MECHANICS OF THE HUMAN ANULUS FIBROSUS PREDICTED BY A FIBER-INDUCED ANISOTROPIC MODEL

**Elliott, D M (A-NIH); **Setton, L A (A-NSF)
+*University of Pennsylvania, Philadelphia, PA. Orthopaedic Research Laboratory (6081), 215-898-8653, Fax: 215-573-2133, delliott@mail.med.upenn.edu

Introduction
The lamellar structure of the annulus fibrosus (AF) contains an oriented collagen fiber structure which contributes to load support and flexibility in the intervertebral disc. Mathematical models of the AF may be used to calculate stresses and strains and to provide insight into the role of the fiber structure in disc mechanics. Models proposing a strain energy function with fiber-induced anisotropy have been applied to the AF (1-3). However, these models have been limited by assumptions of incompressibility (1) or lack of uniquely defined the material properties (2,3). In this study we predict the contribution of fiber structure to the mechanical behavior of the AF under idealized tensile loading using a recently developed model (2) and unique material properties from new experimental data (4). We hypothesize that the inhomogeneous mechanical behavior observed from outer to inner sites in the AF arises solely from changes in fiber angle. We also hypothesize that, in addition to fiber stretch, fiber-fiber interactions (across lamellae) contribute to the AF mechanical behavior. Understanding the mechanical role of these interactions may be important in understanding the etiology of AF tears.

Methods
Predictions are based on a linear material model for the AF, where anisotropic effects arise from two fiber populations representing the alternating fibers in adjacent lamellae, FIG 1 (2). A strain energy density (W) is defined from the irreducible set of invariants constructed from the infinitesimal strain tensor (ε) and two structural tensors (A and B) representing the orientations (or fiber angles, ϕ) of the two collagen populations within the AF.

\[ W = m_1 I_1 + m_2 I_2 + m_3 I_1 I_3 + m_4 I_3 + m_5 I_5 + m_6 I_4 + m_7 I_6 + m_8 I_7 + m_9 I_9, \]

where the set of invariants is defined as,

\[ I_1 = tr \epsilon, \quad I_2 = tr \epsilon^2, \quad I_3 = tr A \epsilon + tr B \epsilon, \quad I_4 = tr A \epsilon^2 + tr B \epsilon^2, \quad I_5 = tr A \epsilon^3 + tr B \epsilon^3, \]

The material properties m₁ and m₂ represent the Lamé coefficients of the shear moduli: G = 0.1 MPa (5,6), and fiber angle: m₈ = 3.26. Using these properties, predictions for the tensile moduli as a function of fiber angle. Deviations of model predictions for the tensile moduli from outer to inner sites may be attributed to variations in fiber angle. Deviations of model predictions for E₁ and E₂ from independent measurements at inner sites may be related to spatial variations in composition that were not explicitly modeled, such as inhomogeneous collagen density and type, proteoglycans, or minor collagen.

Results
The unique set of material properties, mᵢ (MPa), for the outer AF are m₁ = -0.0033, m₂ = 0.10, m₃ = 0.0816, m₅ = 1.26, m₆ = 2.57, m₇ = -0.0037 and m₉ = 3.26. Using these properties, predictions for the tensile moduli as a function of fiber angle (ϕ) are shown in FIG 2. As ϕ increases, the circumferential modulus E₃ decreases and axial modulus E₂ increases.

Discussion
The model predictions in this study suggest that much, but not all, of the measured differences in tensile moduli from outer to inner sites may be attributed to variations in fiber angle. Deviations of model predictions for E₁ and E₂ from independent measurements at inner sites may be related to spatial variations in composition that were not explicitly modeled, such as inhomogeneous collagen density and type, proteoglycans, or minor collagen.

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References

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