A Novel Actuator Design and Modeling Framework for MR Elastography (MRE) Calibration

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Synopsis

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We have developed a novel broadband piezoelectric actuator for MR elastography that can operate at a wide range of frequencies from 5 Hz to 5 kHz. We show it's efficacy using a bilayer agarose phantom with slightly different concentrations. Complex shear waves are introduced into the sample by tapping the gel inside the cylindrical tube from which shear modulus is estimated using algebraic Helmholtz inversion. The results show the superior sensitivity of MRE in distinguishing the two layers compared with diffusion tensor imaging (DTI).

Introduction

Studying the frequency dispersion of mechanical properties provides a means to probe material microstructure at various length scales. Time harmonic MR elastography (MRE) is a method of choice for “palpating” tissue but requires an actuator that can operate over a wide range of frequencies. However, at low frequencies, MRE require large displacements owing to reduced MR sensitivity (i.e., velocity measured with PFG-MR = displacement × frequency) while at high frequencies operation is often limited by vibrations in the actuator system. In this study, we report the development of a new broadband (0 – several kHz) piezoelectric actuator to perform MRE within a micro-imaging MRI scanner and a Finite Element Modeling (FEM) framework to describe system behavior.

Methods

Our material specimen consists of two layers of agarose gel of 0.1% and 0.12% concentration stacked on top of each other in a glass tube. The actuator is constructed from a piezoelectric stack operable from 0 to 5 kHz (Thorlabs, Sterling, VA) with a stroke length of 100 µm, which is mated to a 3D printed plunger that rests on top of the gel (Figure 1). The piezo transducer is driven by a 150V driver which is synchronized with the NMR system and is operated at 10 Hz in this study. The piezo is stabilized by a custom designed holder shown in the figure.

The longitudinal motion of the plunger introduces shear waves in the gel which were captured using a pulsed gradient spin echo (PGSE) experiment triggered at different phases of the actuation cycle spaced 10 ms apart for one full cycle. The cylindrical geometry of the sample container introduces complex shear waves which can be used to study its mechanical properties. 3D MRE data was acquired on a 7T scanner (Bruker Biospin) using a 25 mm quadrature RF probe with the following parameters: $\delta \backslash \Delta$ = 1.5\10 ms (Hadamard scheme with b = 0, 250 s/mm^2), FOV = 30 x 25 x 25 mm, TR\TE = 200\16 ms, and a 0.5 mm isotropic voxel resolution. The shear modulus of the gel was estimated using algebraic Helmholtz inversion. Diffusion tensor imaging (DTI) data was also acquired with b-values = 0, 1000 s/mm^2 and 20 diffusion weighting directions with the actuator turned OFF to compare the sensitivity of DTI and MRE in imaging the layered medium.

Finite element method (FEM) simulations were performed and compared to the observed shear waves and the direct inversion results. Simulated displacement fields were produced in a half-cylinder geometry containing two adjacent linear elastic layers with shear moduli set to 6 Pa (close to the actuator) and 10 Pa (far from the actuator) as estimated from the experimental displacement data. The normal and tangential gel displacements at the walls of the tube were set to zero to model gel adhesion to the rigid boundary. A symmetry boundary condition was prescribed on the remaining flat surface of the half-cylinder. The mesh consisted of 9,216 trilinear hexahedral elements with a maximum side length of 1.87 mm. The model was solved at maximum time steps of 6.25 ms with a dynamic quasi-Newton solver (FEBio) [1].

Results and Discussion

The real part of measured displacement field filtered at 10 Hz along with the simulated displacement field are shown in Figure 2. The measured displacement field shows uniform mechanical excitation of the FOV studied. The simulated displacement fields share many characteristics with the measured displacement fields, such as the radial motion of the gel as indicated by horizontal and out-of-plane displacements, and uniaxial shear wave propagation. However, the measured decrease in wave amplitude in the stiffer gel is not as pronounced in the simulation suggesting that this attenuation may be due to presence of an interfacial layer between the two gel layers with a different stiffness and/or due to differences in viscous dissipation in both the gel layers, which were not modeled. The estimated shear modulus map is shown in Figure 3, which clearly distinguishes the layers having two different gel concentrations based on their differences in stiffness (6 vs 10 Pa on average). The DTI maps, however, fails to capture this subtle difference—the mean diffusivity (MD) and fractional anisotropy (FA) were uniform throughout the material except at the edges where the signal was low as shown in the S_0 map.

