Impact of Microstructural Variations in Collagenous Soft Tissue on Diffusion Magnetic Resonance Imaging Metrics

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Summary

The diffusion of water in collagenous soft tissues, as measured by MRI, can be used to infer microstructural properties of the tissue. By numerically modeling diffusion MRI experiments in simulated collagen fiber networks with varying fiber density, diameter, and dispersion, we found a nonlinear relationship between these microstructural properties and anisotropic diffusion.

Introduction

The microstructural arrangement of collagenous soft tissue is a major determinant of its mechanical behavior. Diffusion tensor imaging (DTI) is a magnetic resonance imaging (MRI) technique that quantifies water diffusion within tissues and has been used to study the microstructural properties of fibrous soft tissues [1]. However, the interaction between properties such as collagen fiber density, diameter, and dispersion as they relate to DTI metrics remains unclear. The microstructural complexity of fibrous tissues presents challenges in experimental assessments of tissue structure-function relationships; however, diffusion simulations are a helpful tool for relating DTI metrics to the underlying tissue microstructure. Therefore, the aim of this study was to determine the relationship between microstructural properties of collagenous soft tissues and DTI metrics via simulation.

Methods

Simulated collagen fiber networks (n=250) were generated within 0.5x0.5x2 mm domains (MATLAB), which represent MRI voxels. Collagen fibers were modeled as straight cylinders since previous work has shown that fiber crimp has a negligible effect on measured diffusion behavior [2]. Fibers were primarily oriented along the long axis of the domain and allowed to intersect, with transverse dispersion based on the Holzapfel-Gasser-Ogden (HGO) model [3]. The dispersion parameter in the HGO model, κ, ranges from 0 (fully anisotropic) to 1/3 (fully isotropic). Domains varied with 5 levels of fiber diameter (30-70 µm), 5 levels of volume fraction (0.75-0.95), and 10 levels of dispersion (0-1/3).

The DTI experiments were numerically simulated using the lattice Boltzmann method [4] with dx=1 µm, dt=111.1 µs, and periodic boundary conditions (Python). Collagen fibers were modeled as impermeable, and only interstitial water generated MR signal. Water was prescribed a self-diffusivity of 2 μm^2/ms. A diffusion gradient duration (δ) of 4 ms, diffusion gradient separation (Δ) of 10 ms, and b-value of 400 s/mm^2 were used. Simulations were performed for 12 gradient directions and a non-diffusion-weighted image, and the diffusion tensor was computed. Fractional anisotropy (FA), which ranges from 0 for fully isotropic diffusion to 1 for fully anisotropic diffusion, was calculated from the diffusion tensor and related to fiber diameter, volume fraction, and dispersion.

Results and Discussion

FA had a nonlinear relationship with fiber diameter and volume fraction (Figure 1). As dispersion increased from κ=0 to κ=1/3, the FA surface flattened towards 0. Interestingly, a local maximum of FA was consistently present for a fiber diameter of 60 µm and volume fraction of 0.9 regardless of the dispersion level.

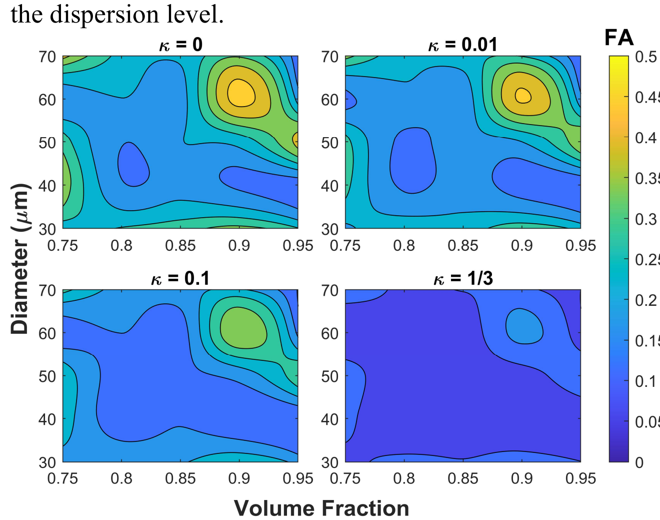

Figure 1: FA as a function of fiber diameter and volume fraction for four levels of dispersion (κ). Cubic interpolation was used between tick marks.

Conclusions

The relationship between FA and fiber density, diameter, and dispersion was highly nonlinear. As a result, further simulations may be necessary to fully characterize this complex relationship and improve the inferential power of DTI in collagenous soft tissues.

References

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