Mapping 3D Fiber Orientation in Disc Anulus Fibrosus with Diffusion Spectrum MRI

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INTRODUCTION

The intervetebral disc AF is crucial to load bearing of spine joints. It consists of layered structures, each about 100 μm thick. Fibers within each layer are oriented in an alternating criss-cross fashion from layer to layer, about ±30° from the horizontal plane. It is impossible to use invasive dissection to study structural variation of AF during in vitro or in vivo load bearing study. Ultrasound techniques were proposed to find the fiber structures in vivo. However, inherent properties of ultrasound limit the observation depth and image resolution [1]. Diffusion tensor imaging (DTI) had been used to study microstructure of AF. However, the information of partial samples, although in high spatial resolution, is incomplete to reveal whole disc fiber information [2]. DSI is a new technique that is capable of mapping complex fiber orientation by probing 3D probability density function of water molecular diffusion [3]. The accuracy of this technique has been validated [4]. Given the capability of resolving criss-cross fibers within each voxel, it is reasonable to employ DSI to overcome limited spatial resolution when 3D fiber orientations are to be mapped over the whole disc. Another challenge faced by DSI is the inherently low SNR of the AF; an optimum diffusion sensitivity, b-max, is required to ensure accuracy of the fiber orientation. Therefore, this study aimed to test the feasibility of DSI techniques in the mapping of 3D fiber orientations in the intact discs.

METHODS

L5-L6 body-disc-body motion segments from 6 month-old swine were used. MRI data were acquired on a 3T MRI Biospect system (Bruker, Germany). A mini coil, 7-cm inner diameter, was used for RF transmission and reception. The images were acquired at 2-mm thickness, FOV=43 mm and the matrix size=16 yielding an in-plane resolution of 2.6 mm. DSI images were acquired with a pulsed gradient spin-echo sequence, TR/TE=1000/38ms. Diffusion-encoding gradients were applied along 515 vectors in the q-space comprising isotropic 3D grid points. The gradient magnitude |g|=182 mT/m, duration □=12 ms, diffusion time □=18 ms, and the b-max=5050 s/mm2. The optimum b-max was determined in advance from a separate DTI study using an identical spatial resolution. The total acquisition time was about 4.5 hr with 2 repetitions. The analysis was based on the Fourier pair relationship between echo signal S(q) and the diffusion probability density function P(r), ie, S(q) = FT{P(r)}. Integration of P(r) r2 along each radial direction gave the orientation density function (ODF) in each voxel, and the vectors pointing at the local maxima of the ODF were determined. The vectors in each ODF were sorted according to the vector lengths; the 1st vectors were assigned to those with the maximum lengths and so forth. The inclination angles between the individual vectors and horizontal plane were calculated and histograms of these angles were analyzed.

RESULTS

Fiber orientations of disc AF were rendered in 3D color codes, i.e., red in left-right orientation, green in front-back and blue in through-plane directions. Figure A shows a perspective view of the maxium vector map. Fibers are oriented in a criss-cross fashion with a finite inclination angle tilting away from the horizontal plane. Figure B shows in-plane orientations of the fibers rotating around the core. The same in-plane orientation pattern is also found in the 1st eigenvector map of DTI in Fig. C. However, the inclination angle of fiber could not be obtained from DTI owing to partial volume effect. Figure D shows all vectors calculated from the local maxima of ODF in each voxel. Among three discs analyzed, the histogram of the inclination angles gave a mean of 29.88° and a median of 26.57° (Fig. E). The peak of the histogram was located within 20° to 30°. The inclination angles determined from the 1st and 2nd vectors constituted the majority of the peak. The other shorter vectors had non-characteristic distributions and could be neglected.

CONCLUSIONS

We have tested the feasibility of DSI in mapping fiber orientation of AF over the whole disc. Using an optimum b-max of 5050 s/mm2, DSI can resolve intra-voxel criss-cross fibers. The average inclination angle of the fibers was about 30°, consistent with the existing knowledge from conventional histology [5]. Therefore, DSI might be useful to assess structure variation of AF in response to different loading conditions.

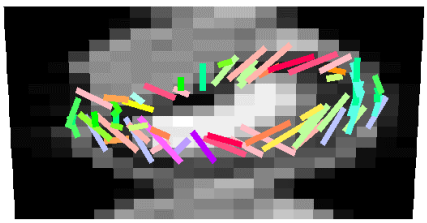


Fig. A

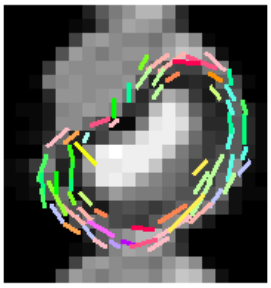


Fig. B

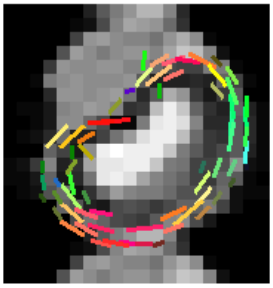


Fig. C

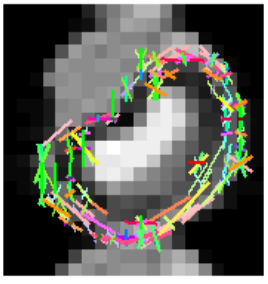
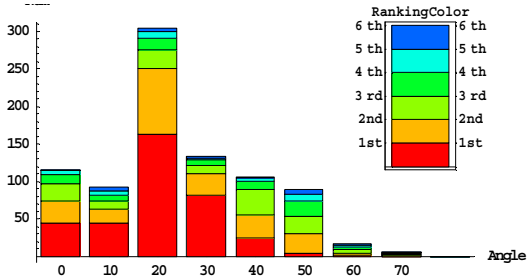


Fig. D

Fig.E



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