Magic Angle Enhanced MR Microscopy of Fibrous Structures in the Eye

Kevin C. Chan[1,2], Zion Tse[3], Ning-Jiun Jan[4], Joel S. Schuman[2], Seong-Gi Kim[1,5], and Ian A. Sigal[2,4]

[1]Neuroimaging Laboratory, University of Pittsburgh, Pittsburgh, Pennsylvania, United States, [2]Departments of Ophthalmology and Bioengineering, University of Pittsburgh, Pittsburgh, Pennsylvania, United States, [3]College of Engineering, University of Georgia, Athens, Georgia, United States, [4]Laboratory of Ocular Biomechanics, University of Pittsburgh, Pittsburgh, Pennsylvania, United States, [5]Department of Radiology, University of Pittsburgh, Pittsburgh, Pennsylvania, United States

INTRODUCTION: The sclera is a dense, fibrous, viscoelastic connective tissue that forms the outer coat of the eye. Like cornea, the sclera contains approximately 90% collagen by weight and its fibrils are arranged in lamellar organization. Recent studies suggested that the sclera is not a static container, but rather a dynamic tissue capable of altering extracellular matrix composition and its biomechanical properties in response to changes in visual environment [1]. The role that such mechanical behavior plays in eye diseases such as glaucoma and myopia remains poorly understood [1,2], partly because of a lack of non-invasive technique to access and monitor the ocular fibrous microstructures globally, longitudinally and reliably without altering the biochemical environment. Although the sclera appears dark in conventional MRI sequences due to short T2/T2*, the magic angle effect can enhance highly-ordered, collagen-rich tissues with short intrinsic T2/T2* and has been demonstrated extensively in clinical MRI studies of fiber structures in tendons, ligaments and cartilages [3]. This study explored the use of high-field magic-angle enhanced MR microscopy to evaluate the layer-specific tissue properties of the fibrous microstructures in the eye.

MATERIALS AND METHODS: 4 sheep eye samples were scanned using the 9.4T Varian horizontal MRI scanner positioned at different orientations to the static magnetic field (B_o) by a custom-designed automated rotating positioner. 2D high-resolution gradient-echo pulse sequences were applied at TR=3000ms with multiple TE from 4 ms to 75 ms. Three sheep Achilles tendon samples suspended in agarose gel were also scanned as a positive control to the sheep eye MRI results [4].

RESULTS: Distinct fibrous microstructures and differential T2*-weighted signal intensity profiles were observed layer-specifically in the anterior and posterior sclera, cornea, lens and optic nerve head at different orientations to B_o (Figs. 1-5). When orientating the tissue samples from 0° to 90° relative to B_o, maximum signal enhancement was found for all sclera, cornea and tendon samples at the magic angle (55° to B_o) by 82%, 24% and 220% respectively compared to 0° (Figure 6).

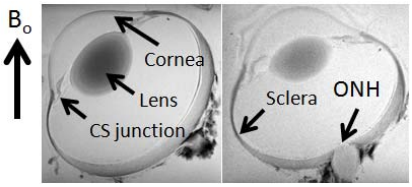

Fig. 1: Gradient-echo (GE) MR images of the sheep eye at 2 different orientations to B_o. (TE=4ms, voxel size = 60x60x800μm^3). Note the signal enhancement in the corneoscleral (CS) shell when the fibers were deviated from 0° or 90° to the B_o direction.

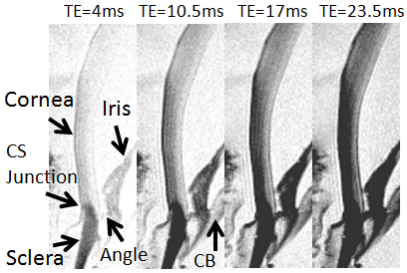

Fig. 2: Enlarged multi-echo T2*-weighted images at the corneoscleral (CS) junction marked in Fig. 1. Note the signal intensity differences across corneal layers and at various orientations to B_o. (CB: ciliary body)

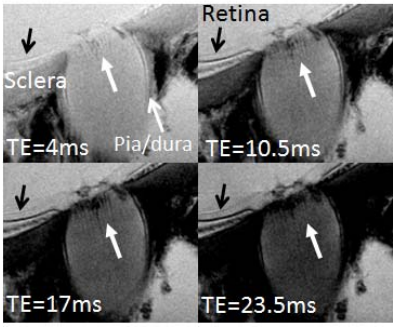

Fig. 3: Enlarged multi-echo T2*W images at the optic nerve head (ONH) marked in Fig. 1. Note the stripes in the ONH near the laminar cribrosa (closed arrows). Retinal layers could also be observed at higher TE (black arrows)

