and for all segments from T1 to T12. One-way Anova test was used to compare the parameters in terms of pleural and spinal cord injury. In order to evaluate which segment was responsible for the significance, Posthoc (Tukey) test was used. Significance was defined as a $P < 0.05$.

Fig. 1 The schematic drawing of the measured parameters

Results

Eight female and four male patients with an average age of 12.7 years (range 7–18 years) were examined.

A total of 144 vertebrae (288 pedicles) were investigated. The most frequent upper and lower end-vertebrae of the thoracic curves were the fifth and the 12th thoracic vertebrae, respectively. The apical vertebrae were T8 in five and T9 in seven of the patients.

The average coronal Cobb angle was 32.9° ($25\text{--}65^\circ$). The average sagittal Cobb angle measured from T5 to T12 was 25° ($15\text{--}50^\circ$) for the thoracic curve. The average apical vertebral rotation as determined by the Aaro–Dahlborn method was 22.5° ($5\text{--}30^\circ$).

The angular values of safe zone measurements to pleural and spinal cord injury for each vertebral segment are shown in Tables 1 and 2.

The minimal angles were $10.9 \pm 3.9^\circ$ at T4 convex and $17.6 \pm 8.6^\circ$ at T3 concave levels regarding risk to pleural injury. At levels T4, T5, T6, T7, T8, and T9, the risk was statistically significant for pleural injury on convex side. At all concave levels, no statistically significant difference was detected for the risk of pleural injury (Table 1).

The minimal angles were $15.5 \pm 5.2^\circ$ at T3 convex and $12.9 \pm 6.8^\circ$ at T5 concave levels regarding risk to spinal cord injury. The risk was statistically significant at T2 and T3 on the convex side and T5, T6, T7, T8, and T9 on concave levels (Table 2).

Upper thoracic (T1–T6), midthoracic (T7–T9), and lower thoracic (T10–T12) segments were also analyzed separately between the convex and concave sides. The mean values for each convex and concave segment were recorded for comparison (Table 3). There were statistically significant risk of pleural injury on the convex side of upper and midthoracic segments ($P = 0.000$). The risk for

Table 1 Angular values of each vertebral segment related to the risk of pleural injury

Segment	Level	Convex	Concave	<i>P</i> value*
Upper thoracic	T1 pleura	16.75 ± 11.68	24.50 ± 14.04	0.15
	T2 pleura	11.41 ± 5.90	19.83 ± 14.13	0.07
	T3 pleura	12.50 ± 6.23	17.66 ± 8.63	0.10
	T4 pleura	10.91 ± 3.91	21.58 ± 12.92	0.012
	T5 pleura	11.75 ± 4.63	28.50 ± 15.48	0.002
	T6 pleura	13.50 ± 5.10	30.91 ± 13.62	0.000
Midthoracic	T7 pleura	12.41 ± 3.20	25.00 ± 12.43	0.003
	T8 pleura	11.75 ± 4.00	22.75 ± 11.40	0.005
	T9 pleura	11.08 ± 4.16	21.25 ± 11.97	0.011
Lower thoracic	T10 pleura	14.75 ± 3.98	18.58 ± 9.07	0.194
	T11 pleura	14.50 ± 5.35	17.33 ± 7.48	0.29
	T12 pleura	16.04 ± 6.56	18.83 ± 9.12	0.39

The values are given as the mean and standard deviation

* Significant values ($P < 0.05$) are marked with bold font

Table 2 Angular values of each vertebral segment related to the risk of spinal cord injury

Segment	Level	Convex	Concave	<i>P</i> value*
Upper thoracic	T1 spinal cord	23.50 ± 12.30	25.33 ± 10.63	0.70
	T2 spinal cord	16.33 ± 9.16	25.25 ± 7.60	0.017
	T3 spinal cord	15.50 ± 5.28	21.91 ± 7.44	0.023
	T4 spinal cord	17.91 ± 6.93	16.16 ± 6.49	0.53
	T5 spinal cord	19.50 ± 4.79	12.91 ± 6.89	0.013
	T6 spinal cord	24.50 ± 9.25	13.08 ± 4.48	0.001
Midthoracic	T7 spinal cord	26.83 ± 6.02	12.66 ± 5.82	0.000
	T8 spinal cord	26.75 ± 9.09	14.50 ± 3.82	0.000
	T9 spinal cord	28.00 ± 7.13	18.00 ± 4.89	0.001
Lower thoracic	T10 spinal cord	24.91 ± 5.72	21.75 ± 8.96	0.31
	T11 spinal cord	25.66 ± 6.42	25.66 ± 8.16	1.00
	T12 spinal cord	28.50 ± 6.66	25.83 ± 5.89	0.31

The values are given as the mean and standard deviation

* Significant values ($P < 0.05$) are marked with bold font

spinal cord injury was significant on the concave side of midthoracic segment ($P = 0.000$).

