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Pedicle Morphology Using CT-based Navigation System in Adolescent Idiopathic Scoliosis

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Manuscript text

Introduction

Pedicle screw fixation, first described by Boos and Webb [1] in 1959 and popularized by Roy-Camille et al. [2,3] in the 1960s, has become one of the most widely used fixation techniques in spinal surgery. The technique makes use of the pedicle, which is in terms of biomechanics, the hardest part of the vertebra, as an anchor for the fixation device, enabling improved correction and maintenance of spinal deformities [1,4]. However, narrow pedicles in scoliotic patients pose a risk of injury to the spinal cord, nerve root, and aorta caused by the screw perforating the pedicle [5,6,7,8,9].

The majority of studies on pedicle morphology in patients with adolescent idiopathic scoliosis (AIS) have used two-dimensional (2D) analysis by magnetic resonance imaging (MRI) or computed tomography (CT) [6,10,11,12]. To our knowledge, the present study is the first to evaluate pedicle morphology in AIS populations by multidimensional analysis using a CT-based navigation system. The purpose of this study was to use multidimensional analysis based on a CT-based navigation system to measure the outer cortical diameter of the pedicle and the maximum screw trajectory length of the pedicle of the thoracic and lumbar spine of AIS patients. Another objective was to identify the pedicles that require cautious insertion of pedicle screws.

Materials and Methods

Fifteen patients with right-side thoracic AIS who underwent pedicle screw fixation between March 2006 and March 2008 were studied. A total of 10 curves were classified as type 1, 2 curves as type 2, and 3 curves as type 3, according to the system of Lenke et al. [13]. A total of 255 vertebrae (510 pedicles) were investigated. The sample of patients included 14 girls and 1 boys, with a mean age of 14.1 ± 1.9 years (mean ± S.D.; range = 11–17 years). The mean Cobb angle of the main curve was 63.6 ± 15.8 degrees (range = 43–100).

The CT-based navigation system used was a Stealth Station® TREON® plus (Medtronic, Sofamor Danek, Memphis, TN, USA) surgical navigation system. Pedicle screws were placed in optimal positions using the CT-based navigation system. Lenke's [14] method was used to determine the insertion point of the screw. The pedicle diameter was measured as the widest outer cortical diameter at the narrowest part of the pedicle between T1 and L5. The maximum pedicle screw trajectory length was measured as the distance between the posterior cortical entry point of the pedicle screw and the anterior vertebral cortex in line with the axis of the pedicle. From the various techniques available for pedicle screw placement, we chose the straightforward technique because of its prevalence and its biomechanical superiority over the anatomic technique [15] (Figure 1).

The values obtained for the parameters measured using the CT-based navigation system and standard axial CT were compared to evaluate the validity of multidimensional analysis by a CT-based navigation system. Preoperative standard axial CT with a slice thickness of 1.25 mm was performed in the axial section through the entire spine. All CT files were analyzed using a DICOM viewer program (ExaView LITE; Ziosoft, Tokyo, Japan). All parameters were measured by the first author (S.K.), who was a neutral party. Window level and diameter were optimized for the measurement of bony structure [16]. Two parameters of diameter, length on both sides of the pedicle were measured for each vertebra. Each section of the image was not always parallel to each intervertebral space. We chose the optimal slice wherein an insertion point and direction were determined to get the largest diameter of a screw in every vertebra. We measured the diameter in the transverse plane as the length from the insertion point to the tip of the simulated screw (Figure 2).

We selected the screws based on data obtained using the CT-based navigation system and postoperatively evaluated whether the screws used were suitable for the pedicles. To evaluate the length of the inserted screws, we measured the length of the screws placed and determined the exact length that would have been needed to reach the far cortex in the postoperative CT scan and compared those data.

To evaluate the diameter of the inserted screws, we measured screw positions by postoperative CT._The screw position was evaluated 1 week after the operation using an axial CT scan at each screw axis. Following Rao et al. [17], the evaluation of screw malposition was classified as Grade 0 (no apparent violation of the pedicle), Grade 1 (<2 mm perforation of the pedicle, with 1 screw thread outside of the pedicle), Grade 2 (between 2 and 4 mm perforation of the pedicle, with half of the diameter of the screw outside of the pedicle), or Grade 3 (>4 mm or complete perforation of the pedicle), with Grades 2 and 3 representing “violation.” On the basis of this grading system, screw misplacement rates were determined. Medial or lateral perforation of the pedicle wall was also evaluated.

Paired *t*-tests were performed using Stat View (SAS Institute, Cary, NC, USA). Means and standard deviations were calculated, and the statistical significance was set at $p < 0.05$.

