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Diffusion-Weighted MR Neurography with Unidirectional Motion-Probing Gradient to Evaluate Lumbar Nerve Roots at 1.5T MR

요추 신경근 평가를 위한 1.5T MR의 단일 방향 경사자장을 사용한 확산강조 자기공명신경조영

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Purpose Recent studies have demonstrated the usefulness of diffusion-weighted MR neurography (DW MRN) for assessing nerve roots. This study aimed to evaluate the utility of DW MRN with a unidirectional motion-probing gradient (MPG) for the lumbar nerve roots at 1.5T MR.

Materials and Methods Sixty-four lumbar spine MRI scans with DW MRN using anteroposterior unidirectional MPG were retrospectively analyzed. Any changes in the 512 lumbar spinal nerve roots from L3 to S1 were evaluated using T2-weighted imaging (T2WI), contrast-enhanced T1-weighted imaging (CE T1WI), and DW MRN, with agreement and correlation analysis.

Results T2WI revealed compression of 78 nerve roots, and CE T1WI revealed 52 instances of nerve root enhancement. Sixty-seven nerve roots showed swelling and hyperintensity on DW MRN. A total of 42 nerve roots showed changes in the CE T1WI and DW MRN sequences. Moderate to substantial agreement and moderate positive correlation were observed between DW MRN and CE T1WI, as well as DW MRN and T2WI ($\kappa = 0.59–0.65$, $\rho = 0.600–0.653$).

Conclusion DW MRN with unidirectional anteroposterior MPG can help evaluate neuritis-related changes in spinal nerve roots and could serve as a sequence capable of complementing or substituting gadolinium CE imaging.

Index terms Diffusion Magnetic Resonance Imaging; Neuroimaging; Unidirectional Motion-Probing Gradient; Spinal Nerve Root

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INTRODUCTION

Lumbar spine MRI is frequently performed to evaluate low back pain. Neuritis due to nerve root compression, commonly caused by conditions such as herniated nucleus pulposus or spinal stenosis, is detected by contrast-enhanced T1-weighted imaging (CE T1WI). Similarly, neuritis-related nerve root changes, such as structural alterations and surrounding inflammatory reactions, are shown on T2-weighted image (T2WI) as swelling and high signal intensity (1, 2). Notably, contrast enhancement of the nerve root may also be observed in individuals who have previously undergone lumbar surgery, have enlarged radicular veins, or are affected by demyelinating disease or tumorous conditions (1, 3-5). Therefore, lumbar radiculopathy cannot be conclusively diagnosed based only on the presence of contrast enhancement on CE T1WI.

Recent advances in diffusion-weighted imaging (DWI) have increased the usefulness of magnetic resonance neurography in evaluating peripheral nerve lesions. Diffusion-weighted MR neurography (DW MRN) is now being used for the diagnosis of peripheral nerve lesions, such as brachial plexopathy, and for the confirmation of peripheral nerve injuries caused by trauma (6-9). The DW MRN typically uses motion probing gradient (MPG) in three directions (X, Y, and Z) (10-12). However, peripheral nerves that run in a straight line show the highest signal intensity on DWI when a single plane of the gradient is applied perpendicularly to the direction of nerve conduction (13). Studies have shown that DW MRN using a single direction of MPG provides better visualization of peripheral nerves than the traditional three or six-gradient directions that have commonly been used (14, 15).

This study aimed to evaluate the feasibility of DW MRN with unidirectional MPG for lumbar spinal nerve roots compared to conventional CE T1WI obtained with 1.5T MR.

MATERIALS AND METHODS

PATIENT INCLUSION

At our institution, 251 patients with acute or chronic low back pain underwent lumbar spine MRI using 1.5T MR from March 19, 2014, to July 31, 2014. Among them, 92 who underwent CE T1WI and DW MRN were selected. Of these, 28 MR images were excluded due to fractures, metastatic tumors, infection, postoperative condition, insufficient fat suppression, or poor image quality, and 64 MR images were included (Fig. 1). Therefore, 512 spinal nerve roots were evaluated by comparing each nerve from L3 to S1 on both sides in each patient.