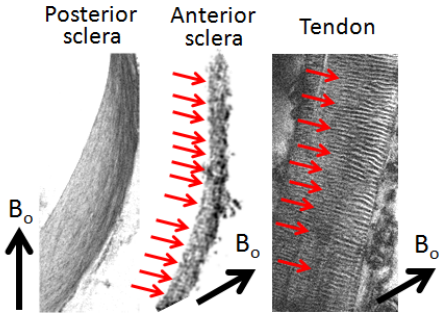

Fig. 4: High-resolution GE-MR images at 20x20 μm^2 in-plane resolution and TE=8ms. Lamellar fibers were observed along both outer and inner layers of the posterior sclera, whereas some crimps or interwoven structures (red arrows) were observed in the anterior sclera and the tendon.

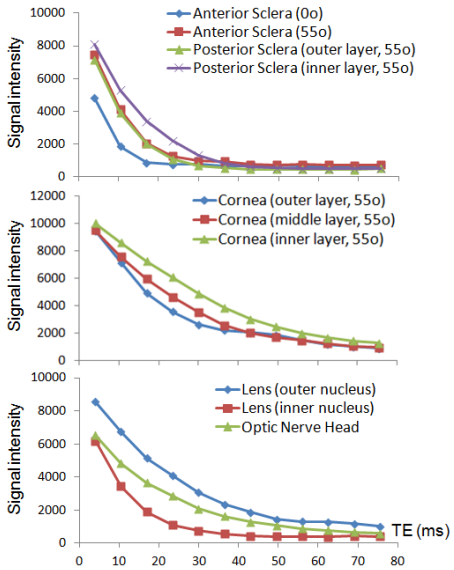

Fig. 5: Layer-specific T2* decay curves of fibrous ocular structures at various degrees to Bo. Differential T2* profiles were found in the anterior and posterior sclera (top), cornea (middle), and lens and optic nerve head (bottom). Scleral layers may be better differentiated at lower TE than corneal layers.

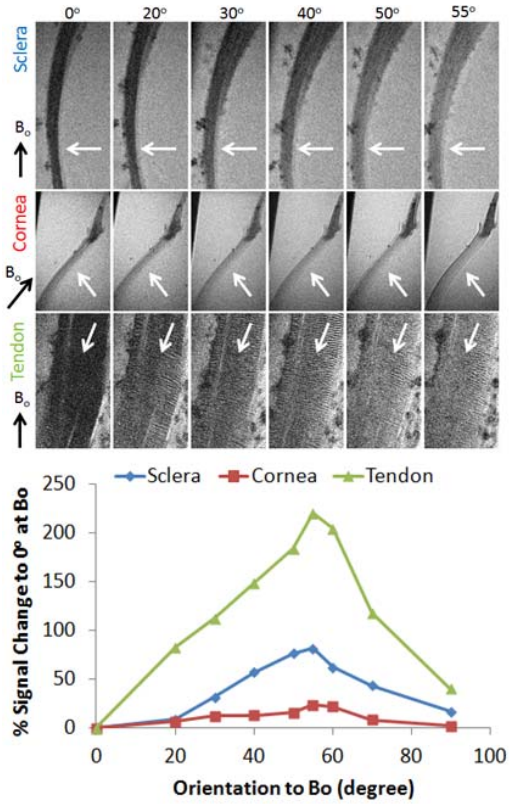

Fig. 6: Magic angle effect in the anterior sclera, cornea and Achilles tendon samples (white arrows) at 0°-90° relative to B_o (black arrows). Maximum signal intensity was found for all 3 structures at about 55° (magic angle) to B_o. The tendon had the largest signal enhancement by 220% relative to 0° whereas the cornea had the smallest increase by 24%. The sclera was enhanced by 82% about the magic angle. (TE=5ms; voxel size = 30x30x500μm^3)

DISCUSSIONS AND CONCLUSION: The results of this study demonstrated the feasibility, sensitivity and specificity of high-field magic-angle enhanced MRI for assessing the magnetic tissue properties in the ocular fibrous structures at high resolution across layers. This technique may open up new areas on non-invasive assessments of biomechanical and biochemical properties of collagen fiber distribution and deformation and remodeling in the eye, and may potentiate future studies on longitudinal monitoring of functional microstructures in diseases involving the corneoscleral shell and optic nerve fibers such as glaucoma, myopia and aging.

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