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Quantitative evaluation on estimation of shear wave propagation speed using phase of particle velocity
粒子速度の位相を用いたせん断波伝搬速度推定に関する定量評価

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1. Introduction

Shear wave elastography (SWE) is useful for quantitative evaluation of the elastic properties in human tissues and many techniques have been developed. One of them is acoustic radiation force impulse (ARFI) imaging, which induces deformation into the tissues by high intensity ultrasound. However, this method involves a risk of tissue injury due to generation of cavitation and/or heat. Therefore, more safe measurement of shear wave propagation speed (SWPS) is needed.

In our proposed method[1], the SWPS was estimated from the particle velocity induced by a heartbeat. The SWPS and propagating direction were estimated from wavenumbers in axial and lateral directions. Because the wavelength of the shear wave induced by the heartbeat was longer than that by ARFI imaging, we proposed the estimation method of the wavenumbers by using the phase of the particle velocity.

In the present study, a quantitative evaluation on the estimation method using the phase of particle velocity is performed. Agar phantoms with different stiffnesses were made for the evaluation, and the results obtained by the proposed method were compared with a static mechanical testing.

2. Materials and Methods

2.1 Experimental setup

In the verification experiments, the agar phantoms were measured using plane-wave based ultrasound imaging with a high frame rate of 976 Hz.[2] A linear array probe with a center frequency of 7.5 MHz was used, and the ultrasound echo signals were acquired at a sampling frequency of 31.25 MHz. The interval of scan lines was 0.2 mm. The soft and hard agar phantoms were made from 0.5% and 0.6% agar. Also, both phantoms contain graphite powder of 3 g as ultrasonic scatterers. Shear waves were induced by exciting a rotation motor (Tokyo Parts Industrial FM34F, rotation speed, 13000 rpm) intermittently, which was placed on the side surface of the phantom.

2.2 Estimation method by phase of particle velocity

The vibration velocity waveform $v(x, z; t)$ in the tissue in the ultrasound beam direction at each scanning line position x and range distance z is measured by a method using the phase of the received ultrasound signal.[3] When a shear wave propagates at a constant speed, the phase of the velocity waveform is proportional to propagating direction.[4] Although the shear wave induced by the heartbeat propagates three-dimensionally, we assumed that the shear wave is locally approximated to a plane wave in a measured two-dimensional plane. In the present study, the mean squared error between the phase of the complex vibration velocity and its linear model is minimized in two directions simultaneously to estimate the SWPS. The model of two-dimensional complex vibration velocity distribution at the time t_0 is expressed as follows:

$$\hat{v}(t_0;\ x,\ z) = v_0 \cdot e^{-j(k_x x + k_z z)}, \qquad (1)$$

where v_0, k_x and k_z indicate complex velocity amplitude, wavenumbers in the x and z directions, respectively.

A choice of t_0, which was the frame used to estimate SWPS, was a key factor. Based on the strength of the particle velocity, the frame when the amplitude of vibration velocity becomes maximum was chosen. However, because the reflected wave may interfere with the shear wave of interest in the measurement area, the SWPS cannot be estimated accurately when the amplitude was maximum. Therefore, to focus on the frame at the rising of the vibration velocity waveform, the accelerogram was calculated as central differences and its peak was detected.

The mean squared error α between the phase

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$\angle v(t_0,;x,\, z)$ of the measured complex vibration velocity and linear model $\{-(k_x x + k_z z)\}$ was expressed as follows:

$$\alpha = \sum_R \{\angle\hat{v}(t_0; x,\, z) + (k_x x + k_z z)\}^2, \quad (2)$$

where R indicates a region of interest.

In order to determine $\hat{k}_x$ and $\hat{k}_z$ where the error α became a minimum, partial derivatives of α with k_x and k_z become zero. Therefore, least square solutions $\hat{k}_x$ and $\hat{k}_z$ were obtained by solving the simultaneous equation given by

$$\frac{\partial\alpha}{\partial k_x} = 0, \qquad \frac{\partial\alpha}{\partial k_z} = 0. \qquad (3)$$

As described above, in this report, the SWPS was estimated by calculating the wavenumbers $\hat{k}_x$ and $\hat{k}_z$ simultaneously using the phases of vibration velocity waveforms.

