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Diffusion tensor imaging with quantitative evaluation and fiber tractography of lumbar nerve roots in sciatica

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ABSTRACT

Objective: To quantitatively evaluate nerve roots by measuring fractional anisotropy (FA) values in healthy volunteers and sciatica patients, visualize nerve roots by tractography, and compare the diagnostic efficacy between conventional magnetic resonance imaging (MRI) and DTI.
Materials and methods: Seventy-five sciatica patients and thirty-six healthy volunteers underwent MR imaging using DTI. FA values for L5–S1 lumbar nerve roots were calculated at three levels from DTI images. Tractography was performed on L3–S1 nerve roots. ROC analysis was performed for FA values.
Results: The lumbar nerve roots were visualized and FA values were calculated in all subjects. FA values decreased in compressed nerve roots and declined from proximal to distal along the compressed nerve tracts. Mean FA values were more sensitive and specific than MR imaging for differentiating compressed nerve roots, especially in the far lateral zone at distal nerves.
Conclusions: DTI can quantitatively evaluate compressed nerve roots, and DTT enables visualization of abnormal nerve tracts, providing vivid anatomic information and localization of probable nerve compression. DTI has great potential utility for evaluating lumbar nerve compression in sciatica.

1. Introduction

Sciatica is known by a range of terms in the literature, including radiculopathy, lumbosacral radicular syndrome, nerve root pain, and nerve root entrapment or irritation; it is characterized by radiating pain in the leg and related impairments [1]. The prevalence of sciatica has been estimated as 5–25%, and it mostly affects the working-age population (incidence peaks between the ages of 35 and 55 years) [2–5]. Disk herniation with nerve root compression is the most common cause of sciatica [2]. Traditionally, herniated lumbar discs have been diagnosed by conventional magnetic resonance imaging (MRI) [6]. However, conventional MRI is inadequate for evaluating sciatica, because it may not clearly identify pathologic extraforaminal lesions or nerve root compression in the extraforaminal area [7]. Considering these shortcomings, better diagnostic imaging techniques that can detect lumbar nerve root entrapment are imminently required.

By applying a motion-probing gradient (MPG) in various directions to monitor the random movement of water molecules that are restricted in tissues, diffusion weighted imaging (DWI), which is based on MR imaging, can provide valuable information regarding the microstructure of tissues [8]. Diffusion tensor imaging (DTI) can detect the movement of water molecules along nerve fibers in neural tissue [9]. Fractional anisotropy (FA) is a quantitative diffusion value that reflects the directionality of molecular diffusion. With the use of DTI, some studies have found lowered FA values in peripheral nerve compression injuries; this is believed to be due to neurodegeneration, such as widening of the interstitial space, Wallerian degeneration, and axonal demyelination, which results in an increased perpendicular diffusion vector compared with normal nerves [10,11]. Several studies have shown that DTI can be used to quantitatively evaluate and visualize peripheral nerves [12].

Previous studies have demonstrated that DTI and tractography of human lumbar nerves can visualize and quantitatively evaluate lumbar nerves [13,14]. However, only limited data are available in the literature, and the diagnostic efficacy of using DTI has not been determined. Therefore, the purpose of this study was to quantitatively evaluate nerve roots in healthy volunteers and in patients

Abbreviations: FA, fractional anisotropy; DTT, diffusion tensor tractography; MPG, motion-probing gradient.

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with sciatica, to visualize the nerve roots by tractography, and to compare the efficacy of diagnosis between conventional MRI and DTI.

2. Material and methods

2.1. Subjects

Seventy-five patients (31 men, 44 women; age, 51.3 ± 14.5 years; median age, 56.0 years; range: 19–78 years), who had unilateral symptoms of radiculopathy, including radicular leg pain associated with numbness or pins and needles below the knee and into the foot and toes that tends to approximate the dermatomal distribution of the nerve root affected (L5 or S1), with or without neurologic deficit such as muscle weakness and reflex changes [15], which were caused by lumbar disk herniation, lateral recess or foraminal stenosis excluding rare reasons such as tumors, cysts or other extraspinal reasons [1], were studied using MR imaging. These patients were referred for imaging by a neurosurgeon with expertise in sciatica. The symptomatic patients' diagnoses were based on the following: a selective nerve root block; a combination of diagnostic images, including plain X-ray, CT, and MR imaging; and neurologic symptoms. The referring physician described the location of the radiculopathy as L5 or S1 nerve root distributed. Radiculopathy that were located as both L5 and S1 nerve root distributed was excluded in this study.

The location of symptomatic radiculopathy was the L5 nerve roots in 52 patients and the S1 nerve roots in 23 patients. Thirty-six healthy volunteers (16 men, 20 women; age, 47.6 ± 14.4 years; median age, 48.0 years; range, 15–73 years) served as controls (Table 1). In total, 150 L5 or S1 foramina and corresponding nerve roots (2 foramina/person) in 75 patients and 144 L5 and S1 nerve roots (4 foramina/person) in 36 volunteer controls were analyzed with MR imaging and DTI to investigate diagnostic performance.

