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***In-Vivo* Three-Dimensional Morphometric Analysis of the Lumbar Pedicle Isthmus**

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Introduction

Pedicle screw instrumentation in the lumbar spine has become the standard method of stabilization for a variety of spinal disorders such as fractures, spondylolisthesis and scoliosis.^{1, 2} Pedicle screws allow short segment fixation and relatively rigid fixation. However, complications associated with pedicle screw instrumentation may include misplacement, pedicle wall fracture, loss of fixation, screw loosening, neurovascular injury, etc.^{3–6} According to the literature, 2.4% of pedicle screw fixation procedures were associated with complications related to the use of pedicle screws.⁷ More accurate knowledge of pedicle morphology and accurate measurement of the pedicle dimension in patients undergoing pedicle screw instrumentation is crucial.

Anatomically, the cross-section of the lumbar pedicle is elliptical and medially angulated in the lower levels.^{8,9} This unique pedicle shape at the lower lumbar levels is not accurately assessed by two-dimensional (2D) planar CT images. Cross-sectional dimensions by 2D CT images may give falsely larger measurements than the actual isthmus dimensions and may contribute to inappropriate pedicle screw insertion.¹⁰

The morphometry of lumbar pedicles has been reported in several articles. Some authors performed direct pedicle measurements^{11–17} on cadaveric spines using calipers and goniometers, others collected measurements on CT images,^{9,10,18–22} and lately direct measurements on planar radiographic image⁸ and combined data on CT, calipers and planar radiographic image were obtained.^{23–27} To the best of our knowledge, there has been no report of *in-vivo* measurement of the human lumbar pedicle three-dimensional (3D) geometry based on the 3D CT model in the literature. The objective of the present study was to obtain 3D geometrical dimensions of the lumbar pedicle isthmus using a novel *in-vivo* CT-based 3D measuring technique, and to compare with the data measured by 2D transverse CT images.

Materials and Methods

One hundred and five volunteers participated in this study (IRB approved) and each subject signed an approved informed consent form. Sixteen volunteers were excluded from further analysis due to spondylolisthesis, spondylolysis, sacralization, lumbarization and malformation of vertebrae. In consequence, a total of 89 subjects (46 males and 43 females, age range 23–59 years, mean $\pm$ SD: 36.5 $\pm$ 10.0 years) were used for the analyses. Three-dimensional vertebral surface models of L1–L5 were created from CT images (Volume Zoom, Siemens, Malvern, PA). The 1.0-mm-thick axial slices from the CT scanner were imported

into a 3D reconstruction software package (Mimics, Materialise Inc., Leuven, Belgium), where a threshold level to define the cortical shell was selected. Each vertebral body was segmented based on the threshold level.²⁸ A point-cloud data-set for each vertebral body was also created using the 3D software package. To determine an isthmus of each pedicle, a custom software program was created in Microsoft Visual C++.2005 with Microsoft Foundation Class (MFC) programming environment (Microsoft Corp., Redmond, WA). Two points were set at approximately centers of anterior and posterior ends of the tubular pedicles in 3D space. Along this axis line, pedicle cross sections were determined at approximately 0.5 mm intervals. A spherical coordinate system was centered at each intersection point of the line and the cross sections (Point O), which served as pivot point for a virtual cone with a vertex angle of 10° (Fig. 1). It was rotated 360° about the point O in 10° increments and the points with least distances within the cone were chosen as boundary points of the cross-section of the pedicle. For each cross section, the least axis and the longest axis were calculated. (Fig. 2) The least axis was determined by the line which connected 2 points with the shortest distance and cross near the Point O. The cross-section having the least axis was defined as the isthmus. The least axis and the longest axis in the isthmus were defined as Least Axis of Pedicle (LEAP) and Longest Axis of Pedicle (LOAP) (Fig. 2 and Fig. 3, respectively). To show the differences caused by using planar images, the largest width of the pedicle in the transverse plane (Transverse Plane Width: TPW) was measured in a plane transverse CT image and used to compute the LEAP/TPW ratio (Fig. 3). The angle between the LEAP and a transverse plane of each vertebral body was defined as the Isthmus Angle (IA) (Fig. 4). The transverse plane was defined by the plane perpendicular to the posterior wall of each vertebral body which was determined by eigenvectors of the posterior wall²⁹ (Fig. 4). These parameters were compared among levels and ages with ANOVA and Fisher's *post-hoc* tests. Comparison between the genders was done by unpaired *t*-tests. The LEAP and TPW were compared by paired *t*-tests. Significance level was set at $p < 0.05$. Results are presented as mean $\pm$ standard error of the mean (SEM).