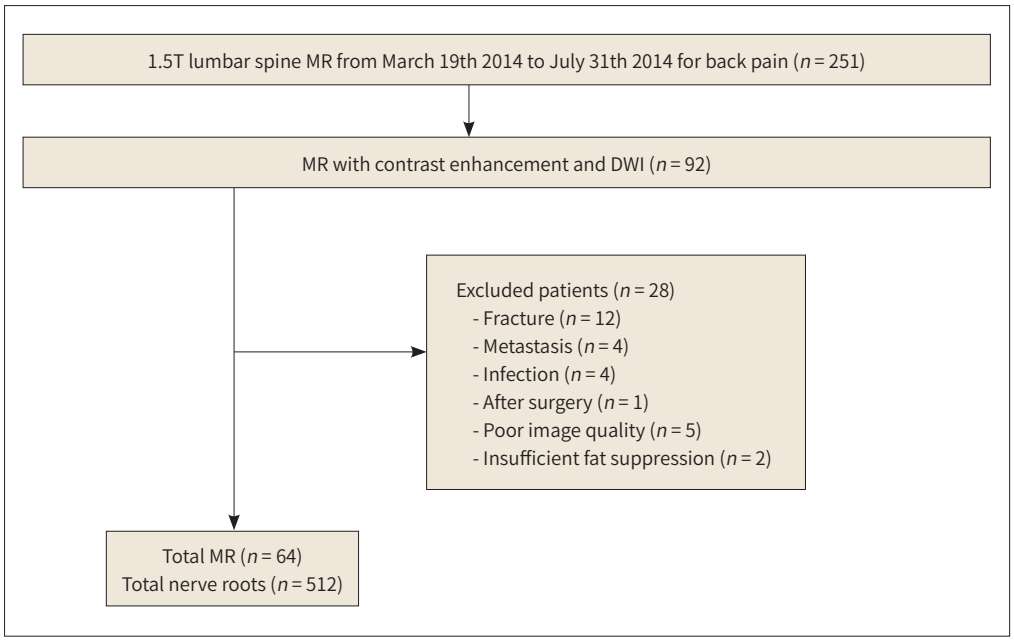
This retrospective study was approved by the Institutional Review Board and the requirement for informed consent was waived (IRB No. BD2014-154).

MRI PROTOCOL

All lumbar spine MRI scans were acquired using two 1.5T MR machines (Signa HDxt; GE Healthcare, Milwaukee, WI, USA and Magnetom Sonata; Siemens, Erlangen, Germany).

For all patients, fast spin echo (FSE) T1WI was obtained in the sagittal and axial plane (repetition time [TR] of 500–800 ms, echo time [TE] of 9–13 ms for a sagittal scan; TR of 500–900 ms, TE of 13–15 ms for an axial scan), as well as FSE T2WI (TR of 4400–4800 ms, TE of 112–122 ms

Fig. 1. Patient selection flowchart.



DWI = diffusion-weighted imaging

Table 1. Imaging Parameters for Diffusion-Weighted MR Neurography

Sequence	Single Shot EPI (GE)	Single Shot EPI (Siemens)
FOV (mm)	30	35
TR/TE/IR (msec)	12000/65.3/180	11200/84/180
NEX	12	12
Acquisition matrix	96 × 128	128 × 96
Bandwidth (kHz)	1953.12	2056
Diffusion gradient	Anteroposterior phase	Anteroposterior phase
Acquisition time (min)	05:00	02:50
b-value (s/mm^2)	0, 500	500
Pixel space (mm)	1.719 × 1.719	1.3672 × 1.3672
Slice thickness (mm)	3.5	5

EPI = echo-planar imaging, FOV = field of view, IR = inversion recovery, NEX = number of excitations, TE = echo time, TR = repetition time

for a sagittal scan; TR of 3000–4450 ms, TE of 92–109 ms for an axial scan) and CE T1WI (TR of 522–934 ms, TE of 7–13 ms for a sagittal scan; TR of 692–950 ms, TE of 11–16 ms for an axial scan). The slice thickness and spacing were 3 and 3.3 mm, respectively, in the sagittal image and 4 and 4.2 mm in the axial images for all T1WI, T2WI, and CE T1WI.

