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DEFORMITY

The Importance of the Pedicle Diameters at the Proximal Thoracic Vertebrae for the Correction of Proximal Thoracic Curve in Asian Patients With Idiopathic Scoliosis

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Study Design. A retrospective comparative radiographic study.

Objective. The purpose of this study was to evaluate differences in the pedicle diameters of proximal thoracic vertebrae in relation to the severity of the proximal thoracic curve in Asian patients with idiopathic scoliosis.

Summary of Background Data. A small pedicle diameter at the proximal thoracic vertebra has been reported in normal population, but the changes of pedicle diameter in patients with a proximal thoracic curve have not been properly evaluated.

Methods. One hundred eighty-two patients with adolescent idiopathic scoliosis involving a greater than 10-degree proximal thoracic curve were analyzed. Sixty-nine and 113 patients had a structural and nonstructural proximal thoracic curve, respectively. The pedicle width was evaluated from T1 to T4 using a reconstructed computed tomography (CT) scan. The pedicle widths were compared between the convex and concave side, and between the structural and nonstructural proximal thoracic curve groups.

Results. The pedicle widths at T3 (0.76 ± 0.92 mm) and T4 (0.50 ± 0.69 mm) on the concave side for the structural proximal thoracic curves were extremely narrow compared with those for the nonstructural proximal thoracic curves (T3,1.17 ± 0.84 mm; T4,0.82 ± 0.72 mm) ($P = 0.002$, 0.003, respectively). However, the T2 pedicle width was comparable on the concave side in both groups (2.44 ± 0.94 mm for the nonstructural and 2.32 ± 0.97 mm for the structural proximal thoracic curve, $P = 0.430$).

Conclusion. A pedicle screw insertion at the T3 or T4 vertebra on the concave side is not always possible in cases of a structural proximal thoracic curve; however, the pedicle width of the T2 vertebra is very wide and safe for the standard pedicle screw insertion. These results should be considered when the surgeon decides the upper instrumented vertebra or the correction method for the structural proximal thoracic curve.

Key words: adolescent idiopathic scoliosis, computed tomography, concave side, convex side, fusion level, nonstructural curve, pedicle diameter, proximal thoracic curve, structural curve, upper instrumented vertebra.

Level of Evidence: 3

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Pedicle screw instrumentation and posterior fusion is a well-accepted surgical method to correct idiopathic scoliosis. Selecting the appropriate upper instrumented vertebra (UIV) and appropriate correction of scoliotic curve are important because of its relationship to postoperative shoulder balance, proximal curve progression, or proximal junctional kyphosis.[1–3] Another consideration is the deformed structure of the vertebrae in patients with scoliosis, as it may not be possible to insert a pedicle screw at the selected vertebra due to the narrow pedicle diameter.[4–11]

Several studies that have reported a smaller pedicle diameter at the concave side in the main thoracic curve have also discussed the pedicle diameter of the proximal thoracic vertebra in patients with scoliosis, but the results have not been consistent.[12–15] Catan *et al*[12] described a similar pedicle diameter between the concave and convex side, whereas Kuraishi *et al*[13] demonstrated a smaller pedicle diameter on the right side. However, neither study

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considered the proximal thoracic curve and the discrepancies between their findings may, therefore, be related to the severity of the proximal thoracic curve.

If patients have the proximal thoracic curve, UIV is usually selected above T4 considering the severity of the proximal thoracic curve, such as structural or nonstructural curve. The T4 pedicle is very small in normal population and the pedicle diameter gradually increases caudally and cranially.[4–11] The small pedicle of T2, T3, and T4 may be smaller on the concave side of the proximal thoracic curve and there may be difference between structural and nonstructural curve. Furthermore, the relationship between the pedicle width and other factors such as race, height, and vertebral rotation has been suggested.[7–10,16–19]

The purpose of this study was to (1) evaluate differences in the pedicle diameters of the proximal thoracic vertebrae between the concave and convex side of a structural (sPT) and nonstructural (non-sPT) proximal thoracic curve, and (2) evaluate factors related to the pedicle diameters of proximal thoracic vertebrae in patients with adolescent idiopathic scoliosis.

