CLINICAL ARTICLE

Magnetic Resonance Neurography in Analysis of Operative Safety of Transforaminal Lumbar Interbody Fusion in Chinese Subjects

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Objective: To measure relevant anatomical variables of lumbosacral nerve root and adjacent structures by magnetic resonance neurography (MRN) and analyze operative safety of transforaminal lumbar interbody fusion (TLIF) in Chinese subjects.

Methods: Twelve normal healthy volunteers (six men, six women) underwent MRN of lumbosacral nerve roots at 3.0 T. Three-dimensional imaging was reconstructed with Osirix software and the following anatomic variables measured: (i) distance between nerve root and upper pedicle; (ii) distance between nerve root and lower pedicle; (iii) angle between nerve root and sagittal plane; (iv) distance between upper and lower nerve roots; and (v) distance between upper and lower pedicles.

Results: Good images of the L₁-L₅ nerve roots were obtained by MRN technology in all 12 volunteers. The distance between nerve root and upper pedicle and the angle between nerve roots and the sagittal plane gradually diminished from L₁ to L₅. However, there were no significant variations in the distance between nerve root and lower pedicle or between upper and lower pedicles. From L₁₋₂ to L₄₋₅, the distances between upper and lower pedicles, which are closely related to the operating space for TLIF in Chinese men and women, were less than 10 mm in most subjects and were significantly smaller in women than in men. The variables did not differ significantly between the left and right sides of the same segment.

Conclusion: Based on the above anatomical study and measurement analysis, we believe that TLIF puts the upper nerve root at risk in some Chinese patients. However, this conclusion requires confirmation by anatomical study of large samples and clinical validation.

Key words: Anatomical study; Lumbar vertebrae; Lumbosacral nerve root; Magnetic resonance imaging; Spinal fusion

Introduction

Since the first clinical report of transforaminal lumbar interbody fusion (TLIF) by Harms and Rolinger in 1982¹, this procedure has been widely used to treat lumbar degenerative disease. In theory, TLIF has certain advantages over posterior lumbar interbody fusion. Because TLIF is performed through a lateral approach and does not involve

putting strain on the dural sac and lower nerve root, it reduces the incidence of nerve root injury. Further, TLIF preserves the posterior tension band structure, resulting in less damage to the posterior structure and little influence on stability. In addition, TLIF results in less postoperative epidural adhesion and scar formation and it is suitable for every lumbar segment¹⁻⁵.

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Large number of clinical studies have verified TLIF has a good clinical effect for lumbar degenerative diseases. And it is associated with shorter operating time, less blood loss, shorter hospital stay, and lower incidence of complications⁶⁻¹¹. In recent years, TLIF also received a good clinical application in treatment of degenerative lumbar scoliosis, recurrent lumbar disc herniation, thoracolumbar fracture or degenerative diseases, and so on¹²⁻¹⁶. And with the continuous development of minimally invasive operating techniques, minimally invasive TLIF gained wide clinical popularity, even became a same-day discharge or outpatient operation^{17,18}.

However, there are some problems with clinical application of TLIF, such as more irritation of the nerve roots during the procedure, probability of damage to upper nerve roots and difficulty in effectively decompressing the central tube²⁻⁵. Tormenti *et al.* reported that intraoperative dural tears occurred in 14.3% of 531 cases of TLIF in their series¹⁹. Salehi *et al.*²⁰, Potter *et al.*²¹ and Hee *et al.*²² have reported rates of 4.2%, 7% and 8.1%, respectively, of transient nerve root injury after TLIF. Li *et al.* reported a rate of nerve root injury of 3.2% after TLIF in 156 cases²³. Xu *et al.*'s rate of transient nerve root injury was 1.7% and of dural tears 3.3% after TLIF in Chinese patients with degenerative lumbar spondylolisthesis²⁴. In a previous anatomic study, we found that the nerve root is exposed completely during TLIF. Because it is a short distance between the nerve root and lower adjacent pedicle and the operating space limited, nerve roots are easily injured during interbody fusion²⁵. Therefore, the safety of TLIF in Chinese people needs further evaluation.