DW MRN was performed using single-shot spin-echo echo-planar imaging with unidirectional MPG in the anterior-posterior direction. DWI was performed from the L3 to S1 nerve roots in the axial plane. The imaging parameters are listed in Table 1. Coronal multiplanar reformation (MPR) images were obtained using the maximum-intensity projection (MIP) method. An apparent diffusion coefficient map could not be obtained due to the unidirectional MPG and single b-value in the machine.

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ANALYSIS OF THE IMAGES

Two experienced musculoskeletal radiologists (approximately 20 and 14 years, respectively), blinded to the clinical information of the patients, first analyzing T2WI and CE T1WI, and then the DW MRN images 2 weeks later. The results were compared, and a final analysis was obtained by consensus in the case of discrepancies.

Neuritis-related nerve root changes were subjectively evaluated. The bilateral nerve roots were compared at each level to determine abnormalities. If the bilateral nerve roots were abnormal, they were compared to the nerve roots at the adjacent level. T2WIs were analyzed to determine the presence of nerve root compression or edema, as well as the presence of disc herniation and spinal stenosis. On CE T1WI, the enhancement of each nerve root and its surrounding structures was evaluated. The axial and coronal images of the DW MRN were subjectively evaluated for the presence of nerve root compression, edema-induced enlargement, changes in signal intensity, and changes in their course compared to the bilateral nerve roots at each level.

STATISTICAL ANALYSIS

The agreement between the presence or absence of CE T1WI and DW MRN positive findings was analyzed using Cohen's kappa (κ) with the T2WI findings as the gold standard, and the concordance of CE T1WI and DW MRN findings was also analyzed. Regarding the interpretation of Cohen's κ proposed by Landis and Koch (16), the levels of agreement were defined as follows: poor (< 0), slight (≥ 0 but < 0.2), fair (≥ 0.2 but < 0.4), moderate (≥ 0.4 but < 0.6), substantial (≥ 0.6 but < 0.8), and almost perfect (≥ 0.8 but ≤ 1).

The correlation between positive findings on DW MRN, T2WI, and CE T1WI was evaluated using a cross-table analysis with Spearman's correlation analysis.

