Magnetic resonance elastography of slow and fast shear waves illuminates differences in shear and tensile moduli in anisotropic tissue

John L Schmidt[1], Dennis J Tweten[1], Maisie M Mahoney[2], Tally Portnoi[3], Ruth J Okamoto[1], Joel R Garbow[4], and Philip V Bayly[1,2]
[1]*Mechanical Engineering and Materials Science, Washington University, St. Louis, MO, United States,* [2]*Biomedical Engineering, Washington University, St. Louis, MO, United States,* [3]*Electrical Engineering, Massachusetts Institute of Technology, Cambridge, MA, United States,* [4]*Biomedical Magnetic Resonance Laboratory, Department of Radiology, Washington University, St. Louis, MO, United States*

Objective: Mechanical anisotropy is a key property of fibrous tissues; the anisotropic mechanical properties of brain white matter may play a key role in the mechanics of traumatic brain injury, or change due to disease or aging. In magnetic resonance elastography (MRE), mechanical properties are estimated from phase-contrast MR images of motion during propagation of shear waves. Most MRE studies assume isotropic material models with single shear (μ) or tensile (E) modulus. Recent studies have provided parameters of anisotropic (transversely isotropic[1,2] or orthotropic[3]) material models. The simplest anisotropic material model for small deformations of soft tissue is a nearly incompressible, transversely isotropic (ITI) material with three parameters: minimum shear modulus (μ_2), shear anisotropy ($\phi = \mu_1/\mu_2 - 1$) and tensile anisotropy ($\zeta = E_1/E_2 - 1$). These parameters, and the angle between the propagation and fiber directions determine the speeds of two types of shear waves: "fast" and "slow", for a given propagation direction. Both fast and slow shear waves are observed in MRE of anisotropic tissue, and can be used to estimate anisotropic shear and tensile moduli.

Methods: Images of shear wave propagation in turkey breast (muscle) tissue *ex vivo* were acquired using MRE. Samples were obtained from retail butcher and tested 3-5 days post-mortem. Two different geometries were used (Fig. 1): **Cylinder – axial excitation** (Fig. 1a): A cylindrical sample ~45 mm dia. was embedded in gelatin in a ~ 48 mm ID container. A 3 mm dia. plastic rod provided axial (z) excitation at 800 Hz, leading to shear waves with radial propagation direction ($\boldsymbol{n} \approx \boldsymbol{e_R}$). **Cube – transverse excitation** (Fig. 1b-c): A ~25 mm cube of tissue was embedded in gelatin in a ~ 30×30×30 mm^3 plastic container. Horizontal (z) 800 Hz excitation led to shear waves propagating downward ($\boldsymbol{n} \approx -\boldsymbol{e_Y}$). The two excitation scenarios (Fig. 1b-c) differ in the direction of excitation relative to fibers. To verify the average fiber orientation of the sample, diffusion tensor imaging (DTI) was performed (30 dir., b=2050 s/mm^2). While both scenarios contain fibers at approximately 45° from the surface, in one case (Fig. 1c) the actuation direction is aligned with $\boldsymbol{m_s} = \boldsymbol{n} \times \boldsymbol{a}$ to induce slow shear waves; in the other case (Fig. 1b) the excitation is aligned with $\boldsymbol{m_f} = \boldsymbol{n} \times \boldsymbol{m_s}$ to induce fast shear waves.

Results: Fig. 2 shows the displacement fields in the cylinder and cube samples. In the cylindrical sample (Fig. 2a), slow shear waves dominate. Elliptical waves are evident with a longer wavelength (Fig. 2a-i) along the fiber direction ($\theta = 0$) and shorter wavelength (Fig. 2a-ii) perpendicular to the fiber direction ($\theta = 90°$). In the cube with $\theta \approx 45°$, when the excitation direction is parallel to $\boldsymbol{m_s} = \boldsymbol{n} \times \boldsymbol{a}$, slow shear waves (Fig. 2c-iv) also dominate, but when the excitation direction is aligned with $\boldsymbol{m_f} = \boldsymbol{n} \times \boldsymbol{m_s}$, fast shear waves (Fig. 2b-iii) dominate. The difference in slow shear wave speeds in the cylinder at $\theta = 0$ and $\theta = 90°$ (Fig. 3) indicates shear anisotropy $\phi \approx 1.6$, from the relationship $c_s^2 = \mu_2/\rho\,(1 + \phi \cos^2\theta)$. The difference between fast and slow shear wave speeds at $\theta = \sim 45°$ indicates tensile anisotropy $\zeta \approx 2.6$, from the equation $c_f^2 = \mu_2/\rho\,(1 + \phi \cos^2 2\theta + \zeta \sin^2 2\theta)$. Shear modulus $\mu_2 \approx 54$ kPa.

