

DIPOLAR ANISOTROPY FIBER IMAGING OF HUMAN ANULUS FIBROSUS

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INTRODUCTION: The anulus fibrosus (AF) is a major component of intervertebral disc,¹ along with nucleus pulposus and cartilaginous endplates. The AF consists of concentric bundles of fibrous lamellae in alternating orientations, $\sim\pm 25^\circ$ relative to the endplates.^{2,3} The fiber bundles are also surrounded by extracellular matrix (ECM). The lamellar structure of the AF is disrupted in disc herniation⁴ and some forms of degeneration⁵, but is not routinely visualized with clinical MR imaging. The magic angle effect influences the MR appearance of many fibrous structures⁶ and including the AF. By imaging a sample in multiple orientations and merging the datasets in a certain way, it is possible to control the extent of magic angle effect in the desirable way. In this study, we describe a technique that exploits the magic angle effect in order to visualize the fiber structure of the human disc using clinical MR system.

METHODS: Samples. A human (61 yrs) lumbar spine disc specimen was cut axially leaving ~ 5 mm of vertebral body on superior and inferior sides of the disc, and obliquely at the pedicles to remove posterior bony structures. **MRI.** The sample was imaged on a GE 3T HDx clinical MR system with a 7 cm surface coil, using a 3D SPGR sequence: TR=38 ms, TE=6.4 ms, FA=20°, FOV=6 cm, axial slice=0.2 mm, matrix=384x384. The sample was positioned at a $\sim 25^\circ$ tilt, then rotated through 6 orientations as shown in **Fig.1**. Thus, different parts of the AF were aligned parallel to B_0 at each orientation. **Analysis.** Datasets were co-registered with FSL software using a 6 parameter rigid body model. Maps of the minimum intensity projection (MINIP) as well as the coefficient of variation (standard deviation divided by the mean) were calculated on a per voxel basis using ImageJ software. The MINIP images were also re-formatted in three orthogonal planes using ImageJ.

RESULTS: The source images of the sample at two different orientations (**Fig.2A,B**) showed areas where the AF fibers (thin arrows) oriented \sim parallel to B_0 appear dark relative to the adjacent high signal ECM, as well as areas of little or no contrast (arrowheads) where fibers (oriented \sim at the magic angle) were isointense with the ECM. The nucleus pulposus (square) maintained a homogeneous high signal regardless of the orientation.

On the axial MINIP images, low signal lamellae (**Fig.3A**, arrows) were demonstrated throughout the disc. AF lamellae were up to 2.1 mm thick, with the thickest layers found near the periphery. On a mid-sagittal MINIP image, an inverted radial bulge of the lamellae (**Fig.3B**, arrows) was identified, possibly due to dehydration of the nucleus and partial collapse. A thin fibrous layer was observed between the nucleus pulposus and the cartilaginous end plate.

The lamellar regions had high coefficients of variation (**Fig.3C**, arrows), suggesting that the region had greater changes in signal intensity as the orientation of the sample was varied, as expected for fiber structures experiencing the magic angle effect. Regions of the ECM and nucleus showed little variation.

DISCUSSION: Classic lamellar patterns of the AF, previously observed with light microscopy,² were seen, along with thickening and inverse bulging of the lamellae. While other techniques such as diffusion tensor imaging⁷ (DTI) might also be used, DTI is difficult for short T2 tissues and is confounded by the magic angle effect. Future validation against a reference (i.e., microscopy) would be of interest, as well as implementation in vertical magnets clinically. Technically, the single axis re-orientation used in this study provides a rapidly acquired but somewhat limited dataset. Work remains to determine optimal number of orientations needed to achieve adequate results; the study may be expanded using a full multi-axial positioning of the sample as was recently reported.⁸

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REFERENCES: ¹Bagdik *Clinical anatomy of the lumbar spine and sacrum*. 3rd Edition, Churchill-Livingstone, 1997. ²Marchand+ *Spine* (Phila Pa 1976) 1990; ³Cassidy+ *Connect Tissue Res* 1989; ⁴Veres+ *Spine* (Phila Pa 1976) 2009; ⁵Schollum+ *Spine* 1976; ⁶Erickson+ *Radiology* 1993; ⁷Hsu+ *Magn Reson Med* 1999; ⁸Szeverenyi+ *Magn Reson Med* 2010

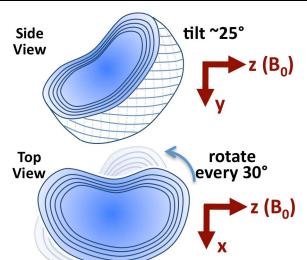


Fig.1: Sample orientation with respect to B_0 .

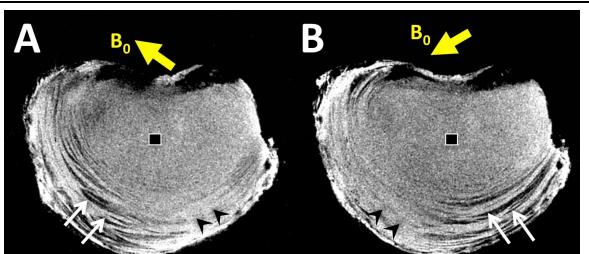


Fig.2: Source MR images taken at different orientations (**A,B**) exhibit magic angle effect. See Results section for detailed description.

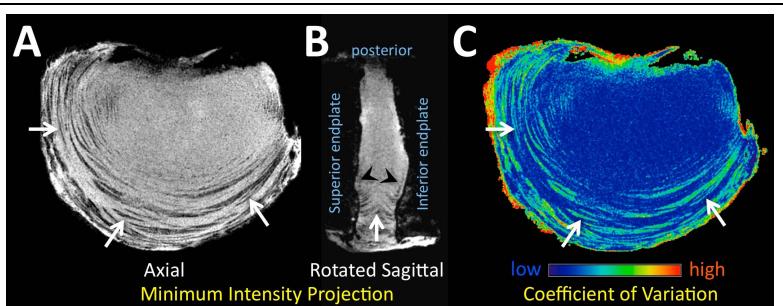


Fig.3: Minimum intensity projection images in (**A**) axial and (**B**) mid-sagittal planes show AF lamellae as dark bands with a high contrast. (**C**) AF lamellae exhibited high coefficients of variations, as expected for structures experiencing the magic angle effect.