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Diffusion tensor imaging focusing on lower cervical spinal cord using 2D reduced FOV interleaved multislice single-shot diffusion-weighted echo-planar imaging: comparison with conventional single-shot diffusion-weighted echo-planar imaging

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ABSTRACT

Purpose: To evaluate the performance of diffusion tensor imaging (DTI) of the cervical spinal cord by comparing 2-dimensional standard single-shot interleaved multisection inner volume diffusion-weighted echo-planar imaging (2D ss-IMIV-DWEPI) and conventional 2D ss-DWEPI in a clinical population, focusing on the lower cervical spinal cord.
Materials and Methods: From July to September 2013, a total of 23 patients who underwent cervical spinal MR imaging with DTI were retrospectively enrolled in this study (M:F = 7:16, mean age 45 years, age range 24–76 years). Exclusion criteria were: previous prosthesis insertion (n = 5), syringomyelia on T2-weighted imaging (n = 4), and spinal cord tumor (n = 0). All MRI examinations were performed using 3.0 T imaging with a phased-array spine coil including two different 2D reduced FOV DTI sequences: 2D ss-IMIV-DWEPI (iDTI) and 2D ss-DWEPI without interleaving (cDTI). For quantitative analysis, two musculoskeletal radiologists who were blinded to the sequence measured fractional anisotropy (FA) and apparent diffusion coefficient (ADC) values throughout the whole cervical spinal cord (C1-T1). For qualitative analysis, the readers rated each image based on spinal cord distortion, dural margin delineation, and depiction of intervertebral disc. Quantitative and qualitative evaluations were analyzed separately for upper and lower segments. The t-test was used for quantitative analysis and two-way analysis of variance (ANOVA) and t-tests were performed for qualitative analysis.
Results: FA was significantly higher and ADC was significantly lower on iDTI compared with cDTI (0.679 versus 0.563, respectively, for FA; 631 versus 1026, respectively, for ADC; $p < 0.001$), and this was consistently observed in the lower segment of the spinal cord. The reviewers rated iDTI as superior in terms of all assessed characteristics. For qualitative analysis, the mean iDTI score was significantly higher than the cDTI score for both the lower and upper segments ($p < 0.001$).
Conclusion: 2D rFOV ss-IMIV-DWEPI demonstrated higher performance than conventional 2D rFOV ss-DWEPI in terms of improving image quality, even in the lower segment of the cervical spinal cord.

1. Introduction

Diffusion tensor imaging (DTI) provides not only structural integrity information, but also directional information by measuring water molecule diffusion within tissues. Obtained metrics from DTI are fractional anisotropy (FA), the values of apparent diffusion coefficient (ADC), and eigenvalues, which provide information on the scalar properties of the diffuse translation for extracellular water molecules [1–4]. Previous studies have shown that these metrics reflect the microstructure of the spinal cord and provides visualization of fiber tractography, enabling tracking of the white matter pathways in the brain and spinal cord. Moreover, the application of DTI at the cervical spinal cord allows characterization of microstructural changes including demyelinating disease, infarction, myelopathy, traumatic injury, and spinal cord tumor [5–15].

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However, in practice, the usefulness of DTI at the cervical spinal cord (CSC) has been impeded by 1) the small dimension of the CSC, 2) partial volume artifacts from surrounding cerebral spinal fluid (CSF) and lipid, 3) motion artifacts from breathing, swallowing, and CSF pulsation, and 4) large bony structures that cause abrupt changes in magnetic susceptibility [16–19]. For DTI of the CSC, standard single-shot diffusion-weighted echo-planar imaging (ss-DWEPI) is widely used in clinical cervical MR imaging. However, this protocol has a long readout time and low bandwidth in the phase encode direction, and is therefore prone to distortions and motion artifacts. In previous studies, these limitations were emphasized in the lower CSC [11,20,21].

Degenerative changes of the cervical spine including spondylosis and disc herniation are known to affect the lower segment because of the relative burden of weight and extensive range of motion [22]. However, several previous studies have emphasized the limitations of cervical DTI of the lower segment. This is mainly because of its location close to the lungs and heart, and negative effects associated with the construction of the surface coil [11,20,21]. Over the past decades, there have been several efforts using various EPI-based methods to overcome these limitations, including line scan imaging [23,24], navigated fast spin-echo [3], propeller-based imaging [25–27], parallel EPI [28–30], ZOOM-EPI [31], multichannel coil [32], and more recently, reduced effective field of view (FOV) in the phase encoding direction, an approach that is currently in the limelight. Reducing the FOV in the phase encode (PE) direction enables a drastic shortening of the readout time and also increases the (pseudo)bandwidth in the phase-encoding direction. In addition, geometric distortion in ss-DWEPI is proportional to the FOV in the phase-encoding direction; therefore, susceptibility-related artifacts and pixel misregistration can be reduced in ss-DWEPI [16,18,19].