MATERIALS AND METHODS

Subjects

This study was approved by our institutional review board (2018-0668). We retrospectively reviewed 229 Asian patients with scoliosis older than 12 years who had been surgically treated by the same spine surgeon (CSL) between June 2016 and February 2018. Spine radiographs, including a standing long-cassette coronal and lateral view as well as supine side-bending views for each proximal thoracic, main thoracic, and thoracolumbar/lumbar curve, were taken in all patients several days before surgery in addition to a low-dose computed tomography (CT) scan as part of the routine standard care used to ensure safer screw sizing.

We excluded 21 patients from the initial population due to the related problems, including an Arnold-Chiari malformation (five cases), congenital scoliosis (four cases), Marfan syndrome (four cases), and one case each of Turner syndrome, Catch syndrome, hypoxic brain damage-induced encephalopathy, and neurofibromatosis. We additionally excluded four patients who had a left-sided main thoracic curve. In the 208 remaining cases with idiopathic scoliosis, 26 patients without an upper thoracic curve (*i.e.*, a less than 10° Cobb angle in the standing posteroanterior view) were additionally excluded because a radiographic diagnosis of scoliosis requires a coronal plane angle of 10° or greater as measured by the Cobb method.[1]

A final cohort of 182 patients was analyzed in this study. A structural PT curve was defined by a failure to correct to $<25^\circ$ as measured on side-bending radiographs and/or a segmental kyphosis of $>20^\circ$ (T2 through T5 kyphosis).[20] Positive T1 tilt angle was defined as the left edge of the T1 vertebral body was up. Flexibility was calculated as described by Vora *et al*.[21]

CT Measurements

CT scans were performed from the T1 to S1 vertebrae with the patient in the supine position using a SOMATOM Definition Edge device (Siemens Healthcare, Erlangen, Germany). The resulting CT images were reconstructed using Advantage Workstation Volumeshare 5 (version 4.6; GE Healthcare, Waukesha, WI). From the reconstructed sagittal and coronal images, a transverse image parallel to the endplate plane in both the sagittal and coronal plane was reconstructed at the center of the pedicle (Figure 1). When the superior and inferior endplate planes were not parallel due to vertebral wedging, an orientation approximately halfway between the two endplate inclinations was selected.[22]

In the reconstructed CT axial images, the vertebral body rotation was measured as the angle between the vertical line and the line that bisects the vertebral body.[23] The transverse pedicle width was measured as the endosteal width at the narrowest part of the pedicle for each thoracic pedicle on the reconstructed axial CT image from T1 to T4.[24,25]

Statistical Analysis

Statistical analysis was performed using SPSS Version 22.0 (IBM Corp, Armonk, NY). Paired *t* tests were used to analyze parameters between the concave and convex side and independent *t* tests were used to analyze those between structural and nonstructural thoracic curves. To estimate any factors related to the pedicle diameter, multivariate linear regression analysis was performed with variables presenting with a $P < 0.1$ in univariate simple linear regression analysis. These factors included age, sex, height, weight, body mass index (BMI), Cobb angle, flexibility, vertebral rotation, vertebral body level, and structural/nonstructural thoracic curve. The pedicle width and vertebral body rotation were measured and recorded twice by a 10-year experienced orthopedic surgeon (KBP), and the intraclass correlation coefficient (ICC) was used to define the intraobserver reliability. The statistical significance level was set at a $P < 0.05$.

