MRE of the Eye: Inversion Using a Thin Spherical-Shell Model

D. V. Litwiller[1], S. Lee[1], A. Kolipaka[1], K. J. Glaser[1], J. S. Pulido[1], and R. L. Ehman[1]
[1]Mayo Clinic, Rochester, MN, United States

Introduction: Like many organs in the body, disease states of the eye, such as macular degeneration, myopia, and cancer, are often indicated by changes in the mechanical properties of its constituent tissues. Assessments of ocular, intraocular and orbital rigidity, however, are currently limited to qualitative assessment by direct palpation, more invasive methods or other conventional methods such as tonometry, which may yield indirect or inaccurate results [1]. Recently, MR Elastography (MRE) has emerged as a promising technique for investigating motion in the eye and other fluid-filled membranes, such as the vascular wall [2,3] Because the eye is not a homogeneous solid, however, reconstructing its shear stiffness with existing wave inversion algorithms is not feasible, because these data violate conventional assumptions of homogeneity, isotropy, and the absence of boundary conditions [4]. In cases such as these, the development of inversion methods specific to the geometry of the tissue or organ are required. In this work, we hypothesize that it is possible to interpret MRE images of flexural waves in the eye using direct inversion in a thin spherical-shell model.

Materials & Methods: Imaging experiments were performed with a 1.5T MRI scanner (GE Health Care, Waukesha, WI). An enucleated bovine globe was suspended in a rigid fixture using surgical suture and imaged using a 3" receive-only RF coil. Cyclic motion was applied orthogonally to the sclera with the tip of a nylon rod fixed to a 1.25" diameter piezo-electric disc, driven at 467 Hz. The intraocular pressure was controlled by infusing saline through a 22 gauge coronary catheter placed in the posterior chamber, and the pressure was measured with a transducer placed in parallel with the catheter tubing. Measurements of intraocular pressure and infused volume were made at 4 discrete points, and both x and y-sensitized MRE data were acquired at the central two pressure-volume points using a GRE sequence: 60/19 ms TR/TE, 30° flip angle, 8 cm FOV, 3 mm slice, 256x64, 1NEX, and 9 motion encoding gradient pairs at 467 Hz. For anatomical imaging, the eye-mount was inverted and immersed in normal saline solution, and the eye was subsequently imaged with a T2W FSE sequence: 3400/102 ms TR/TE, 8 ETL, 8 cm FOV, 3 mm slice, 256x256, 2 NEX. The diameter of the globe and the average thickness of the sclera were then determined from the anatomical images. The 2D wave images were low-pass filtered and a circular, 1D wave profile was placed in the fluid next to the membrane. This profile was then directionally-filtered and used to create a thin shell (20 pixels) of wave data that was inverted to yield measurements of shear stiffness.

Classical stiffness calculation: The pressure-volume data were used to calculate the shear stiffness of the sclera, according to the classical relation given by $\mu = E / 2(1 + \nu)$, assuming a Poisson's ratio of 0.5, where E is the Young's modulus, given by $E = (9/4)\, V\, [\,(1+V/V_w)\,(dP_t/dV) + P_t / V_w]$, where V is the chamber volume, V_w is the wall volume, P_t is the transmural pressure, and dP_t/dV is the wall stiffness [5].

Thin spherical-shell inversion: The propagation of a flexural wave across a spherical membrane can be described by the following equation of motion:

$$(1+\beta^2)\left[\frac{\partial^2 u}{\partial\theta^2}+\cot\theta\frac{\partial u}{\partial\theta}-(\nu+\cot^2\theta)\,u\right]-\beta^2\frac{\partial^3 w}{\partial\theta^3}-\beta^2\cot\theta\frac{\partial^2 w}{\partial\theta^2}+\left[(1+\nu)+\beta^2(\nu+\cot^2\theta)\right]\frac{\partial w}{\partial\theta}-\frac{a^2\ddot{u}}{c_p^2}=0$$

where u and w are the are the circumferential and radial displacements, respectively, $\beta = h^2 / 12a^2$, where h and a are the shell thickness and radius, ν is Poisson's ratio, and c_p is the so-called flexural wave speed [6]. Measuring u and w with MRE makes it possible to solve for c_p, and subsequently, the shear stiffness with the following relation: $\mu = 0.5\,(1-\nu)\,\rho\, c_p 2$ [7].

Results: Figure 1 is an anatomical image of plane where the MRE acquisition was performed. Figure 2 is a y-sensitized wave image of the bovine globe, where the arrow indicates the location of the motion source. Figure 3 is an image of the corresponding constructed thin-shell data, again with an arrow indicating the location of the motion source. Figure 4 is a plot of the classical shear stiffness calculation versus the MRE-based thin-shell inversion result for the bovine globe at two pressures.

Discussion & Conclusion: Figure 4 suggests that the thin-shell inversion and the classical calculation yield similar results. Both stiffness derivations make assumptions of spherical geometry, when, in reality, the geometry of the posterior chamber is more elliptical. In addition, the classical calculation of wall stiffness is sensitive to errors in the measurement of wall thickness (because it is so thin), contributing to the error estimates shown in Figure 4. Outflow in the eye also caused the intraocular pressure to drop slightly during the MRE acquisition, causing a slight mismatch between x & y motion-sensitizations, used to calculate the radial and circumferential displacements. Regardless, these results support the hypothesis that direct inversion of MRE wave data using a thin spherical-shell model is possible and reasonably accurate.

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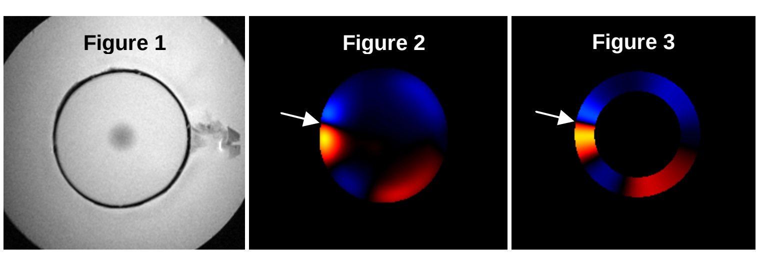

Figure 4