Discussion: Shear wave speed in soft tissue is affected by anisotropy in both shear and tensile moduli, and by the angle between propagation and fiber directions. Both fast and slow shear waves are observed in MRE studies of muscle. Estimates of a minimal set of 3 parameters: shear modulus, shear anisotropy, and tensile anisotropy can be extracted from fast and slow shear-wave speeds. This extends the methods in reference[1,2] for estimation of shear anisotropy but is simpler than other approaches[3] and may be easier to apply. The existence of both types of shear waves may be responsible for variations in parameter estimates if isotropic material models are assumed, or if only slow shear waves are assumed, in MRE of anisotropic tissue. The current approach may enable greater understanding and more accurate measurement of normal and pathological mechanical properties of white matter in the brain.

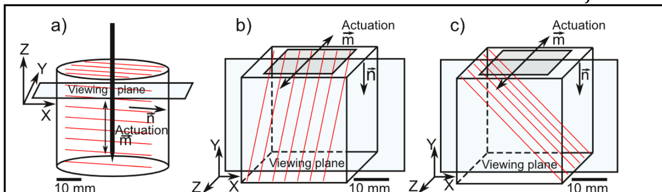

Fig. 1: Schematic images of the MRE experiments. Fiber orientations are shown in red. (a) Cylindrical sample with axial excitation producing slow shear waves. (b-c) Cube with fibers at ≈45 ° from the top surface. The main propagation direction **n** is downward, corresponding to fast (b) or slow (c) shear waves.

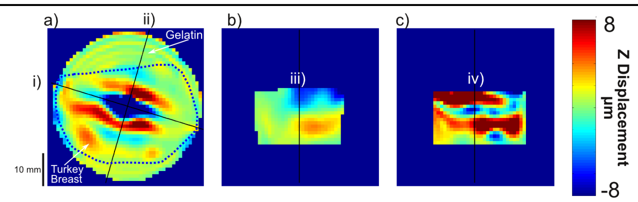

Fig. 2: Out-of-plane displacement fields from 800 Hz MRE of samples in Fig. 1. Lines (i-iv) show propagation (a-i) $\theta = 0$ from fiber axis (Fig. 1a); (a-ii) $\theta = 90°$ from fiber axis (Fig. 1a); (b-iii) $\theta = 49°$ from fiber axis, fast shear mode (Fig. 1b); (c-iv) $\theta = 49°$, slow shear mode (Fig. 1c).

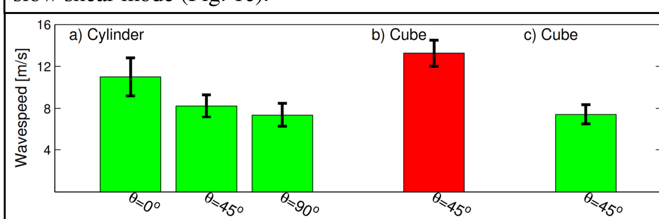

Fig 3: Mean wave propagation speed (±std. deviation) in cylindrical and cubic specimens for different values of θ. Color: slow (green) and fast (red) wave speeds. N=3 samples each.

References: **1.** Sinkus R, et al.. Magn Reson Med. 2005; 53(2): 372-387. **2.** Qin EC, et al.. J Magn Reson Imaging. 2013; 37(1): 217-226. **3.** Romano A, et al.. Magn Reson Med. 2012; 68(5):1410-1422.
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