Results

Mean pedicle diameter

Mean pedicle diameter is summarized in Table 1. On the left side, the diameters decreased successively from T1, with the smallest value at T7 (4.17 ± 0.78 mm), then increased from T8 to T12. Diameters also decreased from L1 to L2, then increased from L3, reaching the maximum at L5 (9.61 ± 1.33 mm). On the right side, pedicle diameter decreased from T1, with the smallest value at T4 (3.73 ± 0.41 mm), then increased from T5 to T12. Diameters decreased at L1 and increased again from L2, reaching the maximum at L5 (9.50 ± 1.50 mm). A mean pedicle diameter less than 4.5 mm was observed at T3, T4, and T5 on the right side, and at T6, T7, T8, and T9 on the left side. The smallest thoracic pedicle screw diameter that can be used in Japan is usually 4.5 mm. Significant differences were observed on the opposite side at T3, T4, and T5 on the right side, and at T8 and T9 on the left side ($p < 0.05$; Table 1). On the right side, the mean pedicle diameters of T3 and T4 candidates for upper-instrumented vertebrae were less than 4.0 mm, and thus, screw fixation was difficult. In summary, the pedicles on the concave side of the main thoracic curve apex and the proximal thoracic curve apex had significantly narrow diameters ($p < 0.05$).

The mean pedicle diameter as measured by the CT navigation system and standard axial CT is summarized in Figure 3. The mean pedicle diameter measured by the CT navigation system was larger than that measured by standard axial CT, except for both sides of T11, T12, and L5 and the left side of L3 and L4. Significant differences were observed as follows: right side, T3 ($p = 0.0009$), T4 ($p = 0.000054$), T5 ($p = 0.0013$), and T7 ($p = 0.039$); left side, T4 ($p = 0.033$), T5 ($p = 0.03$).

Mean maximum pedicle screw trajectory length

The mean lengths of the longest pedicle screw trajectories are summarized in Table 2. The mean screw lengths were longer on the right side, except for T8 and T9, but the difference was not statistically significant. The screws gradually became longer from the cranial thoracic spine to the caudal lumbar spine. Screw size feasibility was as follows: screws between 25 mm and 30 mm were feasible from T1 to T5, screws between 30 mm and 35 mm were feasible from T6 to T12, and screws between 35 mm and 40 mm were feasible from L1 to L5.

On the left side, all pedicle screw trajectory lengths measured by the CT navigation system were significantly shorter than those measured by standard axial CT: T1 ($p = 0.00024$), T3 ($p = 0.010$), T4 ($p = 0.0043$), T6 ($p = 0.010$), L1 ($p = 0.0010$), L2 ($p = 0.0009$), L3 ($p = 0.0051$). As for the right side in thoracic vertebrae, the pedicle screw lengths measured by the CT navigation system, except for T3, were longer than those measured by standard axial CT, and a significant difference was observed for T7 ($p = 0.019$); in lumbar vertebrae, the pedicle screw lengths measured by the CT navigation system were shorter than those measured by standard axial CT, and a significant difference was observed for L2 ($p = 0.025$; Figure 4).

Postoperative assessment of screw placement

The appropriateness of the length of the screw used for surgery was evaluated. The mean difference between the length of the pedicle measured by the CT navigation system and the length of the screw used was 2.3 ± 5.0 mm. This implies that the distance from the tip of the screw to the bone cortex in the direction of screw insertion should be 2.3 mm when the screw is correctly and fully inserted. However, postoperative measurement of the mean distance from the tip of the screw to the bone cortex in the direction of screw insertion by CT resulted in a value of 6.7 ± 4.3 mm. The difference (about 4.4 ± 6.0 mm) between the theoretical value (2.3 mm) and the actual value (6.7 mm) resulted from insufficient insertion of the screw. The values calculated by subtracting the length of the screw used from the pedicle length measured by the CT navigation system on the right and left sides were 3.2 ± 4.7 mm and 1.4 ± 5.1 mm, respectively, showing a significant difference ($p = 0.0076$). These results show that on the left side, the length of the screw selected based on data from the CT navigation system was closer to the pedicle length measured by the same system. However, the distance between the screw tip and the cortical bone as measured by postoperative CT showed no significant difference between the right and left sides. The distance of insufficient screw insertion (actually inserted length of screw - [pedicle length as measured by the navigation - distance from the screw tip to the cortical bone of anterior vertebrae]) was 3.8 ± 5.9 mm and 5.2 ± 5.8 mm, respectively, on the right and left sides; thus, the left side showed a statistically greater tendency for insufficient screw insertion ($p = 0.044$). It is possible that this insufficient insertion on the left side resulted from the fear of arterial injury. A total of 7 of the 215 screws (3.3%) perforated the anterior cortex on the right T1, T5, T12, and L1 and on the left T1, T12, and L1.

The perforation rate was measured to evaluate the appropriateness of the used screw diameter. Of the 215 pedicle screws, 164 (76.3%) were categorized as Grade 0, 47(21.9%) as Grade 1, 3 (1.4%) as Grade 2, and 1 (0.5%) as Grade 3 (Figure 5). All medial perforations of Grade 2 or more were on the right side (T6, T7, and T9). Only 1 Grade 3 screw was seen in a right T9 pedicle. Pedicle violation was observed in 1.9% (4/215) of the inserted screws. Lateral screw perforation was as follows: right side, T3, T4, T5, T12, L1, and L3, and left side, T11 and T12. No intraoperative complications such as neurovascular injury or adverse clinical consequences occurred because of pedicle perforation.