2.3 Static experiment

In static experiment, Young's modulus was determined from the average slope of the stress-strain curve. After the SWPS measurement, agar phantoms were cut in 2 cm square and were compressed at a displacement step of 0.1 mm. The static experiment was performed within an hour because of syneresis of a phantom.

3. Experimental Results and discussion

Figures 1(a) and **(b)** show the propagation speed maps of the soft and hard agar phantoms, respectively. As shown in Fig. 1, the average SWPS in red squares in the phantoms were about 2.4 ± 0.51 m/s and 3.8 ± 1.2 m/s, respectively.

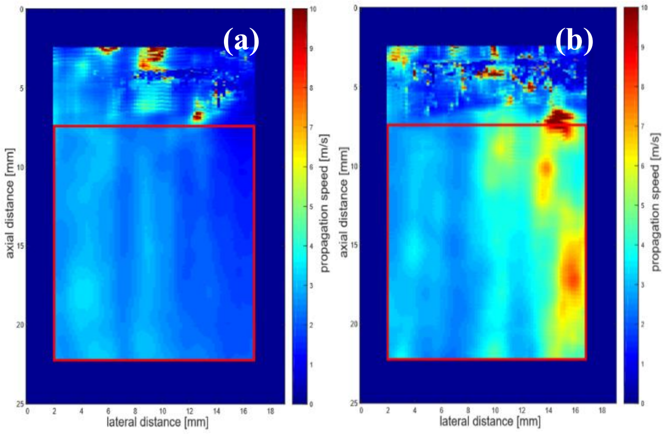

Fig. 1: Propagation speed maps of soft agar (a) and hard agar (b).

Figure 2 shows the stress-strain curves of the agar phantoms. Green (a) and red lines (b) were stress-strain curves of the soft and hard phantoms, respectively. These slopes corresponded to Young's modulus of respective phantoms, and values of (a) and (b) were 7.5 kPa and 10.6 kPa, respectively.

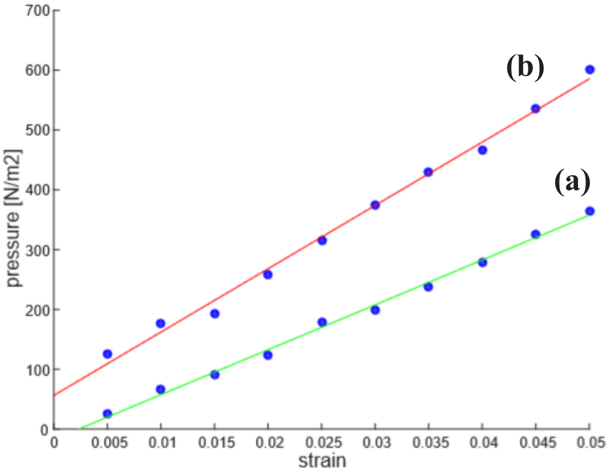

Fig. 2: stress-strain curves of soft and hard agar phantoms

In the proposed method, Young's modulus E was obtained from the SWPS by

$$E = 3\rho {c_s}^2, \qquad (4)$$

where ρ and c_s indicated a density (1000 kg/m^3) and the SWPS, respectively. Young's modulus of soft and hard phantoms calculated by Eq. (4) were about 17 kPa and 43 kPa, respectively. Although differences between results of the proposed method and static experiment were observed, these were considered to be due to the difference in the vibration frequency and viscosity. Consequently, the results by the proposed method reflects the difference in stifnesses of the phantoms, which were quantitatively evaluated by a separate mechanical testing.

4. Conclusion

In the present study, the results on the phantoms obtained by the proposed method were compared with that quantitatively obtained by the static mechanical testing. Consequently, the result obtained by proposed method has a similar tendency to that by the static experiment, and the phantom results indicated that the proposed method can distinguish the difference in stiffnesses.

References

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