Three-Dimensional Visualization of Ultrasonically Induced Shear Waves for Elasticity Imaging

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Introduction

Shear wave elasticity imaging has shown considerable promise for understanding tissue mechanics and its relationship to disease [1–3]. However, most dynamic elasticity imaging has employed steady state [2, 3] or quasi-steady state [1] excitation. Due to reflections, interference, and standing waves, these methods generally require relatively sophisticated elasticity reconstructions [4]. Transient shear wave (TSW) imaging [5–7], however, may allow one to use a simple wave-speed based elasticity reconstruction: $\mu = \rho c^2$, where μ is the shear elastic modulus, ρ is the density, and c is the shear wave speed. It is also possible to employ more complicated methods [7]. To date, all TSW elasticity imaging has employed one- or two-dimensional (2D) reconstructions. However, as was shown for static elasticity imaging [8], three-dimensional (3D) TSW methods may offer more accuracy than 2D methods. Here we present a 3D visualization of ultrasonically induced shear waves in a tissue-like phantom which may be used for 3D elasticity reconstruction.

Methods

Imaging experiments were performed using the phase sensitive, spin echo method described in [6], with the following parameters: TR = 500 ms; TE = 80 ms; a 32×32×256 matrix over a 10×10×20 cm^3 field-of-view; and 70 mT/m, 4 ms motion-encoding gradients. 21 images of each displacement component were taken at wave propagation times of 0–10 ms in 0.5 ms increments. The tissue-like, cylindrical phantom (7 cm diameter, 16 cm length) consisted of two layers; the first, softer layer was 15% (wt/wt) gelatin, while the second, stiffer layer was 20%. The motion source was a single-element ultrasound transducer (7 cm aperture, 10 cm focal length) triggered from the MRI console, which generated a 400 cycle, 512 kHz center frequency pulse that provided ~4 MPa peak pressure. A small, acrylic disc was placed in the focal plane, which was also the bilayer interface, to provide an acoustic impedance mismatch for shear wave generation.

Results

Figure 1 shows a 3D rendering of the phantom's outer surface (light gray). The red interior surface is an isosurface of the z-displacement component ($u_z = -1.3$ µm) 2.5 ms after applying the acoustic pulse. The dark gray surface further in represents the acrylic disc, whose $+z$-surface was flush with the bilayer interface (blue plane) and the transducer's focus. Note the z-directed asymmetry in the isodisplacement surface, indicating different shear wave speeds in the two layers. The wave has clearly propagated further in the harder gel, as would be expected.

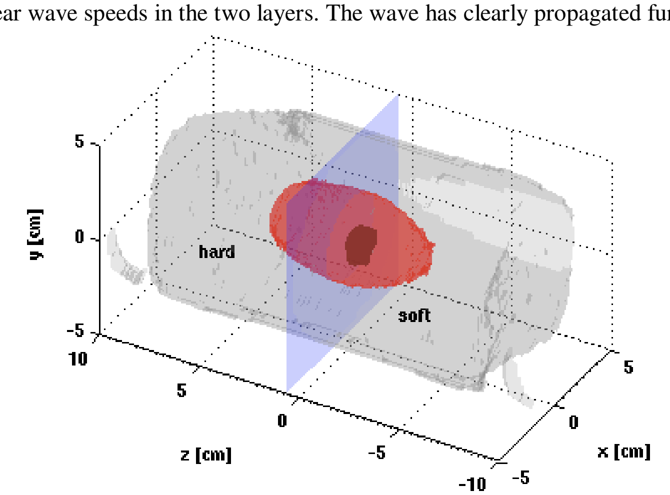

Figure 0: Isodisplacement surface (red) inside cylindrical phantom (gray).

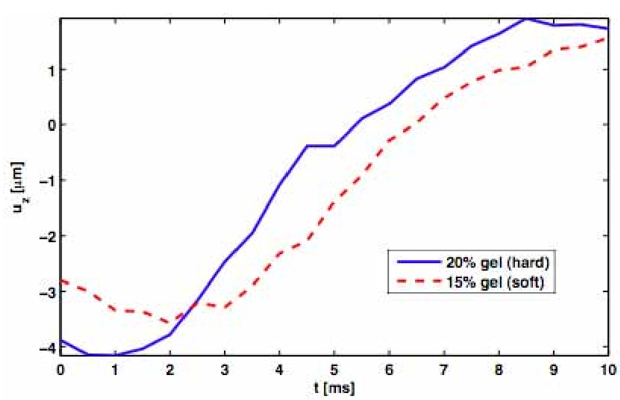

Figure 2: Time plots of z-displacement in axially symmetric voxels.

Figure 2 is a plot of $u_z(t)$ from two voxels along the wave's axis of symmetry (*i.e.*, the z-axis). The solid, blue line is from the 20% gel voxel located +1.88 cm from the $+z$-surface of the disc, while the dashed, red line is from the 15% gel voxel located −1.88 cm from the disc's $-z$-surface. The maximum displacement in the softer gel is delayed compared to that in the harder gel, again indicating different wave speeds in the two layers.

Discussion and Conclusions

TSW imaging is an attractive basis for elasticity imaging due to the potential for using a simple wave-speed reconstruction. However, a previous attempt to use such a method exhibited artifacts due, in part, to the assumption that the measured shear waves were planar [7]. 3D wave data overcome the need for this assumption (at the expense of scan time), and may, then, provide a more robust wave speed estimate. Furthermore, it has been shown for static elasticity imaging that 2D reconstruction methods lead to both geometric and modulus estimate inaccuracies [8]. It is possible that similar behavior will be seen in TSW elasticity imaging.

In addition, ultrasonic excitation allows one to target shear wave generation to a particular region-of-interest, overcoming depth-dependent wave attenuation. It may also allow highly customizable excitation via time-reversed acoustics [6]. Here we have demonstrated 3D visualization of TSWs with ~200 nm displacement resolution of ultrasonically induced shear waves, the first step needed to create a targeted, 3D elasticity image.

References

1. Muthupillai R *et al.*, Science (1995) **269**, 1854–7.
2. Weaver JB *et al.*, Med Phys (2001) **28**, 1620–8.
3. Sinkus R *et al.*, Magn Reson Med (2005) **53**, 372–87.
4. Manduca A *et al.*, Med Image Anal (2001) **5**, 237–54.
5. Swanson SD *et al.*, Proc ISMRM (1998) **6**, 135.
6. Kripfgans OD *et al.*, Proc SPIE (2005) **5746**, 323–32.
7. McCracken PJ *et al.*, Magn Reson Med (2005) **53**, 628–39.
8. Steele DD *et al.*, Phys Med Biol (2000) **45**, 1633–48.