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ORIGINAL RESEARCH

Evaluation of Clinical Symptoms of Unilateral S1 Nerve Injury Caused by Disc Herniation the via High Resolution MRI and DTI

ChaoYang Zhang[1,*], Wei Hao[1,*], Xiaobo Guo[2], Yuna Zhang[1], Hao Fu[1], Jiashan Zhang[1]

[1]Department of Radiology, Jincheng General Hospital, Jincheng, Shanxi, People's Republic of China; [2]Department of Orthopaedics, Jincheng General Hospital, Jincheng, Shanxi, People's Republic of China

*These authors contributed equally to this work

Correspondence: ChaoYang Zhang, Email Zhangchaoyang8717@163.com

Background: The status of the herniated disc or nucleus pulposus and the extent of injury and clinical symptoms of the compressed S1 nerve fiber bundle were evaluated by high-resolution Magnetic resonance imaging (MRI) and Diffusion tensor imaging (DTI) techniques.

Methods: Forty-two clinically proven patients with unilateral S1 nerve root compression were selected as the case group (n=42), and 20 healthy volunteers were selected as the control group (n=20). The general data, MRI features and DTI parameters were compared between groups. The effective indicators of S1 neurologic fiber bundle damage were screened by univariate logistic regression analysis and receiver operating characteristic (ROC) curve, and multi-factor logistic regression models were constructed to analyze the diagnostic efficiency of each model.

Results: There were no significant differences in age, gender, height, weight, fractional anisotropy (FA) value and apparent diffusion coefficient (ADC) value on both sides of S1 nerve root between groups ($P > 0.05$). The FA value and ADC value of the nerve root on the affected side of the patient were significantly different from those on the healthy side and those on the corresponding side of the control group (all $P < 0.05$), and all of them were effective indicators of the damage of S1 nerve. The sensitivity, specificity and area under the curve of the damaged nerve fiber bundle were detected by multi-factor logistic regression models constructed with FA+rFA and FA+rFA+rADC of the affected nerve root, respectively 95.20%, 72.00%, 0.939, and 97.60%, 80.00%, 0.944.

Conclusion: High-resolution MRI and DTI can quantitatively evaluate the degree of nerve fiber bundle injury and clinical symptoms caused by lumbar disc herniation.

Keywords: lumbar disc herniation, high-resolution MRI, DTI, fractional anisotropy, apparent diffusion coefficient

Introduction

As people's pace of life and work changes, the prevalence of Lumbar Disc Herniation (LDH) has increased year by year, significantly reducing the quality of life for affected individuals.[1] Studies indicate that LDH is a leading cause of low back pain and disability, affecting a large proportion of the population, with global prevalence rates ranging from 5% to 20%, and peak incidence occurring in individuals aged 30 to 50 years. The most commonly involved segment is the S1 nerve.[2] It is estimated that approximately 10–15% of individuals with LDH experience compression of the S1 nerve root, resulting in substantial impairment of motor function, sensation, and daily activities.[3] Magnetic resonance imaging (MRI) is the most unique first-line imaging method.[4] However, conventional MRI methods do not provide the necessary quantitative data for analyzing the microstructure and functional condition of compressed nerve roots.[4,5] The impact of S1 nerve compression on patients' quality of life is profound, with many patients reporting chronic pain, limited mobility, and psychological distress.[6]

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In Diffusion weighted imaging (DWI) and Diffusion tensor imaging (DTI), not only the movement of lumbosacral nerve roots can be visually observed continuously, but also the microstructure and functional status of the nerve roots can be quantitatively analyzed.[5]

This study will investigate the change of DTI parameters in S1 unilateral nerve root compression caused by LDH, measure and calculate the fractional anisotropy (FA) value, FA ratio (rFA), apparent diffusion coefficient (ADC) value, ADC ratio (rADC). To compare the diagnostic efficacy of each parameter in the nerve root under compression. Japanese Orthopaedic Association Scores (JOA) were selected as the reference index of clinical symptom severity, and the correlation between DTI parameters and JOA and symptom duration was investigated.

Materials and Methods

General Data

A total of 42 patients with LDH clinically diagnosed with unilateral S1 nerve root compression in Jincheng General Hospital[1] from May 2023 to April 2024 were collected as a case group, including 23 patients with left nerve root compression and 19 patients with right nerve root compression. Another 20 healthy volunteers served as control group. The basic information of all subjects was recorded, including name, gender, age, height and weight, and the body mass index (BMI) was calculated. Study group inclusion criteria: MRI examination confirmed L5/S1 LDH and compression of unilateral S1 nerve root, which was consistent with clinical symptoms. Control group inclusion criteria: MRI showed no LDH. Exclusion criteria: ①Patients with contraindications for MRI examination; ②Patients with multi-segment protrusion and compression of nerve roots or bilateral nerve roots; ③Lumbar spine congenital variation, spinal stenosis, intraspinal tumor, lumbar spine fracture, spondylolisthesis, infectious disease;④History of previous lumbar surgery.

