BMES abstract 2024

## Title

# Wave propagation analysis in agarose gel for low-frequency magnetic resonance elastography

## Authors

Julian A. Rey, Kulam N. Magdoom, Michal E. Komlosh, Peter J. Basser

## Introduction (250 words max)

Magnetic resonance elastography (MRE) is a Magnetic Resonance Imaging (MRI) technique used to estimate a tissue's mechanical properties remotely by measuring and analyzing the propagation of elastic body waves through it. MRE of the liver provides a clinically approved assessment to support the staging of liver fibrosis. In this setting, the mechanical waves are commonly produced at 20-200 Hz by an external actuator. Preclinical MRE in animals is typically performed in a higher frequency range (200-1500 Hz). However, it is important to characterize the mechanical response of tissue at lower actuation frequencies because 1) mechanical properties tend to be frequency dependent, 2) new biomarkers owing to different mechanical phenomena may be available, and 3) body tissues normally experience low-frequency displacements which may be altered by disease or possibly function.

In this study, various material models were employed to analyze and simulate the mechanical response of a cylindrical agarose gel sample to 10 Hz axial actuation. While pressure waves, as opposed to shear waves, are often ignored in MRE, a full viscoelastic inversion method was implemented to ascertain their potential contribution to the displacement field at low frequencies. We developed finite element method (FEM) models of the MRE experiment to complement the inversion results by predicting the displacement field for a range of pressure and shear wave speeds.

## Materials and Methods (250 words max)

A cylindrical sample of 0.12% agarose gel measuring 60 mm in length and 20 mm in diameter contained in a glass vial was used as a phantom for the MRE experiments. The free circular face of the gel was displaced axially by a piston 11 mm in diameter attached to a custom piezoelectric actuator operated at 10 Hz. A pulsed gradient spin echo (PGSE) sequence was used to acquire the 3D MRE data on a 7T Bruker Biospin scanner. The displacement field data were acquired for 0.5 mm isotropic voxels in a 30 x 25 x 25 mm FOV using a Hadamard encoding scheme with b = 0, 250 s/mm$^2$, $\delta/\Delta$ = 1.5/10 ms, and TR/TE = 200/16 ms.

Pressure and shear wave speeds were estimated in each voxel by algebraic inversion of the viscoelastic momentum equations assuming an isotropic, locally homogeneous material. Separately, FEM models were developed to predict the dynamic displacement field within the agarose gel phantom when subjected to loading conditions mimicking the experiment. The gel was modeled as either a compressible, isotropic elastic solid or a biphasic mixture. The biphasic mixture material represents a linear elastic solid matrix with pores through which an incompressible fluid phase may flow according to Darcy's law. The mesh consisted of 9,216 trilinear hexahedral elements with a maximum side length of 1.87 mm. The model was solved with a dynamic quasi-newton solver available in FEBio.

## Results, Discussion, Conclusion (350 words max)

Axial actuation of the cylindrical agarose sample by a circular piston at 10 Hz produced a nearly axisymmetric displacement field consisting of alternately rotating toroids propagating axially

(Fig. 1). Both radial displacement orthogonal to the propagation direction (i.e., transverse wave), and axial displacement parallel to the propagation direction (i.e., longitudinal wave) were observed. An axially alternating pattern of positive and negative dilatation is apparent near the centerline of the sample (Fig. 2). Algebraic inversion of the viscoelastic momentum equation resulted in a shear wave speed estimate of ~0.1 m/s and a pressure wave speed approximately 3 to 6 times greater for many voxels in the sample, although the latter estimate is considerably noisier.

A linear elastic solid FEM model of the MRE experiment showed that in a material with lower compressibility (pressure wave speed = 2.4 m/s) the axial wavelength is longer than in the experiment, whereas in a more compressible material (pressure wave speed = 0.6 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 linear elastic solid model (Fig. 4).

