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In Vivo Three-Dimensional Morphometric Analysis of the Lumbar Foramen in Healthy Subjects

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Structured Abstract

Study Design—*In vivo* three-dimensional (3D) morphometric analysis of the lumbar foramen using 3D computed tomography (CT) models in normal subjects.

Objective—To describe foraminal geometry in an asymptomatic cohort measured in 3D.

Summary of Background Data—Appropriate assessment of the complex 3D lumbar foraminal geometry is key for correct radiculopathy diagnosis and treatment planning. To the best of our knowledge, there is no other study that quantifies the normal lumbar foramen 3D geometry considering gender, age groups and spinal levels *in vivo*.

Methods—Subject-based 3D-CT lumbar models were created in 59 asymptomatic volunteers and foraminal height and width were measured based on the model by custom software. The foraminal height and width were compared by gender, age and lumbar level.

Results—Overall, the foraminal height decreased with age. However, while the foraminal height in males decreased with age at all spinal levels, the foraminal heights in females did not. The foraminal height was significantly larger in the upper lumbar levels in both genders. The foraminal width in males was significantly smaller than in females for all age groups. The foraminal width in both genders also decreased similarly with age. The foraminal widths at the lower lumbar levels were significantly smaller than those at the upper levels. Age-related foraminal width decreases were seen in all lumbar levels as well.

Conclusions—The present study described foraminal geometry *in vivo* in an asymptomatic cohort measured in 3D. Age-related foraminal height decrease was noticeable in males and in the lower lumbar levels. Age-related foraminal width decrease was shown in both genders and in all lumbar levels. Such information can be used as baseline data for diagnosis of foraminal stenosis and treatment modality planning.

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Level of Evidence: N/A

Keywords

Lumbar Spine; Lumbar Foramen; Lumbar Stenosis; 3D model; CT-based analyses; Validation; Foraminal Dimensions; Foraminal Height; Foraminal Width; Foraminal Geometry

Introduction

Lumbar foraminal stenosis is known as one of the many causes for low back pain. Patients with foraminal stenosis initially may show variable degrees of leg pain and back pain.¹ In general, 5%–10% of the patients with low-back pain are estimated to have radiculopathy. Radiculopathy is a relatively common problem that affects approximately 5 to 22 of every 1,000 people on an annual basis.^{2,3} Surgical treatment of radiculopathy due to foraminal stenosis has become more prevalent, including lumbar fusion and correction of lumbar spinal alignment with lumbar foraminal decompression. Spivak *et al.*⁴ and Kaneko *et al.*⁵ reported relationships between the foraminal geometry and radicular pain in their spondylolisthesis and degenerative scoliosis studies, respectively, highlighting the importance of accurate and proper knowledge of the foraminal geometry in order to improve the diagnosis and planning of the treatment in radiculopathy cases.

The geometry of the lumbar foramen has been described as an oval, round, or inverted teardrop-shaped “window” in the lateral aspect of the lumbar spine.⁶ The anatomic boundaries of the foramen consist of the adjacent vertebral pedicles superiorly and inferiorly, the postero-inferior margin of the superior vertebral body, the intervertebral disc, the postero-superior vertebral notch of the inferior vertebral body anteriorly, and the ligamentum flavum and superior and inferior articular facets posteriorly.⁷ Although foraminal morphology, especially with regard to stenotic changes of the foramen, has been investigated in the literature,^{8–12} there is no agreement as to what constitutes a normal lumbar foramen, and much less how the foraminal dimensions vary with spinal level, gender or age. One of the reasons for such variability in measurements is inherently tied to the equally large assortment of available methods to determine the foraminal geometry.

One way to obtain relatively accurate and repeatable geometric measurements is through the use of cadaver spines. Cadaveric studies allow three dimensional (3D) measurement of the foraminal geometry; however, there are inherent limitations of the cadaveric study such as lack of muscle tone which may affect foraminal geometry by altering the lumbar lordosis and the compression forces acting on the motion segment. To mitigate this lack of obvious physiological experimental conditions, researchers have turned to *in vivo* measurements using various clinically-available imaging techniques. This approach constitutes a true translational research, although still affected by some limitations. Namely, the attempt to characterize a 3D feature using planar images. Although MRI and CT can visualize the internal aspect of the musculoskeletal system, in everyday clinical setting, radiologists and clinicians only have access to 2D information. Even with reformatted and re-oriented planes, these measurements do not guarantee that the position and orientation of the selected planes are optimal for the measurement of foraminal dimensions.