This study was approved by the ethics committee of Jincheng General Hospital (LL2024042101). The patient also signed an informed consent form before the examination.

Instruments and Methods

In this study, Siemens MAGNETOM Skyra 3.0T superconducting magnetic resonance scanner was used. The scanning parameters and strategies are shown in Table 1.

Image Analysis

Two imaging physicians with more than 10 years of experience were manually sketched 4–6mm2 ROI and measured DTI parameters at Neuro 3D workstation. Regions of interest (ROIs) were selected at three levels of nerve compression: near the internal foramen, at the foramen, and at the external foramen, with a 3mm interval between each level. For each level, the healthy side nerve root was selected at the corresponding position for comparison. ROIs were chosen symmetrically across both sides of the S1 nerve roots: starting from the internal foramen, moving through the foramen, and extending to the external foramen. At least three ROIs were selected for each nerve root. To ensure consistency across subjects, ROIs were marked symmetrically and compared between the affected and healthy sides. In case of significant discrepancies between measurements, re-measurement was conducted. Select at least 3 ROI for each nerve root. The average value of

Table 1 MRI Scanning Parameters and Strategies

Weighting	TR (ms)	TE (ms)	FOV (mm)	Matrix	LT (mm)	Interval (mm)	Nf (mm)	ETL	Averages	Flip Angle	b (s /mm^2)
T2 TSE sag	4000	110	300×300	314×448	4	0.4	13	25	2	>140	
T2 TSE tra	4000	94	220×220	256×320	3	0.35	15	20	2	>130	
T1 TSE sag	664	10	300×300	240×320	4	0.4	13	3	2	>140	
T1-vibe tra	7	2.46	200×200	248×256	1	0.2	160		3	12	
Ep2d-diff tra	8700	95	230×210	128×128	3	0	30				0/800

the obtained values is used as the FA value and ADC value of the corresponding nerve root. When the agreement is good, the average is taken as the obtained result, and when the difference is large, it needs to be re-measured. The rFA of each group was calculated, definition: Case group rFA= Diseased side FA/ Normal side FA, Case group rADC= Diseased ADC/ Normal side ADC, Control group(volunteer) rFA= Bilateral FA ratio, rADC= Bilateral ADC ratio.

After measuring the FA and ADC values, the image was switched to "Fusion Mode" for tractography. Seed points were manually placed along the S1 nerve root using the left mouse button and Ctrl key to ensure optimal coverage. The aim was to gather as many seed points as possible along the nerve root. Fiber tracking was then initiated by right-clicking and selecting "Start Tractography", which traces the nerve fibers. Afterward, "Delete Diffusion Seed-points" was clicked to generate the final diffusion tensor tractography (DTT) image. This process was repeated for each subject, ensuring consistent data quality and tract visualization across participants. The movement and continuity of nerve roots were observed in all directions.

Clinical Symptom Assessment

In all cases with a more than 10 years working experience in the spine, under the guidance of orthopaedic surgeons use JOA scoring system for the damage to the nerve roots in the corresponding areas to score, and record related symptoms start time and duration JOA. The main content consists of 3 items, each item 3–7 options, can be divided into four levels, 25–29 is excellent, 16–24 is good, 10–15 is moderate, and < 10 is poor. A higher score indicates a better functional state of the lumbar spine, and a lower score indicates a more pronounced dysfunction.

Statistical Analysis

SPSS 26.0 statistical software was used for statistical analysis. The count data were compared by chi-square test or Fisher exact probability method. Measurement data with normal distribution are expressed as mean ± SD. Intra-class correlation coefficient (ICC) was used to analyze the consistency of measurement results between two physicians. Intra-group and inter-group measurement data were compared by *t*-test. Correlation analysis was performed between the parameters of the case group and JOA scores as well as symptom duration, with Pearson correlation used for normally distributed data and Spearman correlation for non-normally distributed data. Univariate logistic regression analysis was applied to the measurement data, and receiver operating characteristic (ROC) curves and area under the curve (AUC) values were used to identify effective indices for detecting nerve fiber bundle damage. Additionally, a multivariate logistic regression model was constructed to evaluate the effectiveness of nerve root injury. The statistical power of the study was assessed based on the sample size of 42 patients and 20 healthy controls, ensuring sufficient power to detect significant differences in DTI parameters. This power analysis confirmed that the sample size was adequate for detecting clinically meaningful outcomes, with a significance level set at $P<0.05$.

Results

General Information Between Groups

There were no significant differences in age, sex, height and weight between groups ($P>0.05$). The difference in BMI was statistically significant ($P<0.05$) (Table 2).

