Slow dilatation waves in agarose gel observed with low frequency magnetic resonance elastography

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Introduction

Intrinsic actuation magnetic resonance elastography (MRE) of the brain relies on endogenous brain motion during the cardiac cycle (about 1 Hz) and is emerging as a complement to conventional MRE conducted at around 60 Hz by external skull vibration. While MRE analysis normally assumes tissue is nearly incompressible or otherwise removes dilatation from the displacement field, oscillatory brain dilatation has been observed in vivo and may harbor valuable information about the tissue.

In this study, low-frequency displacement waves in soft agarose gels were measured to determine whether dilatation waves are present and what material model for the gel best explains the observed displacement field. In particular, we simulate the observed displacement field with the finite element method (FEM) assuming nearly incompressible viscoelasticity, moderately compressible viscoelasticity, and poroelasticity/biphasic theory. Optimizing the material model for low-frequency MRE is important because it dictates the set of mechanical parameters which may be extracted from endogenous brain displacement waves and affects the accuracy of their reconstruction.

Methods

The free circular face of a 0.12% cylindrical agarose gel sample measuring 60 mm in length and 20 mm in diameter was displaced axially by a piston 11 mm in diameter at 10 Hz. The displacement field was acquired on a 7T Bruker scanner with a 3D pulsed gradient spin echo sequence for 0.5 mm isotropic voxels and 10 time points per period (b = 0, 250 s/mm^2, $\delta/\Delta = 1.5/10$ ms, and TR/TE = 200/16 ms). A 3D quintic smoothing spline was fit to the displacement field which enabled analytic second derivatives for dilatation and shear wave speed reconstruction via algebraic viscoelastic inversion (AIDE). Furthermore, FEM models were developed to predict the displacement field assuming either a viscoelastic solid or a biphasic mixture material model for the gel.

Results

The displacement field consisted of alternately rotating toroids propagating axially (Fig. 1). An axially alternating pattern of positive and negative dilatation is apparent near the centerline of the sample (Fig. 2). The dilatation wave speed c_d was only approximately 3 to 6 times greater than the shear wave speed ($c_s = 0.1$ m/s) for many voxels. A viscoelastic FEM model showed that for low compressibility ($c_d = 2.4$ m/s) the axial wavelength is longer than in the experiment, whereas for higher compressibility ($c_d = 0.3$ m/s) it is shorter, more like the experiment (Fig. 3). An FEM model of a biphasic material consisting of a solid matrix with fluid-filled pores produced better agreement with the experiment than the viscoelastic model (Fig. 4).

Discussion & Conclusions

Our viscoelastic inversion and FEM analyses suggest that slower dilatation wave speeds than typically assumed for tissue are present in the sample. The corresponding gel “compressibility” may be a consequence of dynamic changes in local fluid volume fraction, a poroelastic effect relevant at lower actuation frequencies. Thus, material models which account for dilatation may be more suitable to analyze endogenous brain displacement waves and introduce additional parameters for reconstruction which may reflect physical tissue changes with disease.

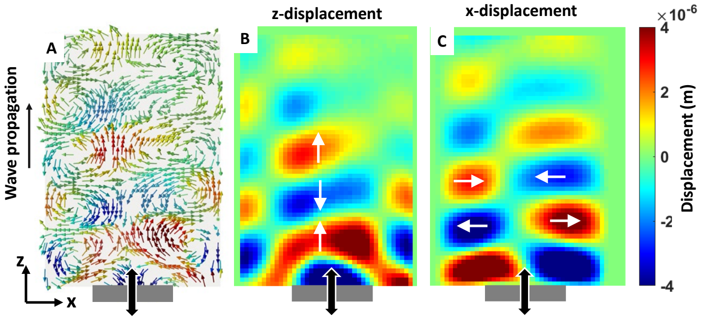

Figure 1. Measured displacement field in a sagittal cross-section. A) Displacement vectors. B) Axial displacement. C) Radial displacement. The gray bar represents the piston oscillating along the sample axis.

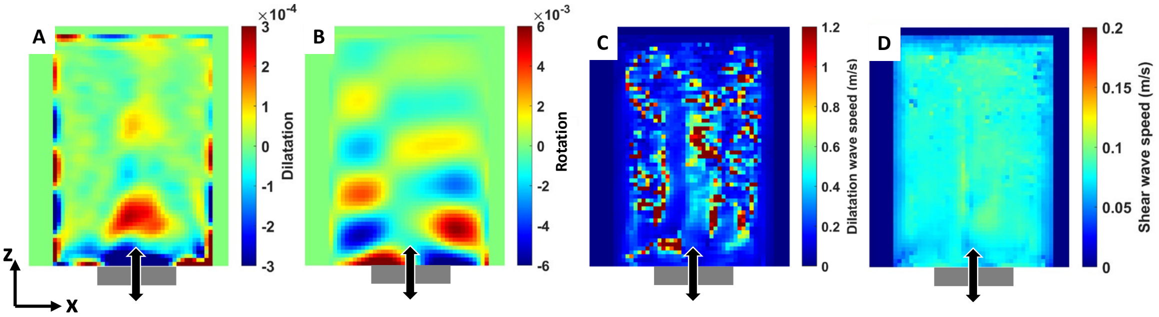

Figure 2. Wave properties. A) Divergence and (B) curl of the displacement field. C) Dilatation wave speed c_d and D) shear wave speed c_s.

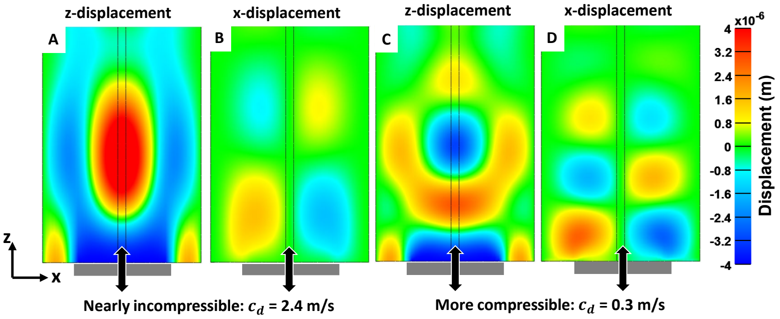

Figure 3. Varying dilatation wave speed in viscoelastic FEM models. A) Axial and B) radial displacement for low compressibility (c_d = 2.4 m/s and c_s = 0.1 m/s). C) Axial and D) radial displacement for moderate compressibility (c_d = 0.3 m/s and c_s = 0.1 m/s).

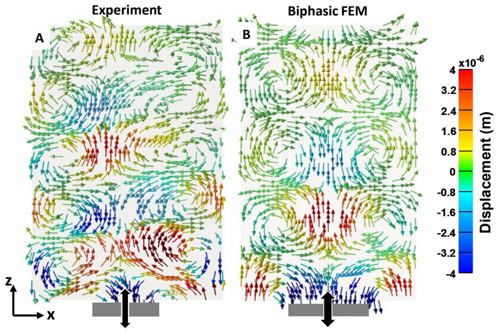

Figure 4. Simulated displacement field for a biphasic material. A) Measured displacement vectors in the experiment and B) simulated displacement vectors for the biphasic model.