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Original contribution

Distortion-free diffusion tensor imaging for evaluation of lumbar nerve roots: Utility of direct coronal single-shot turbo spin-echo diffusion sequence

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ABSTRACT

Purpose: Diffusion tensor imaging (DTI) based on a single-shot echo planer imaging (EPI-DTI) is an established method that has been used for evaluation of lumbar nerve disorders in previous studies, but EPI-DTI has problems such as a long acquisition time, due to a lot of axial slices, and geometric distortion. To solve these problems, we attempted to apply DTI based on a single-shot turbo spin echo (TSE-DTI) with direct coronal acquisition. Our purpose in this study was to investigate whether TSE-DTI may be more useful for evaluation of lumbar nerve disorders than EPI-DTI.
Materials and methods: First, lumbar nerve roots of five healthy volunteers were evaluated for optimization of imaging parameters with TSE-DTI including b-values and the number of motion proving gradient (MPG) directions. Subsequently, optimized TSE-DTI was quantitatively compared with conventional EPI-DTI by using fractional anisotropy (FA) values and visual scores in subjective visual evaluation of tractography. Lumbar nerve roots of six patients, who had unilateral neurologic symptoms in one leg, were evaluated by the optimized TSE-DTI.
Results: TSE-DTI with b-value of 400 s/mm^2 and 32 diffusion-directions could reduce the image distortion compared with EPI-DTI, and showed that the average FA values on the symptomatic side for six patients were significantly lower than those on the non-symptomatic side ($P < 0.05$).
Conclusion: Tractography with TSE-DTI might show damaged areas of lumbar nerve roots without severe image distortion. TSE-DTI might improve the reproducibility in measurements of FA values for quantification of a nerve disorder, and would become a useful tool for diagnosis of low back pain.

1. Introduction

Disc herniation and degeneration of the lumbar spine may cause symptoms such as low back pain, which is often associated with leg pain and numbness. Typically, low back pain has been diagnosed with the aid of conventional magnetic resonance imaging (MRI) [1]. However, conventional MRI would not be adequate for evaluation of neurologic symptoms in the legs, because it may not clearly identify pathologic extraforaminal lesions or nerve root compression in the extraforaminal area [2]. It is well-known that nerve root entrapment caused by lumbar foraminal stenosis and disc herniation would be a cause of neurologic symptoms in the legs, which can commonly occur in the extraforaminal area. Therefore, it is important to evaluate pathologic lesions in the extraforaminal area.

Diffusion tensor imaging (DTI) based on a single-shot echo planer imaging sequence (EPI-DTI) can detect the diffusion of water molecules along nerve fibers in neural tissue [3] and is promising for evaluation of lumbar nerve roots compression in the extraforaminal area. Recently, several studies have shown that EPI-DTI and tractography of human lumbar nerves can visualize and quantitatively evaluate lumbar nerves by fractional anisotropy (FA) [4–6]. FA values can be used as a quantitative assessment of diffusion indicating the preferential diffusion of

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water molecule diffusion. Previous studies on EPI-DTI have indicated that FA values are lowered in peripheral nerve compression injuries, which was believed to be due to neurodegeneration, such as widening of the interstitial space [7,8], Wallerian degeneration and axonal demyelination can result in an increased perpendicular diffusion vector compared with normal nerves, and peripheral nerves were quantitatively assessed by single-shot EPI as well as several methods such as readout-segmented EPI and selective-excitation EPI [9], and T2-mapping [10]. Although EPI-DTI has a great potential for evaluation of lumbar nerve compression, it has several problems such as a long acquisition time, geometric distortion and susceptibility artifacts because of its high sensitivity to magnetic susceptibility.

DWI based on turbo spin echo (TSE-DWI), is originally based on single-shot rapid acquisition with relaxation enhancement (RARE) with phase insensitive preparation [11], has been used to reduce the image distortion and reported for the usefulness in diagnosis of middle-ear cholesteatoma [12]. In fact, TSE-DWI has not been frequently used generally in clinical studies, because it has several drawbacks such as its low signal-to-noise ratio (SNR) theoretically caused by eliminating the magnetization components along the x direction (M_x) signals which include phase errors [11], long acquisition time to sufficiently gain the SNR, and severe image blurring due to long echo trains. Recently, an improved TSE-DWI sequence has been developed. The improved TSE-DWI sequence has several modifications from original Alsop's technique such as magnitude signal averaging, a new RF pulse shape that enables shorter echo spacing and compatibility with parallel imaging (sensitivity encoding: SENSE) to shorten the total of TSE echo train that can improve severe image blurring. Thus, we attempted to apply DTI based on a single-shot turbo spin echo sequence (TSE-DTI) to solve the problems of EPI-DTI. Our purpose in this study was to investigate whether TSE-DTI may be useful for evaluation of lumbar nerve root entrapment compared to EPI-DTI.

2. Materials and methods

All subjects were examined by use of a 1.5 T whole-body clinical system (Ingenia, Philips Healthcare, Best, The Netherlands) with a dedicated 32-channel flexible torso coil. DTI analyses were made by use of a Zio station2 (AMIN, Tokyo, Japan) for depiction of tractography and measurement of FA values. The institutional review board approved the study, and written informed consents were obtained from all subjects.