Consistency Test of DTI Parameter Values

The results of the consistency analysis of the measured parameters of the two physicians reached a high consistency (ICC:0.817–0.911, $P < 0.05$) (Table 3).

Comparison of Parameter Results

There was no significant difference in FA and ADC values of nerve roots on both sides of volunteers at the same level ($P>0.05$) (Table 4).

The ADC value of S1 nerve root on the diseased side was higher than that on the normal side and control group, and the difference was statistically significant ($P < 0.05$) (Figure 1A). The rADC of case group was higher than that of

Table 2 Basic Information of Case Group and Control Group (n=62)

	Case Group (n=42)	Control Group (n=20)	t/χ^2	*P*
Age (years)	43.29±14.28	38.30±9.70	1.375	0.174
Sex			2.718	0.099
Male	30 (71.42%)	10 (50.00%)		
Female	12 (28.58%)	10 (50.00%)		
Height (m)	1.69±0.08	1.69±0.07	−0.242	0.810
Weight (kg)	71.18±13.92	63.95±10.09	2.077	0.042
BMI (kg/m^2)	24.89±3.69	22.23±2.11	2.99	0.004
JOA (score)	12.62±4.14			

Table 3 Parameter Consistency Test Results

	Parameters	ICC	95% CI	*P*
Diseased side	FA	0.817	0.684~0.898	<0.001
	ADC	0.909	0.836~0.950	<0.001
Volunteer	FA	0.862	0.688~0.943	<0.001
	ADC	0.911	0.793~0.964	<0.001

Abbreviations: ICC, Intra-class correlation coefficient; FA, Fractional anisotropy; ADC, Apparent diffusion coefficient.

Table 4 Comparison of FA and ADC Values of Nerve Roots in Volunteers (n=20)

	LEFT	RIGHT	t	*P*
FA	0.351±0.031	0.353±0.028	−0.259	0.797
ADC	1.541±0.145	1.530±0.135	0.297	0.768

Abbreviations: FA, Fractional anisotropy; ADC, Apparent diffusion coefficient.

control group, and the difference was statistically significant (P = 0.002) (Figure 1B). The FA value of S1 nerve root on the diseased side was lower than that on the normal side and control group, and the difference was statistically significant (P < 0.001) (Figure 1C); The rFA of the case group was lower than that of the control group, and the difference was statistically significance (P < 0.001) (Figure 1D).

Correlation Analysis of Case Group Parameters with JOA and Duration of Symptoms

There was no significant correlation between ADC, rADC and JOA (P>0.05). FA value, rFA of the diseased side and JOA were positively correlated (P<0.05, P<0.001). There was no significant correlation between the parameters and the duration of symptoms (P>0.05) (Figure 2A–D and Table 5).

Model Building

The results of univariate logistic regression analysis showed that FA, rFA and rADC were independent predictors of nerve fiber bundle damage. Multivariate logistic regression models Model 1 and Model 2 were constructed with FA+rFA and FA+rFA+rADC respectively. The sensitivity, specificity and AUC of the former were 95.20%, 72.00% and 0.939, respectively, and the sensitivity, specificity and AUC of the latter were 97.60%, 80.00% and 0.944, respectively (Figure 3A and B and Table 6).

DTT Nerve Fiber Tracer Imaging

In all patients, the nerve fibers on both sides of S1 level were asymmetrical and unnatural, and the nerve fiber bundles on the affected side were sparse, disordered and deformed, and some of them showed continuity interruption. The S1 nerve root fiber bundle of volunteers was symmetrical in shape and natural in movement, without continuous interruption, sparse or missing (Figures 4 and 5).

Discussions

According to research data, 95% of LDH occurs at L4/5 and L5/S1 levels, and the corresponding compressed nerves are L5 and S1 nerve roots, and only S1 nerve roots were studied in this study. By report,[7] The prevalence of LDH in men over 35 years old was slightly higher than that in women (4.8% and 2.5%, respectively). When BMI exceeds 24 kg/m^2, there is a linear increase in disc degeneration, which may be related to the increased load on the spine, thus significantly increasing the risk of LDH.[8]

FA is a unitless measure of axon anisotropy and is extremely sensitive to microstructure. The FA value of this study is consistent with that of previous studies of 0.200–0.400. This study showed that there was no statistical difference in the parameter values of nerve roots on the left and right sides of the volunteers at the same level of S1, and the parameter values of nerve roots on the healthy side of the case group and the volunteers at the same level, while the FA value of S1 nerve roots in LDH patients under pressure was smaller than that on the healthy side of the volunteers at the same level, which was consistent with most literature reports.[9–11] This may be related to the destruction of nerve root barrier, increased vascular permeability, congestion of nerve fiber bundle, edema, ischemia and hypoxia, demyelination, and

