Clinical applications of diffusion magnetic resonance imaging of the lumbar foraminal nerve root entrapment

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Abstract Diffusion-weighted imaging (DWI) can provide valuable structural information about tissues that may be useful for clinical applications in evaluating lumbar foraminal nerve root entrapment. Our purpose was to visualize the lumbar nerve root and to analyze its morphology, and to measure its apparent diffusion coefficient (ADC) in healthy volunteers and patients with lumbar foraminal stenosis using 1.5-T magnetic resonance imaging. Fourteen patients with lumbar foraminal stenosis and 14 healthy volunteers were studied. Regions of interest were placed at the fourth and fifth lumbar root at dorsal root ganglia and distal spinal nerves (at L4 and L5) and the first sacral root and distal spinal nerve (S1) on DWI to quantify mean ADC values. The anatomic

parameters of the spinal nerve roots can also be determined by neurography. In patients, mean ADC values were significantly higher in entrapped roots and distal spinal nerve than in intact ones. Neurography also showed abnormalities such as nerve indentation, swelling and running transversely in their course through the foramen. In all patients, leg pain was ameliorated after selective decompression ($n = 9$) or nerve block ($n = 5$). We demonstrated the first use of DWI and neurography of human lumbar nerves to visualize and quantitatively evaluate lumbar nerve entrapment with foraminal stenosis. We believe that DWI is a potential tool for diagnosis of lumbar nerve entrapment.

Keywords Diffusion-weighted imaging · Apparent diffusion coefficient · Lumbar foraminal stenosis · Magnetic resonance (MR) imaging · Neurography

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Introduction

In patients with degenerative lumbar disease, lumbar foraminal stenosis often causes nerve root entrapment, which is characterized by radicular symptoms affecting the leg [1–6]. This condition unfortunately results in failed back surgery syndrome and is the cause of continued postoperative pain because of the difficulty of making a correct diagnosis [7, 8]. Conventional magnetic resonance (MR) imaging (MRI) has been inadequate for evaluating symptomatic foraminal stenosis, because of the high incidence of false-positives found in asymptomatic elderly patients [9]. New diagnostic imaging techniques to detect lumbar nerve root entrapment are urgently required.

Diffusion-weighted imaging (DWI) based on MRI can provide valuable information regarding the microstructure of tissues by monitoring the random movement of water

molecules, which is restricted in tissues by applying a motion probing gradient (MPG) in some directions [10–13]. The diffusion data can be used for determination of quantitative diffusion values such as the apparent diffusion coefficient (ADC). DWI has been widely used for clinical applications in evaluation of the central nervous system for the diagnosis of diseases such as acute brain stroke [14]. Recently, it has been reported that DWI is useful for the evaluation and diagnosis of lesions such as multiple sclerosis [15, 16] and peripheral nerve compression disorders such as carpal tunnel syndrome [17–19], using diffusion values such as ADC. An increase in the mean diffusivity (ADC) values was observed in injured nerves with demyelination [15, 16, 19, 20]. Imaging of the spinal cord is challenging because of technical limitations such as the relatively small size of the cord, susceptibility artifacts because of tissue–bone interfaces, and the motion artifacts arising from respiratory activity [21].

To date, quantitative DWI has not been applied to evaluate the pathology of lumbar nerve root entrapment, which may contribute to radicular symptoms in patients with lumbar foraminal stenosis. The purpose of this study was to measure ADC of the fourth and fifth lumbar nerve roots (at L4 and L5) and the first sacral nerve root (at S1) in healthy volunteers and patients with lumbar foraminal stenosis using MRI at 1.5 T. This study also investigates the morphology of the nerve root in symptomatic foraminal stenosis using neurography [22, 23]. This study included those patients in whom performing a selective decompression or a selective nerve root block ameliorated leg pain.