Discussion

The study of pedicle morphology for screw placement in scoliosis is important because screw misplacement results in lower pullout strength and could cause serious complications including nerve, blood vessel, or visceral injury [5,6,7,8,9]. Multiple reports of using pedicle measurement to identify the morphology of AIS [10,11,12,18,19] have been made, but these used 2D analysis by CT or MRI. Parent et al. [12] measured and compared normal and scoliotic pedicle morphology by fixing each vertebral body to a frame and reconstructing the 3D image by plotting the vertebrae using a 3D digitizer. Their results showed significantly narrower scoliotic pedicles on the concave side of the main (T8) and proximal (T4) thoracic curves compared to the normal vertebrae. They suggested that pedicle screw insertion for scoliotic patients in the apex of the curve on the concave side should be avoided. Similarly, Liljenqvist et al. [10] measured scoliotic vertebrae by MRI and reported narrower pedicles on the concave side in the apex region of the main thoracic curve (T7–T10) than the convex side.

Takeshita et al. [20] reported on the diameter, length, and direction of pedicle screws by multiplanar reconstruction of CT for various conditions of Japanese scoliotic spine. To our knowledge, the present study is the first to use multidimensional analysis based on a CT-based navigation system to evaluate pedicle morphology only in AIS patients. The results of this study show that the narrowest mean pedicle diameters were observed at T7 and T4 on the left side and right side, respectively. In the study by Takeshita et al. [20] 62% of the concave T3–T9 screw diameters were less than 4 mm, and 37% of these pedicles did not hold the 4-mm diameter screw even with 25% expansion. These results indicate that the pedicles on the concave side of the main thoracic curve apex and proximal thoracic curve apex have significantly narrow diameters, consistent with previous reports (Table 3). These results highlight the necessity of practicing caution when inserting pedicle screws on the concave side of the main and proximal thoracic curve, and suggest that extrapedicular screws should be considered in the preoperative plan if pedicle screw insertion is judged to be difficult.

Extrapedicular screw placement has been advocated as a safe and effective option to the thoracic transpedicular screw [15,21]. However, screws placed in the extrapedicular position have about 75% of the pullout failure load of those placed in the transpedicular position [22,23]. These concerns emphasize the value of using a CT navigation system to measure pedicle diameter for transpedicular screw insertion. Although the powerful corrective force and maintenance of segmental pedicle screws is fascinating, surgeons need not always use pedicle screws. They can use other anchoring methods like hooks, wires and polyethylene cables, when preoperative evaluation reveals narrow pedicles that are not appropriate for pedicle screw placement.

Under such conditions, the anatomic trajectory technique could be the technique of choice, although the screws placed by the anatomic trajectory are biomechanically weaker than those placed by the straightforward trajectory. However,Takeshita et al.[20] found that pedicles too narrow for the straightforward technique generally had impracticable results for the anatomic technique as well.They did not try to simulate the anatomic trajectory because simulation of screw placement would have been too complicated, and they concluded that future analysis of the feasibility of using the anatomic trajectory is warranted.

Parent et al. [12] reported distinct technical limitations of 2D analysis by CT or MRI in terms of obtaining sectional images of the narrowest pedicle levels in the vertebrae. They also suggested the necessity of 3D evaluation of scoliotic change to avoid large measurement error caused by slight changes of image. They measured pedicles by 3D reconstruction of vertebrae by plotting fixed individual vertebrae using a 3D digitizer. However, the reconstructed image obtained was irregular.

Liljenqvist et al. [10] stated that CT could control table position only in the direction of the sagittal axis, and that table adjustment along the axis of the coronal plane is not possible. This limitation could cause skewing of vertebral image sections except for in the apex region, resulting in error in measurement.

We compared the diameters and lengths of the pedicles as measured by the CT navigation system and preoperative standard axial CT. The pedicle diameter measured by the CT navigation system was larger than that measured by standard axial CT. Thus, the use of a navigation system could make screw insertion feasible even when evaluation by standard CT judges screw insertion to be impossible. The pedicle length measured by the CT navigation system was shorter on the left side and longer on the right side, compared to that measured by standard CT. This is because of the technical limitations of standard axial CT, and the tilting or rotation of the vertebrae could be the cause. Standard axial CT possibly results in the preoperative selection of a smaller screw diameter, and on the left side, a longer screw length. Because the artery is located on the left side, screw length selection based on standard axial CT carries a higher risk of injury to the artery than selection based on the CT navigation system.

Catan et al. [11] measured the morphology of scoliotic pedicle by MRI, and reported that MRI could not clearly describe the structure of the cortical bone. In our study, the pedicle diameter tended to be wider than in other studies (Table 3). The mean pedicle diameter on the concave side of the main thoracic curve has been reported as follows: 3.8 mm (T6) by Parent et al. [12], 2.5 mm (T8) by Liljenqvist et al. [10], 2.6 mm (T9) by Thomas et al. [19], 4.3 mm (T5, T6, T7) by Catan et al. [11], and 4.0 mm (T3–T9) by Takeshita et al. [20].