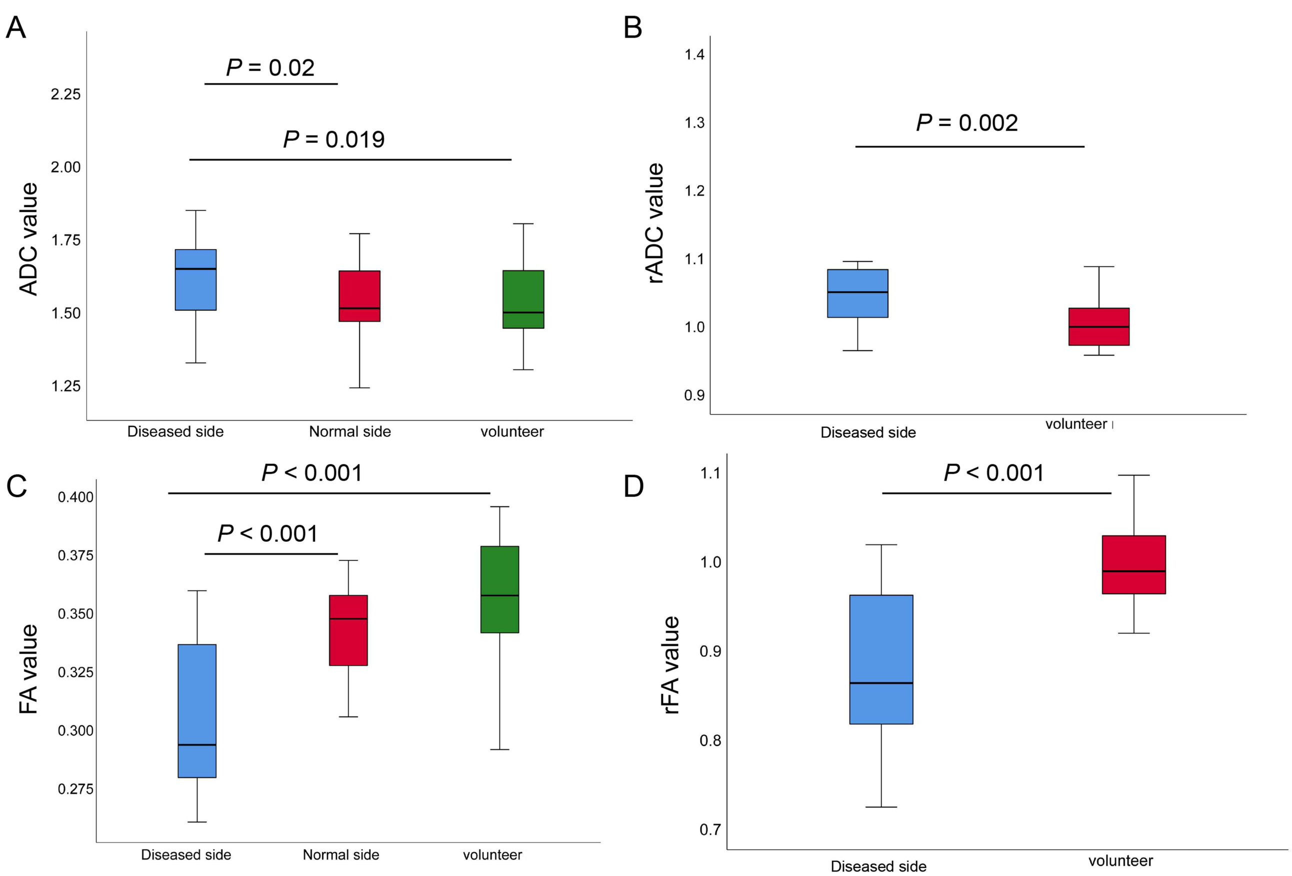

Figure 1 Comparison of FA and ADC values between the case group (patients with unilateral S1 nerve root compression) and the control group (healthy volunteers). (**A**) Apparent diffusion coefficient (ADC) values in the diseased side (blue), normal side (red), and volunteer group (green); (**B**) ADC ratio (rADC) comparing the diseased side (blue) to the volunteer group (red); (**C**) Fractional anisotropy (FA) values in the diseased side (blue), normal side (red), and volunteer group (green); (**D**) FA ratio (rFA) comparing the diseased side (blue) to the volunteer group (red).