Materials and methods

Subjects

Fourteen patients [8 male, 6 female, median age 62.0 years (40–76)] who had unilateral radicular symptoms affecting leg pain with lumbar foraminal stenosis and without central lumbar canal stenosis were studied using MRI. The final diagnoses were as follows: 11 foraminal stenoses, 1 lateral recess stenosis, 1 extraforaminal disk herniation, and 1 intraforaminal disk herniation (Table 1). Fourteen healthy volunteers [7 male, 7 female, median age 55 years (37–75 years)] served as controls. The diagnoses were based on neurologic symptoms, a selective nerve root block, and a combination of diagnostic images including plain radiographs, computerized tomography (CT), and MRI. The locations of symptomatic foraminal stenosis in 14 patients were 10 at the L5 nerve root, 4 at the L4 nerve root, and none at the S1 nerve root. The patient exclusion criteria were as follows: (1) those who had lumbar spine surgery before this DWI study, (2) those who had multiple levels of lumbar canal stenosis, and (3) those who had myelopathy. Nine patients underwent surgical treatment for lumbar foraminal stenosis: one medial fenestration and eight total facetectomies with spinal fusion. Leg pain was ameliorated in all selected patients after selective decompression. The operative result was evaluated using a visual analog scale (VAS) scoring system from 100 (extreme amount of pain) to 0 (no pain).

Table 1 Summary of diagnosis, visual analog scale (VAS), and surgical method in patients

No.	Age (years)	Diagnosis	Symptomatic root	VAS		Surgical method
				Presurgery	Postsurgery	
1	76	Foraminal stenosis	L4 (Rt)	60	20	Facetectomy + TLIF
2	61	Foraminal stenosis	L5 (Rt)	100	0	Facetectomy + TLIF
3	40	Foraminal stenosis	L5 (Rt)	100	0	Facetectomy + TLIF
4	71	Lateral recess stenosis	L5 (Lt)	70	10	Medial fenestration
5	76	Foraminal stenosis	L5 (Lt)	60	10	Root block
6	65	Foraminal stenosis	L5 (Rt)	80	0	Facetectomy + TLIF
7	54	Extraforaminal disk herniation	L4 (Rt)	40	0	Root block
8	65	Foraminal stenosis	L4 (Rt)	90	0	Root block
9	47	Intraforaminal disk herniation	L5 (Lt)	80	0	Root block
10	68	Foraminal stenosis	L5 (Lt)	80	15	Facetectomy + TLIF
11	56	Foraminal stenosis	L5 (Lt)	60	10	Root block
12	66	Foraminal stenosis	L5 (Rt)	90	0	Facetectomy + TLIF
13	61	Foraminal stenosis	L4 (Rt)	75	20	Facetectomy + TLIF
14	64	Foraminal stenosis	L5 (Lt)	90	15	Facetectomy + TLIF
Mean	62			76.8	7.1	

Rt right, Lt left

MRI protocol

A 1.5-T MRI scanner (Philips Medical Systems, Philips Electronics Japan, Ltd. Achieva 1.5 T Nova Dual) was used in this study. Subjects were scanned in the supine position using a Sense XL Torso coil. DWI was performed using diffusion-weighted whole-body imaging with a background body signal suppression (DWIBS) and short TI inversion recovery–echo planar imaging (STIR–EPI) sequence with a free breathing scanning technique, which allows screening for malignancies in the whole body in a manner similar to that used in positron emission tomography (PET) [24, 25]. The following imaging parameters were set: 1,000 s/mm² *b* value, MPG direction phase, 7,130/66/170 ms frequency and slice for TR/TE/TI, respectively, axial slice orientation, 4/–1 mm slice thickness/gap, 400 mm field of view (FOV), 160 × 125 matrix, 2.5 × 3.19 × 4.0 mm³ actual voxel size, 1.6 × 1.6 × 4.0 mm³ calculated voxel size, 6 excitations, 70 signals averaged, 9 min 18 s scan time.

Image analysis

After DWI data were transferred to a PC, PRIDE software (Philips Medical Systems) was used for neurography and ADC mapping. Neurography in the coronal plane was constructed from coronal maximum intensity projection (MIP) on DWI with *b* values of 1,000 and an inverted black-and-white gray scale. Neurography is based on the concept of DWIBS, which enables a multiple thin-slice scan with adequate signal-to-noise ratio without breath-hold. This sequence depicts tissues with an impeded diffusion such as spinal cord, and peripheral nerves. Furthermore, the use of a short T1 inversion recovery for fat