Recent 3D imaging techniques and analysis methods have allowed various anatomical *in vivo* measurements in true 3D using subject-based 3D image-based models.^{13–16} These techniques would be especially beneficial to measure the foraminal geometry due to its complex 3D geometry. Taking advantage of the methodology developed by our laboratory, the purpose of the present study was to measure the lumbar foraminal 3D dimensions *in vivo* using subject-based 3D CT models.

Materials and Methods

Subjects

A total of 67 asymptomatic volunteers (35 males and 32 females) participated in this IRB-approved study with all subjects signing an informed consent form. Eight subjects were excluded from the study due to the presence of transitional lumbosacral vertebrae (n=7) and scoliosis (n=1). This resulted in a total of 59 asymptomatic subjects (31 males and 28 females, age range; 22–58 years, mean age; 35.4±9.7 [SD] years) who were included for analysis (Table 1). The foramina from L1-L2 to L5-S1 were measured bilaterally in each subject, comprising a sample size of 590 individual foramina.

Creation of 3D CT Foramen Model

Each subject underwent lumbar CT scan in a supine position (Volume Zoom®, Siemens, Malvern, PA). Three-dimensional vertebral surface models of L1-S1 were created from 1.0 mm thick axial slice CT data. These CT images were imported into a commercially-available 3D reconstruction software package (Mimics®, Materialise, Inc., Leuven, Belgium), where a threshold level to define the cortical shell was selected. Each vertebra was segmented based on said threshold level. A point-cloud dataset for each vertebra was also created based on the segmented model using Mimics. Data was segregated by lumbar spinal level, gender, side and decade-based age groups (20s, 30s, 40s and 50s).

Measurement of 3D Foramen Geometry

In order to calculate foraminal dimensions at each lumbar level, a custom-written program was prepared in Microsoft Visual C++®.2005 with Microsoft Foundation Class (MFC) programming environment (Microsoft Corp., Redmond, WA). The origin of a floating spherical coordinate system initially located at an arbitrary point within the foramen was moved along with a virtual axis line that followed the path of the nerve root within each lumbar foramen. This constituted the reference to search the closest points around the path that comprised the 3D boundaries of the foramen (Fig. 1). These boundary limits consisted of the superior and inferior pedicles, the postero-inferior margin of the superior vertebral body, the postero-superior margin of the inferior vertebral body, and the superior and inferior articular facets. Along this virtual axis line, components of the temporary foramen boundary were determined at 0.5 mm intervals.

A spherical coordinate system was located at each intersection point of the axis line and the cross sections (the apex of the search cone, termed here Point O), which served as pivot point for a virtual cone with a vertex angle of 20° (Fig. 1). It was rotated 360° about the apex of the cone in 10° increments and the points with least distances within the cone were

chosen as boundary points of the cross-section of the foramen. In order to provide a continuous anterior foramen border at the intervertebral disc space, the postero-inferior corner of the superior vertebral body and the postero-superior corner of the inferior vertebral body were connected with a straight line in each foraminal boundary (Fig. 2).

Measurement of Foraminal Height and Foraminal Width

The foraminal height was defined for each temporary boundary as the line segment connecting the 2 points in the boundary furthest apart from each other, in similar fashion to a major axis concept. Among the temporary boundaries set at 0.5 mm increments, the boundary which had the minimal foraminal height was determined as the final foraminal boundary. Once the final foraminal boundary was set, the foraminal width was defined as the least-distance between the postero-inferior corner of the proximal vertebral body for each motion segment and the closest point on the opposing boundary line (Fig. 3a).

Validation of 3D CT Model-Based Measurement of the Foramen Geometry Using Cadaveric Lumbar Specimens

To validate the accuracy of 3D CT-based measurement, a total of 15 fresh-frozen whole cadaveric lumbar spines were prepared (5 males and 10 females, age range; 50–76, mean age; 64.1 ± 7.3 [SD]). 3D CT models were created for each lumbar specimen and foraminal height and width were measured on the 3D CT models using the same procedures used for the *in vivo* measurements. After CT scanning, any soft tissue covering the lumbar foramina was removed taking care not to disturb ligamentous and disc structures. The foraminal height and width were measured by means of the following two digital calipers methods:

- a. Direct measurement using a digital caliper: The foraminal height and width were measured using a digital caliper with a resolution of 0.01 mm (Brown and Sharpe, North Kingstown, RI). The foraminal height was measured as the largest longitudinal diameter. The foraminal width was measured at the same points defined in the 3D CT-based technique (Fig. 3b)
- b. Measurement using silicon rubber casts: A silicon rubber cast of each foramen was created using liquid silicon rubber (Microfil, Flow Tech, Inc., Carver, MA). The dimensions of the cast at the same points defined in the direct measurement of the cadaveric specimen were measured using the digital caliper (Fig. 3c).