Results

The male subjects showed higher LEAP or smallest effective outer diameter at all levels compared with female subjects. LEAP gradually increased with lower levels in both genders. (Fig. 5) Similarly, the male subjects showed higher LOAP at all levels. LOAP also increased with lower levels in both genders. While the LOAP showed similar values among L1~L4, the values at L5 were pronouncedly higher compared with other levels. The values of LOAP at L5 were 125 ~ 131% higher in male and 126 ~ 136% higher in female compared to other levels. (Fig. 6) The Isthmus Angles at L1 and L2 were almost parallel to the transverse plane but increased pronouncedly at L3, L4, and L5. The female subjects showed higher Isthmus Angle at L5 compared with male subjects (Fig 7).

Transverse Plane Width (TPW) measured in the transverse CT planes showed a similar pattern as the LEAP. The male subjects showed higher values at all levels ($p < 0.001$). TPW was higher than the LEAP at each level. While the LEAP/TPW ratio at L1, L2 and L3 showed similar values, the ratio at L4 was lower than those at upper levels ($p < 0.0001$) and that at L5 was lower than those at all other levels ($p < 0.0001$) (Table 1).

Discussion

The transpedicular screw fixation technique pioneered by Roy-Camille² has become the standard procedure for posterior spinal instrumentation world-wide. In order to acquire rigid fixation, precise measurement of the pedicle isthmus and selection of proper size screws are crucial. There are several factors that contribute to the biomechanical strength of pedicle screw constructs such as screw length, diameter, thread design, bone quality, etc. An increase in

pedicle screw diameter has been shown to be a major factor that increases pull-out strength.²⁴ Hence, the ideal pedicle screw diameter should be the largest possible. Pedicle morphometry has been reported in a variety of ways in the literature, but to the best of author's knowledge, this study is the first to describe *in-vivo* 3D measurements using clinically available CT images.

Several studies measured the 3D dimensions of the lumbar pedicles on cadaveric lumbar spines and determined the least diameter of the pedicle. Robertson and Stewart⁸ determined the outer contour of the pedicle isthmus by wrapping fine and malleable wires tightly against the outer border of the pedicle of the cadaveric lumbar spines and measured the dimensions of the pedicle isthmus using coaxial radiographs taken in the perpendicular plane to the pedicle axis. Several studies determined the least diameter of the pedicle by direct measurement of the cadaveric lumbar spines using vernier calipers.^{11–17} The measurement using the caliper allows finding the largest and narrowest diameters of the pedicles by physically changing location and orientation of the caliper. However, the measurement of the least diameter of the pedicle using vernier calipers may overestimate the dimension due to difficult access to the anatomical landmarks of the pedicles with complex 3D geometry, especially at L5, in which mechanical measurement uses parallel “outside jaws” of the vernier calipers for more angulated non-parallel pedicle geometry. Moreover, it is obvious that these measurements can not be applied *in vivo*.

In the previous cadaveric studies, diameter of the least axis of pedicle (LEAP) increased towards the lower lumbar levels.^{8,11–17,24} This result is consistent with the result in the current *in vivo* study although slight differences were seen in the lower level. Lien *et al* measured dimensions of the pedicle using the vernier caliper and reported greater least axis of pedicle at L5 compared to those in the current study.¹⁶ In a 2D radiographic study, Olsewski *et al* also reported greater pedicle dimensions in lower level, in an outcome similar to our results.²⁶ When using 2D planar images, the increased value of the pedicle dimension could be in part due to the non-parallel inclination of the least axis of pedicle, particularly in the lower lumbar spine.

In the present study, the values of the longest axis of pedicle (LOAP) were greater than those of the least axis of pedicle at all levels and increased toward the lower levels. In upper levels, the values of the longest axis of pedicle measured in the present study were within the same range as those reported in the previous studies.^{8,10,17,30} However, Olsewski *et al* showed lower level values smaller than our results.²⁶ Lien *et al*, Kadioglu *et al* and Zindrick *et al* also reported that the longest axis of pedicle decreased at the lower levels and L5 showed the smallest values.^{16,23,27} Since the pedicle inclination was greater at the lower levels especially at L5, the pedicle height dimension may be measured falsely smaller when the height is measured in the sagittal plane without considering its inclination.