This study demonstrates that low-frequency actuation of agarose gel can produce complex displacement fields exhibiting both transverse and longitudinal waves. While the longitudinal wave evident along the sample centerline may be a “longitudinal shear wave” resulting from the interaction of shear waves with different propagation directions, our viscoelastic inversion (Fig. 2B) and FEM analyses (Fig. 3) suggest that slower pressure wave speeds (0.3 - 0.6 m/s) than typically assumed for tissue (~1540 m/s) are present in the sample. The corresponding gel “compressibility” may be a consequence of dynamic changes in the local fluid volume fraction, a poroelastic effect that may be relevant at lower actuation frequencies. Indeed, our biphasic model (Fig. 4) matches the measured displacement field better than the solid model (Fig. 3). The unexpected wave features observed at 10 Hz suggest the need to characterize tissue mechanical properties at low frequencies to better understand their mechanical response to normal physiological loading.

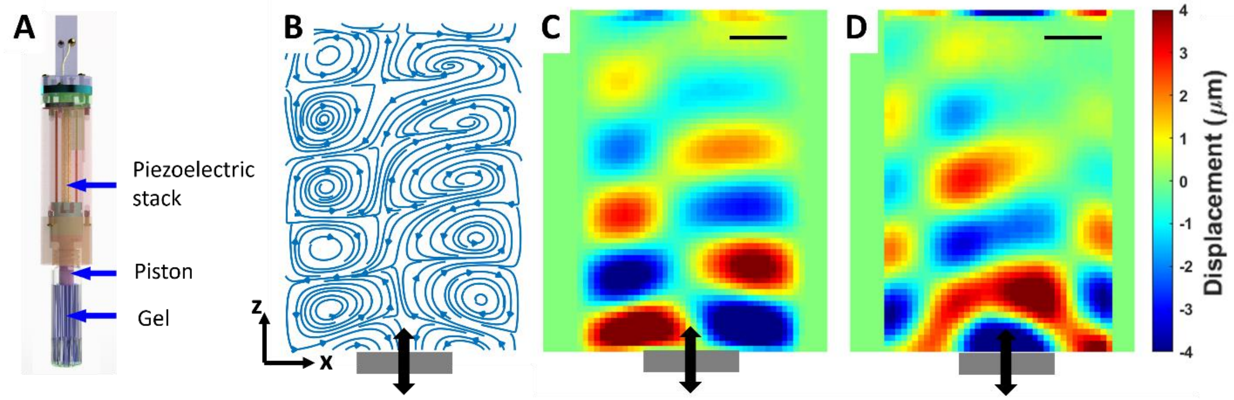

**Figure 1: Measured displacement field in a sagittal cross-section. A) Piezoelectric gel actuator. B) Displacement streamlines. C) X-direction displacement. D) Z-direction displacement. Scale bar = 5 mm. The piston is represented by a gray bar at the bottom of each panel which oscillates along the sample axis.**

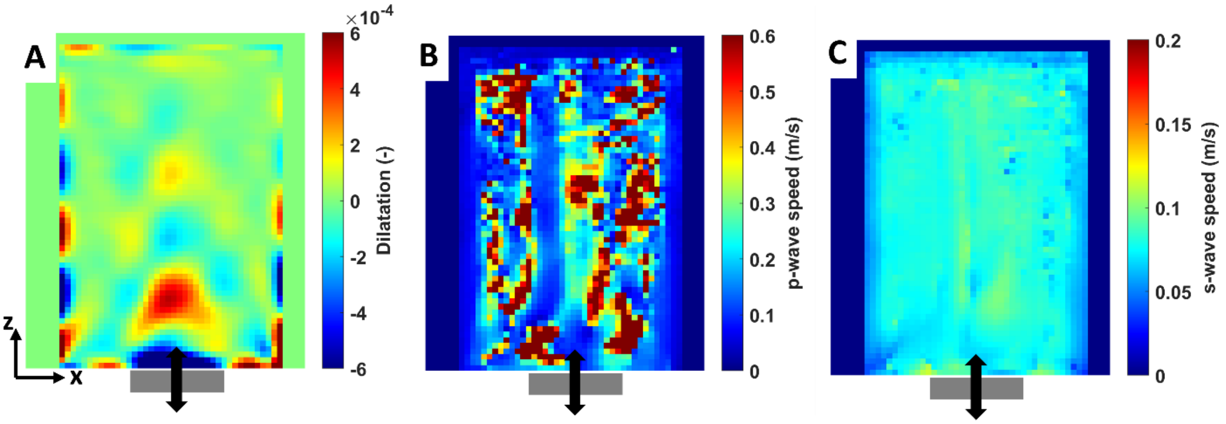

**Figure 2: Viscoelastic wave properties derived from the displacement field. A) Divergence of the displacement field. B) Pressure wave speed. C) Shear wave speed.**

