Diffusional kurtosis imaging (DKI) in the normal cervical spinal cord at 3 T : Baseline values and diffusion metric correlations

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Background

The spinal cord is a focus of many radiological diagnostics of such debilitating pathologies as multiple sclerosis, amytrophic lateral sclerosis, spondylosis, and post-traumatic injury. Since these disease states differentiate at the cellular level, diffusion-weighted imaging plays an important role due to its sensitivity to tissue microstructure and white matter connectivity. Most studies confine themselves to the diffusion tensor model, which is a gaussian approximation to the tissue structural scale and directionality. Some higher order approaches employing high diffusion-weighting (e.g. q-space)[1,2] or high angular sampling (e.g. q-ball)[3] have also been applied to the spinal cord, probing parenchymal compartmentation and/or secondary transverse nerve fibers. This work presents application in healthy volunteer spinal cords of a non-gaussian diffusion protocol, diffusional kurtosis imaging (DKI), which has sensitivity to tissue microstructure while maintaining acceptable clinical scan times.

Methods

The cervical spine regions of N = 10 healthy volunteers were scanned in a full body Siemens Tim Trio 3 T scanner. The study was approved by the local Institutional Review Board and informed consent was obtained from all subjects. Imaging used a 4-channel neck coil and 8-element spine array. Anatomical images included (i) sagittal T2-weighted turbo spin echo (TSE), (ii) axial T2-weighted fast low angle shot (FLASH), (iii) axial T1-weighted FLASH, and (iv) sagittal T1-weighted TSE. Diffusion imaging used a twice-refocused spin-echo bipolar diffusion gradient echo planar (EPI) sequence with 30 diffusion encoding directions, and 6 b values for each direction (0, 500, 1000, 1500, 2000, 2500 s/mm^2). TR:3100 ms, TE:110 ms, 2 averages, FOV:160×160 mm^2, matrix size:128×128, slice thickness 3 mm, 20 axial slices. DKI data analysis used an analysis package (Diffusional Kurtosis Estimator (DKE)) written in Matlab 7 (Mathworks, Sherborn, MA, USA) for simultaneous estimation of the diffusion tensor and kurtosis tensor, as well as various derived indices of both. Outputs include diffusion tensor metrics of mean diffusivity MD, fractional anisotropy FA, axial diffusivity D_{ax}, and radial diffusivity D_{rad} (the latter two obtained from DTI eigenvalues) as well as analogous metrics of the kurtosis tensor: mean kurtosis MK, axial kurtosis K_{ax}, and radial kurtosis K_{rad}. Axial and radial parameters correspond to projections of either tensor parallel or perpendicular, respectively, to the primary diffusion tensor eigenvector. Whole cord regions of interest (ROI) were drawn to sample diffusion metrics on each slice, and for each vertebral body (C1 to C4), metrics from 5 contiguous slices were averaged. Tractography was performed on selected cases (MedINRIA, Asceplios, Greece) using b = 0, 1000 s/mm^2 weightings and 30 directions.

Results

Figure 1 shows diffusion metric averages and standard deviations for the N = 10 healthy volunteers of this study at each of the 4 locations (C1, C2, C3, C4) as well as the average of all positions. FA is uniform near 0.58. Radial kurtosis and axial diffusivity are higher than axial kurtosis and radial diffusivity, respectively. Average kurtosis and diffusion metrics were all negatively correlated across the subject group, with the largest correlation coefficient found between K_{ax} and D_{ax} (r = 0.98). Example parametric maps of each metric are shown in Figure 2 along with an unweighted reference image (b0) and a direction-encoded colormap (DEC), which shows the rostral-caudal fiber orientation (blue). The parametric maps also show opposite value ordering for diffusion and kurtosis metrics, i.e. $D_{ax} > MD > D_{rad}$, while $K_{ax} < MK < K_{rad}$. Figure 3 shows example tractography results for the rostral-caudal fiber direction.