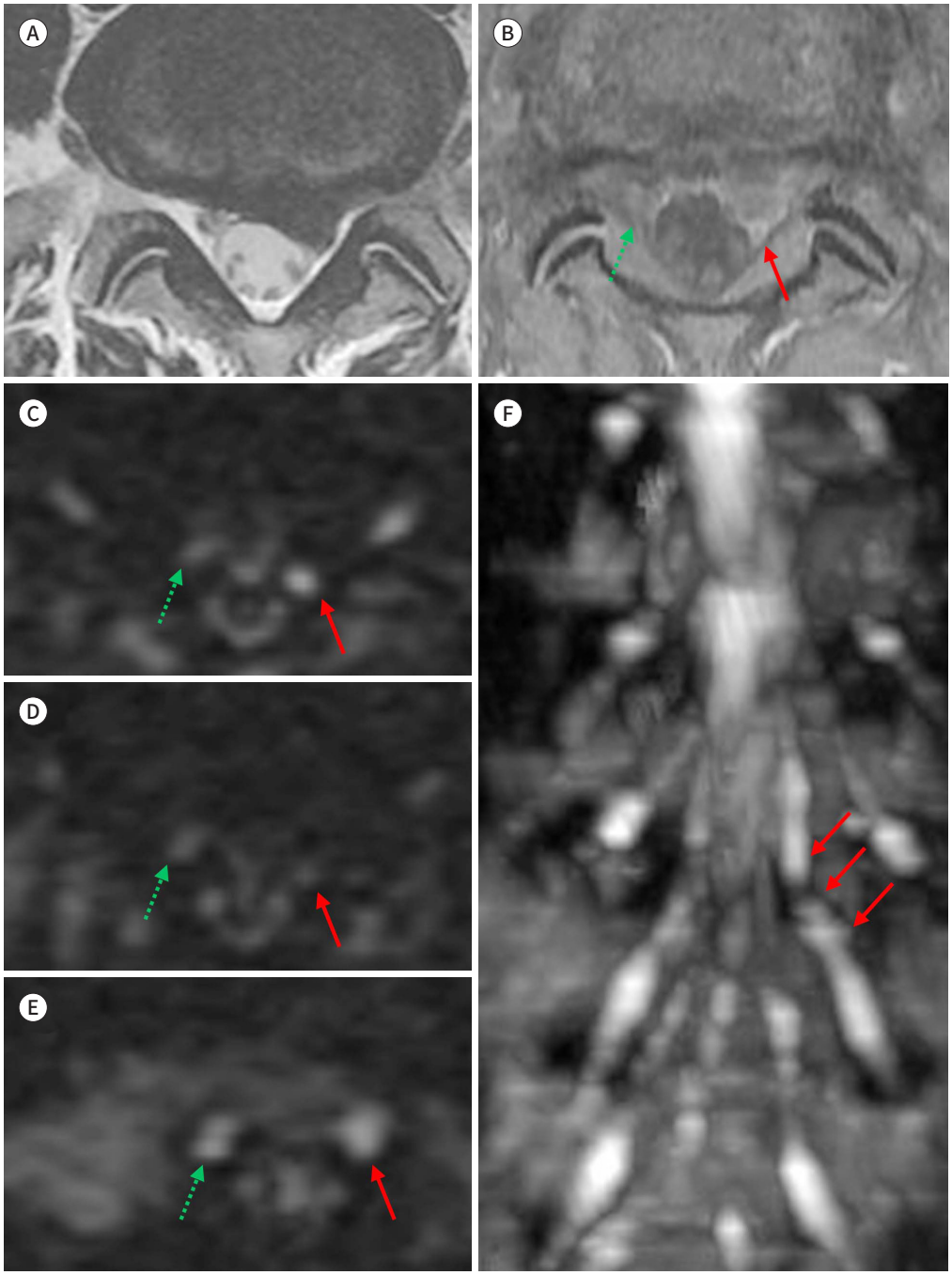
Cohen's κ coefficient and correlation analyses were performed using SPSS version 27.0 (IBM Corp., released in 2020. IBM SPSS statistics for Windows, version 27.0. IBM Corp., Armonk, NY, USA).

Table 2. Number of Nerve Roots Showing Changes at Each Level based on Analysis of Diffusion-Weighted MR Neurography, T2-Weighted Image, and Contrast-Enhanced T1-Weighted Image from L3 to S1

Nerve Root	T2-Weighted Image	Contrast-Enhanced T1-Weighted Image	DW MRN
Right L3	7	6	5
Left L3	3	2	2
Right L4	7	4	7
Left L4	7	4	5
Right L5	16	9	14
Left L5	15	10	13
Right S1	10	7	9
Left S1	10	7	9
Total	78	52	67