The clinical application of 3D computer-assisted surgery has significantly reduced the rate of screw misplacement [1,8,22,23,24,25,26]. Clinical studies have demonstrated an improved accuracy in pedicle screw insertion because of the use of a CT-based navigation system, which eliminates exposure to fluoroscopic radiation. Kotani et al. [5] evaluated the accuracy of pedicle screw placement in posterior scoliosis surgeries with and without the use of computer-assisted surgical techniques. They showed that perforation was observed in 11% of cases without the use of computer-assisted surgical techniques and 1.8% of cases with the use of such techniques. We predicted screw diameter and length from the preoperative plan with the CT navigation system, and the rate of Grade 2 or more perforation (4 right pedicles; levels T6, T7, and T9) was 1.9%. In our department, pedicle insertion on the left and right sides is performed by a senior surgeon (J.T.) and fellows, respectively, and thus, the occurrence of perforation could be related to the learning curve of the surgeon. The absence of left medial perforation of the thoracic vertebrae indicates the value of the CT navigation system.

In our study, the pedicle diameters were wider than those found in previous studies. This is possibly because the previous studies used 2D analysis, which could not obtain accurate sectional planes, whereas the multidimensional analysis based on CT-based navigation used in the present report enabled screw insertion in favorable directions. Pedicle screws were placed in optimal positions by using the CT-based navigation system. However, the reported pedicle diameters found by Takeshita et al. [20] by using multidimensional analysis based on CT-based navigation were narrower compared to our data, resulting from the inclusion of syndrome-related scoliosis cases in the study by Takeshita et al.

Finally, in this study, the feasible screw length tended to be between 25 mm and 30 mm from T1 to T5, between 30 mm and 35 mm from T6 to T12, and between 35 mm and 40 mm from L1 to L5. These results could be used as an indicator for screw length selection. Takeshita et al. [20] reported that 11% of the convex T4–T8 diameters were 25 mm or less, and required careful screw insertion.

In conclusion, the pedicle diameter in patients with AIS is narrower on the concave side of the scoliotic curve, and therefore, caution should be exercised when inserting screws on this side. A wider angle and trajectory selection of screw insertion achieved by multidimensional analysis with a CT-based navigation system resulted in wider pedicle diameter values, compared to the previous studies that used 2D analysis systems.

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Figure Legends

Figure 1. Screen image of Stealth Station® TREON® plus during measurement

Figure 2. Illustration of a thoracic vertebra showing the pedicle length (AC) and the transverse pedicle diameter (DE)

Figure 3. Comparison of mean pedicle diameter as measured by the computed tomography (CT) navigation system and standard axial CT

Diameters measured by the CT navigation system were larger than those measured by standard axial CT, except for both T11, T12, and L5 and left L3 and L4. $p < 0.05$*, $p < 0.01$**, $p < 0.001$***.

Figure 4. Comparison of mean pedicle trajectory length as measured by the computed tomography (CT) navigation system and standard axial CT

On the left side, all pedicle lengths measured by the CT navigation system were shorter than those measured by standard CT. On the right side, the pedicle lengths measured by the CT navigation system in the thoracic and lumbar levels were longer and shorter, respectively, than those measured by standard axial CT. $p < 0.05$*, $p < 0.01$**, $p < 0.001$***.

Figure 5. Actual screw position of each vertebral level

Table (No Excel Files! Submit all tables as MS Word doc!)

Table 1. Mean pedicle diameter and comparison between left side and right side

Level	Left (mm)	Right (mm)	p value
T1	5.81±0.89	5.79±1.06	n.s.
T2	5.15±0.74	5.02±0.84	n.s.
T3	4.85±0.44	3.87±0.59	p<0.01
T4	4.65±0.44	3.73±0.41	p<0.01
T5	4.79±0.59	4.09±0.76	p<0.01
T6	4.45±0.59	4.62±0.89	n.s.
T7	4.17±0.78	4.77±0.75	n.s.
T8	4.28±0.73	5.07±0.86	p<0.05
T9	4.29±0.81	5.24±0.68	p<0.01
T10	4.96±1.05	5.26±0.84	n.s.
T11	6.13±1.45	6.27±1.19	n.s.
T12	6.34±1.22	6.45±1.62	n.s.
L1	5.87±1.22	5.79±1.10	n.s.
L2	5.65±0.94	6.16±0.90	n.s.
L3	7.05±1.21	7.38±1.16	n.s.
L4	8.37±1.18	8.42±1.23	n.s.
L5	9.61±1.33	9.50±1.50	n.s.

(shaded): Mean pedicle diameter was less than 4.5mm

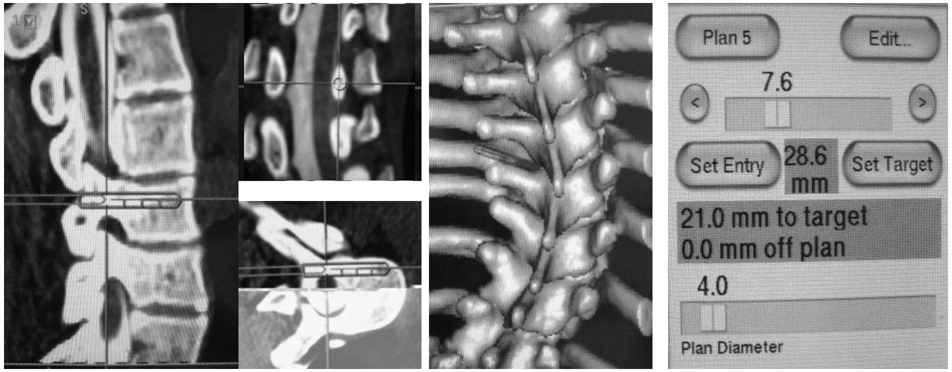
Table 2. Mean maximum pedicle screw trajectory length

