Measurement and Visualization of Shear Wave Attenuation by Magnetic Resonance Elastography

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Synopsis

Magnetic resonance elastography (MRE, [1]) can visualize and quantitatively measure propagating acoustic strain waves in materials subjected to harmonic mechanical excitation. Such data can be inverted to determine local values of wave speed or shear modulus. In a viscoelastic medium, the wave speed is a function of frequency, and attenuation is present. Viscosity (or attenuation) is an independent material parameter potentially useful in tissue characterization [2-4]. We show that the phase lag between stress and strain due to viscoelastic properties observed in mechanical testing can be directly visualized with MRE, and that attenuations calculated with MRE compare closely to those derived from damped sinusoid fits, although they tend to be significantly affected by noise.

Methods

In mechanical testing with applied harmonic forces, a phase lag is observed between stress and strain, and the tangent of this angle is the ratio of the loss modulus to the storage modulus. This angle is zero for lossless materials, and increases as the attenuation increases. The tangent of this angle is the inverse of the acoustic quality factor Q. In MRE, if one assumes a linear, elastic, homogeneous, isotropic and incompressible material, it has been shown that the equation of harmonic motion reduces to $\mu = -\rho\omega^2 u_i / \nabla^2 u_i$, satisfied separately by each orthogonal component u_i of the vector displacement [4,5], with ρ the density of the material, ω the mechanical driving frequency, and the Lame constant μ the shear modulus. In a viscoelastic medium, μ can be considered to be a complex quantity ($\mu = c + i\omega\eta$ [6]). This method of solving for μ is termed direct inversion [4,5]. The storage modulus is then its real part c, the loss modulus is ωη, and the viscosity is η. A non-zero loss modulus implies a phase lag between $-u_i$ and $\nabla^2 u_i$, and this is the *same* phase lag as between stress and strain (since $-u_i$ has the same phase as the acceleration $-\omega^2 u_i$, which is proportional to force, which is the divergence of the stress tensor [6]; while the Laplacian of the displacement component can be equated to the divergence of the strain tensor, and for harmonic motion the phase shift between stress and strain is maintained through the divergence operator). It has not been previously reported that MRE directly observes this phase lag, although this is implicit in direct inversion calculations [4]. Attenuation in the low-loss case is given by $\alpha^2 = (\omega/2)(\rho/c)^{1/2}(\omega\eta/c)$, where α denotes attenuation by the factor $e^{-\alpha k}$ in the direction of propagation k. The attenuation per wavelength is proportional to the inverse of the acoustic quality factor $Q = c / \omega\eta$ [6].

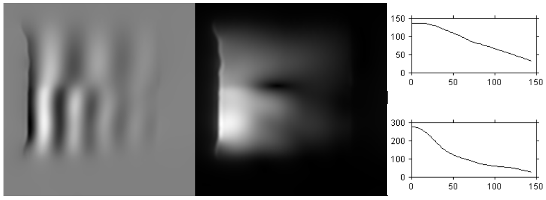

Fig. 1. Sample phase offset from the MRE data excitation (left), the amplitude of the first harmonic of the data, and horizontal profiles through the amplitudes in the two regions.

A phantom was created consisting of two regions: an upper region of 2% agar gel and a lower region of 20% bovine gel. MRE measurements were made with 256x64 GRE acquisitions with an FOV of 24 cm, slice thickness of 5 mm, and 8 phase offsets between the mechanical and gradient waveforms equally spaced over a 100 Hz cycle. Shear motion was applied to the top (here left) of the object in the out of plane direction, and shear waves propagate primarily from left to right (Fig. 1). A Fourier transform along the time dimension at each pixel isolates the 100 Hz component of motion, which is the complex data analyzed here, and directional filtering [7] is applied.

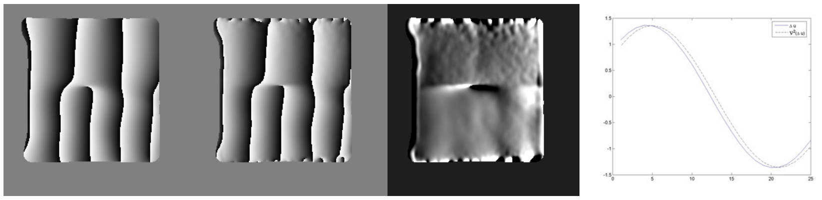

Fig. 2. Phase of first harmonic of negative displacement (left), Laplacian of displacement (2nd), and their difference (3rd). The different phase lags between the agar and bovine gel regions are evident. The fourth image shows the two temporal waveforms at one point in the bovine gel.

Results

Fig. 1 shows a sample phase offset from the data, the amplitude of the first harmonic, and profiles through the amplitude. From exponential fits to the profiles, attenuation can be estimated as 12.8 m^{-1} for the agar and 28.4 m^{-1} for the B-gel. Fig. 2 shows the phase of $-u_i$ and $\nabla^2 u_i$ the difference between the two across the image and the temporal waveforms at one point in the B-gel. The two gels have different phase lags that are clearly visualized. Fig. 3 shows images of μ, η and α, and although the η and α maps are noisier than the μ map, the differences in viscosity and attenuation between the regions are clearly distinguishable. The value of α in the upper and lower ROIs are 12.4 m^{-1} and 23.4 m^{-1}, in good agreements with the exponential fits.

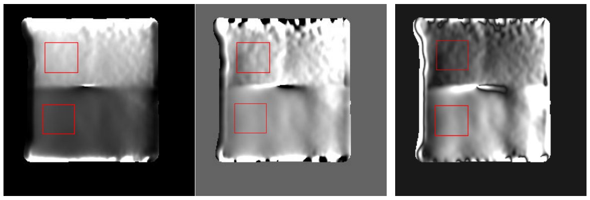

Fig. 3. Images of μ, η and α for the object.

Discussion

The phase lag between stress and strain due to viscoelastic properties, familiar in mechanical testing, can be directly visualized with MRE. Attenuations calculated from this phase lag (or, equivalently, from direct inversion) in this manner closely match attenuations derived from damped sinusoid fits in this plane wave case. Measurements of attenuation and viscosity are therefore feasible with MRE, although they tend to be significantly affected by noise and artifacts and are likely to be challenging in complex situations.

References

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