RESULTS

The average age of patients was 16 years and 5 months (range, 12 years–29 years 11 months). The average height was 159.7 ± 6.2 cm, the average weight was 50.2 ± 8.4 kg, and average BMI was 19.7 ± 2.9 kg/m^2. Nine patients were male and 173 patients were female. The clinical characteristics of the patient spines were as follows: King[26] type I (n = 17), type II (n = 49), type III (n = 30), type IV (n = 25), and type V (n = 61); Lenke[20] curve type 1 (n = 67), type 2 (n = 53), type 3 (n = 31), type 4 (n = 16), and type 6 (n = 15). The upper end vertebra was T1 in 176 patients and T2 in six patients. The lower end vertebra was T4 in 24 patients, T5 in 91 patients, T6 in 50 patients, T7 in 14 patients, T8 in one patient, and T9 in two patients. One patient had a C7 cervical rib. A structural proximal thoracic curve was present in 69 cases and classified as sPT group, whereas 113

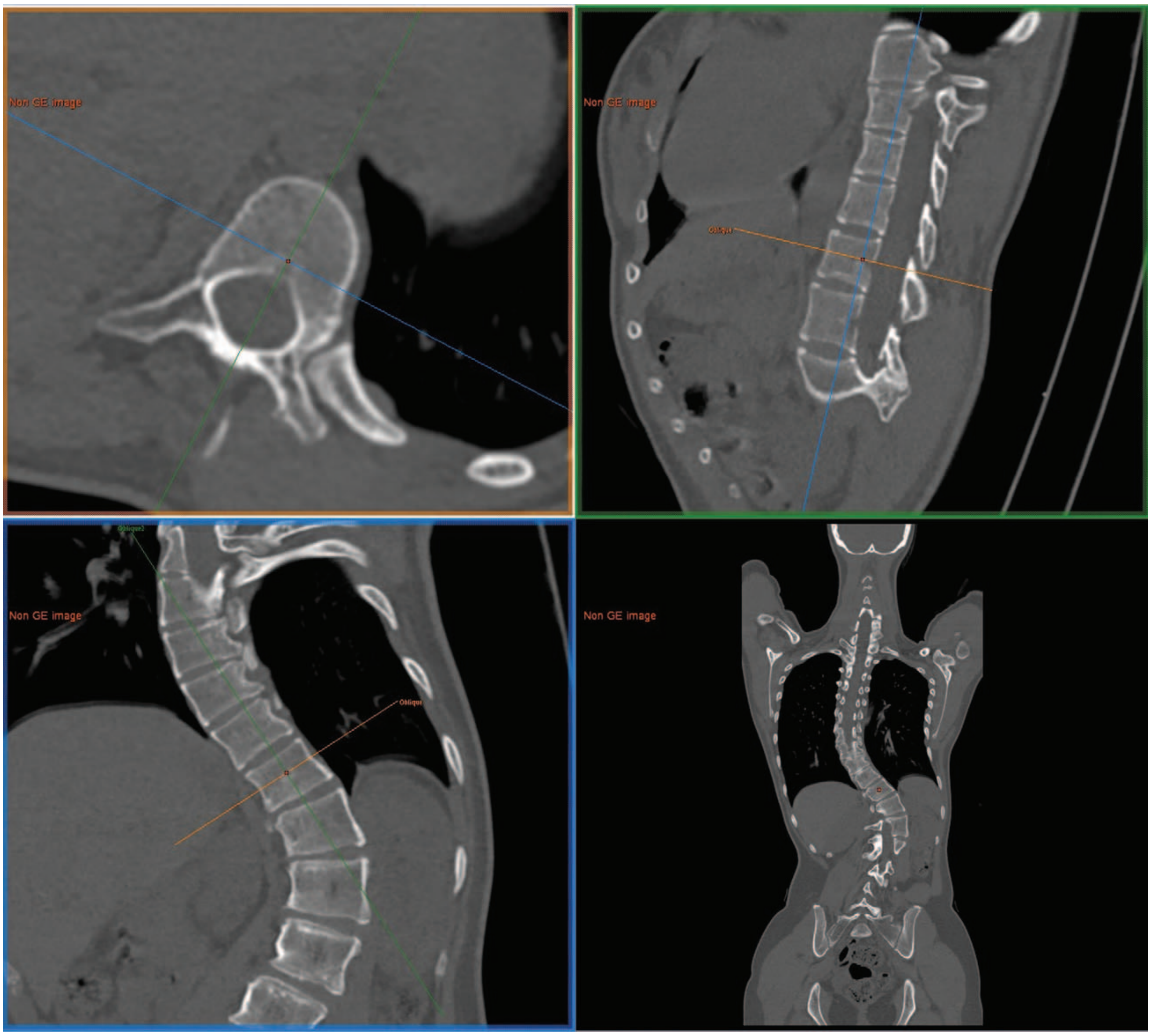

Figure 1. Reconstruction of a CT image (left upper corner) taken parallel to the end plate in the sagittal plane (right upper corner) and coronal plane (left lower corner).

patients had a nonstructural proximal thoracic curve and classified as non-sPT group. The average T1 tilt was $3.3 \pm 4.8^\circ$ in sPT group and $0.8 \pm 4.3^\circ$ in non-sPT group ($P \leq 0.001$). The ICC was 0.969 (0.964–0.974) for the pedicle width and 0.989 (0.986–0.991) for the vertebral body rotation.

Pedicle Widths in the sPT and Non-sPT

There was no difference in sex, age, height, weight, and BMI between sPT and non-sPT group, except Cobb angles and flexibility (Table 1). In both the sPT and non-sPT group, the pedicle width from T2 to T4 was smaller on the concave side (Table 2). However, the