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Morphometric Measurement of Lower Lumbar Intervertebral Foramina Based on Digital Three-Dimensional Simulation

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ABSTRACT

AIM: To investigate the morphology of the lower lumbar intervertebral foramina through using a digital three-dimensional (3D) simulation model to guide the endoscope through the intervertebral foramina.

MATERIAL and METHODS: Individuals without disease affecting the lumbar vertebrae underwent computed tomography (CT) scanning in the supine position. The CT images obtained were imported to medical software to reconstruct a 3D model of the lumbar vertebrae. The stereoscopic longitudinal and transverse diameters of the lumbar intervertebral foramina were measured directly on the established simulation model. Comparisons in terms of sex and age were performed using t-test or analysis of variance.

RESULTS: In total, 100 individuals were included in the study. Average longitudinal and transverse diameters of the lower lumbar intervertebral foramen decreased moving inferiorly. The transverse diameters of the lower lumbar intervertebral foramina were similar between sexes and between age groups. However, the longitudinal diameter decreased with age ($p<0.05$).

CONCLUSION: The reconstructed lumbar vertebrae simulation model presented in this study has high fidelity to the structure of the human lumbar spine. This approach provides individualized, accurate, standardized, and detailed guidance for endoscopic surgery through the lumbar intervertebral foramen.

KEYWORDS: Lumbar intervertebral foramina, Applied anatomy, Digitization, 3D simulation, Endoscopy

ABBREVIATIONS: 3D: Three-dimensional, **PELD:** Percutaneous endoscopic lumbar discectomy, **CT:** Computed tomography, **LDH:** Lumbar disc herniation, **MRI:** Magnetic resonance imaging, **ANOVA:** One-way analysis of variance

INTRODUCTION

Lumbar disc herniation (LDH) is the major cause of chronic lower back pain. LDH can be treated conservatively or with surgery (either open or minimally invasive) (8,13). Percutaneous endoscopic lumbar discectomy (PELD) was recently developed as a minimally invasive technique that utilizes a posterolateral approach for spine surgery in the treatment of LDH (8,13). Compared to the traditional open surgery approach, PELD has numerous advantages, such as a shorter operation time, less bleeding, minimal postoperative pain, shorter hospital stay, and early recovery, without affecting functional outcomes, the risk for complications, or the rate of reoperation (6,8,13,15).

The most important parameter for the minimally invasive PELD approach is the size of the Kambin triangle formed between the nerve root and the outer edge of the intervertebral foramen. Accurate localization of the intervertebral foramen is important for identifying operation depth and tissue structure during microendoscopy. Pre-operative measurement of the intervertebral foramen is very useful for exposing the Kambine triangle and helping to enlarge the area of the foramen. At present, our knowledge of lumbar intervertebral foramen mor-

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phology and the related clinical anatomy is based primarily on skeletal markers as identified in cadaver studies. However, after the body has been soaked in formaldehyde, the tissue structure atrophies, which alters the morphology and tissue structure of the intervertebral foramen. Therefore, data obtained from traditional anatomical research may not be accurate with respect to the living body (11,18). In order to reduce the number of errors based on data obtained from cadaver specimens, researchers have used numerous techniques to study the morphology and anatomy of lumbar intervertebral foramina. The techniques used to date include two-dimensional (2D) X-ray (2), computed tomography (CT) (5), and magnetic resonance imaging (MRI) (3,4). However, it is difficult to use 2D X-ray projection to image the plane perpendicular to the sagittal center-line plane of the lumbar intervertebral foramen. Therefore, the data still have some limitations (10). Ordinary CT or MRI also provides 2D information, which is associated with the limitations described above.

With the development of three-dimensional (3D) CT reconstruction of the lumbar spine, 3D MRI of neurons and the lumbar spine, and 3D printing technology, 3D imaging technology has been used successfully for preoperative imaging of the lumbar intervertebral foramen and other aspects of the surgical field (14,16). Using digital 3D simulation technology, the present study aimed to characterize the anatomy of the lower lumbar intervertebral foramina. This approach may provide an intuitive physical demonstration model for preoperative use in judging the need for enlargement and/or plasty of the intervertebral foramen.

PATIENTS and METHODS

Participants

This study included individuals without lumbar spine disease, 18–75 years of age, who had undergone lumbar spine CT for multiplanar reconstruction at our institution during the period from April 2016 to April 2017. The exclusion criteria were: 1) history of lower back pain, lower limb pain, and numbness; 2) history of lumbar spine trauma and surgery; 3) imaging data showing lumbar instability, lumbar spondylolisthesis, LDH, lumbar spinal stenosis, and/or spinal deformity. The study protocol was approved by the local committee at our hospital (2016-03-12; 09:00). All patients provided written informed consent.

