3D Model for MR Image Contrast in the Annulus Fibrosus of the Intervertebral Disc

Alexander C. Wright[1], Edward J. Vresilovic[2], and Dawn M. Ellliott[3]

[1]*Laboratory for Structural NMR Imaging, Department of Radiology, University of Pennsylvania, Philadelphia, PA, United States,* [2]*Department of Orthopaedics and Rehabilitation, Penn State University, Hershey, PA, United States,* [3]*Department of Biomedical Engineering, University of Delaware, Newark, DE, United States*

Target Audience: Those using MRI to study the annulus fibrosus of the intervertebral disc.

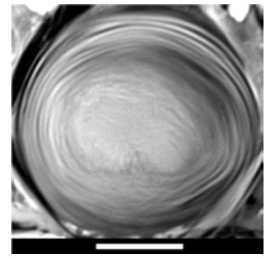
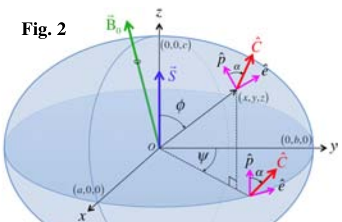


Fig. 1 7T TSE of a bovine tail motion segment showing inter-lamellar contrast in the annulus fibrosus. bar = 1 cm

Purpose: Integrity of the collagen fiber microstructure in the annulus fibrosus (AF) of the intervertebral disc of the spine is relevant to the health of the disc, and loss of this integrity is associated with a cascade of disc degeneration, symptoms of pain, and reduced spinal mobility. MRI is ideal for non-invasively evaluating the status of tissues such as the disc, however sufficient SNR, image resolution, and image contrast are necessary to observe structural details in the AF. The purpose of this study is to provide a theoretical model for the visibility (image contrast) of collagen lamellae in the AF as seen in MRI (Fig. 1). The model is based on the assumption that the observed anisotropic modulation of signal intensity reflects the underlying microstructure of collagen fibers.

Methods: MRI intensity in anisotropic tissue with oriented collagen has been characterized by a T2 relaxation mechanism for water protons[1, 2] that depends on the angle between the ^{1}H–^{1}H axis and static magnetic field B_0 as $(3cos^2\theta - 1)$. The microstructural anatomy of collagen fibers within the AF also has been described[3] as having: 1) fibers arranged in roughly concentric cylindrical sheets (lamellae) around the nucleus, 2) parallel fibers within each lamella, 3) fibers within adjacent lamellae oriented alternatively at about +60° or -60° relative to the spinal axis, i.e., ~ 120° relative to each other, at the central axial plane of the disc, and 4) lamellae curved inward toward the spinal axis above or below the central axial plane of the disc. Because the collagen fiber angle, measured from the longitudinal spinal axis, is known from histology to be in the range 50°-60°, the angle θ varies in a predictable manner along a path in the AF for a fixed orientation of a disc relative to B_0. We therefore developed a theoretical model to account for intensity variations in the AF seen on MRI, and used it to predict the appearance of AF lamellae under various experimental conditions. A 2D model for disc AF tissue has been reported previously[4, 5] and works well for the central xy-plane. However a 3D model is needed to account for the through-plane curvature of the AF, and for this we used a set of concentric ellipsoids. Such a model is based on the equation for a tri-axial ellipsoid, which can be expressed as a surface in parametric form with $x = a\ sin\phi\ sin\psi$, $y = b\ sin\phi\ cos\psi$, and $z = c\ cos\phi$. Here (a, b, c) are the semi-major and semi-minor axes along the (x, y, z)-axes, ϕ is a polar angle measured from the positive z-axis and ψ is an azimuthal (equatorial) angle measured from the positive y-axis (Fig. 2). Unit vectors can be defined on this surface, pointing in the equatorial and polar directions, respectively: $\hat{e} = \vec{e}/\|\vec{e}\|$ and $\hat{p} = \vec{p}/\|\vec{p}\|$. The magnetic field vector $\vec{B}_0$ makes an angle ϕ_B relative to the spinal axis vector $\vec{S}$, which points along the z-axis, and the collagen fiber unit vector $\hat{C}$ makes an angle α relative to $\hat{p}$. Thus for a voxel (i, j, k) centered on point (x, y, z) within the AF, the MRI intensity is