Foraminal height and width of 150 foramina (both sides, from L1-L2 to L5-S1) were measured using the 3D CT-based measurement method and these two calipers methods. Accuracy of the 3D CT-based measurement was evaluated by linear regression analyses considering the measurements using the digital caliper as the gold standard. Correlation coefficients and the Root Mean Square Error (RMSE) were calculated for both foraminal dimensions and measurement methods.

Statistical Analysis

The foraminal height and foraminal width were compared between genders by unpaired t-tests. The parameters among different age groups and lumbar levels were compared by

ANOVA with Fischer's *post hoc* test. Significance level was set at $p < 0.05$. All data were reported as mean $\pm$ standard error of the mean (SEM).

Results

There were no significant age differences between genders either in the whole sample ($p = 0.69$) or when the data was segregated by decades (20s; $p = 0.87$, 30s; $p = 0.09$, 40s; $p = 0.44$, 50s; $p = 0.27$).

Validation Results of 3D CT Model-Based Foraminal Geometry Measurements Using Cadaveric Lumbar Specimens

Strong correlation was demonstrated between 3D CT-based measurement and caliper measurement of the cadaveric spine in the foraminal height ($r = 0.94$, $p < 0.001$) and in the foraminal width ($r = 0.92$, $p < 0.001$). The RMSE values between these measurements were 1.03 mm in the foraminal height and 0.72 mm in the foraminal width, respectively. The correlation between 3D CT-based measurement and caliper measurement of the silicon rubber model was also strong in the foraminal height ($r = 0.96$, $p < 0.001$) and in the foraminal width ($r = 0.92$, $p < 0.001$). The RMSE values between these measurements were 0.74 mm in the foraminal height and 0.77 mm in the foraminal width, respectively.

Foraminal Height

The foraminal height decreased in the lower lumbar levels (L1-2 > L3-4; $p = 0.001$, L1-2 > L4-5, L5/S1; $p < 0.0001$, L2-3 < L3-4, L4-5, L5-S1; $p < 0.0001$, L3-4 < L4-5, L5-S1; $p < 0.0001$, L4-5 < L5-S1; $p < 0.0001$, Table 2). The foraminal height for males in their 20s' was significantly greater than in their female peers, but differences between genders disappeared after the third decade. Overall, the foraminal height decreased with age (20s > 40s; $p = 0.008$, 20s > 50s; $p < 0.001$, 30s > 50s; $p < 0.001$, 40s > 50s; $p = 0.004$). However, when the data were split by gender, while the foraminal height in males decreased with age at all spinal levels (Fig. 4a), the foraminal height in females did not (Fig. 4b). When considering spinal level, the foraminal height was significantly smaller in the lower lumbar levels in both genders (Figs. 5a, 5b). The foraminal height in the lower lumbar levels decreased more with age compared to that in the upper levels. Gender and age also had influence on the foraminal height and spinal level: males in their 30's saw a decrease in foraminal height, but females did not show differences at any lumbar level, with the exception of a decrease in 50s at L5-S1.

Foraminal Width

The foraminal width decreased in the lower lumbar levels (L1-2 > L3-4; $p = 0.0014$, L1-2 > L4-5, L5/S1; $p < 0.0001$, L2-3 < L4-5, L5-S1; $p < 0.0001$, L3-4 < L4-5, L5-S1; $p < 0.0001$, L4-5 < L5-S1; $p = 0.037$, Table 2). Table 2 also shows the foraminal width at different levels only in the fifth-decade subjects for the comparison with the previously published results. The foraminal width in males was significantly smaller than in females in all age groups. Overall, the foraminal width decreased with age. Unlike the foraminal height, the foraminal width in both genders decreased similarly with age (Figs. 6a, 6b). The foraminal width at the

lower lumbar levels was significantly smaller than those at the upper levels (Figs. 7a, 7b). Age-related foraminal width decreases were shown in all lumbar levels as well.