DW MRN = diffusion-weighted MR neurography

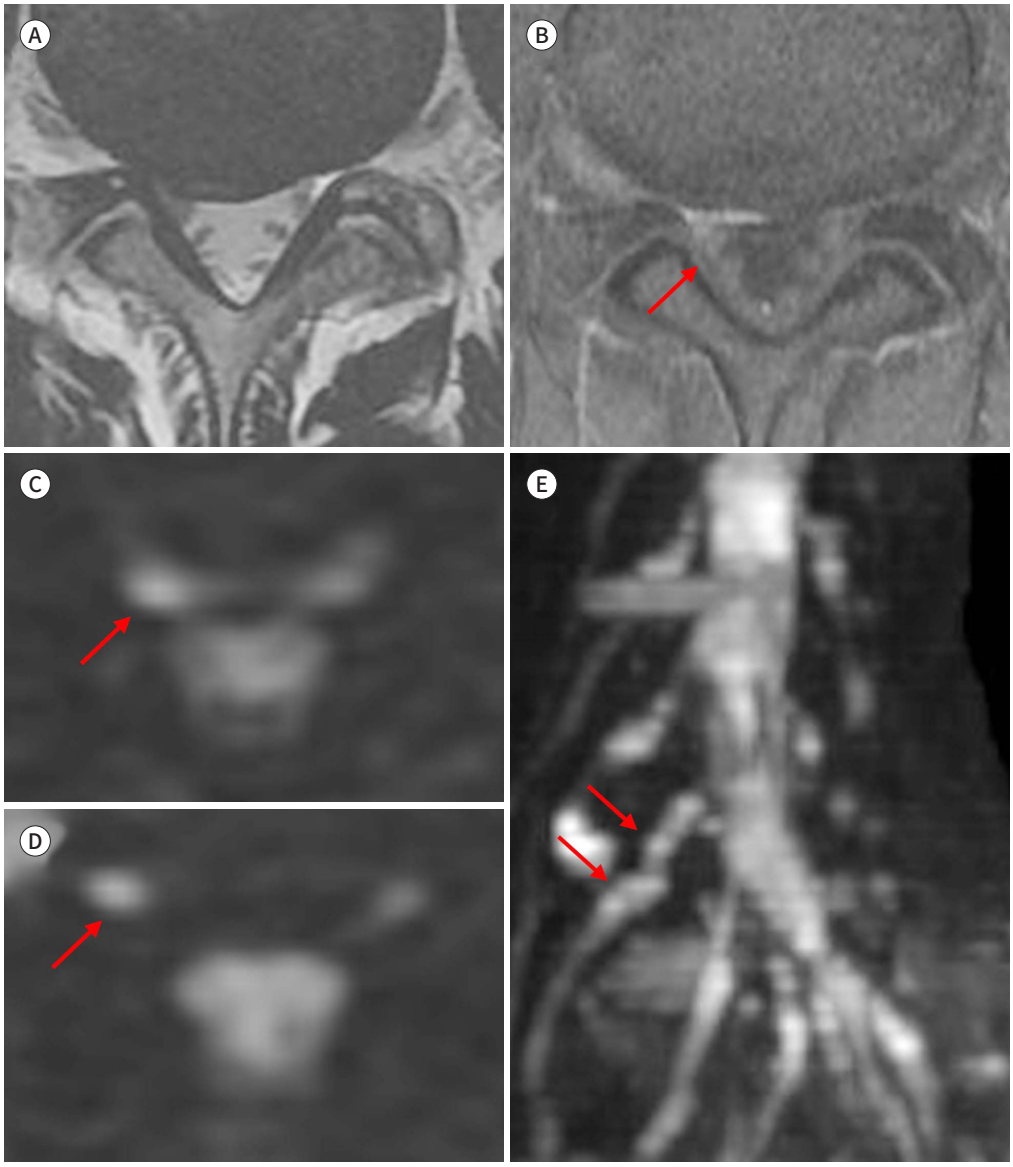
Fig. 2. Nerve root change on both contrast-enhanced T1-weighted image and diffusion-weighted MR neurography. A 44-year-old female with pain radiating from the left thigh to the calf for 4 weeks.
A. Axial T2WI shows compression of the left S1 nerve root due to a left subarticular herniation at the L5/S1 level.
B. Axial contrast-enhanced T1WI reveals compression and perineural enhancement of the left S1 nerve root (red arrow) compared to the right (green dotted arrow).
C-E. Axial DW MRN shows pre-compression (C), compression (D), and post-compression (E) states of both S1 nerve roots. In post-compression (E), marked swelling with hyperintensity due to increased longitudinal diffusivity is observed in the left S1 nerve root (red arrows) compared to the right (green dotted arrows).
F. The reformatted DW MRN in the coronal plane shows a compressive defect in the left S1 nerve root (arrows) with proximal and distal swelling due to disc herniation.
DW MRN = diffusion-weighted MR neurography, WI = weighted image