In this study, cases were not consecutive. The exclusion criteria for patients were as follows: (1) central lumbar canal stenosis, (2) multiple levels of radiculopathy, (3) myelopathy, (4) listhesis or scoliosis, and (5) previous lumbar spinal surgery or metal implants. The duration of clinical symptoms prior to MR imaging ranged from 4 to 12 months. This study received approval from our Institutional Review Board.

2.2. MR imaging protocol

MRI was performed with a 1.5 T scanner (Signa HDxt Echospeed, GE Healthcare, Milwaukee, WI). Sagittal T2-weighted fast spin-echo (TR/TE, 3000/109) and sagittal T1-weighted (TR/TE, 640/8.5) sequences were obtained using a 320 matrix × 224 matrix, 320-mm FOV, and 4/0.5-mm section thickness/gap. Axial T2-weighted fast spin-echo (TR/TE, 2640/118) sequences were obtained using a 320 matrix × 192 matrix, 200-mm FOV, and 4/0.5-mm section thickness/gap.

2.3. DTI protocol

Subjects were scanned in the supine position using a HD 8-Channel Cardiac Array Coil (GE Healthcare, Milwaukee, WI). DTI was performed using an array special sensitivity encoding technique, factor: 2; an echo-planar imaging sequence; and chemical shift selective suppression with a free-breathing scanning technique. The following imaging parameters were established: MPG, 11 directions; 800 s/mm^2 *b*-value; 7000/90 ms for TR/TE, respectively; axial section orientation, 5/0-mm section thickness/gap; 420 mm × 420 mm FOV; 96 matrix × 128 matrix; 4.38 mm × 3.28 mm × 5.0 mm actual voxel size; 1.64 mm × 1.64 mm × 5.0 mm calculated voxel size; 4 excitations; 32 total sections; and a scan time of 5 min 43 s.

2.4. Image analysis

GE Functool 6.3.1e software (GE Healthcare, Milwaukee, WI) was used for FA mapping and tractography. A log-linear fitting method was used to calculate the diffusion tensor. FA was calculated with the software at the level of the symptomatic nerve root (L5 or S1) in patients and at both L5 and S1 nerve roots in healthy volunteers. The regions of interest (ROIs) were placed at three levels of the nerve root: proximal, medial, and distal to the lumbar foraminal zone. ROIs were placed on axial images at 4 levels. Level 1, that was located in the mid-portion of L5 lumbar transverse process, contained bilateral proximal L5 nerve ROIs; Level 2, that was located in the lower edge of L5 lumbar transverse process, contained both bilateral medial L5 nerve ROIs and proximal S1 nerve ROIs; Level 3, that was located in the mid-portion of S1 sacral vertebra, contained both bilateral distal L5 nerve ROIs and medial S1 nerve ROIs; Level 4, that was located in the lower edge of S1 sacral vertebra, contained bilateral distal S1 nerve ROIs (Fig. 1). To avoid partial volume effects, the area of the ROIs (25–50 mm^2) was accurately selected on the respective nerve roots when the mean FA was calculated. The calculated voxel size is 1.64 mm × 1.64 mm × 5.0 mm, that is smaller than the dorsal root ganglia (10 mm long and 5 mm wide). The small calculated voxel used in this study could minimize the effect of CSF contamination on the related measurement. Measurements of all DTI data were made twice by each of the two different trained radiologists who were blind to the study design and clinical symptoms for each case separately. The FA values of each ROIs were an average of values calculated by the four separate measurements. Tractography of lumbosacral nerve roots were performed by another two different trained radiologists who were blind to the study design and clinical symptoms for each case separately. The evaluation with tractography included identifying nerve root abnormalities such as narrowing, indentation, and disruption. The evaluation of tractography made the contralateral asymptomatic nerves as controls in this study [11]. Conventional MRI findings such as disk herniation, nerve root compression were blindly evaluated by a trained radiologist.

2.5. Statistical analysis

Data were entered into a database and analyzed using SPSS statistical software (version 18.0.0; SPSS Inc., Chicago, IL). The comparison of FA values among the three levels of the nerve root in both patients and healthy volunteers was performed by one-way ANOVA followed by Student–Newman–Keuls analyses. Comparisons between nerve root FA values (at the symptomatic level) from the symptomatic side and asymptomatic side in the same subject were performed using the paired-samples *t*-test. Receiver operating characteristic (ROC) analysis was performed to clarify the diagnostic value of the three levels of FA values for sciatica using MedCalc (version 11.4.2.0; MedCalc Software, Mariakerke, Belgium). Comparisons of the area under the ROC curve (AUC) between the three levels of the nerve roots in patients were performed by the McNemar test. Data are presented as mean ± SD. Values of $p < 0.05$ were considered statistically significant.

3. Results

In healthy subjects, FA values (mean ± SD) of the nerves were 0.217 ± 0.015 for L5 and 0.214 ± 0.016 for S1. At the same lumbar segment, no significant differences were observed between the left and right sides of nerves at the same level, and no significant