pedicle widths on the concave side were smaller at T3 ($p = 0.002$) and T4 ($P = 0.003$) in the sPT group than the non-sPT group. The pedicle width of the T2 vertebra was suddenly increased compared with the T3 vertebra and there was no difference between groups at the T2 ($P = 0.430$) and T1 ($P = 0.443$) vertebrae (Figure 2). On the convex side, only the pedicle width at T4 showed a difference and that was smaller in the non-sPT group than in the sPT group ($P = 0.002$). The frequency of pedicles without a cancellous channel on the concave side was 1.5% (1/69) at T2, 42.0% (29/69) at T3, and 55.1% (38/69) at T4 in the sPT group and 2.6% (3/113) at T2, 15.9% (18/113) at T3, and 19.5% (22/113) at T4 in the non-sPT group.

Linear Regression Analysis of the Pedicle Widths on the Concave Side

Univariate linear regression analysis revealed that the pedicle width is associated with sex, height, Cobb angle in a stress view, vertebral body rotation, vertebral body level, and structural/nonstructural curve type (Table 3). In multivariate linear regression analysis (adjusted $R^2 = 0.636$, $P < 0.001$), the pedicle width was increased with an increase

TABLE 1. Demographics of Patients With Structural and Nonstructural Proximal Thoracic Curves

	sPT	non-sPT	*P*
Sex (male:female)	6:63	3:110	0.110
Age, yrs	15.8 ± 3.1	15.6 ± 2.9	0.705
Height, cm	160.1 ± 6.9	159.5 ± 5.7	0.502
Weight, kg	49.4 ± 7.1	50.7 ± 9.1	0.299
Body mass index, kg/m^2	19.9 ± 3.2	19.2 ± 2.3	0.134
Standing view, °*	36.9 ± 8.6	23.9 ± 5.8	<0.001
Stress view, ° *	29.7 ± 7.3	15.6 ± 4.3	<0.001
Flexibility (%)*	19.0 ± 8.4	34.2 ± 13.6	<0.001

*$P < 0.05$.

non-sPT indicates nonstructural proximal thoracic curve; sPT, structural proximal thoracic curve.