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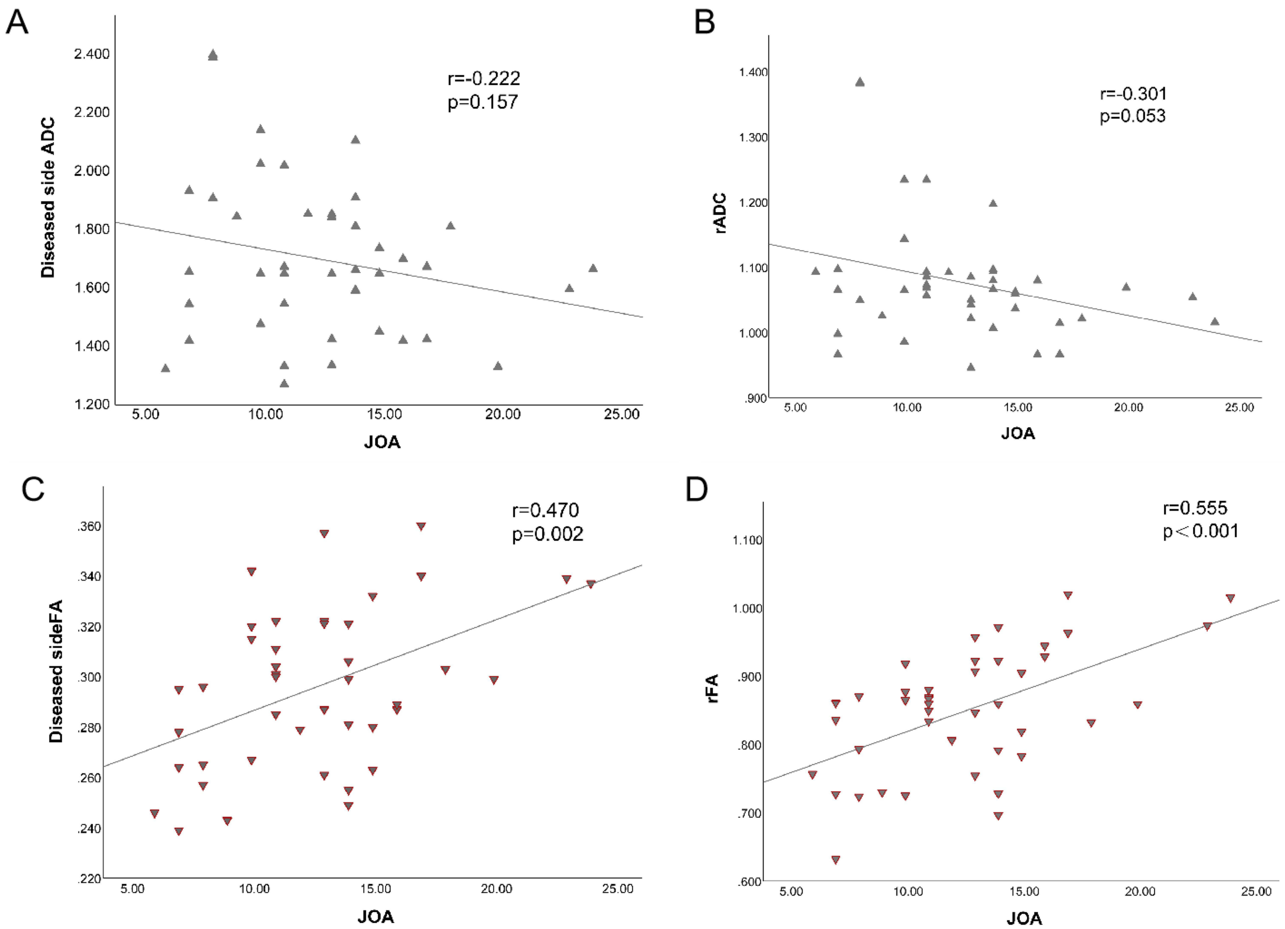

Figure 2 Correlation analysis of DTI parameters on the diseased side. (**A**) Correlation between JOA and ADC; (**B**) Correlation between JOA and rADC; (**C**) Correlation between JOA and FA; (**D**) Correlation between JOA and rFA.

Waller's degeneration.[12] However, it is important to note that the resolution of DTI may not be sufficient to accurately assess small nerve structures, such as cranial and spinal nerves. DTI is primarily capable of detecting potential injury, but its ability to measure the extent of injury in these fine structures is limited by the spatial resolution of current imaging techniques.

Most studies suggest that the ADC value of the affected nerve root is greater than that of the normal nerve root.[13] Similar results were found in this study. This may be related to nerve edema, myelinolysis, increased cellular space, and increased diffusion of water molecules. While these findings suggest potential injury, it is critical to acknowledge that

Table 5 Correlation Analysis Was Performed Between Case Group Parameters and JOA and Symptom Duration (n=62)

	JOA		**Symptom Duration**	
	r	***P***	**r**	***P***
ADC	−0.222	0.157	−0.230	0.143
rADC	−0.301	0.053	−0.111	0.483
FA	0.470**	0.002	−0.069	0.666
rFA	0.555**	<0.001	−0.034	0.832

Notes: **: Indicates highly significant correlation (P < 0.01).