The above data suggest that evaluation of the safety of TLIF requires measurement of the lumbosacral nerve root and adjacent structures, especially the distance between nerve root and adjacent pedicle. However, there are few previous published reports concerning the anatomy of the lumbar region and sacral nerve roots in Chinese subjects. In recent years, magnetic resonance neural neurography (MRN) has improved and it now provides good images of lumbosacral nerve root, thus providing good data concerning their anatomy^{26,27}.

In this study, MRN was used to image lumbosacral nerve roots and adjacent structures in healthy volunteers to achieve the following objectives: (i) to measure and analyze relevant anatomic variables of lumbosacral nerve roots and their adjacent structures; and (ii) to use the results of measurement and analysis to evaluate the safety of TLIF in Chinese people and provide a guide to clinical practice.

Materials and Methods

Inclusion Criteria

Twelve adult healthy volunteers (six men, six women) aged 20–35 years (mean 26.2 years) were included in this study. They had no low back or lower extremity symptoms, no difficulty walking, no previous lumbar trauma or surgery, and no contraindications to MRI. In addition, they underwent further X-rays to exclude osseous structure abnormalities. This study was approved by the local institutional review board.

MRI Scanning Method and Parameters

A Siemens (Erlangen, Germany) magnetic resonance MAGNETOM Verio 3.0 T was used to perform the MRN examinations. A 30° cushion was placed under the volunteers' legs to reduce the impact of lumbar lordosis on imaging when scanning.

Conventional MRI Image

Scan parameters for the sagittal FRFSE-XL sequence of T₂WI images were as follows: TR/TE/NEX, 2000 ms/100 ms/4; Thk/Sp, 1.1 mm/1.0 mm; Num, 12. The parameters for the sagittal T₁-FLAIR images were: TR/TE/NEX, 2700 ms/25 ms/2; Thk/Sp, 4.0 mm/1.0 mm; Num, 12. The parameters for the axial FRFSE-xL weighted T₂WI images were: TR/TE/NEX, 1800 ms/120 ms/4; Thk/Sp, 3.5 mm/0.5 mm; Num, 12. The sagittal range included the T₁₂–S₁ vertebrae and the axial range included discs of L₁₋₂, L₂₋₃, L₃₋₄, L₄₋₅ and L₅S₁.

MRN Imaging

Coronal T₂WI FRFSE-XL sequences were used as the MRN basic sequence and FAT SAT fat suppression techniques were utilized for the T₂WI images. T₂WI sagittal and axial images were combined for locating and scanning coronal MRN of the target area. The posterior edge of the locating line covered the posterior edge of the spinal canal for 2–3 layers; the midpoint of the locating line was at the midpoint of the L₃ vertebral body. The range of coronal MRN images included from the upper edge of T₁₂ to the lower edge of S₁. A Samsung LED S27A350H HD external display (Gyeonggi-do, South Korea) was used for anatomic measurement.

Measurement Parameters

(1) The distance between nerve root and upper pedicle was defined as the distance between the horizontal tangent of the upper edge of the ganglion and horizontal tangent of the lower edge of the upper pedicle (a in Fig. 1).

(2) The distance between the nerve root and lower pedicle as the distance between the horizontal tangent of the lower edge of the ganglion and horizontal tangent of the upper edge of the lower pedicle (b in Fig. 1).

(3) The angle between the nerve root and sagittal plane as the angle between the line through the ganglion midpoint and initial dural sac midpoint and the midline of the dural sac (α in Fig. 1).

(4) The distance between the adjacent nerve roots as the distance between the lower edge of the upper ganglion and the upper edge of the lower ganglion (c in Fig. 1).

(5) And the distance between the adjacent pedicle as the distance between the lower edge of the upper pedicle and upper edge of the lower pedicle, which is the longitudinal diameter of the intervertebral foramen (d in Fig. 1).