TABLE 2. Comparison of the Pedicle Width (mm) Between the Concave and Convex Side

		Convex	Concave	*P*
sPT	T1	3.65 ± 0.89	3.63 ± 0.92	0.833
	T2*	3.12 ± 0.84	2.32 ± 0.97	<0.001
	T3*	2.67 ± 0.81	0.76 ± 0.92	<0.001
	T4*	2.48 ± 0.83	0.50 ± 0.69	<0.001
non-sPT	T1	3.76 ± 0.84	3.74 ± 0.91	0.662
	T2*	3.05 ± 0.76	2.44 ± 0.94	<0.001
	T3*	2.51 ± 0.77	1.17 ± 0.84	<0.001
	T4*	2.12 ± 0.69	0.82 ± 0.72	<0.001

*$P < 0.05$.

non-sPT indicates nonstructural proximal thoracic curve; sPT, structural proximal thoracic curve.

in height and decreased with increased vertebral rotation, female sex, a structural proximal thoracic curve, and being more distal until T4 from T1 vertebra (Table 4).

DISCUSSION

Motion preservation is less important when making a UIV decision because the thoracic spine is rigid due to the stabilizing effects of the rib cage and sternum.[3] The T1 tilt, shoulder balance, and presence of a structural/nonstructural thoracic curve are the principal considerations in deciding the UIV[2,3] and generally, the T2, T3 or T4 vertebra is selected. Another concern, however, is the narrow pedicle diameter of these proximal vertebrae because an optimal screw placement is important for minimizing possible complications, such as a breach of the cortex or misplacement of the screw.[27,28] We evaluated the pedicle width of the

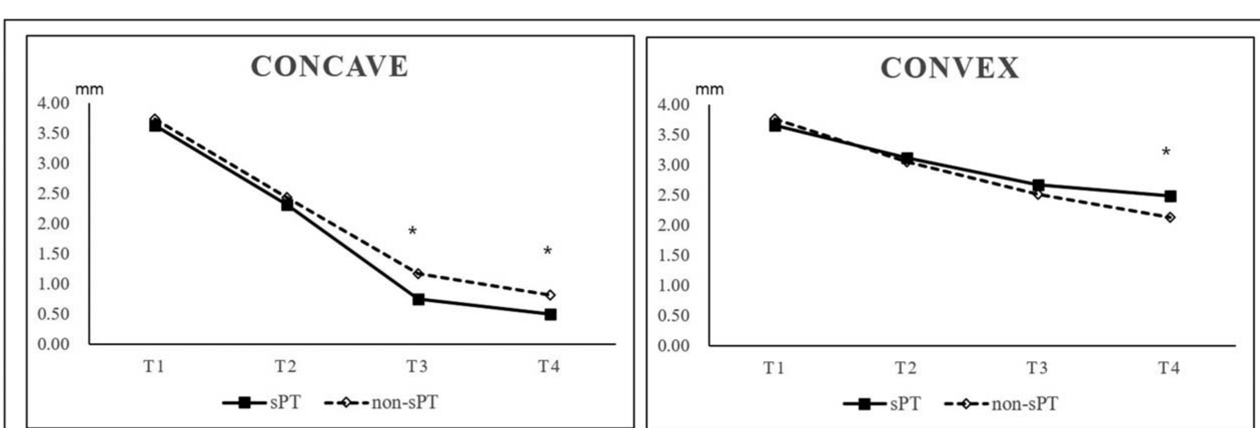

Figure 2. The pedicle diameters at the T3 and T4 vertebrae (asterisk) on the concave side are smaller in patients with a structural proximal thoracic curve, but there was no significant difference at T2 vertebrae. On the convex side, the pedicle diameter at the T4 (asterisk) is smaller in patients with a nonstructural proximal thoracic curve.

TABLE 3. Univariate Linear Regression Analysis for Variables Associated With the Pedicle Width on the Concave Side

Variable	Beta	Standard Error	*P*
Age	−0.021	0.018	0.263
Sex (Female)*	−0.546	0.252	0.030
Height*	0.022	0.009	0.013
Weight	−0.001	0.007	0.834
BMI	−0.028	0.019	0.136
Cobb angle in standing view	−0.008	0.006	0.184
Cobb angle in stress view*	−0.010	0.006	0.090
Flexibility	0.526	0.388	0.175
Vertebral body rotation*	−0.029	0.015	0.055
Vertebral body level (T1-T4)*	−1.037	0.030	<0.001
Structural proximal thoracic curve*	−0.239	0.113	0.034

*$P < 0.1$.

proximal thoracic vertebra in 182 patients with a proximal thoracic curve of more than 10° to estimate the safest pedicle screw insertion. We also compared these values between sPT and non-sPT group.