Convex and concave sides of the curve were also analyzed between the ipsilateral three segments for the risk of pleural and spinal cord injury (Tables 4 and 5). On the convex side, there was statistically significant difference between all segment couples for the risk of pleural injury; however, only the T7–T12 (midthoracic and lower thoracic) convex segment couple were responsible for the significance ($P = 0.04$). The risk for spinal cord injury was significant between all segment couples on the convex and

concave sides of the curve ($P = 0.000$). On the convex side, upper thoracic–midthoracic and upper thoracic–lower thoracic couples were responsible for the significance ($P = 0.000$). On the concave side, all three couples were found to be responsible for the significance (Table 5). Assessment of the mean angular values of each segment revealed that the T7–T9 segment (midthoracic) is the most vulnerable segment on the concave side. However, on the convex side, only the T2–T3 segment (upper thoracic) demonstrated a statistically significant risk in terms of spinal cord injury.

Table 3 Angular values of preapical, apical, and postapical segments for the convex and concave sides related to the risk of pleural and spinal cord injury

Segment	Structure	Convex	Concave	<i>P</i> value*
Upper thoracic	Pleural	12.80 ± 6.79	23.83 ± 13.67	0.000
	Spinal cord	19.54 ± 8.76	19.11 ± 8.96	0.77
Midthoracic	Pleural	11.75 ± 3.74	23.00 ± 11.70	0.000
	Spinal cord	27.19 ± 7.33	15.05 ± 5.27	0.000
Lower thoracic	Pleural	15.09 ± 5.29	18.25 ± 8.37	0.06
	Spinal cord	26.36 ± 6.30	24.41 ± 7.79	0.24

The values are given as the mean and standard deviation

* Significant values ($P < 0.05$) are marked with bold font

Table 4 Assessment of the risk of pleural and spinal cord injury between the three groups for the convex and concave sides

Structure	Side	Upper thoracic	Midthoracic	Lower thoracic	P value*
Pleural	Convex	12.80 ± 6.79	11.75 ± 3.74	15.09 ± 5.29	0.04
	Concave	23.83 ± 13.67	23.00 ± 11.70	18.25 ± 8.37	0.07
Spinal cord	Convex	19.54 ± 8.76	27.19 ± 7.33	26.36 ± 6.30	0.000
	Concave	19.11 ± 8.96	15.05 ± 5.27	24.41 ± 7.79	0.000

The values are given as the mean and standard deviation

* Significant values ($P < 0.05$) are marked with bold font

Table 5 The relationship in couples between the three segments for the convex and concave sides regarding the segment that is responsible for the significance

Significant values ($P < 0.05$) are marked with bold font

Structure	Side	Upper thoracic–midthoracic	Upper thoracic–lower thoracic	Midthoracic–lower thoracic
Pleural	Convex	0.64	0.13	0.04
	Concave	0.93	0.06	0.22
Spinal cord	Convex	0.000	0.000	0.89
	Concave	0.03	0.004	0.000

Aorta-vertebral distance decreased gradually from the cephalad aspect of the thoracic spine to the caudad (Table 6). The shortest distance was seen at T12 with a mean of 1.2 mm. The largest distance was seen at T1 with a mean of 4.8 mm.

Discussion

The superiority of pedicle screw fixation in biomechanical properties, fusion rate, early mobilization, and versatility had been shown conclusively [4, 13, 23]. There exists a lot of controversy, however, on the use of pedicle screws in the middle and upper thoracic spine as the complex pedicle morphology might imply significant risk to spinal cord,

aorta, and parietal pleura, especially in patients with spinal deformity [7, 14, 28].