Procedures for Measuring the Selected Variables(L₄ Nerve Root as an Example)

1. The distances between the nerve root and upper and lower pedicles were measured by located the sagittal plane on

Fig. 1 Photographs of dissected specimens showing anatomical parameters measured. A, distance between the nerve root and superior pedicle; b, distance between the nerve root and inferior pedicle; α , angle between the nerve root and sagittal plane; c, distance between the superior and inferior nerve roots; and d, distance between the superior and inferior pedicles.

Fig. 2 Procedure for measuring the distances between the nerve root and superior pedicle and between the nerve root and inferior pedicle. The position of the dorsal root ganglion of the nerve root is measured on a three-dimensional image. The distance between the nerve root and superior pedicle is the distance between the two horizontal tangents of the upper edge of the ganglion and the lower edge of the ipsilateral upper pedicle.

Fig. 3 Procedure for measuring the distances between the nerve root and superior pedicle and between the nerve root and inferior pedicle. The position of the dorsal root ganglion of the nerve root is measured on a three-dimensional image. The distance between the nerve root and inferior pedicle is the distance between the two horizontal tangents of the lower edge of the ganglion and the upper edge of the ipsilateral lower pedicle.

posterior margin of the L₄ vertebral body. The horizontal plane at the midpoint of the nerve root was located and the distance between the nerve root and upper pedicle defined as the vertical distance between the upper edge of the ganglion and lower edge of the upper pedicle in the coronal plane (Fig. 2). The distances were measured in three

continuous anatomical sections and the average selected. The distance between the nerve root and lower pedicle was defined as the vertical distance between the lower edge of the ganglion and upper edge of the lower pedicle in the coronal plane (Fig. 3), the measurement procedure being as described above.

Fig. 4 Procedure for measuring the angle between the nerve root and sagittal plane. The position of the dorsal root ganglion of the nerve root is measured on a three-dimensional image. The angle is between the following two lines: one connecting the midpoints of the vertical diameter of the nerve root ganglion and dural sac at the origin of the nerve root and the other is the vertical line parallel to the midline of the dural sac.

2. To measure the angle between the nerve root and sagittal plane (Fig. 4): the sagittal plane was located on the posterior margin of the L₄ vertebral body. The violet line in this figure represents the horizontal plane through the ganglions and the yellow line in the coronal plane the midline of the dural sac. A line was drawn through the midpoint of the superior inferior diameter of the ganglion and the midpoint of the superior inferior diameter of the dural sac at the point where the nerve root exits the dura. A line was then drawn parallel to the midline of the dural sac. The angle between these two lines was defined as the angle between the nerve root and sagittal plane.

3. The distance between adjacent nerve roots was defined as the distance between the lower edge of the upper nerve root and upper edge of the lower nerve root the measurement procedure being as described above.

4. The distance between adjacent pedicles was defined as the distance between the lower edge of the upper pedicle and upper edge of the lower pedicle, the measurement procedure being as described above.

Statistical Analysis

Statistical analysis was performed with SPSS13.0 statistical software (SPSS). Student's paired *t*-test was used to assess bilateral variables in the same segment. Data are expressed as mean $\pm$ standard deviation. *P* < 0.05 was considered statistically significant.

Results

Good imaging by MRN of the L₁–L₅ nerve roots was achieved in all 12 volunteers. The analysis of related variables is shown in Tables 1 and 2. Because of lumbar lordosis at L₅–S₁, some S₁ nerve roots images were not good. As a result, it was not possible to assess S₁ nerve root anatomic variables.

There were no statistically significant differences between bilateral variables in the same segment according to Student's paired *t*-test (*P* > 0.05).

Further analysis showed that changes in L₁–L₅ anatomic variables followed a pattern. For example, the spacing between the L₁–L₅ nerve root and upper pedicle gradually decreased, whereas the angle between the L₁–L₅ nerve root and sagittal plane gradually decreased from L₁ to L₅. These findings are consistent with those previously published²⁸. However, the value for the space between the L₅ nerve root and upper pedicle is negative, which means the ganglion is higher than the lower edge of the upper pedicle. Thus, clinicians need to understand this particular relationship to avoid damaging the ganglion.

