Inversion Algorithm by Integral Type Reconstruction Formula for Magnetic Resonance Elastography

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INTRODUCTION

The stiffness of tissue is related to physiological and pathological states. Magnetic resonance elastography (MRE) is a technique that can noninvasively visualize shear waves patterns within tissue with a modified phase-contrast MR sequence [1]. In order to generate shear waves within tissue, external vibration systems are used. A very low vibration frequency of about 60Hz is typically used to avoid attenuation of shear waves, and the shear wavelength is sometimes longer than the size of region of interest (ROI). The local quantitative values of tissue stiffness (defined as elastogram) are calculated from the shear wave pattern using an inversion algorithm. The general approach to estimating stiffness from MRE data is by the use of a local frequency estimation (LFE) algorithm [2]. LFE estimates the local spatial frequency of the shear wave propagation pattern and is relatively insensitive to noise; however, LFE estimate is blurred at sharp boundaries and the correct estimate is reached only half a wavelength into a given region. LFE treats the problem separately from the physics of mechanical motion. As a result, it is not clear whether LFE is applicable to general motion. Other methods are based on the equations of motion [3,4]. Using these methods, we don't have to deal with reflections and interferences; however, they tend to be very sensitive to noise because the equations involve spatial Laplacian operations at each point. To reduce the noise effect, noise-reduction filters or least-square fitting procedure are adapted, but they reduce the spatial resolution of the elastogram and may cause artifacts. The purpose of this work is to propose an inversion algorithm that is applicable for noisy long shear wave images and estimation of the shear modulus quantitatively with high resolution.

THEORY

Mechanical properties are formulated by a differential equation of motion. Assuming incompressible material and Helmholtz motion gives the direct inversion (eq. 1), we propose an integral type reconstruction formula (ITRF) by applying Green's formula to equation 1 (eq. 2). We assume that shear modulus μ is constant in some domain D. The function T is a test function whose support is in D and normal derivative vanishes on the boundary D. We use trigonometric function (eq. 3) in the current research.

$$\mu = -\rho\omega^2 \frac{\theta\Delta\theta + \theta'\Delta\theta'}{\Delta\theta^2 + \Delta\theta'^2} \quad \ldots (1), \qquad \mu = -\rho\omega^2 \frac{\int_D \theta(\Delta T)dV \int_D \theta T dV + \int_D \theta'(\Delta T)dV \int_D \theta' T dV}{\left\{\int_D \theta(\Delta T)dV\right\}^2 + \left\{\int_D \theta'(\Delta T)dV\right\}^2} \quad \ldots (2), \qquad T = \begin{cases} 1 + \cos\pi\dfrac{r}{R}, & r < R, \\ 0, & r \geq R. \end{cases} \quad \ldots (3)$$

Where ρ is density (assumed to be 1 g/cm^3), ω is angular frequency, θ and θ' are the shear wave images with phase offsets (0 and $\pi/2$), $dV = dx\,dy\,dz$ and r = $\sqrt{x^2+y^2+z^2}$. ITRF is robust to noise as it avoids second order derivative for noisy shear wave images.

MATERIALS AND METHODS

The first phantom is a 3D data set that simulates a plane shear wave propagating through three layered regions separated by a sharp boundary. The three regions have no attenuation. Their simulated shear moduli are 2.2 kPa at first and third layer, and 6.1 kPa at second layer. The height of the second layer is 30 mm. Four phase offsets simply sinusoidal waves were simulated with Gaussian noise added to simulate a wave image SNR of 8. Other parameters are as follows: field of view 256 x 256 mm^2, matrix size = 256 × 256, number of slices = 11 and vibration frequency = 60 Hz

The second phantom is 15.8 kPa polyacrylamide (PAAm) gel phantom. The shear waves were generated using a piezoelectric longitudinal driver. MR examinations were performed on a 3.0 Tesla MRI (SIGNA EXCITE 3.0T, GE). MRE imaging protocols were as follows: single-shot EPI, TR = 2000 ms, TE = 31.4 ms, number of slices = 11, slice thickness = 2 mm, field of view 128 x 128 mm^2, matrix size = 64 × 64, number of excitations = 1, MSG cycles = 3, phase offsets = 4, and vibration frequency = 62.5 and 250 Hz.

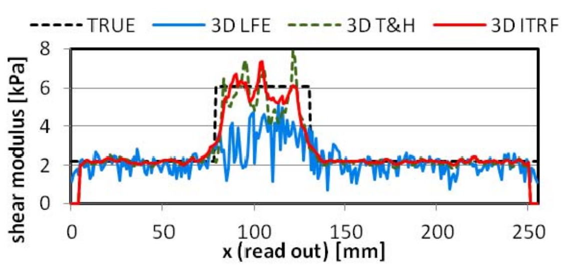

Fig.1 Profiles of the elastogram of the simulated 3D data set by LFE, T&H and ITRF (R=5)

Table 1 The mean and standard deviation (SD) in each region of the elastogram of the simulated 3D data set

True [kPa]	3D LFE		3D T&H		3D ITRF	
	Mean	SD	Mean	SD	Mean	SD
2.2	1.45	0.23	2.18	0.15	2.19	0.08
6.1	3.50	0.97	5.29	0.91	5.90	0.58

Table 2 The mean and standard deviation (SD) at each vibration frequency of the PAAm gel Phantom

	True [kPa]	3D LFE		3D T&H		3D ITRF	
		Mean	SD	Mean	SD	Mean	SD
62.5Hz	15.80	2.87	1.39	13.25	2.23	15.09	2.45
250Hz		15.67	3.39	16.27	1.92	15.99	2.34

RESULTS AND DISCUSSION

Fig. 1 shows profiles through the reconstructed images of the 3D data set by LFE, Helmholtz inversion with trigonometric test function as a noise reduction filter for shear wave images (T&H) and ITRF (R=5; heuristically determined). A more quantitative result of these differences is presented in Table 1. Fig.2 and Table 2 show results from the gel phantom. The LFE algorithm underestimated the shear modulus especially at long shear wave images.

CONCLUSION

In this study, we propose the ITRF inversion algorithm for noisy long shear wave images in MRE. From the results of the simulation and experimental studies, ITRF increases the shear modulus quantitatively without reducing the spatial resolution as compared to LFE.

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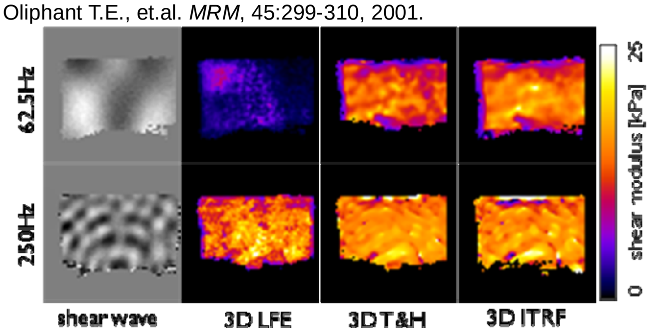

Fig.2 The shear wave images of the PAAm gel Phantom at each vibration frequency and the elastogram by LFE, T&H and ITRF (R=5)