Discussion

The present study measured the foraminal height and width *in vivo* using subject-based 3D CT models to characterize the complex 3D structure the lumbar foramen. The method used in this study allowed the measurement of foraminal dimensions without considering specific obliquity of individual foramen due to lumbar lordosis and/or functional scoliosis, which may cause measurement errors.⁵ The results presented here showed a decrease in the foraminal height with age even in asymptomatic male young adults. However, such finding was not observed in females. Cinotti *et al.*⁹ and Schlegel *et al.*¹⁷ reported foraminal height and disc height change were closely related to each other. Therefore, it is assumed that disc height decrease begins earlier in males resulting in a decline in foraminal heights. Miller *et al.*¹⁸ noted that lumbar intervertebral disc degeneration first appears in 11- to 19-year-old males and approximately 10 years later in females in their autopsy study. There is also evidence of gender difference in the degeneration progression rates. An MRI study¹⁹ and a surgical study²⁰ reported that male discs were more degenerated than female discs at most ages. In addition, the prevalence of the lumbar disc degenerative change has been reported to be significantly higher among young male adults.²¹

But changes were not limited in the cranio-caudal direction. The foraminal width also decreased with age in both genders and in all lumbar levels. Foraminal stenosis can be attributed, among other factors, to the presence of bony spurs arising from the postero-lateral vertebral body or articular facet and extending into the foramen.¹ In a large-scale population-based cohort study, Yoshimura *et al.*²² reported that in subjects from both genders older than 40 years old, the prevalence of lumbar spondylosis was 81.5% and 65.5%. O'Neill *et al.*²³ explored osteophytosis within a UK adult population segment aged over 50 years old, finding that 84% of men and 74% of women showed osteophyte formation. Although the authors didn't investigate early young adult osteophyte formation, they postulated that minor osteophyte growth could have been initiated before the fourth decade of life in both genders.

Previous reports in the literature contributed with initial data on foraminal height and width evaluated in cadaveric studies (Table 2).^{9,11} Although differences exist with respect to analysis methods and sample sizes, both our cadaveric and *in vivo* results agree with these earlier descriptions of the foraminal dimensions, especially with respect to the finding that the upper lumbar levels have larger foraminal sizes than the lower levels. For practical reasons, the most common method used to measure the foramen dimensions in cadaver spines is the use of a pair of calipers. This hand-held tool has the advantage of mechanically locating the largest dimensions, but there is uncertainty about its location: is this dimension a width or a height, or is it within a margin of error? The measurement is also subject to operator variability and presence of compliant soft tissue that might confound the final result obtained through this method.

An improvement in the robustness of this measurement concept was achieved by replicating it computationally using the subject-based 3D CT model presented here. However, the absolute values of the foraminal height measured in this present study *in vivo* were evenly smaller than in the previous cadaver study results, although our validation study showed high accuracy of the CT-based measurement by comparing the direct measurements on the same cadaveric specimens used for CT scanning. This discrepancy may be explained by lack of physiological compressive forces in the cadaveric spine which increases disc height.²⁴ Decrease in this lumbar lordosis in the cadaveric lumbar spine may be another possible reason for the increased foraminal height in the cadaveric studies.

One of the important limitations of the present study is that soft tissues were not taken into account for the geometrical analysis of the foramen due to the imaging modality used to create the models. The anatomic boundaries of the foramen include not only bony structures but also the intervertebral disc and the ligamentum flavum. In addition, transforaminal and intraforaminal ligaments are present in the inferior aspect of the foramen.^{1,25,26} These soft tissue components are considered as important for the pathogenesis of radiculopathy; nonetheless, the bony structure is still important since they are attached to them. The bony structure of the foramen might be also important for preoperative planning and postoperative evaluation of the decompression surgery for the foraminal stenosis. Recent advances in minimally invasive surgery have allowed bone resection with transforaminal approaches and, therefore, information on 3D bony geometry could be used to determine location and degree of the bone resection.²⁷ Transforaminal approaches include endoscopic techniques to perform foraminotomy or discectomy and transforaminal lumbar interbody fusion techniques. The preoperative 3D assessment of the intervertebral foramen might help choosing appropriate size tubes or endoscopic instruments and help planning for the location and amount of facet joint resection for the procedure.²⁸

Another limitation of this study is that the measurements of the foraminal geometry were conducted by using CT images taken in the supine position without axial loading. Iwata *et al.* demonstrated effects of axial loading on the lumbar foraminal geometry *in vivo*.²⁹ Although the data shown in the present study may be compared with the patient foraminal geometry measured by CT images taken in the current clinical setting, possible differences of the foraminal geometry in the non-weight bearing supine position and in standing position under physiological loading should be considered to understand patient symptoms caused by foraminal stenosis.