Discussion

Comparison of Different Methods of Measuring Variables Related to Lumbosacral Nerve Roots

Data on lumbosacral nerve roots has mostly been obtained from preservative treated specimens; therefore, there may be

TABLE 1 Measurements of variables relating to lumbosacral nerve roots and adjacent structures from L₁–L₅ in men (mean $\pm$ s.d.)

segment	Distance between nerve root and upper pedicle (mm)		Distance between nerve root and lower pedicle (mm)		Angle between nerve root and sagittal plane (°)		Distance between adjacent nerve roots (mm)		Distance between adjacent pedicles (mm)	
	R	L	R	L	R	L	R	L	R	L
Men										
L ₁	5.00 $\pm$ 0.60	4.58 $\pm$ 0.39	9.23 $\pm$ 0.69	9.82 $\pm$ 0.43	36.22 $\pm$ 2.27	37.81 $\pm$ 3.71	29.78 $\pm$ 3.06	30.22 $\pm$ 2.02	18.63 $\pm$ 0.60	18.17 $\pm$ 0.47
L ₂	4.98 $\pm$ 0.35	5.08 $\pm$ 0.69	10.03 $\pm$ 0.90	10.72 $\pm$ 1.01	37.73 $\pm$ 3.10	32.52 $\pm$ 3.51	30.04 $\pm$ 2.91	31.28 $\pm$ 2.55	18.85 $\pm$ 0.67	19.62 $\pm$ 0.78
L ₃	3.67 $\pm$ 0.41	3.73 $\pm$ 0.53	9.20 $\pm$ 0.62	9.05 $\pm$ 0.72	34.74 $\pm$ 2.49	31.62 $\pm$ 2.07	27.88 $\pm$ 2.72	28.15 $\pm$ 2.79	17.95 $\pm$ 0.81	18.65 $\pm$ 0.78
L ₄	2.65 $\pm$ 0.27	2.37 $\pm$ 0.34	8.99 $\pm$ 0.88	9.23 $\pm$ 0.71	32.41 $\pm$ 1.97	30.27 $\pm$ 2.80	24.17 $\pm$ 2.42	24.53 $\pm$ 2.86	18.05 $\pm$ 0.35	17.82 $\pm$ 0.41
L ₅	-6.60 $\pm$ 2.17	-7.33 $\pm$ 2.00	—	—	24.65 $\pm$ 2.13	24.93 $\pm$ 2.38	—	—	—	—
Women										
L ₁	4.88 $\pm$ 0.71	4.79 $\pm$ 0.54	8.22 $\pm$ 0.34	7.99 $\pm$ 0.45	38.42 $\pm$ 2.22	37.54 $\pm$ 3.10	28.40 $\pm$ 2.12	29.60 $\pm$ 1.78	17.70 $\pm$ 0.75	17.47 $\pm$ 1.01
L ₂	4.54 $\pm$ 0.54	4.76 $\pm$ 0.32	8.54 $\pm$ 0.65	8.11 $\pm$ 0.45	37.65 $\pm$ 2.49	36.46 $\pm$ 3.11	28.19 $\pm$ 2.22	27.67 $\pm$ 2.43	17.34 $\pm$ 1.23	18.48 $\pm$ 0.99
L ₃	3.54 $\pm$ 0.35	3.66 $\pm$ 0.56	7.76 $\pm$ 0.46	7.86 $\pm$ 0.81	34.19 $\pm$ 2.78	33.76 $\pm$ 3.56	25.65 $\pm$ 2.83	25.89 $\pm$ 1.98	17.13 $\pm$ 1.27	16.53 $\pm$ 1.36
L ₄	3.31 $\pm$ 0.31	3.12 $\pm$ 0.34	8.01 $\pm$ 0.47	8.23 $\pm$ 0.77	31.99 $\pm$ 2.76	32.65 $\pm$ 3.18	21.88 $\pm$ 2.13	22.43 $\pm$ 2.56	16.13 $\pm$ 1.98	15.90 $\pm$ 1.87
L ₅	-4.78 $\pm$ 0.23	-5.21 $\pm$ 0.43	—	—	22.87 $\pm$ 4.23	23.98 $\pm$ 4.89	—	—	—	—