CT Scanning

CT images of the lumbar vertebrae were acquired using Emotion 16 (Siemens, Forchheim, Germany) with the patient in the supine position. Scanning was performed at 130 kV, 21.6 mA, 0.625 mm pitch. For scanning and reconstruction, section thickness was set to 0.625 mm. To reconstruct 3D CT images, images with a 512×512 matrix were output in Dicom format through the PACS system.

3D Reconstruction

Images in Dicom format were imported to Mimics software (Version 17.0). The threshold value in CT images was set at 160 Hu (Figure 1A), and region growing was performed (Figure 1B). Then the 3D visualization of the lumbar vertebrae was reconstructed (Figure 1C, D).

Morphometric Measurement

The longitudinal and transverse diameters of each intervertebral foramen (foraminal height and width) in the lower lumbar spine (L3/4, L4/5, L5/S1) were stereoscopically measured on the 3D simulation model. In Figure 2A, the vertical line (red) represents the longitudinal diameter of the intervertebral foramen, while the horizontal line (green) represents the transverse diameter of the intervertebral foramen. In order to ensure that measurements of the longitudinal and transverse diameters were obtained where the sagittal area of the intervertebral foramen was largest, the data were analyzed after multi-angle rotation and magnification of the model. Twelve data sets were obtained for the lower lumbar vertebrae in each participant, and values were output in ".txt" format.

Statistical Analysis

Data were analyzed using SPSS 16.0. Comparisons between male and female patients and comparisons between age groups were analyzed by independent-sample t-test and one-way analysis of variance (ANOVA) with Tukey or Scheffe post-hoc analysis. A p value < 0.05 was considered statistically significant.

RESULTS

In total, 100 individuals (50 males, 50 females) were included in the study. Mean age was 45.2 ± 10.5 years (range 18–75 years). Average weight was 62.4 ± 10.9 kg (range 44–94 kg). Average height was 163.7 ± 6.9 cm (range 148–180 cm).

Although the average longitudinal and transverse diameters of the lower lumbar intervertebral foramina decreased moving in the inferior direction, no significant difference between sexes was observed for the longitudinal or transverse diameter of the lower lumbar intervertebral foramina (Tables I, II).

The participants were divided into three groups according to age: 20–40 yr; 40–60 yr; 60–80 yr. No significant difference in the transverse diameter of the lower lumbar intervertebral foramina was observed between age groups (Table III). However, the longitudinal diameter of the lower lumbar intervertebral foramen was found to decrease with age ($p<0.05$, Table IV). The L3/4 lower lumbar intervertebral foramen had the greatest longitudinal and transverse diameter (18.35 ± 1.83 mm and 10.06 ± 1.10 mm, respectively) (Table V).

DISCUSSION

The present study measured the longitudinal and transverse diameters of lower lumbar intervertebral foramina using 3D digital reconstructions. The data showed that the diameters decreased moving inferiorly down the spine, with no difference between male vs. female patients. The longitudinal diameter varied with age, while the transverse diameter did not. Longitudinal and transverse diameters were greatest in the L3/4 intervertebral foramen.