RESULTS

Of the 64 patients, 38 were female and 26 were male, with a mean age of 51.2 years (range, 19–79 years). Discovertebral pathologies included disc bulging at 75 levels, disc herniation at 50 levels, spinal stenosis at 33 levels, and spondylolisthesis at eight levels. Eighteen patients complained of pain in the lower back and buttocks, while 46 complained of lower back and leg pain (radiating pain to the right side, 14; left side, 22; and bilateral, 10).

Fig. 3. Nerve root changes on diffusion-weighted MR neurography, but no contrast enhancement on contrast-enhanced T1WI. A 19-year-old male with a history of pain radiating to his right leg for 2 years.
A. Axial T2WI shows compression of the right L5 nerve root due to a right central protrusion at the L4/5 level.
B. The axial contrast-enhanced T1WI does not reveal an enhancement of the right L5 nerve root (arrow).
C-E. Axial DW MRN (C, D) and reformatted DW MRN in the oblique plane (E) show marked swelling and hyperintensity of the right L5 nerve root (arrows) due to increased longitudinal diffusivity.
DW MRN = diffusion-weighted MR neurography, WI = weighted image



The total number of nerve roots that changed from L3 to S1 is shown in Table 2. On the T2WIs, of the 78 nerve roots that were compressed at the L3 to S1 level, five nerve roots also showed swelling. A total of 52 nerve roots were enhanced on contrast enhanced T1WI. A total of 67 nerve roots showed hyperintensity with swelling and angulation on the DW MRN.

Neuritis-related nerve root changes on CE T1WI and DW MRN were divided into three categories: nerve roots with enhancement on CE T1WI and changes on DW MRN; nerve roots with any change on DW MRN but no enhancement on CE T1WI; and nerve roots with enhancement on CE T1WI but no changes on DW MRN. Across all levels from L3 to S1, there were 42 nerve roots with changes in both sequences (Fig. 2), 25 nerve roots with swelling or angulation on DW MRN but no enhancement on CE T1WI (Fig. 3), and 10 nerve roots with enhancement on CE T1WI but no change in DW MRN.

The agreement test for each CE T1WI and DW MRN with T2WI as the gold standard to assess nerve root changes showed moderate agreement ($\kappa = 0.59$) and substantial agreement ($\kappa = 0.65$) between CE T1WI and DW MRN.

Moreover, Spearman's correlation analysis revealed a statistically significant and moderate positive correlation between T2WI and DW MRN (correlation coefficient $\rho = 0.600$, $p < 0.001$) and T2WI and T1CE (correlation coefficient $\rho = 0.619$, $p < 0.001$), and a moderate positive correlation between T1CE and DW MRN (correlation coefficient $\rho = 0.653$, $p < 0.001$).

DISCUSSION

Back pain develops when the herniated nucleus pulposus physically compresses the spinal nerve root, leading to a chemical inflammatory response. When the surrounding structures compress the spinal nerve root directly or indirectly, changes occur in the permeability of the perineural microvasculature. This phenomenon can be visualized as an enhancement of the nerve root on contrast-enhanced imaging (1, 2, 17, 18). In addition, leakage of fluid components and macromolecules from the blood vessels into the endoneural space can cause intraneural edema, which is easily detected on T2WI (1).

However, nerve root enhancement on CE T1WI does not always correlate with radiating pain. When there are neuritis-related nerve root changes on CE T1WI and DW MRN, it has previously been established that there is no correlation between the patient's neurological symptoms and imaging findings (1, 3-5). Our study in the patient cohort also confirmed this lack of correlation. As it was not known which nerve dermatome radicular pain followed, there was no statistical significance when analyzing radicular pain and the presence of nerve root abnormalities as simply left, right, bilateral, or absent.

