Diffusion Tensor MRI of Human Disc Tissue at 90 µm Isotropic Resolution

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INTRODUCTION:

The objective of this work is to measure the micro-architecture of collagen fibers in the annulus fibrosus of the intervertebral disc (IVD) using diffusion tensor imaging (DTI) methods at ultra-high resolution.

Within the annulus fibrosus of the IVD the structural organization of collagen fibers is believed to play an important role in the distribution of mechanical forces. However, details of the three-dimensional (3D) structure, changes with degeneration, and reorientation behavior in response to mechanical loading have been difficult to measure. In principle, the non-destructive and non-perturbing nature of magnetic resonance imaging (MRI) is ideal for following changes in fiber microstructure under stress; yet due to low signal-to-noise ratio (SNR) the fibers are not easily resolved (1). Most previous MRI studies of annulus fibrosus microstructure until now have inferred fiber integrity from lower-resolution DTI or relaxation parameter maps (2, 3). Of these, DTI more directly probes microstructure, as it aims to measure water diffusion directions within each image voxel under the hypothesis that water close to collagen fibers will diffuse more easily along the fibers than across them. DTI however is extremely demanding on SNR. Using techniques to enhance SNR, we present here DTI data at 90 µm isotropic resolution, the highest done to date on disc tissue. At this resolution the collagen fibers in the annulus are directly resolved, revealing their 3D nature, and supporting our hypothesis that fiber tracts determined via DTI correspond to actual fibers. In this preliminary experiment, we used a section of the anterior region of the annulus fibrosus of a human lumbar IVD.

METHODS:

Specimen preparation

Human IVD tissue was acquired by an institutional review board approved protocol with informed consent. Annulus fibrosus tissue was excised from the anterior part of a human lumbar IVD (L5S1, age 76). A cylindrical plug approximately 1 cm dia. was removed, placed in neutral buffer, and then frozen in a vacuum sealed bag to maintain in situ hydration until needed for MRI. Prior to the MRI experiment, the annulus tissue section was thawed at room temperature for about 4 hrs. The tissue section then was placed in a 1 cm dia. plastic cylinder and surrounded by a perfluorinated oil to provide magnetic susceptibility similar to the tissue, a standard practice in MRI microimaging. The plastic cylinder then was inserted into the RF resonator of the MRI system.

Data acquisition

DTI data were acquired on a high-field (9.4 T) vertical-bore MRI microimaging system (Varian), having 25 G/cm tri-axial gradients and a custom-made 1.5 cm dia. loop-gap RF resonator for high SNR. A 3D fast spin echo imaging pulse sequence was used which had been optimized for DTI. Imaging parameters were as follows: TR = 1 s, ETL = 6, echo spacing = 12 ms, voxel size = 90x90x90 μm^3, six diffusion directions, δ/Δ = 9/10 ms, 2 averages, scan time = 17 hrs.

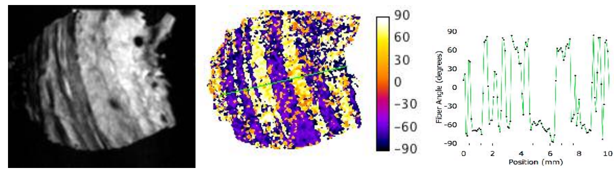
Data analysis

The apparent diffusion coefficient (ADC), diffusion tensor eigenvectors and eigenvalues, and quantities derived from these, were calculated using the free software DTI-Studio (4). Subsequent calculation of fiber angles was performed with custom software written in IDL and also with the free software ImageJ (NIH). The Fiber Assignment by Continuous Tracking (FACT) algorithm of DTI-Studio was used to estimate from the DTI data the tracts of collagen fibers within the annulus tissue section. Fiber angles obtained from DTI data were compared with those of directly resolved fibers.

RESULTS:

A single MRI slice of the annulus fibrosus section, orthogonal to the spinal axis, shows that individual fibers are not resolved and that lamellae can appear as bands of different intensity (Fig. 1a). However, the principle eigenvector of water diffusion within each voxel, visualized by a color map of the angle with respect to the normal of the image plane (Fig. 1b), shows an approximate +/- 60° variation in adjacent lamellae. This also is seen in a line profile drawn across the image (Fig. 1c).

The 3D isotropic-resolution MRI data were re-sliced along planes parallel to the lamellae (Fig. 2a), directly revealing the fibers in the raw images (spinal axis ~ vertical). In the re-sliced DTI data the correspondence is obvious, where color refers to the angle from image vertical of the principle diffusion eigenvector (Fig. 2b). A histogram of angles in this slice shows two groups: +60° ± 24° and −70° ± 12° (Fig. 2c). Further agreement between MRI and DTI is supported qualitatively by fiber tracts obtained from the FACT algorithm, shown penetrating the MRI slice of Fig. 1a (Fig. 3).



(a) (b) (c)

Fig. 1 (a) MRI slice of a human annulus section. (b) DTI data from the same slice, showing the angle (color in degrees) of the principle diffusion eigenvector from an axis normal to the image plane. (c) Line profile drawn across the DTI data (green line in (b)).

(a) (b) (c)

Fig. 2 (a) Reformatted slice from MRI data set, orthogonal to image in Fig. 1a. (b) Same slice from DTI data, showing principle diffusion eigenvector angle from image vertical. (c) Histogram of angles in (b).

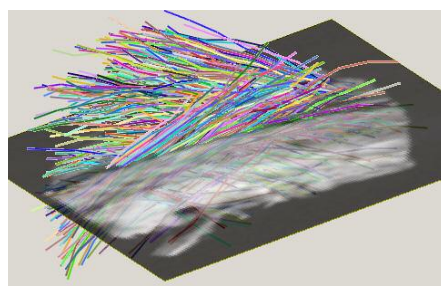


Fig. 3 Collagen fibers calculated from DTI data using FACT algorithm.

DISCUSSION:

These DTI data represent the highest resolution yet reported for annulus fibrosus tissue. By directly resolving the fibers the data support the hypothesis that the principle eigenvector of the diffusion tensor points along the direction of the collagen fibers. Furthermore, the collagen fiber angles measured here are comparable to results in the literature using optical microscope techniques (angle = 45-62º) (5). Limitations include a long scan time and the use of only an annulus section rather than a whole IVD. A next step will be to incorporate tension or compression into the DTI experiment.

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