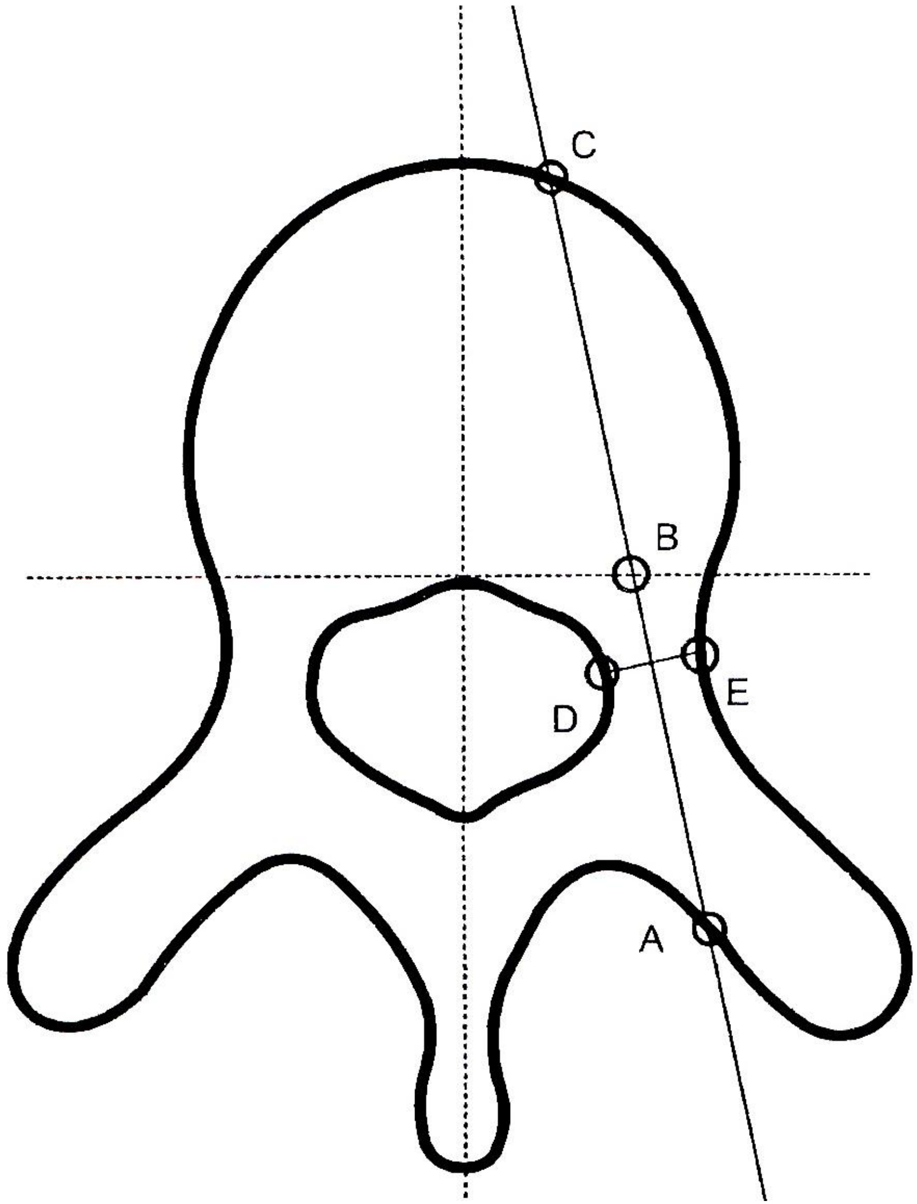
Level	Left (mm)	Right (mm)	p value
T1	24.98±3.73	25.71±3.44	n.s.
T2	28.55±3.21	31.45±3.46	n.s.
T3	28.35±2.46	31.89±3.18	n.s.
T4	28.26±2.60	33.93±3.22	n.s.
T5	29.31±3.32	34.94±4.53	n.s.
T6	30.23±5.06	35.23±5.06	n.s.
T7	30.99±4.47	34.67±3.89	n.s.
T8	34.23±4.86	33.03±5.34	n.s.
T9	35.33±4.05	34.79±4.15	n.s.
T10	34.47±4.67	34.89±4.03	n.s.
T11	31.30±4.64	34.15±4.82	n.s.
T12	33.93±7.45	35.45±4.80	n.s.
L1	36.63±5.31	40.35±6.95	n.s.
L2	39.06±4.08	42.10±3.60	n.s.
L3	40.05±4.24	43.22±4.49	n.s.
L4	41.17±5.00	42.09±3.07	n.s.
L5	39.70±5.09	41.16±4.30	n.s.