According to Robertson *et al*⁸ and Seranan *et al*⁹, pedicle cross-sectional morphology can be assumed to be elliptical and it becomes oblique to the vertical plane with each successive inferior level. The results of the current study agree with their data. In the current study, the Isthmus Angle increased pronouncedly at L4 and L5, whereas L1 and L2 were almost parallel to the transverse plane. (Fig 8) These results indicate that the least axis of pedicle isthmus especially at L4 and L5 does not exist on the anatomical transverse plane. Therefore, the measurement of the pedicle width using the coronal section has been reported to be more suitable compared with the transverse plane, especially in the lower lumbar levels.^{9,10} However, the anatomical coronal section is not always perpendicular to the pedicle axis, especially at lower levels, and determination of perpendicular planes of the pedicle axis itself would be difficult. The method developed in the current study automatically searches the least diameter of the pedicle in the 3D space throughout the pedicle length and the least diameter of the pedicle measured in this way represents the true least axis in the pedicle.

The transverse CT images are commonly used for the measurements of the pedicle width in the clinical setting at the present time. Therefore, the present study also measured the pedicle diameter in the transverse plane (Transverse Plane Width, TPW) and the pedicle diameter measured in the transverse CT images was compared with the 3D diameter measured using the technique developed in the current study. Chadha *et al*¹⁹ and Krag *et al*²¹ measured the pedicle diameter in the transverse plane from selected transverse CT images where right and left pedicles appeared largest. They referred to this plane as the midpedicle cut and measured the pedicle width as a diameter of the isthmus. They demonstrated that L5 diameter was as twice larger as L1. In the present study, TPW was measured using the same concept, thus obtaining results similar to these previous papers. When the transverse plane width was compared to least axis of pedicle, the transverse plane width was greater than the least axis of pedicle at all levels, especially at L4 and L5. While the transverse plane width (TPW) was 8.0~9.7% larger than the least axis of pedicle at L1~L3, the transverse plane width was 16.3~17.7% larger at L4 and 40.9~47.2% larger at L5 compared with the least axis of pedicle. The larger transverse plane width in the L4 and L5 were caused by the elliptical geometry of the pedicle and inclination of the pedicle axis at L4 and L5. When the least axis of pedicle to transverse plane width ratio is calculated, the ratios ranged 91%~93% at L1~L3 levels, 85%~86% at L4 and 69%~72% at L5 (Table 1). These values could be used to correct overestimation of the least pedicle width measured using the transverse CT images.

The technique developed in the current study required to place two points in the 3D model to set an axis to navigate the pivot point for searching the pedicle cross sections. Since the cross sections were determined in multiple planes inclined from the perpendicular plane to the axis with a window range of $\pm 5^\circ$, the axis is not necessary to be a pedicle axis and the axis can be set easily in the 3D model in an interactive manner. However, this method only allows measurement of the outer boundary of the pedicle and can not measure endosteal diameter of the pedicle. Since this method uses 3D CT model and can obtain 3D coordinate of the data points consisting the outer boundary of the isthmus, data on bone density represented by Hounsfield number adjacent to the outer boundary will be incorporated in the analysis as a way to measure the endosteal diameter of the pedicle in the future study.

This paper has demonstrated the utility of CT scan 3D reconstruction images with additional custom software to determine the 3-D anatomy of the lumbar spine dimensions. This technique could be useful for future research or diagnostic application to accurately measure other areas of the spine such as spinal canal, intervertebral foramen, etc in the normal and symptomatic patients. The novel findings from this study are the 3D anatomy of the lumbar pedicles, particularly the isthmus obliquity and angulation in the lower lumbar spine in that the 2D transverse CT images tend to overestimate the smallest outer diameters of the pedicles. Clinically, measurement of the inner diameter of the pedicle is more relevant than the outer diameter. By measuring the width of the pedicle cortex by CT scan (bone windows), the inner diameter could be indirectly measured in most cases. Research is ongoing to measure the inner diameter of the pedicle using this technique.

In summary, this paper presents a novel technique developed using a subject-based CT model that allowed 3D measurements of the true isthmus width and inclination independent of the position and orientation of each vertebra. Furthermore, this algorithm's ease of application enables its clinical use. The results of the present study demonstrated that the true pedicle isthmus is inclined from the anatomical transverse plane especially at L4 and L5 levels. This finding supports the fact that determination of the size of pedicle screws using the transverse CT images may cause overestimation of the screw diameter. Three-dimensional inclination of the least axis of the pedicle should be taken into account for the measurement of the pedicle diameter in the lower lumbar vertebrae.