suppression and heavy diffusion weighting will ensure the suppression of unwanted signals, like those of fat, muscles, tendons, and blood vessels. Using this technique, the trajectory of the nerves is well visualized on MIP images. Circular regions of interest (ROIs) were placed in anatomic locations on the lumbar nerve root in expected axial ADC maps based on information from the coronal and sagittal image and the software gave the measured quantitative parameters: mean ADC value (Fig. 1). ROI placement was made at two levels: the proximal nerve root at the dorsal root ganglia (DRG) and the distal spinal nerve. Mean ADC values were calculated with the software at two levels of the nerve root from L4–S1 in patients and healthy volunteers (Fig. 2). ROIs smaller than the nerve were selected to avoid partial volume effects when the mean ADC was calculated. The neurography was also used for evaluation of morphometric parameters such as angulation, length, and width of the DRG in patients and healthy volunteers and to investigate abnormalities such as swelling and indentation of nerve roots in their course through the foramen (Fig. 2). All DWI analyses were performed by two radiologists and three trained spine surgeons.

Statistical analysis

Statistical analyses were performed with Stat View software (version 5.0). A post hoc test was used to compare ADC between healthy volunteers and patients with lumbar foraminal stenosis at L4–S1 nerve roots. *P* < 0.05 was considered significant.

All subjects were studied after informed consent, and the study had prior approval of the Chiba University ethics committee.

Fig. 1 Example of mean ADC values on a nerve root in expected axial ADC maps based on information from the coronal and sagittal image using the software

Fig. 2 Schematic drawing showing measurement of angulation of dorsal root ganglia (a), length of dorsal root ganglia (b), and width of dorsal root ganglia (c)

Results

Normal subjects

In healthy volunteers, neurography clearly visualized all L2–S1 nerve roots and spinal nerves that symmetrically coursed obliquely downward (Fig. 3). Mean ($\pm$ SD) L4–S1 angulations of DRG were 38.5 ± 3.3 degrees for L4, 39.0 ± 4.8 degrees for L5, and 25.4 ± 4.6 degrees for S1, and differences were not found between the right and the left side nerves. The angulations of DRG decreased from L4 to S1 (Fig. 4a). Mean ($\pm$ SD) L4–S1 sizes of DRG (in length and in width) were 7.3 ± 1.1 and 5.0 ± 0.8 for L4, 9.6 ± 1.5 and 6.2 ± 0.8 for L5, and 12.4 ± 1.9 and 5.6 ± 0.7 for S1, and differences were not found between the right and the left side nerves. The length of DRG increased from L4 to S1 and the width of DRGs increased progressively to a maximum at L5 and decreased at S1 (Fig. 4b). Mean ($\pm$ SD) L4–S1 ADC values of nerves (proximal nerve root and distal spinal nerve) were $1.228 \pm 0.121 \times 10^{-3}$ and $1.059 \pm 0.174 \times 10^{-3}$ mm²/s for L4, $1.247 \pm 0.068 \times 10^{-3}$ and $1.144 \pm 0.139 \times 10^{-3}$ mm²/s for L5, and $1.296 \pm 0.085 \times 10^{-3}$ and $1.169 \pm 0.099 \times 10^{-3}$ mm²/s for S1, and differences were not found between the right and left side nerves at the same lumbar segment. Mean ADC was higher in the nerve root than in the distal spinal nerve (Fig. 4c).

Subjects with foraminal stenosis

In patients, neurography frequently showed abnormalities such as nerve indentation, swelling, and running transversely in their course through the foramen (Figs. 5, 6). For L5–S1 foraminal stenosis, the entrapped nerve shifted upward and ran transversely in the foramen (Fig. 5). For intraforaminal disk hernia, neurography can reveal the L5 nerve swelling and indentation clearly. The ADC of L5 nerve on the side of entrapment was 1.71×10^{-3} mm²/s, higher than the 1.09×10^{-3} mm²/s on the intact side. On the other hand, the ADC of intact S1 nerve was 1.39×10^{-3} mm²/s on the right side and 1.37×10^{-3} mm²/s on the left side, and differences were not found between the right and left side (Fig. 6).