Fig. 2



$$I(x, y, z) = I_{ijk} = I_0 exp\left(-T_E \cdot R_2(\phi, \psi)_{ijk}\right),\ \text{where}\ R_2(\phi, \psi)_{ijk} = \frac{K}{4}\left(3\left[cos\left(\theta(\phi, \psi)\right)_{ijk}\right]^2 - 1\right)^2 + R_2^0,\ \text{and}$$

$$cos\left(\theta(\phi, \psi)\right)_{ijk} = a_{ijk}\left(\frac{-sin\alpha\ sin\phi_{ijk}\ cos\psi_{ijk}}{\|\vec{e}\|_{ijk}} - \frac{cos\alpha\ cos\phi_{ijk}\ sin\psi_{ijk}}{\|\vec{p}\|_{ijk}}\right) sin\phi_B\ sin\psi_B + b_{ijk}\left(\frac{sin\alpha\ sin\phi_{ijk}\ sin\psi_{ijk}}{\|\vec{e}\|_{ijk}} - \frac{cos\alpha\ cos\phi_{ijk}\ cos\psi_{ijk}}{\|\vec{p}\|_{ijk}}\right) sin\phi_B\ cos\psi_B + c_{ijk}\left(\frac{cos\alpha\ sin\phi_{ijk}}{\|\vec{p}\|_{ijk}}\right) cos\phi_B.$$

For the most general case, α, K, and R_2^0 would also depend on (x, y, z), but here they are set as global constants to simplify the model. Furthermore we can compute inter-lamellar contrast as a function of α and ψ: $C(\alpha, \psi) = |I_\alpha(\psi) - I_{-\alpha}(\psi)|$, corresponding to the intensity difference between adjacent lamellae at a given ψ angle that would be generated by replacing α with $-\alpha$. This can be plotted as a two-dimensional surface.

Results: Using values that correspond to actual human disc dimensions and MRI pulse sequence parameters, a simulated 3D MRI data set was generated (Fig. 3). The MRI intensity at each point in the AF was computed as a function of polar angle ϕ and azimuthal angle ψ around the circumference of the disc. The collagen fiber structure in the AF was revealed by dipolar relaxation effects at different orientations of the disc within the MRI scanner. It was seen that when the spinal axis is parallel to $\vec{B}_0$ ($\phi_B = 0°$) there is no dependence on ψ, but that for other orientations of the disc ($\phi_B \neq 0°$) there is an azimuthal intensity variation. Furthermore, when $\phi_B = 0°$ it can be shown that by replacing α with $-\alpha$ there is no change in the resulting MRI intensity, however there is an α-dependent change when $\phi_B \neq 0°$. In addition, the 3D model was used to calculate inter-lamellar image contrast as a function of collagen fiber angle and of position in the AF, for several orientations of the disc relative to the static magnetic field, which revealed the critical dependence of MR image quality on the experimental arrangement. As an example, contrast is shown for $T_E = 20$ ms, $\phi_B = 5°$, $\psi_B = 1°$, and assuming an MRI slice positioned 1 mm above the xy-plane (Fig. 4). In Fig. 4, the horizontal null corresponds to the magic angle $\alpha = 54.7°$ where the dipolar term is zero.

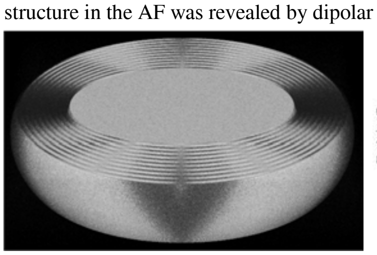


Fig. 3 Simulated MRI data set for an intervertebral disc oriented 90° to B_0.

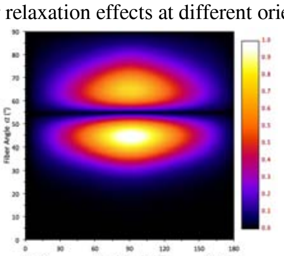


Fig. 4 Computed inter-lamellar image contrast.

Conclusion: The 3D model developed here will be useful for predicting experimental conditions that will optimize inter-lamellar contrast and/or minimize intensity variations on MR images of the annulus fibrosus of the intervertebral disc. Furthermore, it may also find application in the non-invasive characterization of collagen microstructure in the disc as required for the construction of accurate biomechanical models.

Acknowledgements: The work was supported by NIH grants R01AR050052 and P30AR050950.

References

1. Xia Y, et al., Magn Reson Med 48, 460-9 (2002). **2.** Navon G, et al., J Magn Reson Imag 25, 362-80 (2007). **3.** Cassidy JJ, et al., Connect Tissue Res 23, 75-88 (1989). **4.** Hardy PA, Radiology 200, 143-7 (1996). **5.** Wright AC, et al., ISMRM 12th Meeting, p.1519 (2004).