2.1. TSE-DTI pulse sequence and DTI protocol

Fig. 1 shows two sequence diagrams of the original Alsop's technique (Fig. 1a) and the improved TSE-DWI we used in this study (Fig. 1b). The improved TSE-DWI sequence includes some modifications from original Alsop's technique; image based signal averaging on the magnitude (image) data instead of complex (k-space) data to offset the signal drop owing to phase inversions among multiple acquisitions, a narrower RF pulse shape that enables three-times shorter echo spacing (4.7 ms) compared to original sequence (14 ms), and compatibility with SENSE that leads to shorten data acquisition time and yield high image quality. Consequently, this sequence can improve image blurring and signal un-uniformities.

EPI-DTI was acquired with SENSE with factor of 2 and spectral selective fat suppression. The following imaging parameters were employed; motion proving gradients (MPG) of 15 directions, b-value of 800 s/mm^2, TR and echo time (TE) of 3000 and 54 ms, axial slice orientation, slice thickness and slice gap of 3.0 and 0 mm, field-of-view (FOV) of 320 mm × 253 mm, matrices of 96 × 114, actual voxel size of 3.33 mm × 2.21 mm × 3.0 mm, calculated voxel size of 1.67 mm × 1.67 mm × 3.0 mm, 2 excitations, 50 slices, and an acquisition time of 6 min 36 s.

TSE-DTI was acquired with SENSE with factor of 3 and spectral

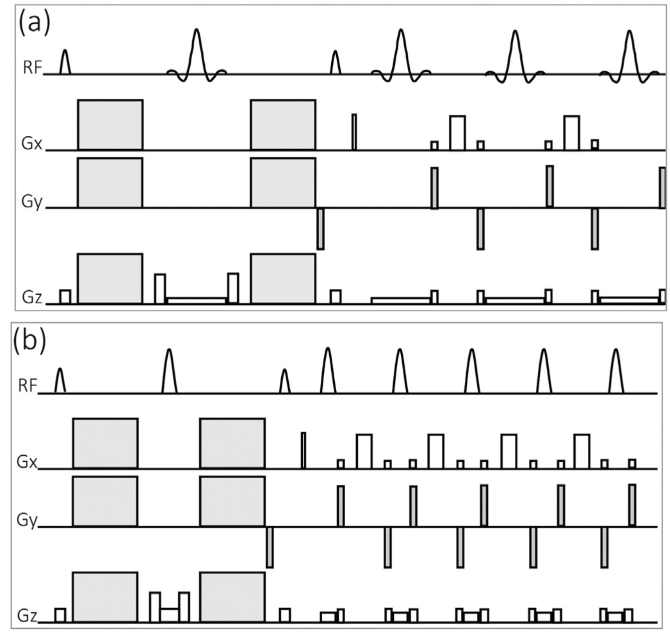

Fig. 1. Sequence diagrams of the original Alsop's technique (a) and the improved TSE-DWI we used in this study (b). Improved TSE-DWI is based on the Alsop's phase-insensitive RARE technique which contains additional 90-degree pulse after the MPG and dephasing gradients in My direction to eliminate the magnetization components along the Mx direction signals which include phase errors. Furthermore, a shorter RF pulse shape enables three times shorter echo spacing compared to original sequence.

selective fat suppression. In addition, to reduce the total acquisition time, we applied to set coronal section. The phase encoding direction was right-left direction and phase-oversampling was applied to prevent aliasing artifacts. The following imaging parameters were employed; MPG of 32 directions, b-value of 400 s/mm^2, TR and TE of 3000 and 49 ms, echo train length (ETL) including phase-oversampling of 24, coronal slice orientation, slice thickness and slice gap of 4.0 and 0 mm, FOV of 350 mm × 350 mm, matrices of 88 × 88, actual voxel size of 3.98 mm × 3.98 mm × 4.0 mm, calculated voxel size of 1.56 mm × 1.56 mm × 4.0 mm, 2 excitations, 16 slices, and an acquisition time of 6 min 36 s.

The two imaging datasets (the images series of b = 0 and that in high b-value) were applied image-based distortion correction [13] to avoid the eddy current effects.

2.2. Parameter optimization based on subjective visual evaluation of tractography

Lumbar nerve roots (L4 to S1) of five healthy volunteers (one woman and four men; median age, 32.6 years; range, 24–45 years) were evaluated to optimize the imaging parameters for TSE-DTI.

In diagnosis of lumbar nerve disorder, it would be important to clearly visualize the lumbar nerves and their pathologies by using DTI and its tractography. To accurately assess the quality of tractography, there are several important points: whether the lumbar nerve roots can be visualized continuously distal to the extraforaminal area, and whether they may be visualized accurately without image distortion. To evaluate such important points fairly, the image quality of tractography was assessed by subjective visual evaluation using a pair comparison method (two alternative-forced choice method: 2AFC) by three trained observers. We compared the quality of tractography using three different b-values (200, 400, 800 s/mm^2) and three different MPG directions (6, 15, 32 directions). Since the small number of MPG directions and the low b-values basically shorten acquisition times, the actual acquisition times were kept constant by changing the number of signal averages in respective b-values/MPG directions.