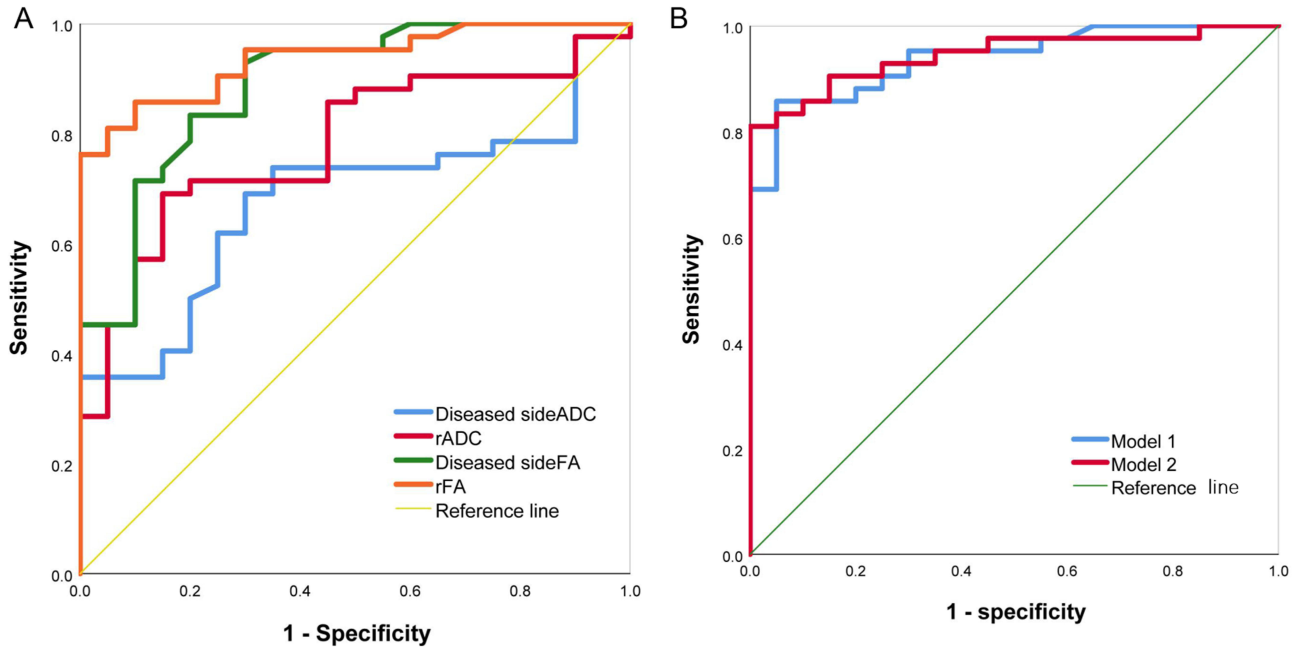

Figure 3 ROC curve of nerve fiber bundle damage. **(A)** FA, rFA, ADC and rAD; (**B**) Model 1 and Model 2.Significant differences between the curves for the case and control groups are observed, indicating the effectiveness of the DTI parameters (FA, rFA, and rADC) in distinguishing nerve fiber damage.

DTI is not always able to accurately quantify the degree of damage in smaller nerve structures, particularly in the cranial and spinal nerves, due to the limitations in imaging resolution. In order to avoid the interference of patients' baseline characteristics on FA and ADC, rFA and rADC were also used as parameter indicators in this study, and the results showed that rFA and rADC in the case group were statistically different from those in the volunteers. This is consistent with a study of DTI parameters.[14]

Furthermore, Diffusion Tensor Imaging (DTI) has gained prominence for its application in evaluating structures such as cranial nerves, especially in complex surgical contexts like cerebellopontine angle (CPA) surgeries. Recent research has demonstrated that DTI can provide high-resolution, three-dimensional imaging of nerve pathways, crucial for preoperative planning and intraoperative nerve monitoring. DTI aids in identifying nerve fibers, guiding their preservation, and potentially reducing the risk of nerve damage during delicate surgeries such as CPA resection.

For instance, Lian et al[9] found that DTI-guided tractography greatly enhanced the precision of nerve identification in lumbar spine surgery. Additionally, Chuanting et al[10] used 3.0T MRI tractography to visualize lumbar nerve roots in patients with herniated discs and observed significant improvement in surgical outcomes, highlighting DTI's role in enhancing nerve preservation.