The mean ADC of proximal nerve roots on the side of entrapment was $1.387 \pm 0.172 \times 10^{-3}$ mm²/s, higher than the $1.206 \pm 0.105 \times 10^{-3}$ mm²/s on the intact side; and distal spinal nerve ADC on the side of entrapment was $1.507 \pm 0.162 \times 10^{-3}$ mm²/s, higher than the $1.154 \pm 0.116 \times 10^{-3}$ mm²/s seen on the intact side ($P < 0.001$, Table 2; Fig. 7a). The comparisons of stenotic level (L4 $n = 4$, L5 $n = 10$) to non-stenotic level (S1 $n = 14$) in the same subject are also shown in Fig. 7b. The differences of ADC values (nerve root and distal spinal nerve) between entrapped and intact side were $0.181 \pm 0.171 \times 10^{-3}$ mm²/s and $0.354 \pm 0.173 \times 10^{-3}$ mm²/s, higher than the $0.013 \pm 0.087 \times 10^{-3}$ mm²/s ($P < 0.01$) and the $0.010 \pm 0.121 \times 10^{-3}$ mm²/s ($P < 0.001$) on the non-stenotic level (S1) between right and left side in the same subject.

The angulation of DRG on the side of entrapment was $55.6 \pm 15.8^\circ$, more than the $44.9 \pm 9.5^\circ$ on the intact side ($P < 0.05$, Table 2). The sizes of DRG (in length and in width) on the side of entrapment were 12.4 ± 3.1 and 6.3 ± 0.8 mm, more than the 8.9 ± 2.2 mm ($P < 0.01$) and 5.3 ± 0.6 mm ($P < 0.001$) on the intact side (Table 2).

Nine patients underwent surgical treatment for lumbar foraminal stenosis: one medial fenestration without abnormal nerve course, and eight total facetectomies and transforaminal interbody fusion (TLIF) with abnormal nerve course such as transverse running. In all of the patients, the nerve root compression in the narrowed lumbar foramen was observed and radicular pain was ameliorated after selective decompression. The average VAS scores of 12 patients were significantly improved from 76.8 before surgery to 7.1 one month after surgical method including root block (Table 1).

Discussion

Lumbar foraminal stenosis is a condition in which a nerve root or spinal nerve is entrapped in the narrowed lumbar

Fig. 3 Coronal diffusion-weighted image of a lumbar nerve root in a healthy volunteer. **a** The $b = 0$ image, **b** neurography using $b = 1,000$, as described in the “Materials and methods”. L4, L5,

and S1 indicate the fourth and fifth lumbar root and first sacral root. **c** The calculated ADC map based on the DWI

Fig. 4 The angulation of dorsal root ganglia (**a**), the size of dorsal root ganglia in length and in width (**b**), and mean ADC values at proximal nerve root and distal nerve (**c**) in healthy volunteers. The angulations of the ganglia remain 40° for L4 and L5, decreasing acutely to 25° at S1. The length of the ganglia increased from L4 to S1 and the width increased progressively to a maximum at L5 and decreased at S1. Mean L4–S1 ADC values of nerve were approximately $1.2 \times 10^{-3} \text{ mm}^2/\text{s}$ in the nerve root higher than $1.1 \times 10^{-3} \text{ mm}^2/\text{s}$ in the distal spinal nerve

foramen in degenerative lumbar spinal disorders [1–6]. The incidence of nerve root entrapment has been reported to be between 8 and 11% in degenerative lumbar disease [26, 27]. A higher incidence of foraminal stenosis is found in the lower lumbar segments [28, 29]. Jenis and An [4] reported that the most common roots involved are the L5 root (75%), followed by the L4 root (15%), the L3 root (5%), and the L2 root (4%), which is consistent with our findings. In its clinical presentation, severe leg pain at rest

and limited lumbar extension to the painful side (Kemp’s sign) were observed at high frequency [27]. Although imaging studies including radiography, CT, and MRI [30–33] provide an effective means for evaluating the foraminal stenosis, these conventional imaging techniques do not detect foraminal stenosis with any certainty because false-positive findings may be frequently observed. Evaluation of clinical findings and selective nerve root infiltration and block are necessary to make a correct diagnosis [34]. This

Fig. 5 Diffusion-weighted image of a lumbar nerve root in a 66-year-old man with L5–S1 foraminal stenosis (referenced as patient no. 12 in Table 1). **a** Parasagittal T1-weighted image. The *arrowhead* shows L5 foraminal stenosis with loss of the perineural fat signal. **b** The coronal $b = 0$ image. **c** The coronal neurography using $b = 1,000$

image, as described in the “Materials and methods”. L4, L5, and S1 indicate the fourth and fifth lumbar root and first sacral root. **d** The coronal calculated ADC map based on DWI. The *arrow* shows the entrapped nerve shifted upward and ran transversely in the foramen

condition unfortunately results in failed back surgery syndrome because it is difficult to make a correct diagnosis, for which advanced neuroimaging techniques are required.