Several previous studies[12–15] that have reported the narrow pedicle diameters on the concave side of the main thoracic curve in scoliosis have also described the pedicle diameters of the proximal thoracic curve apex. Catan *et al*[12] evaluated 13 patients with a right-sided main thoracic curve and found no significant difference between the pedicle diameters on the convex and concave side from T1 to T6. However, the most common end vertebra of the main thoracic curve was T4, so it was difficult to estimate whether there was a proximal thoracic curve. Takeshita *et al*[14] reported a smaller pedicle diameter on the concave side of the curve at T2-T10 but included scoliosis cases related to other syndromes and did not separate right- and left-sided curves in the analysis. In the studies of Parent *et al*[15] and Kuraishi *et al*,[13] the pedicle diameter of the proximal thoracic vertebra on the right side was found to be smaller. However, neither study evaluated the severity of the proximal thoracic curve.

In our current analysis of adolescent idiopathic scoliosis patients with a left-sided proximal thoracic curve of more than 10°, the pedicle width on the concave side (right side) was lower than that of the convex side from T2 to T4 in both the sPT and non-sPT groups. In previous studies that have described the pedicle diameters in healthy people, the T4 vertebra was reported to show the smallest value, which then gradually increased both caudally and cranially.[4–11] These trends were also found in our current cases with a proximal thoracic curve. The pedicle width was the narrowest at T4 on both the concave or convex side in both groups and gradually increased up to T1.

The pedicle widths at the T3 and T4 vertebrae on the concave side in the sPT group were very narrow compared with those in the non-sPT group. However, the average pedicle width on the concave side was suddenly increased at T2 compared with T3. The pedicle widths at T2 on the concave side were above 2 mm in both the sPT and non-sPT groups and were not statistically different between groups. Clinically, a firm pedicle screw fixation at the UIV is very important for deformity correction and fusion. Furthermore, the T2 vertebra has been recommended as UIV by many authors in patients with a double thoracic curve for the correction of the proximal thoracic curve and the better postoperative shoulder balance.[1,3,29] We recommend T2 as the UIV in terms of both safety and optimal pedicle screw fixation when correcting the sPT.

TABLE 4. Multivariate Linear Regression Analysis for Variables Associated With the Pedicle Width on the Concave Side

Variable	Beta	Standard Error	*P*
Sex (Female)*	−0.451	0.160	0.005
Height*	0.019	0.006	<0.001
Cobb angle in stress view	0.004	0.006	0.489
Vertebral body rotation*	−0.024	0.009	0.010
Vertebral body level (T1-T4)*	−0.319	0.111	0.004
Structural proximal thoracic curve*	−1.036	0.030	<0.001

*$P < 0.05$.