Shi et al showed a strong correlation between the FA value of compressed nerve roots and JOA score. This study showed that FA value and rFA of the affected nerve root were positively correlated with JOA score, which was consistent

Table 6 ROC Curve Was Used to Screen the Effective Indexes of Nerve Fiber Bundle Damage (n=62)

	AUC	Sensitivity	Specificity	Cut off	*P*
ADC	0.678 (0.544–0.812)	0.738	0.700	1.536	0.024
rADC	0.779 (0.662–0.896)	0.813	0.710	1.014	<0.001
FA	0.889 (0.803–0.976)	0.833	0.800	3.096	<0.001
rFA	0.936 (0.880–0.993)	0.905	0.750	1.037	<0.001
Model 1	0.939 (0.883–0.994)	0.952	0.720	0.652	<0.001
Model 2	0.944 (0.890–0.998)	0.976	0.800	0.476	<0.001

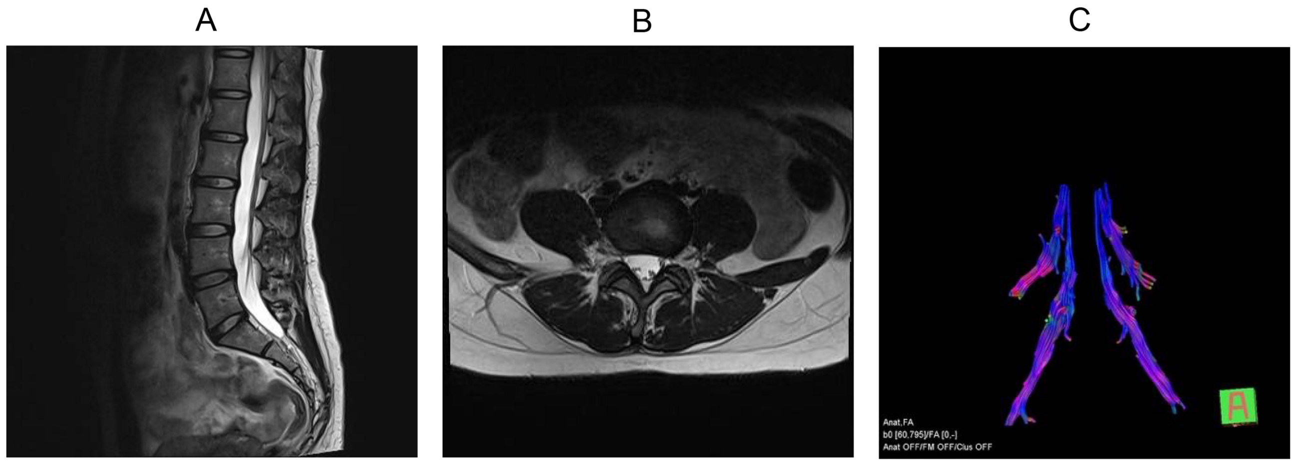

Figure 4 Healthy male volunteer, 30 years old, with no history of back and leg pain. (**A**) T2WI sagittal view showing no disc herniation. (**B**) T2WI transverse view showing no abnormalities. (**C**) DTT (Diffusion Tensor Tractography) image showing intact and symmetric L5 and S1 nerve fiber bundles, with no evidence of thinning, interruption, or missing fibers. (**A**) the frontal view, meaning it is viewed from anterior to posterior.

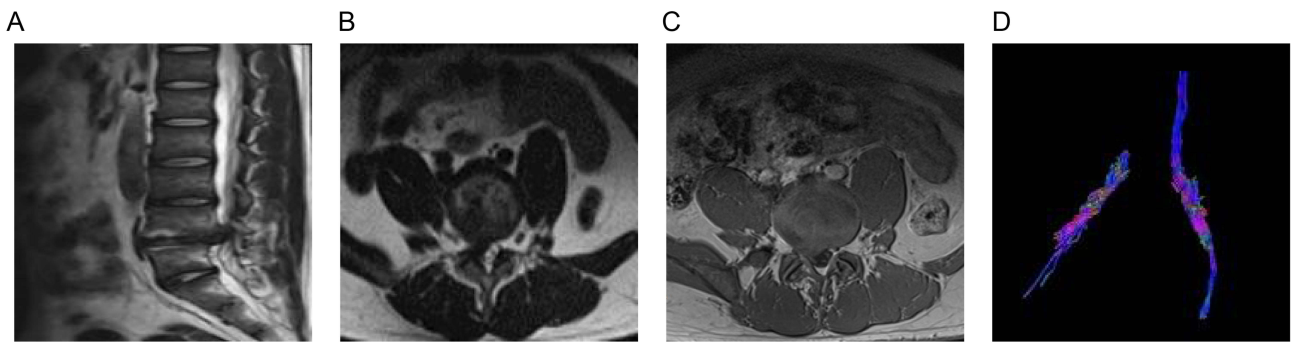

Figure 5 Male volunteer, 40 years old, L5/S1 LDH(RIGHT). (**A**) T2WI showing a curved indentation and substantial compression of the dural sac at the L5/S1 disc, located posteriorly on the right. (**B**) T2WI transverse view showing a posterior shift of the nucleus pulposus on the right, loss of the L5 right recess, compression of the ipsilateral L5 and S1 nerve roots, and removal of the foraminal adipose space. (**C**) Anatomical image showing the deformation and thinning of the affected nerve roots. (**D**) DTT image showing asymmetric nerve fiber bundles, with deformation and local discontinuity in the right S1 nerve root at the herniation site.