An equally important method is the interleaved multisection inner volume (IMIV) technique, which provides double inversion/refocusing radio-frequency pulses at 2D ss-DWEPI. This allows for acquisition of the entire cervical spinal cord with 1 interleaved image in the sagittal plane [7]. A few reports on the application of IMIV techniques at the CSC have been published [7,33–35], but there are no direct comparisons with conventional protocols focusing on the lower CSC.

Therefore, the purpose of this study was to evaluate the performance of DTI in the cervical spinal cord by comparing 2D ss-IMIV-DWEPI (iDTI) and conventional 2D ss-DWEPI (cDTI) in a clinical population, focusing on the lower cervical spinal cord.

2. Materials and methods

2.1. Study population

This retrospective study was approved by the institutional review board for human research. A total of 34 consecutive patients underwent cervical spinal MRI between July 2013 and September 2013. Any patients with unstable vital signs, history of interbody fixation, syringomyelia, or spinal cord tumor were excluded. As a result, 9 of the 31 patients were excluded; 5 patients had a clinical history of interbody fixation and 4 showed increased signal of the CSC due to compressive myelopathy and syringomyelia. Thus, 23 patients who underwent cervical spinal cord DTI performed by iDTI and conventional cDTI were enrolled in this study. The study population comprised 7 men and 16 women (age range, 24–76 years; mean age, 45.0 years) who underwent cervical spinal MRI for the following reasons: cervical compressive myelopathy, n = 12; neck pain, n = 6; bone metastases, n = 2, anomaly screening, n = 2; health check-up, n = 1.

2.2. Imaging study

All MRI examinations were performed using a 3.0 T whole body MR imaging system (Trio, Siemens Healthcare, Erlangen, Germany) with a phased-array spine coil and without cardiac gating. Conventional 2D cervical spinal MR imaging was performed first, followed by DTI. Conventional 2D cervical spinal MR imaging consisted of sagittal and axial T1-weighted fast spin echo (FSE) sequences and sagittal and axial T2-weighted FSE sequences. The parameters for the sequences were as follows. Spin echo sagittal T1WI scans: TR/TE 400/10 msec; FOV 260 mm; acquisition matrix 448 × 336; slice thickness 3 mm with 0.3 mm gap; number of excitations (NEX) 2. Sagittal fast spin-echo fat-suppressed T2WI scans: TR/TE 3500/110 msec; FOV 260 mm; acquisition matrix 512 × 358; slice thickness 3 mm with 0.3 mm gap; NEX 2. Axial T1WI scans: TR/TE 400/10 msec; FOV 180 mm; acquisition matrix 320 × 256; slice thickness 3 mm with 0.3-mm gap; NEX 2. Axial T2WI scans: TR/TE 3800/106 msec; FOV 180 mm; slice thickness 3 mm with 0.3-mm gap; resolution 320 × 256; NEX 2.

2D iDTI was performed with the following parameters: TR/TE 4000/65 msec; FOV 192 × 48 mm; acquisition matrix 128 × 32; 10 sagittal slices; slice thickness 2 mm without gap; voxel size 1.5 × 1.5 × 2.0 mm; EPI factor 32; number of excitations 8; b factors of 0 and 500 s/mm^2; and 10 interleaved sections. Diffusion-weighted gradients were applied in 12 noncollinear directions. Total scanning time was 7 minutes. Additional comparison cDTI was performed using the same section thickness and location with TR/TE 1100/65 msec and a total scanning time of 2 minutes (Table 1).

2.3. Image interpretation

DTI images were retrospectively reviewed by two musculoskeletal radiologists (one [Y.H.L.] with more than 8 years of experience in musculoskeletal imaging and one [E.H.P.] in musculoskeletal fellowship) who were blind to imaging information.

2.4. Quantitative analysis

DTI metrics of eigenvalues were calculated and measured for both iDTI and conventional cDTI as follows: fractional anisotropy (FA), apparent diffusion coefficient (ADC; $\times 10^{-3}$ mm^{2}s^{-1}). Regions of interest (ROIs) for FA and the ADC map were measured manually using anatomy and cord morphology from the T2WI scan as a reference. Seven ROIs, ranging from 7 to 13 mm^2 (mean 9.2 mm) in size, were selected from a sagittal section throughout the whole intervertebral disc level of the cervical spine. Each ROI was applied both in white and gray matter, where each level of CSC was depicted in maximum volume, and care was taken to exclude at least 2 voxels from the edge of anterior and posterior margins.

2.5. Qualitative analysis

The following three characteristics were rated to evaluate the clinical utility of iDTI and cDTI: spinal cord distortion, dural margin

Table 1
Imaging parameters for the DTI sequences.

	cDTI	iDTI
TR/TE (ms)	1100/65	4000/73
FOV (frequency × phase encode) (cm)	192 × 48	192 × 48
resolution	128 × 32	128 × 32
Bandwidth (Hz/pixel)	1562	1562
Slice thickness (mm)	2	2
b value (s/mm^2)	0, 500	0, 500
Acquisition time (min:s)	1:59	7:00