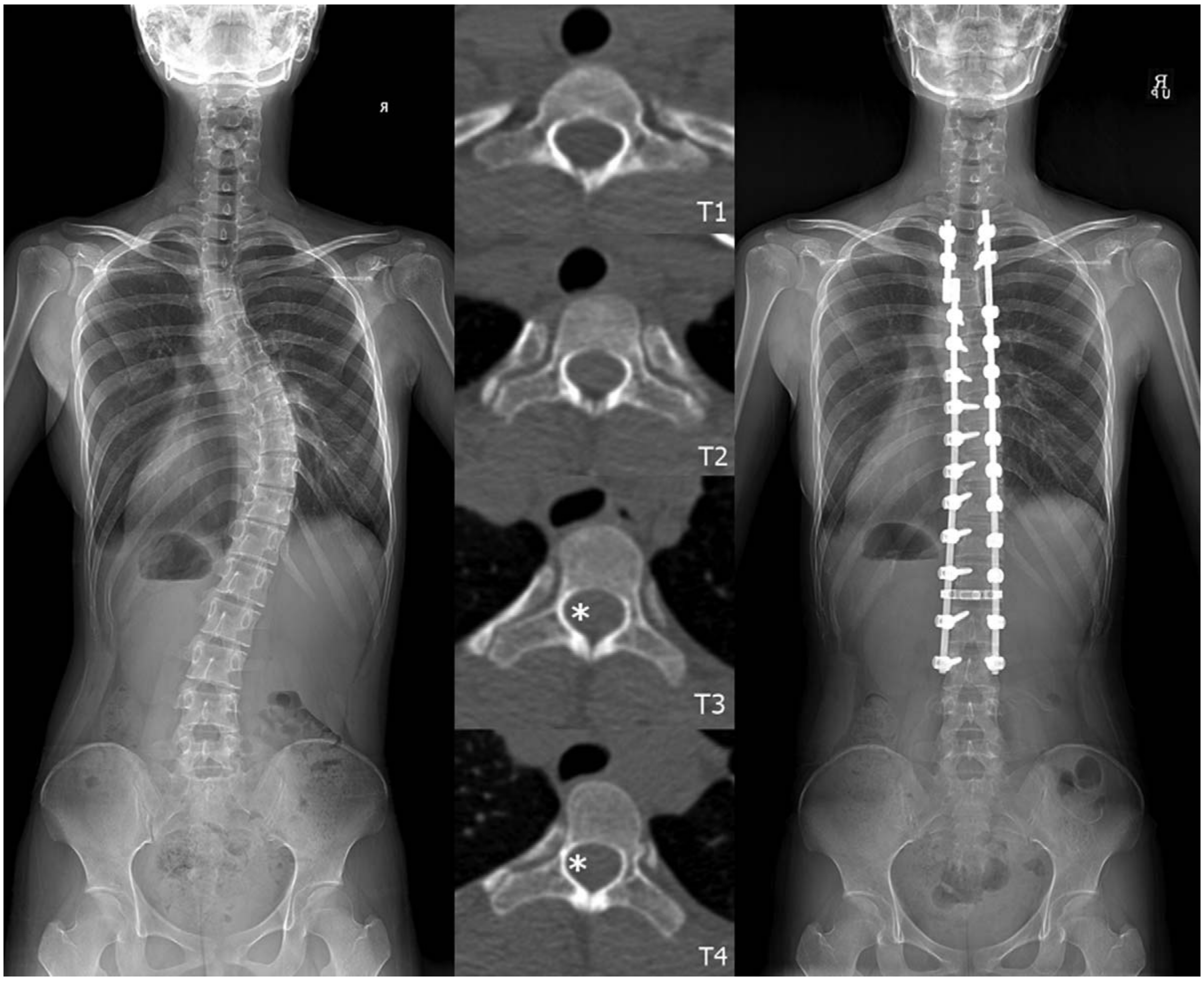

Figure 3. A 16-year-old female subject from the study cohort. She was 158.9 cm in height and has an upper thoracic curve (T1-T6) of 36° in a standing posteroanterior view and 27° in a stress view. There was no cancellous channel at the T3 and T4 vertebrae on the concave side (asterisk). Pedicle screw was not inserted at the concave side of T4 and the correction of proximal thoracic curve was achieved by compression on the convex side.

If a screw needs to be used at the small pedicle of T3 or T4 vertebrae, medial targeting or extrapedicular thoracic pedicle screw technique may be considered.[30,31] If the pedicle screw can be inserted, a screw that is larger in diameter than that of the native pedicle has been shown as the lateral expansion of pedicle and increases pullout strength.[27,32] However, pedicles without a cancellous channel at T3 and T4 on concave side were 42.0% and 55.1%. Screws placed in the extrapedicular position have only about 75% of the pullout failure load of those placed in the transpedicular position.[33] If firm pedicle screw fixation cannot be guaranteed at the apex of the scoliotic curve, the derotation technique on the concave side is not effective. We recommend compression on the concave side for the correction of the proximal thoracic curve with properly bent rod along the normal kyphosis (Figure 3).