Conclusion

We have developed a new MRE actuator to study frequency-dependent mechanical properties of soft materials. The wide range of frequencies achievable with this new actuator and the ability to model gels and more complex media using FEM methods could help advance the scope of applications of MRE to studying tissues and biomaterials.

Acknowledgements

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References

[1] Maas, S.A., et al., FEBio: Finite Elements for Biomechanics. Journal of Biomechanical Engineering-Transactions of the ASME, 2012. 134(1): p. 10.

Figures

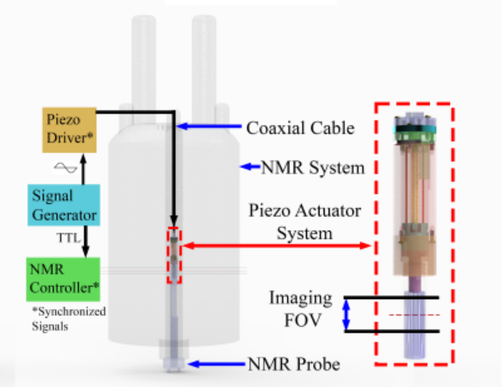

Figure 1: Actuator design and setup in the MRI system. The piezo driven by the driver which gets as input a sinusoidal signal from the function generator. The acquisition is triggered using the TTL sent by the signal generator to the NMR console. Due to the high aspect ratio of the piezo, it supported using a rubber band to prevent damage during operation.

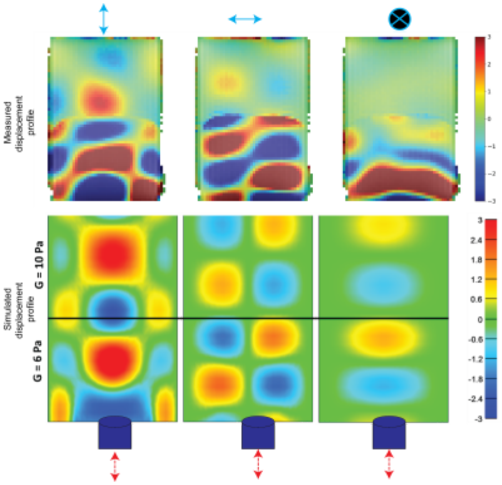

Figure 2: The three components of the measured and simulated displacement profiles for slice close to the center of the FOV with the component direction indicated using arrows on top of the figure. A fair match between the experiment and simulation can be noted although differences exist. The circular piston is in contact with the inner portion of the bottom surface of each panel (shown in the figure) and the displacement waves propagate mainly along the axis of the tube. The black horizontal line in the simulation result indicates the boundary between the two layers.

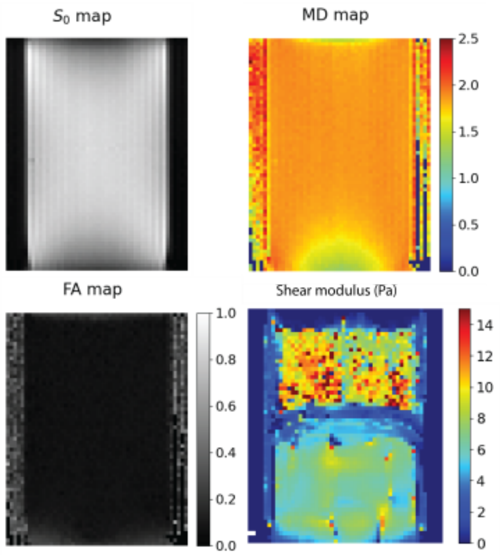

Figure 3: Comparison of DTI and MRE results from the bilayer phantom for a slice close to the center of the FOV. S_0 is the non-diffusion weighted magnitude image, MD is the mean diffusivity map (μm^2/ms), and FA is the fractional anisotropy map. The separation of the layers is clearly visible in the shear modulus map but is absent in the DTI-provided MD and FA maps.