Discussion

The normal control data in this work indicates kurtosis parameters are inversely related to diffusion counterparts (e.g. high K_{rad} with low D_{rad}). This correlation is likely related to the highly ordered axonal geometry, where high axonal density both restricts average displacement and perturbs gaussianity. Departures from the correlations found here in intact spinal cords may help differentiate different types of neurodegeneration. Generally, the combination of diffusion and kurtosis metrics may aid in comparison with biophysical models, and to distinguish pathologies (axonal loss, edema, demyelination). Just as intuition on diffusion eigenvalues has emerged (i.e. D_{ax} is associated with axonal loss and D_{rad} with demyelination), sufficient clinical data and modeling of spinal cord DKI may to provide a guide to the added value of kurtosis metrics in the spinal cord.

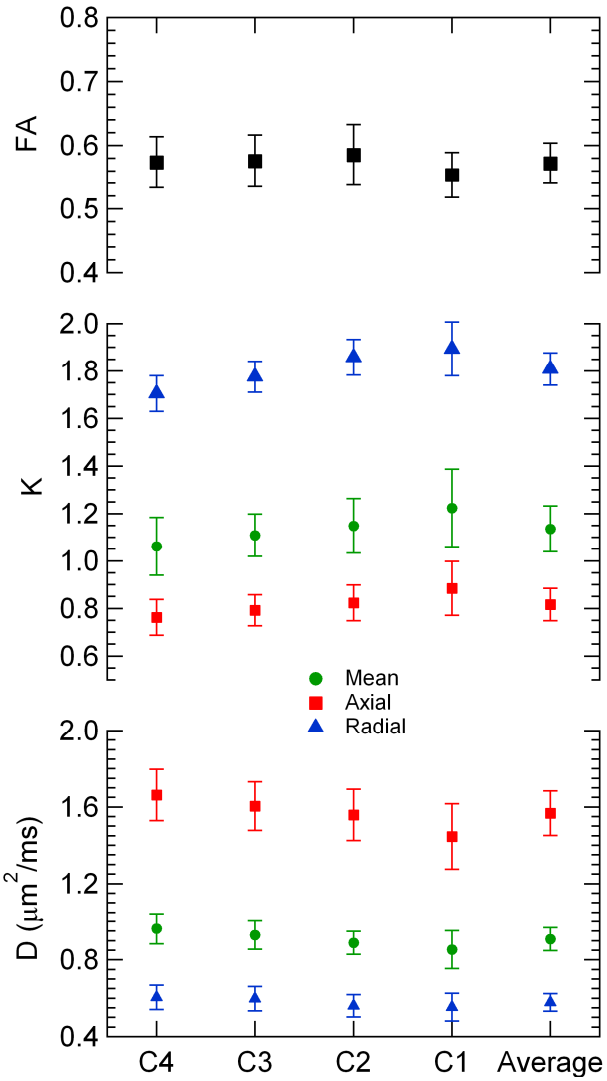

Figure 1: Average and standard deviation of diffusion kurtosis imaging (DKI) indices for normal healthy volunteers at 3 T (N = 10).

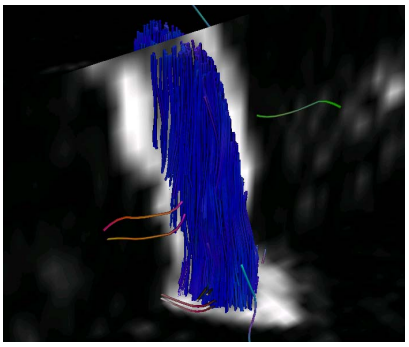

Figure 3: Spinal cord tractography.

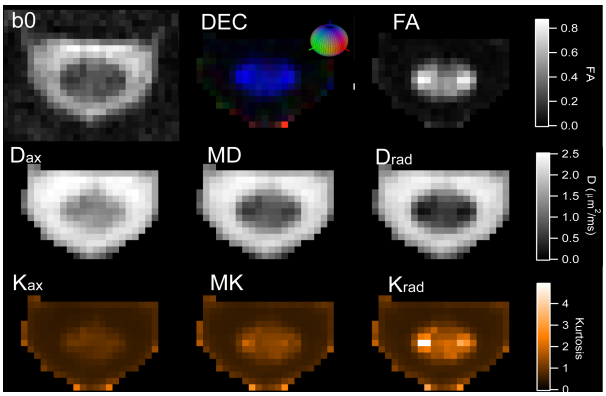

Figure 2: Diffusion and kurtosis parametric maps of healthy volunteer spinal cord at 3 T. See text for details.

References

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