MRI of the subjects would have evaluated the status or grades of disc degeneration more precisely than CT scans. The purpose of this study was to obtain an initial benchmark reference on the lumbar intervertebral foramen, not necessarily to correlate between disc degeneration, symptoms and intervertebral foramen, but also because to the best of the authors' knowledge the literature does not include a true 3D description of the foramen. Further studies are needed to evaluate the effect of disc degeneration on the dimensions of the intervertebral foramen and symptoms.

In summary, the present study described foraminal geometry *in vivo* in an asymptomatic cohort measured in 3D. Although the geometry is limited to the bony structures, such

information can be used as baseline data for diagnosis of foraminal stenosis and treatment modality planning.

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Key Points

- Lumbar foraminal geometry can be measured in 3D with high accuracy independent of the motion segment orientation.
- Age-related foraminal height decrease was noticeable in males and in the lower lumbar levels.
- Age-related foraminal width decrease was shown in both genders and in all lumbar levels.

Figure 1.

The search cone (white) is shown locating the foramen boundary points (red spheres). The cone pivots from the floating spherical coordinate system coincident with its apex (Point O mentioned in the text) in the direction of the yellow arrow.

Figure 2.

The foramen contour including the intervertebral disc gap shown at several rotation positions about the vertical axis to show its non-planar shape. The normal vector of the foramen contour is shown as a white arrow for illustration purposes only.

Figure 3.

A) Location of the foraminal width (blue line) and height (white line) *in situ* in the virtual model of the foramen boundary (red contour). B) Representative view of the measurement of the foraminal height with calipers in the cadaver model. C) A view of the silicon rubber cast of the same foramen from (B). Note that the calipers are shown measuring the foraminal height as well.

Figure 4.

Influence of age on foraminal height when the data is grouped by lumbar level. Separate plots for Males (A) and Females (B). Data is shown as mean $\pm$ SEM. Significance is defined by *: $p < 0.05$ and **: $p < 0.01$.

Figure 5.

Influence of level on foraminal height when the data is grouped by age group. Separate plots for Males (A) and Females (B). Data is shown as mean $\pm$ SEM. Significance is defined by *: $p < 0.05$ and **: $p < 0.01$.

Figure 6. Influence of age on foraminal height when the data is grouped by lumbar level. Separate plots for Males (A) and Females (B). Data is shown as mean $\pm$ SEM. Significance is defined by *: $p < 0.05$ and **: $p < 0.01$.

Figure 7. Influence of level on foraminal width when the data is grouped by age group. Separate plots for Males (A) and Females (B). Data is shown as mean $\pm$ SEM. Significance is defined by *: $p < 0.05$ and **: $p < 0.01$.

Table 1

Study population categorized by gender and age.

	Male (n=31)	Female (n=28)
20s	9	10
30s	11	10
40s	8	6
50s	3	2

Table 2

Comparison of this study's results to others in the literature.

Hasegawa <i>et al.</i>		Cinotti <i>et al.</i>		Present Study	
Study Design	Cadaveric	Cadaveric		<i>in vivo</i> 3D CT	
Sample Size	18 (5 M, 13 F) n=100 foramina	16 (9 M, 7 F) n=160 foramina		59 (31 M, 28 F) n=590 foramina	
Age Range (mean), yrs	35–86 (60)		38–79 (59)		22–58 (36)
Spinal Level	Foraminal height	Foraminal width	Foraminal height	Foraminal width	Foraminal width
L1/2	20.0	5.7	20.0	6.6	7.2 (5.6)*
L2/3	21.2	5.1	20.0	6.4	6.8 (4.5)*
L3/4	21.4	5.1	21.1	5.8	6.5 (5.3)*
L4/5	20.1	4.1	21.1	5.1	5.5 (3.7)*
L5/S	19.9	5.4	19.1	5.4	5.0 (4.3)*

M indicates male; F female.

* Numbers in parentheses are the mean values of the fifth-decade subjects in the present study.