In this study, we have shown that DWIBS can clearly show lumbar nerve roots and determine ADC values of the nerve roots in the patients and healthy volunteers using MRI at 1.5 T. DWIBS using STIR–EPI sequences and a free breathing scanning technique can provide 3D reconstructed images for whole-body imaging with adequate fat suppression that may allow us to use this method, as well as PET scanning, as a screening tool for malignancies [24, 25]. Since tumors have larger cells and higher cellularity than normal tissue, the ADC values of tumors may be decreased [35]. Although peripheral nerves cannot be selectively visualized by the conventional MRI using T1- and T2-weighted imaging, Takahara et al. [23] have demonstrated the feasibility of whole-body magnetic resonance neurography with the use of DWI that could depict tissues with an impeded diffusion such as tumors, brain, spinal cords, and peripheral nerves. In this study, DWIBS can provide DWI and neurography of an entire lumbar nerve root in about 10 min. In morphometric analysis of healthy volunteers, the angulations of the ganglia remain 40° at L4 and L5, decreasing acutely to 25° at S1. The

length of the ganglia increased from L4 to S1 and the width increased progressively to a maximum at L5 and decreased at S1. Our results are consistent with those reported by Cohen et al. [28] and Hasegawa et al. [29, 30]. On the other hand, in patients, the angulation and the size of DRG on the side of entrapment were higher than on the intact side, indicating abnormalities such as swelling and transverse running of nerve roots in the foramen. Moreover, the mean ADC in nerve root entrapment with foraminal stenosis was higher than in intact nerve roots.

Olmarker et al. [36] reported that slow onset of compression caused edema and demyelination in spinal nerve roots of the pig cauda equine. MacDonald et al. [20] used a mouse brain injury model and showed that relative anisotropy and axial diffusivity were reduced by 6 h to 4 days after trauma, corresponding to axonal injury, while 1–4 weeks after trauma, relative anisotropy remained decreased, whereas radial diffusivity increased, corresponding to demyelination, edema, and persistent axonal injury. Previous studies of ADC values in central nerve lesions such as spinal cord injury and multiple sclerosis and peripheral nerve compression such as found in carpal tunnel syndrome are controversial [15]. To date, there are no studies assessing ADC values of lumbar nerve root

Fig. 6 Diffusion-weighted image of a lumbar nerve root in a 47-year-old man with L5–S1 intraforaminal disk hernia (referenced as patient no. 9 in Table 1). **a** Parasagittal T1-weighted image. The *arrowhead* shows L5 foraminal stenosis with loss of the perineural fat signal. **b** Axial T2-weighted image. The *arrowhead* shows intraforaminal disk hernia on the left side. **c** The coronal $b = 0$ image. **d** The coronal

neurography using $b = 1,000$ image, as described in the “[Materials and methods](#)”. L4, L5, and S1 indicate the fourth and fifth lumbar root and first sacral root. **e** The coronal calculated ADC map based on DWI. The *arrow* shows nerve swelling and indentation compared with intact side

Table 2 Summary of apparent diffusion coefficient (ADC), angulation of dorsal root ganglia (DRG), and size (length and width) of DRG in patients