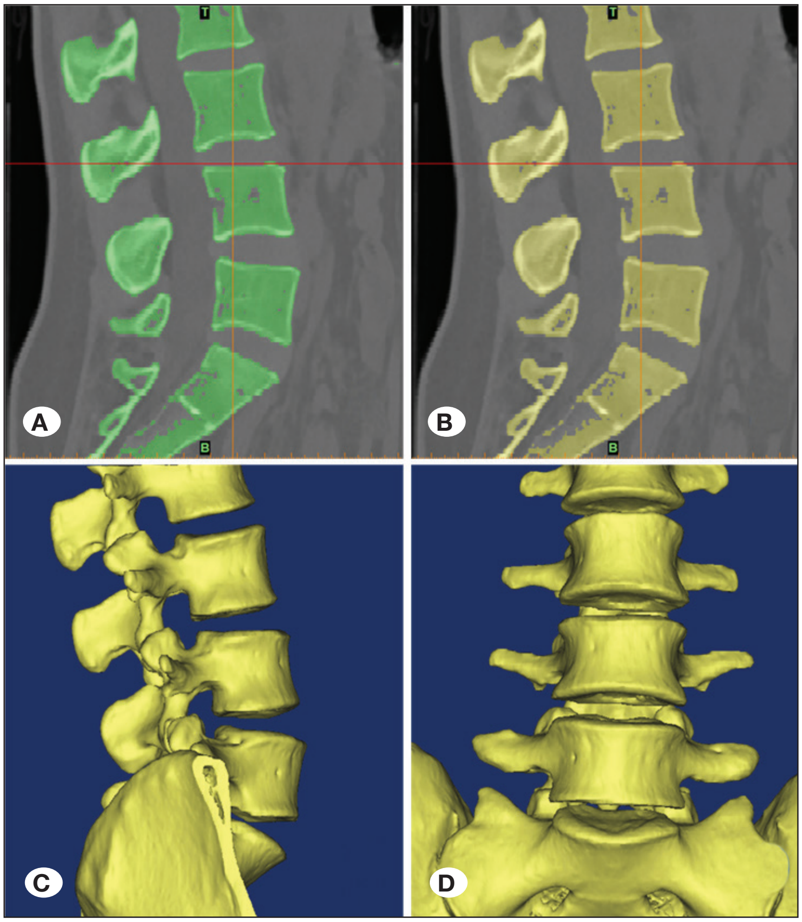

Figure 1: 3D reconstruction of the lumbar vertebrae using Mimics. **A)** Threshold setting; **B)** Region of growth; **C, D)** 3D simulation model.

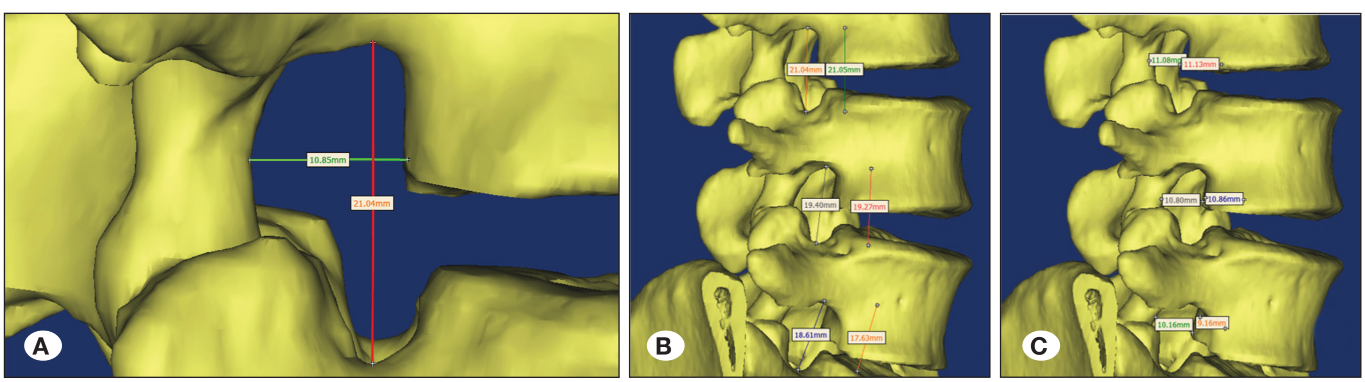

Figure 2: Measurement of longitudinal and transverse diameters of intervertebral foramina. **A)** 3D measurement of the longitudinal and transverse diameters of intervertebral foramina; **B)** longitudinal diameter of lower lumbar intervertebral foramina; **C)** transverse diameter of lower lumbar intervertebral foramina.

Table I: Transverse Diameter of Lower Lumbar Intervertebral Foramina in Male vs. Female Patients

Lumbar spine segments	Transverse diameter (mm)			
	Male	Female	t	p
L3/4	10.03 ± 1.73	10.23 ± 2.15	-0.232	0.172
L4/5	9.18 ± 1.51	9.01 ± 1.70	-1.071	0.399
L5/S1	8.07 ± 1.46	8.40 ± 1.52	0.946	0.481

Table II: Longitudinal Diameter of Lower Lumbar Intervertebral Foramina in Male vs. Female Patients

Lumbar spine segments	Longitudinal diameter (mm)			
	Male	Female	t	p
L3/4	18.05 ± 1.79	18.73 ± 2.36	0.239	0.330
L4/5	17.53 ± 2.01	17.15 ± 2.26	-0.788	0.701
L5/S1	15.12 ± 2.22	16.25 ± 2.07	1.073	0.562

Table III: Transverse Diameter of Lumbar Intervertebral Foramina Across Age Groups

Lumbar spine segments	Transverse diameter (mm)			
	20-40 years group	40-60 years group	60-80 years group	p
L3/4	10.29 ± 1.13	10.14 ± 2.10	9.23 ± 1.88	0.068
L4/5	9.16 ± 1.57	9.24 ± 1.96	8.81 ± 1.74	0.390
L5/S1	8.21 ± 2.08	8.09 ± 2.37	7.09 ± 1.92	0.152

Table IV: Longitudinal Diameter of Lumbar Intervertebral Foramina Across Age Groups

Lumbar spine segments	Longitudinal diameter (mm)			
	20-40 years group	40-60 years group	60-80 years group	p
L3/4	18.60 ± 1.39	18.49 ± 1.87	16.13 ± 1.76	**<0.001**
L4/5	18.05 ±1.86	17.44 ± 1.59	15.06 ± 1.77	**<0.001**
L5/S1	16.64 ± 1.98	16.02 ± 1.67	13.56 ± 1.90	**<0.001**

