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Measurement of Elastic Properties of Tissue by Shear-Wave Propagation Generated by Acoustic Radiation Force (I)

音響放射力によるずり波伝搬を用いた組織弾性計測(1)

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1. Introduction

Focused, impulsive acoustic-radiation-force (ARF) methods to investigate the mechanical properties of soft tissue have been developed by several groups. ARF excitation directly generates shear waves in the tissue of interest. Sarvazyan et al. [1] characterize tissue structures by using shear acoustic waves. The benefit of that method is quantification of the absolute elastic modulus of tissue. Palmeri et al. [2] used time-to-peak displacement to estimate shear-wave speed under three assumptions: homogeneity of tissue, shear-wave propagation in the lateral direction, and negligible dispersion of the shear wave. The goals of the current work are to experimentally and computationally reveal the characteristics (including tissue heterogeneity, anisotropy, and frequency dependence of ARF) of shear-wave propagation in tissue.

2. Acoustic radiation force

ARF, which is caused by a transfer of momentum from an acoustic wave to a propagation medium, is applied to attenuating media [3]. In soft tissues, where the majority of acoustic attenuation results from absorption, under plane-wave assumptions, the following equation can be used to determine ARF:

$$F=2\alpha I / c \qquad (1)$$

where F is ARF, c is the speed of sound in the medium, and α is the absorption coefficient of the medium. In regard to this equation, soft tissues are assumed as linear, elastic, isotropic solids at low excitation frequencies.

3. Experiment

As shown in Fig. 1, a pig liver, a focusing transducer, and a linear-array probe were set in a degassed water tank at constant temperature (37°C). The focused transducer (radius of curvature: 35 mm; and aperture: 40 x 20 mm^2) generates ARF within the liver in the direction of the ultrasound beam and a corresponding shear wave in the direction perpendicular to the beam (Fig. 2(a)). A focused beam was generated at 2.2-MHz driving

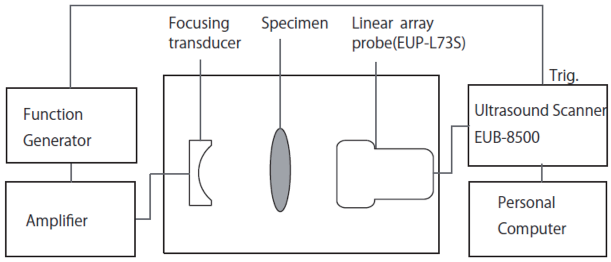
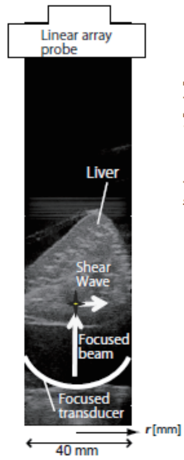
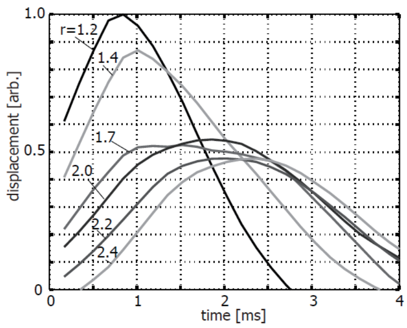


Fig. 1: Experimental setup for measuring shear-wave propagation.

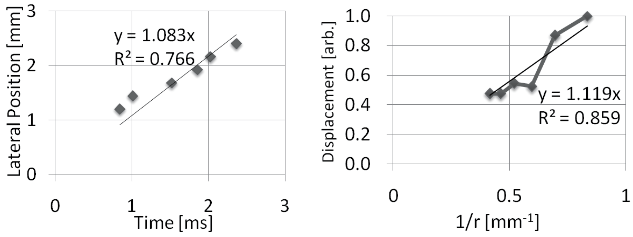


(a)



(b)

Fig. 2: (a) B-mode image of liver and (b) displacement of tissue with time data at focal depth.



(a) (b)

Fig. 3: (a) Lateral position vs. Tp and (b) Maximum displacement vs. inverse of lateral position.

frequency and applied for 1 ms. The spatial-average-time average intensity I_{sata} was 1140 W/cm^2. The linear-array probe (EUP-L73S, Hitachi Medical Corp.) and the ultrasound scanner (EUB-8500, Hitachi Medical Corp.) were used to track the shear-wave propagation. To investigate the temporal and spatial response of the liver, A-mode interrogations at lateral positions *r* offset from the excitation location were designed. Shear-wave velocity *v* within the depth of field, *v* =

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r/(tracking time corresponding the peak displacement, hereafter, "Tp"), was calculated under the assumption that the peak displacement of the shear wave propagates at its group velocity. At each lateral position, interrogation consists of a reference tracking pulse followed by ARF excitation and a series of tracking pulses. The tracking data were stored on a PC for off-line processing. Displacements were then estimated using correlation calculation.