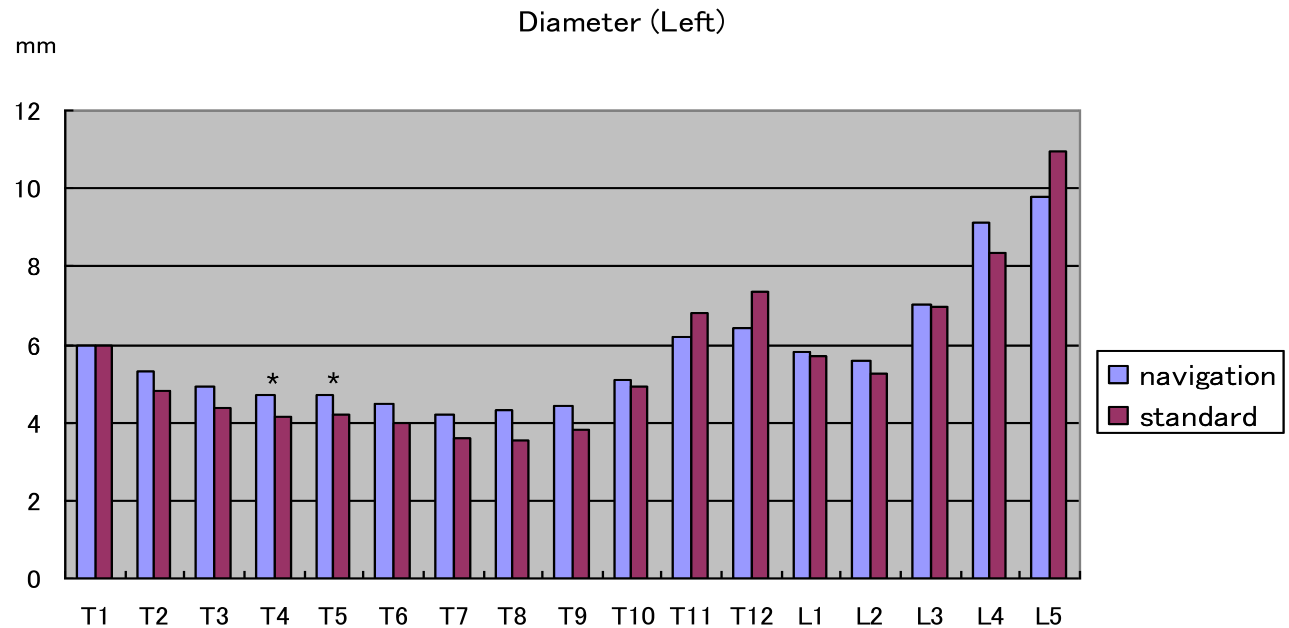
Table 3. The reports of the mean thoracic pedicle diameter (mm)

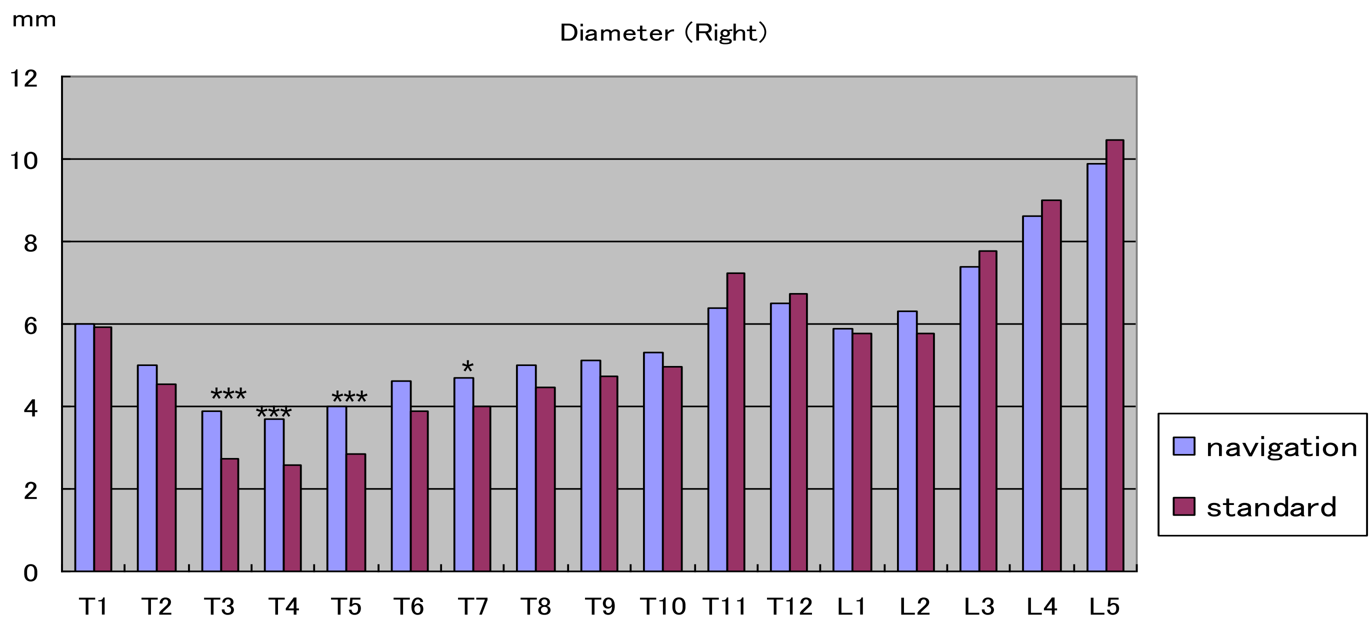
	Parent et al.		Liljenqvist et al.		Thomas et al.		Catan et al.		Takeshita et al.		Our study	
	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
T1	6.7	6.8					5.1	4.8	6.0	6.3	5.8	5.8
T2	5.0	4.7					4.7	4.9	4.9	5.5	5.2	5.0
T3	4.3	3.2					4.4	4.4	3.3	4.7	4.9	3.9
T4	4.0	2.6					4.5	4.5	2.7	4.3	4.7	3.7
T5	4.0	3.6	3.1	3.7	4.6	3.5	4.3	4.5	3.0	4.5	4.8	4.1
T6	3.8	4.7			4.5	4.8	4.3	4.6	3.5	4.4	4.5	4.6
T7	4.0	5.2	3.1	4.1	3.7	5.7	4.3	4.7	3.7	4.6	4.2	4.8
T8	4.0	5.2	2.5	4.2	3.4	6.4	4.4	4.7	3.8	4.6	4.3	5.1
T9	4.9	5.4	3.3	4.2	2.6	6.1	5.1	4.8	4.1	4.9	4.3	5.2
T10	5.8	6.1	4.2	5.0	2.6	7.8	5.0	4.9	5.2	6.0	5.0	5.3
T11	7.2	7.6	5.4	5.7	3.4	8.0	5.2	5.7	6.7	7.2	6.1	6.3
T12	7.2	7.1	5.2	5.9	5.0	7.2	5.7	5.9	6.8	7.1	6.3	6.5