Acknowledgments

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Point-clouds

Figure 1.
Determination of cross sections using point cloud data in a spherical coordinate system. O: origin of the spherical coordinate. A and B: approximate center points in both ends of the tubular pedicle.

Figure 2. Pedicle wireframe rendering a) A–P view, b) lateral view. Blue lines: boundary lines of the pedicle determined at 0.5 mm increments. Yellow dot in the center: Point “O.” Green line: least axis of pedicle (LEAP). Yellow line: longest axis of pedicle (LOAP). Red line: isthmus boundary.

Figure 3.

Depiction of the measured parameters. Least Axis of Pedicle (LEAP): shortest axis of diameter. Longest Axis of Pedicle (LOAP): longest axis of diameter. Transverse Pedicle Width (TPW): largest width of pedicle calculated from projection of transverse plane.

Figure 4. Definition of a transverse plane for individual vertebra determined by eigenvectors of the posterior wall of each vertebral body. The angle between the LEAP and a transverse plane of each vertebral body was defined as the Isthmus Angle (IA)

Figure 5.

Least axis of pedicle (LEAP) split by level and gender. a: $p < 0.0001$, vs. L1–3 and $p < 0.002$, vs. L4 in same gender. b: $p < 0.0001$, vs. L1,2 and $p < 0.01$, vs. L3 in same gender. c: $p < 0.0001$, vs. L1,2. d: $p < 0.0001$, vs. L1,2 and $p < 0.0006$, vs. L3. e: $p < 0.0001$, vs. L1,2 and $p < 0.009$, vs. L3 in same gender.

Figure 6.

Longest axis of pedicle (LOAP) split by level and gender. a: $p < 0.0001$, vs. L1–4 in same gender. b: $p < 0.007$, vs. L2, $p < 0.003$, vs. L3 in same gender. c: $p < 0.005$, vs. L1 in same gender. d: $p < 0.02$, vs. L1. e: $p < 0.003$, vs. L2, $p < 0.02$, vs. L3 in same gender.

Figure 7.

Isthmus Angle (IA) split by level and gender. a: $p<0.0001$, vs. L1–4 in same gender. b: $p<0.0001$, vs. L1–3 in same gender. c: $p<0.0001$, vs. L1,2 in same gender.

Figure 8. Changes in orientation of the least axis of the isthmus from L1 to L5. Red contours depict the isthmus outer boundary, and the isthmus' least axes are shown as green lines.

Table 1
Isthmus dimensions split by level and gender (mean±SEM) LEAP: Least Axis of Pedicle, TPW: Transverse Plane Width

Dimension	Sex	L1	L2	L3	L4	L5
LEAP (mm)	F	7.5 ±	7.7 ±	9.3 ±	10.2 ±	11.4 ±
		0.27 [*]	0.26 [*]	0.26 [*]	0.25 [*]	0.24 [*]
	M	9.3 ±	9.6 ±	11.2 ±	11.9 ±	12.2 ±
		0.20 [*]	0.18 [*]	0.17 [*]	0.19 [*]	0.22 [*]
TPW (mm)	F	8.1 ±	8.4 ±	10.1 ±	11.9 ±	16.0 ±
		0.27	0.26	0.28	0.27	0.35
	M	10.1 ±	10.5 ±	12.3 ±	14.0 ±	17.8 ±
		0.21	0.18	0.18	0.19	0.30
TPW / LEAP (%)	F	109.1 ±	108.7 ±	108.0 ±	116.3 ±	140.9 ±
		0.98	0.83	0.68	1.16	2.17 ^a
	M	109.0 ±	109.5 ±	109.7 ±	117.7 ±	147.2 ±
		0.91	0.75	0.80	1.22	2.04
LEAP / TPW (%)	F	92.0 ±	92.2 ±	92.7 ±	86.4 ±	71.7 ±
		0.76	0.67	0.56	0.84	1.10 ^b
	M	92.0 ±	91.5 ±	91.3 ±	85.4 ±	68.5 ±
		0.71	0.60	0.59	0.82	0.99

F: Female M: Male

^{*} $p < 0.0001$ compared between LEAP and TPW in same gender.

^a $p < 0.04$ TPW / LEAP ratio compared between gender.

^b $p < 0.04$ LEAP / TPW ratio compared between gender.