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Phys. Med. Biol. 49 (2004) 911–922 PII: S0031-9155(04)69394-8

Sonoelastographic imaging of interference patterns for estimation of the shear velocity of homogeneous biomaterials

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stiffness (modulus) of the tissue. One way of quantifying the change is to measure the shear velocity in the tissue (Yexler et al 1999). In a linear elastic medium the shear modulus is equal to the square of the shear velocity times the density (Love 1944, Achenbach 1973a). When the tissue is better characterized as a linear viscoelastic medium, the shear modulus will be complex and the shear velocity may exhibit frequency dispersion (Achenbach 1973b).

Yamakoshi et al (1990) developed an approach to measure shear velocity. External low frequency vibration was applied to the region of interest, then both amplitude and phase of the vibration were mapped using a Doppler detection technique. The vibration phase image was used to measure the wave propagation velocity. It was found that refraction and re ection of the propagating vibration waves at internal tissue boundaries can create bias in the phase map. Standing waves whose wavelength differs from that of the shear wave propagation can occur.

Magnetic resonance imaging (MRI) has also been applied to this problem. Muthupillai et al (1995) sensitized a gradient-echo imaging pulse to harmonic motion permitting them to generate a MRI phase image which allowed measurement of wavelength among other properties. Bishop et al (1998) applied this technique to the problem of visualizing shear wave propagation in excised tissue samples. Later, Smith et al (1999) proposed a method to lter out the other modes of motion such as re ections, vibrations and ambient background motions that sometimes obscure the accurate measurement of the shear waves when using this technique.

Catheline et al (1999) proposed an ultrasound technique, which they call transient elastography, to deal with some of artefact issues caused by wave re ection and standing

45 normal volunteers, 153 patients with liver cirrhosis and 83 patients with chronic hepatitis. In the mean, the measured velocity in patients with liver cirrhosis was twice that measured in the healthy volunteers. This implies that shear velocity is a speci c indicator of diffuse liver disease such as cirrhosis.

In this paper, new techniques are introduced to measure the wavelength and velocity of shear waves in bio-materials. In these techniques, two shear wave sources are placed on either side of a region of interest. When the sources are vibrated in phase at the same frequency the resulting interference pattern, when visualized by sonoelastography imaging, shows stationary peaks and troughs which are located at intervals equal to half the shear wavelength. Furthermore, when the sources are vibrated at slightly different frequencies the interference pattern moves from the higher frequency source to the lower frequency source. This apparent motion, which might be termed a 'crawling wave' (i.e. falling between travelling and standing waves), is shown to have a velocity which depends directly on the shear velocity but is scaled by a certain ratio of the frequency difference to twice of the frequency of the lower source. This can effectively slow down the shear waves by one or two orders of magnitude, allowing commercially available ultrasound systems to be used for imaging. We experimentally validate these methods by comparing our results to conventional time-of- ight experiments which are described in the literature (McAleavey et al 1999, Vexler et al 1999). The results are shown to be accurate within 4% on various homogeneous tissue-mimicking phantoms.

2. Theory

2.1. Basic theory

It is well accepted that the speed of the shear wave propagation in a linear elastic medium is directly related to the mass density ρ and the shear modulus G of the medium.

$$v_{shear} = \sqrt{\frac{G}{\rho}}. \tag{1}$$

Therefore, the shear modulus G can be determined by measuring the speed of the shear waves and the density, provided that the medium is homogeneous and isotropic. By noting the identity that $v_{shear} = f * \lambda$

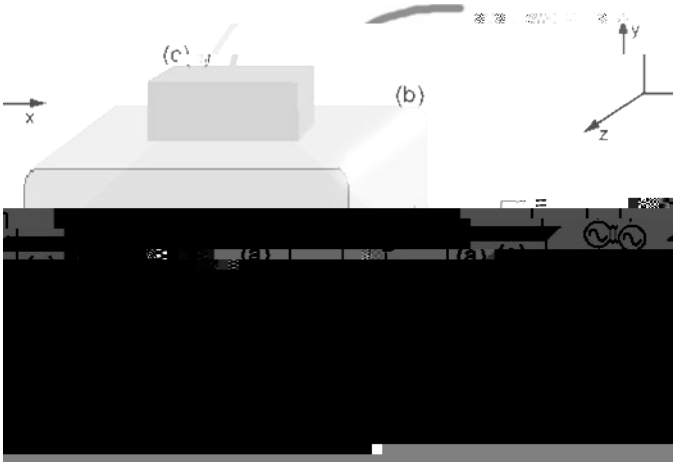

Figure 1. Schematic drawing of the experiment set-up. Two bimorphs (a) are in close contact with the phantom (b). The arrows indicate the motion vectors of the tips of the bimorphs. The sector shape depicts the imaging plane of the ultrasound probe (c).