Recently, many studies have suggested that DW MRN may play an important role in the diagnosis and treatment of peripheral nerve lesions, especially considering the widespread use and technical advances in 3T MRI (19, 20). DW MRN has the advantage of assessing nerve swelling and related features even at the neural foramen and nerve root levels because it can visualize the proximal portion of the nerve. In MRN, it is important to suppress signals from nerves surrounding the fat tissue or blood vessels and increase the contrast of the peripheral nerves (21). Several imaging techniques have been used to achieve this objective. Recently, the short tau inversion recovery (STIR) and Dixon techniques have been used to reduce in-

sufficient fat suppression caused by inhomogeneous magnetic fields in large field of view (21). In addition, three-dimensional (3D) DW reversed fast imaging with steady-state precession or 3D nerve-sheath signal increased with inked rest tissue rapid acquisition of relaxation enhancement imaging (SHINKEI®) techniques are used to suppress blood flow signals from vessels that travel close to the nerves (21). Techniques using magnetization transfer imaging to increase the contrast of peripheral nerves have also been reported (21).

In DW MRN, MPGs are typically applied in three directions (X, Y, and Z) (10-12). However, for peripheral nerves that run straight, the highest diffusivity on DWI is obtained when a single plane of the gradient is applied perpendicular to the trajectory of nerve conduction, specifically in the anterior-to-posterior direction (13). Studies have shown that DW MRN with a single MPG direction is better in terms of signal-to-noise ratio and contrast-to-noise ratio (14, 15). Takahara et al. (14) reported that multidirectional gradients can cause image distortion and blurred diffusion trace images with reduced signals due to ineffective averaging of single-axis images.

Mürtz et al. (22) compared the DW MRN of the brachial plexus and lumbosacral plexus at 1.5T and 3T and found that the 3T DW MRN showed superior nerve conspicuity on MIP images of the lumbosacral plexus. However, the image quality of 3T MR may be limited by stronger susceptibility artifacts and less uniform fat suppression compared to 1.5T MR. Furthermore, the use of unidirectional MPG can help shorten the imaging time for 1.5T DW MRN. In our study, moderate to substantial agreement was observed between T2WI, CE T1WI, and DW MRN at 1.5T regarding the detection of neuritis-related nerve root changes in the lumbosacral nerve roots.

A previous study by Andreou et al. (20) reported that unidirectional DW MRN is beneficial in localizing and detecting diseases in the proximal brachial plexus when combined with conventional MR sequences due to uniform trajectories of the nerves and the relatively increased distance between the nerve roots and their adjacent structures. Takahara et al. (14) also reported the superiority of using a unidirectional MPG in the anterior-posterior direction compared to using a three- or six-directional MPG in the DW MRN of the sacral plexus. They used the soap-bubble MIP post-processing technique for improved visualization instead of the conventional processing technique. This technique includes user-defined curved subvolumes that encompass the entire nerve plexus in a single plane, resulting in better visualization without superimposition of anatomical structures. In our study, we found that DW MRN in the anteroposterior direction of the MPG was also useful for evaluating lumbosacral nerve roots.

In some cases, despite the presence of disc herniation that causes nerve root compression, CE T1WI may not show significant changes in the nerve root or appear normal. This discrepancy may occur because the enhancement of the nerve root can be obscured on axial scans using conventional CE T1WI. In contrast, in DW MRN, because peripheral nerves have a longer T2 relaxation time than surrounding tissues, 3D neurological imaging can be obtained, similar to angiography (23). Therefore, the DW MRN can more accurately trace the course of the nerve root and identify changes. Furthermore, DW MRN provides continuous imaging without gaps between scans, allowing for a more precise assessment of nerve root changes. If a transitional vertebra is present, abnormal angulation of the nerve or extraforaminal compression can be detected on DW MRN but may be missed on T2WI or CE T1WI.