Figure (TIF or EPS Only!!! Resolution of at least 300 dpi!)

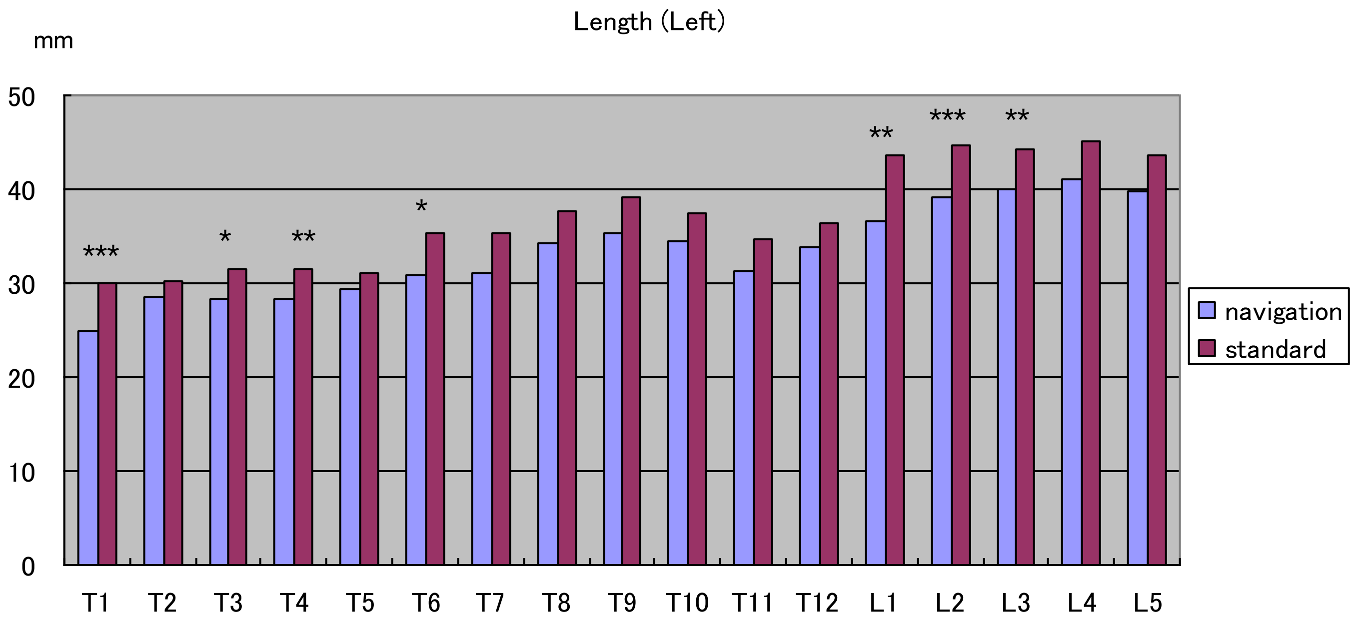


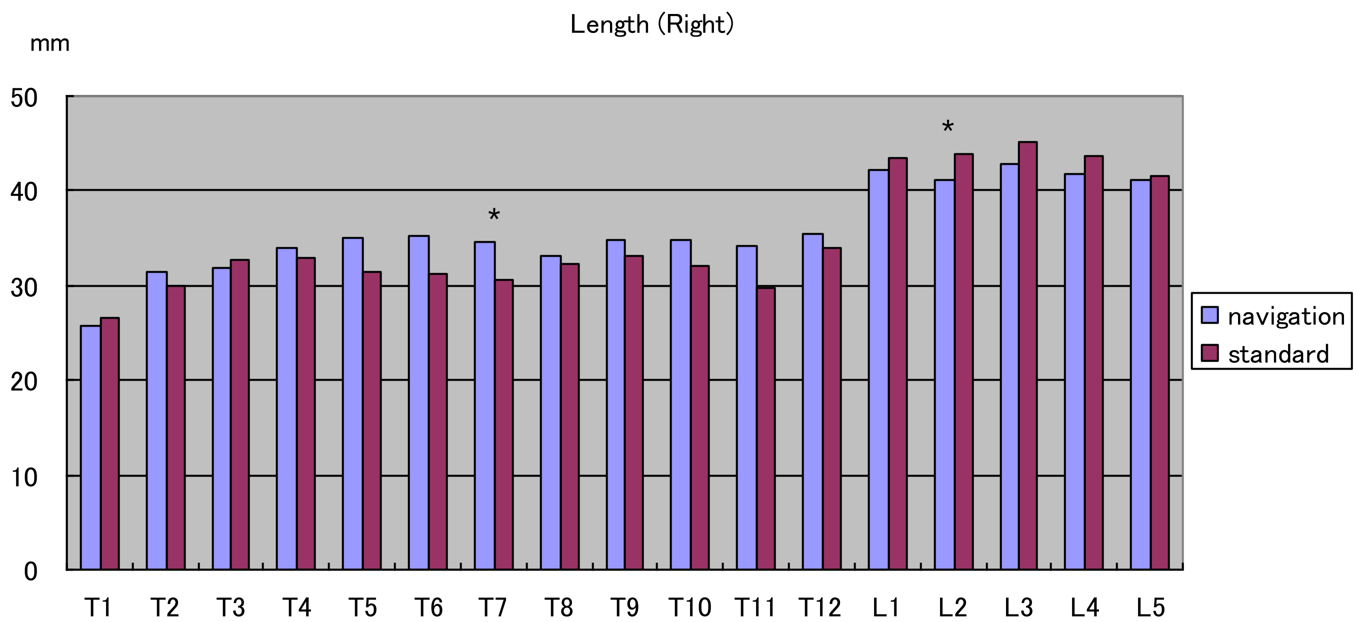

C
B
D
E
A


Diameter (Left)
mm
12
10
8
6
4
2
0
*
*
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
T12
L1
L2
L3
L4
L5
navigation
standard

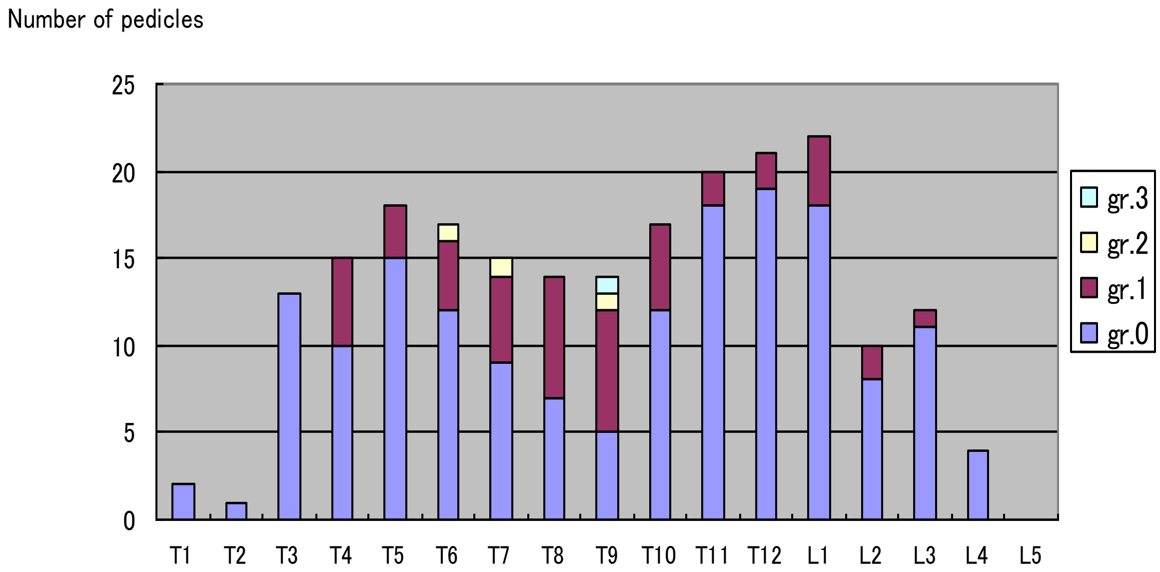

mm
Diameter (Right)
12
10
8
6
4
2
0
***
***
***
*
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
T12
L1
L2
L3
L4
L5
navigation
standard

* p<0.05, ***p<0.001





* p<0.05, **p<0.01, ***p<0.001



Number of pedicles
25
20
15
10
5
0
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
T12
L1
L2
L3
L4
L5
gr.3
gr.2
gr.1
gr.0