L, left; R, right. Because the S1 nerve roots were not clear in the MRN images from some volunteers, the relevant measurements were not available.

apparent discrepancies between them and our *in vivo* data. For example, in this study, distances between the nerve root and lower pedicle on the right side from L₃–L₅ in men were 10.03 ± 0.90 mm, 9.20 ± 0.62 mm and 8.99 ± 0.88 mm, respectively, and 10.72 ± 1.01 mm, 9.05 ± 0.72 mm and 9.23 ± 0.71 mm, respectively, on the left side. In women, the values were 8.54 ± 0.65 mm, 7.76 ± 0.46 mm and 8.01 ± 0.47 mm, respectively, on the right side and 8.11 ± 0.45 mm, 7.86 ± 0.81 mm and 8.23 ± 0.77 mm, respectively, on the left side. However, Ebraheim *et al.*²⁹ and Söyüncü *et al.*³⁰ reported that the pedicle–superior nerve root distances from L₃–L₅ are 5.6 mm, 5.7 mm and 5.5 mm, respectively, and 4.7 mm, 5.1 mm, 5.5 mm, respectively, on each side; these distances are shorter than those in our study. One possible explanation is that the cited studies were on preservative-treated and elderly specimens and degenerative changes in the vertebral body may have affected the measurements. In theory, anatomical study of fresh corpses provides data that are more applicable to clinical situations because they more truly reflect what is encountered during surgery and thus provide better guidance for clinical spine surgeons. Data obtained from fresh corpses are more accurate because dehydration has not yet occurred. However, there are no published measurements of spinal anatomic structure obtained from fresh corpses. On the other hand, there are not only few fresh cadavers available, but they also can have degenerative changes in their lumbar spines; therefore, data from such anatomic measurement cannot represent the normal population.

MRN technology is so far the optimal means of imaging spinal nerve shape and the reconstruction mode includes multiplanar reconstruction (MPR), maximum intensity projection (MIP) and volume rendering (VR). VR images, which are obtained non-invasively, are better than MPR and MIP for displaying spinal nerves, surrounding muscle, vascular structures and fascia and their anatomic relationships. Published studies have confirmed this spinal nerve imaging technology is reliable, clear and accurate^{26,27}. We therefore believe that

MRN is a good choice for studying lumbar-sacral nerve root anatomy and that anatomical study using MRN technology on healthy volunteers is useful clinically.

Analysis of the Safety of TLIF in Chinese subjects

The mean distance between adjacent pedicles at L₁–L₅ was 18 mm and 17 mm in men and women, respectively. However, the space for TLIF is the distance between the nerve root and lower pedicle, the mean values of which were 9 mm and 8 mm in men and women, respectively; the values for each segment were less than 10 mm in most of the volunteers. However, patients with lumbar degenerative disease always have subsidence of the intervertebral space; therefore, these values are significantly smaller in them than in normal individuals. Thus, during traditional TLIF surgery, especially during cage implantation, irritation and damage to the nerve roots is theoretically inevitable: we have confirmed by performing TLIF on cadavers²⁴. In light of our findings concerning lumbosacral nerve roots and surrounding structures, we believe that care must be taken to protect the upper nerve roots in patients with lumbar degenerative disease undergoing TLIF. There is also a risk of nerve root injury during surgery on patients with intervertebral stenosis. Our anatomical findings and preliminary clinical experience indicate that the procedure of posterior lumbar interbody fusion should be appropriately modified for Chinese patients with lumbar degenerative disease undergoing surgery. To minimize disturbance to and injury of the nerve roots during surgery, appropriate changes should be made to the traditional TLIF procedure^{25,31}.

This study has some limitations. Some S₁ nerve root images were unclear for technical reasons. We therefore were unable to evaluate the safety of TLIF at L₅–S₁ segment in Chinese subjects. In addition, this was a small study, and individual differences, lumbar curvature and other factors may influence the measured variables. This study was purely theoretical; analysis of large samples is needed, as well as verification by clinical procedures.

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