No.	ADC ($\times 10^{-3}$ mm ² /s)				DRG angulation (°)		DRG size (mm)			
	Nerve root		Spinal nerve				Length		Width	
	Entrapped	Intact	Entrapped	Intact	Entrapped	Intact	Entrapped	Intact	Entrapped	Intact
1	1.735	1.157	1.52	1.321	69	62	13.5	10.9	8.3	6.8
2	1.366	1.306	1.441	1.064	75	51	13.1	7.6	6.1	5.1
3	1.125	1.155	1.812	1.159	70	53	14.4	10.1	7	5.7
4	1.436	1.2	1.465	1.125	30	32	8	6.2	5.1	4.4
5	1.444	1.18	1.432	1.056	37	41	13.7	10.9	6.5	5.3
6	1.339	1.236	1.711	1.118	59	43	10.7	6.8	7	5.5
7	1.568	1.278	1.421	1.183	51	39	9.6	5.7	6	5
8	1.305	1.028	1.355	1.038	63	39	8.6	7.3	5.3	5
9	1.342	1.074	1.712	1.09	42	40	15.4	11.1	6.7	6.1
10	1.232	1.261	1.319	1.252	67	55	9.4	7.4	6.2	5.6
11	1.641	1.326	1.311	1.149	29	30	9.8	7.3	5.5	5.1
12	1.443	1.278	1.74	1.414	58	41	18.6	11.6	6.1	4.8
13	1.102	1.033	1.36	0.954	75	58	12.9	8.9	5.9	4.5
14	1.345	1.378	1.505	1.23	53	45	15.8	12.1	6.6	5.1
Mean	1.387***	1.206	1.507***	1.154	55.6*	44.9	12.4**	8.9	6.3***	5.3

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$ (nerves on the entrapped side vs. the intact side)

Fig. 7 Mean ADC values at the proximal nerve root and distal spinal nerve in patients with foraminal stenosis (a). The mean ADC of the proximal nerve root on the side of entrapment is $1.387 \pm 0.172 \times 10^{-3} \text{ mm}^2/\text{s}$ and higher than the $1.206 \pm 0.105 \times 10^{-3} \text{ mm}^2/\text{s}$ seen on the intact side; that of the distal nerve root on the entrapment side is $1.507 \pm 0.162 \times 10^{-3} \text{ mm}^2/\text{s}$ and higher than the $1.154 \pm 0.116 \times 10^{-3} \text{ mm}^2/\text{s}$ on the intact side. Comparisons of stenotic level (L4 $n = 3$, L5 $n = 9$) to non-stenotic level (S1 $n = 12$) in the same subject (b). The differences of ADC values (nerve root and distal spinal nerve) between entrapped and intact side were $0.181 \pm 0.171 \times 10^{-3}$ and $0.354 \pm 0.173 \times 10^{-3} \text{ mm}^2/\text{s}$ higher than the $0.013 \pm 0.087 \times 10^{-3}$ and the $0.010 \pm 0.121 \times 10^{-3} \text{ mm}^2/\text{s}$ on the non-stenotic level (S1) between right and left side

using DWI. In this present study, mean ADC values in entrapped nerve roots were higher than they were in intact nerve roots, suggesting demyelination and edema by slow compression caused by an increased degree of diffusion as indicated by ADC compared to that of normal tissue microstructure. Our study also demonstrated that neurography can provide anatomical information and accurate localization of nerve compression in the foramen, which can be helpful in surgical planning. In this study, fenestration was performed in a patient who was presurgically diagnosed with lateral recess stenosis without nerve course abnormality, such as transverse nerve running, on neurography. On the other hand, in patients who were diagnosed with foraminal stenosis with nerve course abnormality on neurography, facetectomy was selected. In all of the patients, radicular pain was ameliorated after selective decompression.

Almost all previous studies used MRI at 1.5 T, so further studies are needed using a stronger magnetic field to significantly improve image quality, for example, by reduction of the signal-to-noise ratio in MRI.

We acknowledge that our study has several limitations. The first limitation is that a small number of subjects were

investigated. Further studies are needed to investigate whether our findings are valid in a large population. Second, we could not repeat the DWI after surgery because of artifacts of spinal instrumentation such as a pedicle screw system. Third, ADC maps were limited because the tissue contrast between nerves and surrounding tissues is poor. Therefore, the ADC values were measured within ROI that was placed in anatomic locations on the nerves using neurography.

Conclusion

This preliminary study demonstrates that neurography can be used to visualize abnormalities such as nerve indentation, swelling, and running transversely in their course through the foramen and to quantitatively evaluate lumbar nerve entrapment in patients with foraminal stenosis. We believe that DWI has the potential to be used as a tool for the diagnosis of lumbar nerve entrapment.

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