There are several methods of thoracic pedicle screw insertion to enhance safety, such as guide pins into the pedicle [22], intraoperative C-arm image intensifier [11, 14], direct visualization of the medial wall after laminectomy [10, 27], and image guided systems based on CAT scan or fluoroscopy [2, 17, 18, 26].

Used in a fairly limited number of cases than adults, thoracic screw misplacement in immature spinal deformities ranges from 3 to 25% [5, 22, 29].

Significant progress in accuracy and safety of open pedicle screw insertion has been achieved by the clinical use of computer navigation systems. From a practical standpoint, these new systems are too complicated to be used widely, whereas the accuracy remains suboptimal and highly dependent on multiple variables [24]. However, the technology continues to evolve, increasing its overall ability.

Medial penetration is certainly the most feared screw misplacement as it may lead to spinal cord injury. Our study is in accordance with the previous studies indicating a higher risk with concave screws in general with respect to spinal cord injury [5, 19, 22]. T5–T9 concave segments had the greatest risk. Although undertapping followed by the insertion of a large diameter screw may enhance pullout strength, it represents a real risk of pedicle screw breakthrough, especially at these levels with a smaller than average pedicle diameter.

In the lower thoracic spine (T9–T12), the larger transverse convergence angles typically used in the upper and middle thoracic spine may well result in an increased risk of medial cortical perforation [3]. On the convex side, T2–T3 screws are risky with respect to cord injury due to

Table 6 The distance from vertebral body to the outer wall of the aorta

thickness of the spinal cord at these levels where a rather straight trajectory might be preferred.

A shorter pedicle and cord length in the upper thoracic spine is most likely associated with an increased risk of anterior cortical perforation at T1–T4 levels [3].

The majority of perforations occur laterally, reflecting the structural advantage of the thicker medial wall versus the lateral cortex [9, 12, 19]. The study of Vaccaro et al. [25] suggested lateral pedicle perforations endangering lung and/or segmental vessel injury, while Dvorak et al. [8] found that laterally perforated extrapedicular screws caused no pleural violations because the rib head shielded the intrathoracic contents. Higher incidence of lateral cortical breakthrough in the upper and middle thoracic spine is attributed to the intentional use of the in–out–in technique typed by smaller pedicle dimensions. Our study supports concave side screws with lateral misplacement to be almost without any risk of pleural injury unless extreme divergence is given in the axial plane. On the convex side, T4–T9 segments with lateral violation had the greatest risk of pleural injury. Due to superior migration of the costovertebral joints on the convex side of scoliotic curves, the rib head may not be able to prevent pleural injury in the in–out–in technique, especially in case of an inadvertent more caudal screw entrance. Using a geometric model, Rampersaud et al. [17] noted a maximum permissible translational error of less than 1 mm and rotational error of less than 5° at the normal midthoracic spine. In our study, we have found a margin of approximately 12° for rotational error with respect to medial perforation in the most risky T5–T7 segments. In lateral perforations by convex sided screws, having a risk to pleura margin of rotational error is approximately 10°.

In right-sided idiopathic scoliosis, the aorta begins at its origin from the aortic arch at approximately the fourth thoracic vertebra, at which point it is anterior to the midaxis of the vertebral body. It then travels more laterally and posteriorly at the apical region of the deformity and migrates anteriorly as it approaches the lumbar spine [6, 20]. The difference in position is accentuated with larger coronal thoracic curves, greater axial rotation of the apical segments, and hypokyphosis [20]. While the convex screws with lateral perforation seems relatively safe with respect to aorta injury in upper thoracic segments, the margin of error is especially small on concave side especially at T4–T9 segments due to posterolateral displacement of aorta [20]. In these periapical segments the in–out–in technique on the concave side might pose significant risk by a screw with a small transverse screw angle and a too lateral entry. By the rotation of aorta from posterolateral to anteromedial position in the right-sided scoliotic patient, the aorta may well be injured by concave screws at T4–T8 segments during curve correction.

The present study shows the aorta to be at risk by the convex screws at T11–T12 levels due to close and anteromedial position of the aorta.

With a growing interest in the pedicle fixation of upper and middle thoracic segments of pediatric idiopathic scoliosis, it should be well known that pedicle structure is significantly more complex than that of a simple cylinder [16], and that every segment deserves special consideration. Preoperative computer scanning might be routinely recommended for surgical planning especially in immature spine and in patients with severe deformity.

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