Figure 2. Coordinate system for equations (2) and (3). The right travelling and the left travelling shear waves from two sources are depicted. Two sources locate at 0 and D, respectively. In the static pattern case $k_1 = k_2 = k$ and $\omega_1 = \omega_2 = \omega$. In the moving pattern case $k_2 = k_1 + \quad k = k + \quad k$ and $\omega_2 = \omega_1 + \quad \omega = \omega + \quad \omega$.

2.3. Static interference pattern estimates

In order to measure the wavelength of the propagating shear waves, we propose to apply two vibration sources of identical frequencies and amplitudes. The two sources are placed on

The interference patterns are the superposition of the two waves

$$\exp(ikx - i\omega t) + \exp(ik(D - x) - i\omega t)$$

where k is the shear wave number $k = \frac{\omega}{v_{shear}}$ and ω is the angular frequency $\omega = 2\pi f$.

Take only the real part of the terms

$$u(x, t) = \cos(kx - \omega t) + \cos(kD - kx - \omega t)$$
$$= 2\cos\left(kx - \frac{kD}{}\right.$$

travelling wave. The apparent speed of these 'crawling waves' can be derived by using: $v_{pattern}^2 = \frac{\partial^2 u}{\partial t^2} \Big/ \frac{\partial^2 u}{\partial x^2}$, thus

$$v_{pattern} = \frac{\omega}{2\left(k + \frac{k}{2}\right)}. \tag{4}$$

It is interesting to analyse two mathematical extremes of equation (4). Firstly, if we keep one of the sources vibrating and completely mute the other source, that is let k be small and k be large, $v_{pattern} = \frac{\omega}{k} = v_{shear}$. Even though sonoelastographTD -g0.51i not-327.86(able-327.8(s)-0.5(ho-327.97i)-0.2

Figure 3. Schematic drawing of the transient shear wave speed measurement. The time lag between the two signals indicates the shear wave time-of- ight.

Figure 4. Sonoelastography image of shear wave interference pattern on GE Logiq 700. The medium is 5% gelatin phantom. Both sources vibrate at 200 Hz. The peak vibration amplitude in the direction of the ultrasound wave is mapped to a grey scale.

Two gelatin phantoms, both 8 $\times$ 9 $\times$ 12 cm^3 in size and rectangular solids in shape approximately, are constructed for the experimental veri cation of the theory. The phantoms are made from 800 ml degassed, deionized water, 5% and 10% (by weight) food gelatin (Knoxx), respectively, and 10% formaldehyde (v/v), 10% glycerol (v/v) and 0.5% graphite powder as scatterers. The manufacturing procedure is described as follows. The water is rst heated to boiling and then placed on the stirring plate, with a magnetic rod stirring the water. Gelatin is slowly added to the water. After all gelatin has been added, the solution is reheated to boiling in a microwave oven for 2 min with plastic wrap covering the container. Then the graphite power is mixed into the solution. The mixture is cooled for about 50 min while stirring. Finally the formaldehyde and the glycerol are mixed into the solution. A bowl-shaped

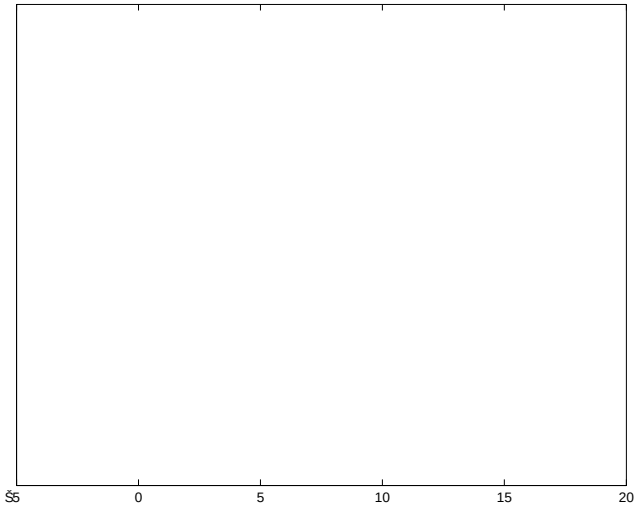
Š5
0
5
10
15
20

Table 1.

Figure 6. Sonoelastography image of shear wave interference pattern on a Zerdine phantom with a lesion in it. Both sources vibrate at 250 Hz. The image is 'histogram equalized' to enhance the visibility of details.

depends on the material property and the imaging eld area. Below this frequency limit, the shear wavelength may be so long that only one or less wavelength appears in the imaging eld.