with Shi et al. This may cause immune reaction in the epidural space with the herniated intervertebral disc or nucleus pulposus tissue, causing the proliferation of immune cells, and eventually leading to the accumulation of local inflammatory factors, inducing the occurrence of nerve root pain[15] Wu et al[16] believed that FA would decrease significantly with the increase of time. The parameters of this study were not correlated with the duration of clinical symptoms, which was inconsistent with the results of Wu et al. This may be caused by the different time of case collection and treatment stage.

Zhang et al[17] believed that FA was the most sensitive index to distinguish normal nerves from regenerative nerves. Wu et al[18] believe that FA value and rFA on the affected side have good predictive performance for surgical outcome. In a study evaluating the sciatic nerve, rFA is considered to be important in the diagnosis of the degree of nerve damage.[19] In this study, logistic regression showed that rFA was the best index to evaluate the degree of nerve fiber bundle injury and clinical symptoms caused by lumbar disc herniation, followed by FA value and rADC. While these parameters provide useful insights, the use of DTI for small nerve structures, such as cranial and spinal nerves, is constrained by the imaging resolution. Further analysis through multivariate logistic regression models (Model 1 and Model 2) demonstrated that combining multiple DTI parameters, such as FA, rFA, and rADC, significantly improved the diagnostic efficiency. Specifically, Model 2, which included FA, rFA, and rADC, achieved an AUC of 0.944, a sensitivity of 97.60%, and a specificity of 80.00%, which were notably higher than those of individual parameters. This suggests that incorporating multiple parameters in the logistic regression models enhances the overall diagnostic accuracy, making them more robust for identifying nerve fiber bundle damage. AUC and Sensitivity of diagnostic Specificity were improved by combining several parameters, though specificity still remains suboptimal, indicating a potential area for further refinement in future studies.

Zhang et al[17] used DTT to detect axial three-dimensional T2-weighted images to evaluate the fiber rupture of severely and mildly compressed nerve roots. The incidence of fiber rupture was 50% and 19% respectively, which realized the visualization of spinal nerve roots, and the location and degree of compression of nerve roots could be directly observed, thus providing certain guiding significance for subsequent surgical treatment. In the DTT images reconstructed in this study, the nerve roots of healthy control group walked naturally and symmetrically. In the case group, the nerve roots of the affected side were distorted and disordered, and the shape was asymmetrical compared with that of the contralateral side. However, it is essential to recognize that DTT's ability to visualize small structures, such as cranial and spinal nerves, is limited by the resolution of the imaging system. While DTT successfully visualizes large nerve roots, it may not provide the same level of clarity or accuracy for smaller, finer nerve fibers. Embodiments of different degrees could be seen. Continuity interruption was observed in some nerve roots, and the compression parts could be accurately identified in the images.

Conclusions

In summary, DTT images can continuously and intuitively display the condition of nerve fiber bundles. High-resolution MRI and DTI can quantitatively evaluate the degree of injury and clinical symptoms of nerve root compression caused by lumbar disc herniation. JOA was positively correlated with FA and rFA, but not ADC and rADC. There was no correlation between the duration of symptoms and FA, ADC, rFA and rADC. The combination of parameters in the construction of logistic regression model significantly enhances the diagnostic efficiency. This approach allows for a more accurate differentiation of damaged nerve fiber bundles, which is crucial for early detection of nerve root compression. Moreover, the use of logistic models in clinical practice could streamline the diagnostic process and improve the overall accuracy of diagnosis, potentially leading to better clinical outcomes, such as more timely interventions and improved patient management. However, DTI does not directly quantify the degree of nerve damage but provides valuable information on nerve fiber integrity through parameters such as FA and ADC. In addition, this study is a single-center study with limited positioning, and the parameters included in the multi-factor logistic regression model are constrained by the available data, suggesting the need for further refinement in future research.

Data Sharing Statement

The data used to support the findings of this study are available from the corresponding author upon request.

Ethics Approval and Consent to Participate

This study was approved by the ethics committee of Jincheng General Hospital (LL2024042101) and was conducted in accordance with the Declaration of Helsinki and clinical practice guidelines. The patient also signed an informed consent form before the examination.

Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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Disclosure

The authors report no conflicts of interest in this work.

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