3. Results

Figure 2(b) shows tissue displacement with tracking time at the focal depth. Larger displacements and shorter Tp are detected at the lateral positions closer to the ARF excitation point. Maximum displacement is about 20 μm. Figure 3(a) plots lateral positions r as a function of Tp. Estimated shear-wave velocity in a linear approximation was 1.08 m/s, which agrees well with the literature data, namely, 1 to 3 m/s. Shear modulus μ , of the liver, calculated by $v = (\mu/\rho)^{1/2}$, where ρ is tissue density, is 1.2 kPa.

To estimate the sound-source shape of the shear wave from the relation between shear-wave amplitude and wave-propagation distance, peak displacement was examined as a function of the inverse of lateral position. Generally, wave attenuation results in diffraction, scattering, absorption, and so on. The amplitude of a spherical wave (i.e., a point sound source) is inversely proportional to the square of distance. The amplitude of a cylindrical wave (i.e., a line sound source) is inversely proportional to distance [4]. From the experimental results, the peak displacement is proportional to the inverse of lateral position (Fig. 3(b)). It is concluded from this figure that the sound source of the shear wave (generated by ARF) is a line. Moreover, the F numbers of the focusing transducer are 1.8 for the short axis and 0.9 for the long axis; therefore, focal width in the depth direction is longer than that in the lateral direction. This fact supports the conclusion that the sound source shape is a line.

4. Simulation

Time-averaged radiation stress tensor and corresponding shear-wave generation were simulated with the FEM package PZFlex [5][6]. Note that the radiation stress differs between the propagation and transverse directions, hence it is a stress tensor, not an isotropic pressure.

First, a focused beam (2.2 MHz; F number: 0.9; radius of curvature: 35 mm) was induced in homogeneous tissue (ρ : 1000 kg/m^3; bulk velocity: 1500 m/s; shear velocity: 10 m/s) (Fig. 4(a)). Corresponding time-averaged acoustic stress tensor was calculated (Fig. 4(b)). Next, the calculated

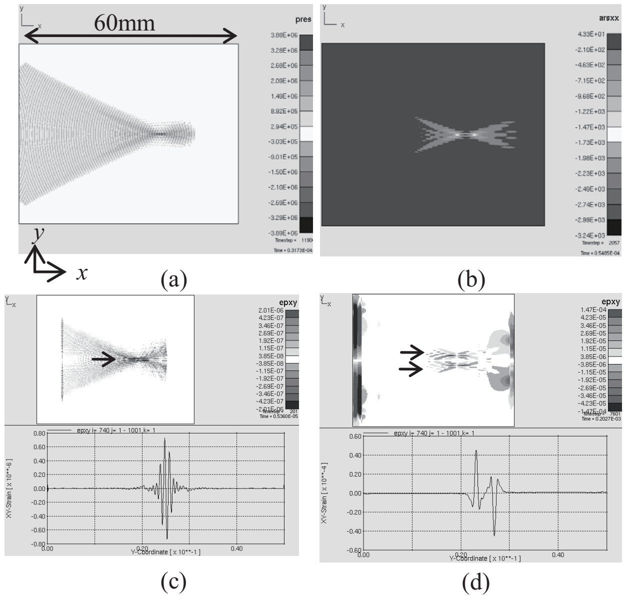

Fig. 4: (a) focused-beam pressure field; (b) acoustic-radiation force; (c)(d) x-y strain field (top) and x-y strain plot vs. y-coordinate at the focal depth (bottom) at 0 and 0.2 ms after radiation stress was applied.

stress was imported a second model and applied for 1 ms to study tissue deformation. The acoustic stress generates a shear wave in the y direction (perpendicular to beam direction x). Figures 4(c) and (d) show the shear stress in the x direction due a y-direction wave. These calculations demonstrate the feasibility of using FEM calculation to study the propagation characteristics of the shear wave.

5. Future work

More detail of the sound-source shape (such as beam width) will be determined from the results presented above and compared with the shape of the focused beam. At the same time, to examine tissue structure, anisotropy, and frequency dependence of ARF, further shear-wave experiments will be performed.

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