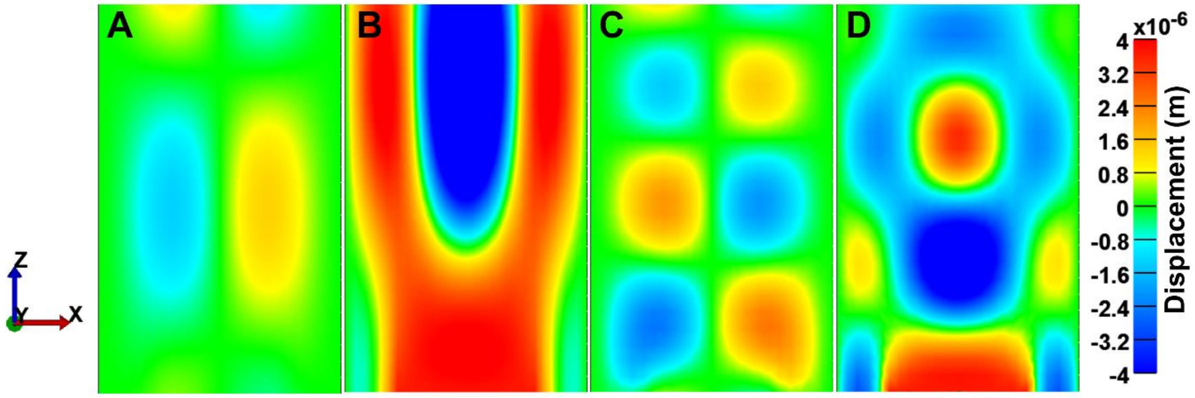

**Figure 3: Varying pressure wave speed in solid FEM models. A) X-direction displacement and (B) Z-direction displacement for $c_p$ = 2.4 m/s and $c_s$ = 0.1 m/s. C) X-direction displacement and (D) Z-direction displacement for $c_p$ = 0.6 m/s and $c_s$ = 0.1 m/s.**

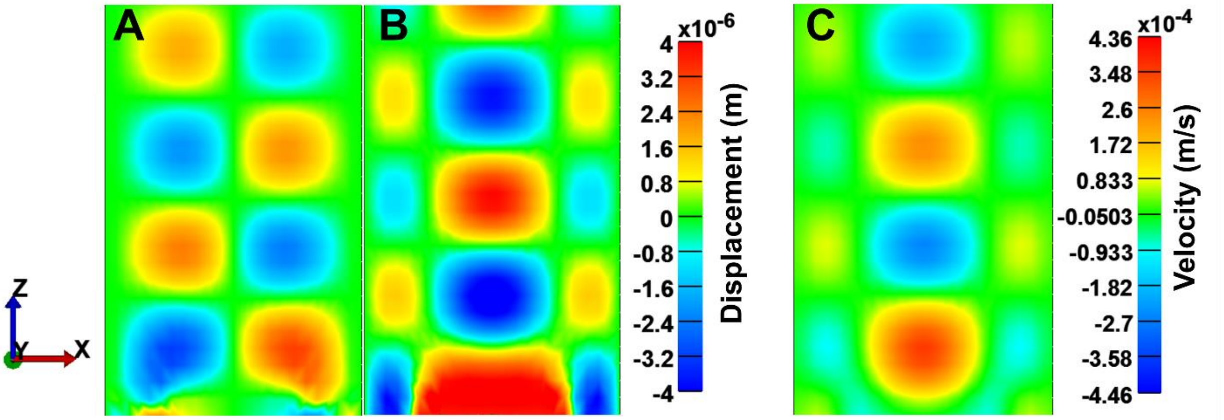

**Figure 4: Modeled displacement and velocity fields for a biphasic material. A) X-direction displacement. B) Z-direction displacement. C) Solid and fluid phase velocity (same appearance).**