Table V: Longitudinal and Transverse Diameters of the Lower Lumbar Vertebrae

Lumbar spine segments	Longitudinal diameter (mm)	Transverse diameter(mm)
L3/4	18.35 ± 1.83	10.06 ± 1.10
L4/5	17.26 ± 1.89	9.04 ± 1.29
L5/S1	15.84 ± 1.70	8.14 ± 1.11
p	**<0.001**	**<0.001**

LDH is one of the main causes of chronic back pain and is always complicated by nerve root canal stenosis, which often occurs in the lower lumbar vertebrae (9). The present study therefore focused on the anatomy of the lower lumbar spine. The lumbar intervertebral foramen, which is shaped like an inverted teardrop, forms the tunnel where the segmental spinal nerve exits the spinal canal. The lumbar intervertebral foramen is also where blood vessels supplying soft tissue, nerves, and bone in the spinal cord enter the spinal canal. The longitudinal diameter of the lumbar intervertebral foramen gradually decreases from top to bottom, leading to a relatively small lower lumbar nerve root-to-foramen ratio. Discovery of the lumbar intervertebral foramen ligament showed that spinal nerve roots are confined to certain tunnels under physiological conditions (11). The spine segments most susceptible to degeneration are located in the lower lumbar spine (19). Lumbar nerve root canal stenosis is there most common in the lower lumbar intervertebral foramina, especially those connecting the L4/5 and L5/S1 segments, respectively (19). For these reasons, the present study measured the longitudinal and transverse diameters of lower lumbar intervertebral foramina that could be used to guide an endoscope through lumbar intervertebral foramina, as is required for PELD. Our data showed that the longitudinal and transverse diameters of the intervertebral foramina decreased moving inferiorly down the spine. This finding supports previous reports that lumbar intervertebral foramen stenosis occurs mostly in the lower lumbar vertebrae.

Previous studies on lumbar intervertebral foramina were mostly based on static imaging data from X-rays (1), CT, (12,17) or cadaveric specimens (11,18) (2,7). These data were 2D and therefore limited. Using MRI images from 233 lumbar spine segments, Hasegawa et al. measured the longitudinal diameter of lumbar intervertebral foramina. Patients with lumbar symptoms or lumbar degeneration were excluded. The authors measured 2D, rather than 3D, MRI scans (3). Park et al. measured the longitudinal and transverse diameters of intervertebral foramina in fresh cadaver specimens using a Vernier caliper, which sometimes provides inaccurate measurements (11). Torun et al. measured 80 lumbar spine specimens using a surgical microscope, reporting average transverse diameter of 8.8 ± 1.7 mm and average longitudinal diameter of 19.4 ± 2.7 mm (18). However, the stiffness of the corpse and the shrinkage of tissue structures after soaking in formalin may have distorted the relevant anatomy. Because foramina are 3D and characterized by irregular bone structure, it is difficult to find the widest cross-section in a 2D sagittal plane. Therefore, measurements of lumbar intervertebral foramina based on digital 3D simulations will be more accurate. Our data showed that for L3/4, the longitudinal diameter was 18.35 ± 1.83 mm, and the transverse diameter was 10.06 ± 1.10 mm; for L4/5, these values were 17.26 ± 1.89 mm and 9.04 ± 1.29 mm, respectively; for L5/S1, these values were 15.84 ± 1.70 mm and 8.14 ± 1.11 mm, respectively.

Our data should be more accurate than those reported previously for several reasons. First, with the use of digital 3D simulation, CT images are used to reconstruct the lumbar vertebrae. The resulting simulation model has high fidelity in restoring lumbar vertebral structure. Second, the digital simulation model constructed can be rotated at any angle and magnified, which is useful for determining the optimal position and maximum point for obtaining a cross-sectional view of the intervertebral foramen. Third, each measurement position can be directly compared with the upper and lower segments as well as the left and right sides of the intervertebral foramen, thus increasing measurement accuracy.

This study had several limitations. First, the study was performed in southern China, so the data represent the characteristics of a population in southern China. Second, this study had a small sample size (100 patients); therefore, additional studies with more patients should be conducted to further confirm our results.

CONCLUSION

We measured the longitudinal and transverse diameters of lower lumbar intervertebral foramina using digital 3D reconstructions. The data were consistent with previous reports. The digital 3D simulation technology is fast and simple, making it possible to rapidly create a 3D simulation model that can be used to measure intervertebral foramina and to guide endoscopy. This is important for cases with obvious intervertebral foramen stenosis. The simulation model can be used to simulate intervertebral foraminal structure before surgery, and 3D printing of lumbar intervertebral foramina can be performed when necessary to optimize treatment. However, more studies are needed to better guide endoscopy through the intervertebral foramen in the clinic.

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