A previous cadaver study for normal population by Cho *et al*[27] has reported that the smallest pedicles at T4 could be fractured even with the smallest diameter screws. In both groups in our study, the pedicle width of the T4 vertebra on the concave side was extremely small, suggesting that pedicle screw insertion at T4 may be very difficult and potentially dangerous even in cases of non-sPT. And also, the pedicle width at T4 on the convex side in the non-sPT group was smaller than that in the sPT group. Although there are no specific guidelines for making a UIV decision for a patient with non-sPT, the small diameter of the T4 pedicle should be considered in these cases. If the pedicle screw fixation is difficult in the selected UIV, skipped pedicle screw fixation or extrapedicular thoracic pedicle screw technique may be considered.[31,34]

We performed a multivariate linear regression analysis to identify factors related to a smaller pedicle diameter on the concave side. The patient's height was found to be positively related to the pedicle width, consistent with a previous report.[19] But, with increasing vertebral body rotation and a classification of a structural proximal thoracic curve, the pedicle width was found to be decreased. When the patient is small in height and has a structural proximal thoracic curve and more rotated vertebra, the pedicle width may be smaller from T1 to the caudal direction until T4. Several studies have indicated that asymmetrical growth of the neurocentral junctions of the vertebrae can lead to the vertebral rotation.[16,17] However, Brink *et al*[18] suggested that asymmetrical vertebral growth does not initiate rotation, but rather follows it as a secondary phenomenon. We cannot conclude definitively from our present observations that a small pedicle width is a primary or secondary phenomenon and further studies will, therefore, be needed to elucidate this.

This study had several limitations. First, we did not measure the height of pedicles. However, the pedicle width, which is taken as the smallest cross-sectional dimension, is the crucial clinical parameter that dictates the maximum pedicle screw diameter.[22,24] Furthermore, the measurement reliability has been found to be highest for the pedicle width.[22] Second, we included only Asian patients in our analysis and this may affect the general applicability of our findings. Previous studies have reported larger pedicle size in Caucasian than in Asian populations.[10,19] The pedicle width of the upper thoracic vertebrae may be larger in Caucasians than in Asians. However, there may be also a trend toward a smaller diameter at T3 and T4, and a larger diameter at T2 on the concave side in the structural thoracic curve. Third, although female sex was related to the small pedicle diameter in the linear regression analysis, only nine patients (4.9%) were male in this study. Because the idiopathic scoliosis is more common in female, the statistical limitation should be considered. We included only adolescent idiopathic scoliosis and excluded patients with congenital scoliosis or neuromuscular scoliosis. Because mechanical factors alone may be related to the pedicle diameter in adolescent idiopathic scoliosis, a similar trend in terms of pedicle size would be expected in other types of scoliosis. These will need to be explored in future studies.

CONCLUSION

The pedicle widths of the proximal thoracic vertebra are smaller on the concave side in Asian patients who have a proximal thoracic curve of more than 10°. The T4 pedicle width on the concave side is very narrow and gradually increases up to the T1 vertebra. The pedicle width at the T3 and T4 vertebrae on the concave side is more severely narrowed in patients with the structural proximal thoracic curve but suddenly widens at T2 on the concave side. When the surgeon corrects the structural proximal thoracic curve with pedicle screw instrumentation and posterior fusion, these findings should be considered. Because safe and firm pedicle screw fixation is related to the decision of the UIV or the correction method, such as the derotation and distraction-compression technique.

➢ Key Points

- ❑ The pedicle widths at T3 and T4 on the concave side for the structural proximal thoracic curves were extremely small for standard screw insertion.
- ❑ The T2 pedicle width was very wide and comparable on the concave side in structural and nonstructural thoracic curve.
- ❑ These findings should be considered when the surgeon correct the structural proximal thoracic curve by pedicle screw instrumentation and posterior fusion.

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