High-Resolution 3D Diffusion Tensor Imaging of the Cervical Spinal Cord at 3T

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INTRODUCTION: There is a need for high-resolution diffusion tensor imaging (DTI) measurement of the cervical spinal cord, with reduced susceptibility and motion artifact. DTI of the spinal cord requires high spatial resolution because of the small cross-sectional dimension of the spinal cord(< 15 mm). However, the field inhomogeneities induced by vertebral bone and CSF pulsation artifact present significant challenges. Magnetic susceptibility differences cause substantial image distortion when using conventional singleshot diffusion-weighted echo-planar imaging (ss-DWEPI). Unstable phase errors between different shots are the major source of error in multishot DTI. Various approaches to reduce or correct the phase error have been proposed, such as using driven equilibrium,[2] navigator echoes, or PROPELLER[3] We have developed a 3D multishot DTI technique (3D ms-DWEPI) based on multishot segmented 3D echo-planar acquisition with peripheral gating. We have used this technique to obtain useful DTI of the cervical spinal cord of normal volunteers.

MATERIALS AND METHODS: A 3D ms-DWEPI technique was developed using segmented 3D EPI on a 3T MRI system, inserting a Stejskal-Tanner DW waveform just before and after the refocusing RF pulse of a spin echo EPI sequence. 3D DWEPI was applied to (a) a uniform agar phantom, and (b) the cervical cord of a human volunteer, with acquisition resolution of 1x1x2 mm^3. B values were 0 and 400 for phantom and 250 sec/mm^2 for the human subject, along 7 non-collinear directions ((0,1,0), (1,0,0), (0,0,1), (1,1,1), (-1,-1,1), (-1,1,-1), (1,-1,-1)). A custom-made 4 channel coil was used. Echo-train length (ETL) was selected (<32) to reduce both the magnetic susceptibility artifact and imaging time for full 3D DTI acquisition. Peripheral gating was used to reduce the phase error caused by CSF pulsation. The DTI acquisition time was about 10 min for human cervical spinal cord with an imaging matrix of 128x96x12, FOV 128 mm along the cord axis, and an ETL of 24.

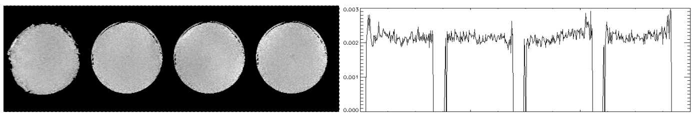

***Figure 1**. ADC maps of ss-DWEPI along (1,1,0) direction (a) and 3D DWEPI along 3 directions (0,1,0), (1,0,0), (0,0,1), (b-d). ADC values across the phantom shown to the left are plotted on the right graph*

RESULTS: 3D DW images of a uniform phantom are compared to that of single-shot DWEPI (ss-DWEPI) in Fig. 1. The uniformity and the accuracy of the ADC values measured by 3D DTI were comparable to those of ss-DWEPI. DTI of a volunteer's cervical spinal cord using our 3D ms DWEPI technique is shown in (Fig. 2A). The substantially improved image quality on both DWI and calculated ADC maps compared to 2D ss-DWEPI is evident in Fig 2B. DTI measurement of the cervical spinal cord is displayed in RGB color in Fig. 3. The sagittal view on the left represents 8 contiguous slices across the cord. The gray matter in the cord is clearly visible in the RGB fiber map in Fig. 3 and the fractional anisotropy map in Fig. 4, especially in cross-sectional view. The calculated longitudinal (//) and transverse (⊥) diffusivities were 1.50±0.25 (//), 0.87±0.07 (⊥) and 0.33±0.14 (⊥), respectively. These values were close to the measured ADC values, 1.38±0.29 along the cord direction (//), and 0.47±0.10 (⊥) and 0.63±0.12 (⊥) on the plane perpendicular to the cord axis. These results indicate a cylindrical symmetry of the diffusivity in the spinal cord.[1]

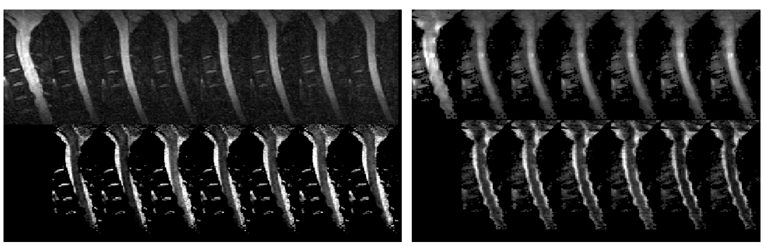

***Figure 2.** DWI (top row) with b=0 and 250 sec/mm^2 and the corresponding ADC maps (bottom row) of a slice, (A) along 7 non-collinear diffusion encodings, using 3D DWEPI with peripheral gating. The spinal cord is clearly defined on both source DWI and the ADC maps, because of the reduced (or removed) susceptibility artifact. The comparative 2D ss-DWEPI images are displayed in (B), along* (1,1,0), (-1,1,0), (1,0,1), (1,0,-1), (0,1,1), (0.1.-1).

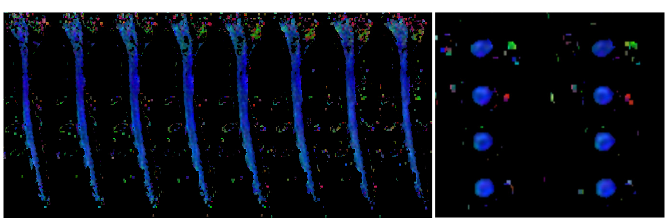

***Figure 3.** Sagittal and cross-sectional view of the principal eigenvector in RGB color. The whole cervical spinal cord is covered contiguously in 1x1x2 mm^3 resolution. The color blue indicates that the water molecules are more freely diffusive along the magnet bore direction, which is the SI direction of the human anatomy. The grey matter along the center of spinal cord is clearly visible*

DISCUSSION: There are very few reports of 3D high-resolution DTI of human subjects in vivo. Our preliminary results using 3D DTI of in vivo human cervical cord show detailed cord fiber direction. The image quality and the accuracy of the DTI measurement may be greatly improved by implementing phase correction using navigator echoes.

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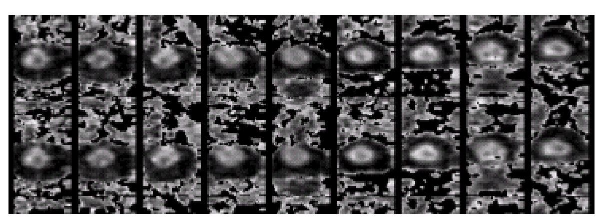

***Figure 4.** Cross-sectional view of the calculated FA maps. The dark area at the center of the cord represents the gray-matter.*