There are some limitations to this study. First, the data were collected retrospectively. Interobserver agreement could not be obtained due to subjective judgment and the use of data based on consensus from two experienced radiologists. No direct comparison was conducted between unidirectional and multidirectional MPG and no comparison was made with techniques such as STIR or Dixon. Second, no patients underwent surgery or showed confirmed neurological complications following MRI. Most patients received conservative treatment or were lost to follow-up after MR. Most of the patients were not tested using electromyographic or nerve conduction studies. Therefore, in this study, the gold standard was defined as T2WI within the imaging sequence. Due to the absence of descriptions of pain patterns based on dermatomes in the records, we were unable to individually match levels with symptoms and neuritis-related nerve root changes on MRI. Third, DW MRN has limitations that can affect image quality, such as motion artifacts, poor resolution, and image distortion. Due to the difference in slice thickness between the DW MRN images obtained from the two MRI machines, we adjusted the pixel spacing of the images to make them similar. Artifacts from surrounding blood vessels and chemical shift artifacts due to inadequate fat suppression may occur (10, 22). Additionally, DW MRN is a time-consuming imaging procedure because the creation of MIP and 3D MPR images for nerve trajectories requires manual segmentation to remove vessels (10). Finally, using a 1.5T machine is a limitation, as it may result in longer acquisition times than using a 3T machine.

Gadolinium-based contrast agents commonly used in spinal MRI are relatively safe, but not without limitations. Repeated use can result in bone or brain deposition or nephrogenic systemic fibrosis (24). As the administration of gadolinium-based contrast agents is restricted to patients with chronic renal dysfunction, DW MRN may be an attractive alternative.

In conclusion, DW MRN with unidirectional anteroposterior MPG may be a valuable method for evaluating changes in spinal nerve roots when combined with T2WI and CE T1WI and could serve as a sequence capable of complementing or substituting gadolinium contrast-enhanced imaging.

Availability of Data and Material

The datasets generated or analyzed during the study are available from the corresponding author on reasonable request.

Author Contributions

Conceptualization, H.D.H.; data curation, all authors; formal analysis, Y.N.Y., H.D.H.; methodology, Y.N.Y., H.D.H.; writing—original draft, Y.N.Y.; and writing—review & editing, Y.N.Y., H.D.H.

Conflicts of Interest

Doo Hoe Ha, who holds a respective position on the Editorial Board Member of the Journal of the Korean Society of Radiology, was not involved in the editorial evaluation or decision to publish this article. The remaining author has declared no conflicts of interest.

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요추 신경근 평가를 위한 1.5T MR의 단일 방향 경사자장을 사용한 확산강조 자기공명신경조영

윤나연 · 하두회* · 이상민 · 최혜정

목적 최근 확산강조 자기공명신경조영(diffusion-weighted MR neurography; 이하 DW MRN)이 신경근 평가에 도움이 된다고 보고되었다. 본 연구는 1.5T MR에서 단일방향 경사자장을 사용한 DW MRN의 요추 신경근 평가의 유용성을 확인하고자 한다.

대상과 방법 앞뒤 방향 경사자장의 DW MRN을 포함한 64요추 MR을 후향적으로 분석했다. 제3 요추에서 제1 천추까지 총 512개 요추 신경근의 변화를 T2 강조영상, 조영증강 T1 강조영상, 그리고 DW MRN에서 평가하고 일치도와 상관관계 분석을 했다.

결과 T2 강조영상에서 78개의 신경근 압박이 있었고, 조영증강 T1 강조영상에서 52개 신경근이 조영증강되었다. DW MRN에서 67개 신경근의 부종과 고신호강도가 있었다. 조영증강 T1 강조영상과 DW MRN 모두 신경근의 변화가 나타난 경우는 42개였다. DW MRN과 조영증강 T1 강조영상, T2 강조영상 간에 중간 또는 상당한 일치도와 양의 상관관계를 보였다($\kappa = 0.59–0.65$, $\rho = 0.600–0.653$).

결론 앞뒤 단일방향을 사용한 DW MRN은 척추 신경근의 변화 평가에 도움이 되며, 가돌리늄 조영증강을 대체 또는 보완하는 역할을 할 수 있을 것이다.

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