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Basic study on estimation of two dimensional wavenumbers using phase of particle velocity

粒子速度の位相を用いたせん断波の 2 次元波数推定に関する基礎的検討

Masato Minagawa[1†], Hideyuki Hasegawa[1], Tadashi Yamaguchi[2], Shin-ichi Yagi[3] ([1]Graduate School of Science and Engineering, Toyama Univ.; [2]Center for Frontier Medical Engineering, Chiba Univ.; [3]Professor Emeritus, Meisei Univ.)
皆川真聖 [1†], 長谷川英之 [1], 山口匡 [2], 八木晋一 [3] ([1] 富山大院 理工, [2] 千葉大 フロンティア医工学センター, [3] 明星大 名誉教授)

1. Introduction

Estimation of shear wave propagation speed using the particle velocity that is occurred by heartbeat is useful as a method of measuring the elastic property of liver [1]. Recently, a method of evaluating the hardness of tissue by measuring shear wave occurred by an ultrasonic push pulse has been developed [2]. However, more safety assessment of shear wave propagation speed is preferable because the method induces a risk of tissue injury by cavitation [3]. If it is possible to use shear wave occurred by heartbeat, it is possible to estimate the elastic property of liver tissue more safely.

We have previously showed that it is possible to estimate shear wave propagation speed occurred by heartbeat by plane-wave high frame rate ultrasound with parallel receive beamforming [4]. The propagation direction and speed were estimated by estimating the wave numbers in the range and lateral directions to obtain shear wave propagation speed in a two dimensional plane of an ultrasonic image. In the present study, a method for simultaneous estimation of the wave numbers in two directions was examined, and the two dimensional distribution of shear wave propagation speed occurred by heartbeat in a liver was estimated.

2. Materials and Methods

In validation experiments using agar phantoms, ultrasound B-mode image was constructed with high temporal resolution of 1302 Hz by high frame rate ultrasound with plane wave transmission [1] and each B-mode image was constructed by 4 transmissions. The measurement was done using linear array at a center frequency of 7 MHz. The interval of scan lines was 0.2 mm and sampling frequency of ultrasound RF signals was 31.25 MHz.

In the measurement of a liver, the imaging frame rate was 2500 Hz also with plane wave imaging. The measurement was done using linear array at a center frequency of 5 MHz, and each B-mode image was constructed by two transmissions. The interval of scan lines was 0.36 mm and the sampling frequency of ultrasound RF signals was 31.25 MHz. The vibration velocity waveform $v(x, z; t)$ of the liver 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 [5].

We have developed a method for estimation of a pulse wave propagation speed in the carotid artery by using the phase of the vibration velocity $v(x, t)$ of the arterial wall measured at scan line position x [6]. In that method, time-frequency spectrum $\tilde{v}(t_0; x, f)$ of the velocity at time t_0 is estimated by short-time Fourier transform. Two dimensional frequency spectrum $V(t_0; k, f)$ of the velocity is obtained by applying Fourier transform with respect to position x to the complex vibration velocity $\tilde{v}(t_0; x, f)$ as follows:

$$V(t_0; k, f) = \int \tilde{v}(t_0; x, f) \cdot e^{-jkx} dx. \qquad (1)$$

Equation (1) corresponds to the two-dimensional Fourier transform of the vibration velocity $v(x, t)$. In this report, we focus on the term $\tilde{v}(t_0; x, f) \cdot e^{-jkx}$ of Eq. (1). When a shear wave propagates in direction x at a constant speed, the phase of the velocity waveform is proportional to x [6]. When the change rate of the phase coincides with wavenumber k in the term e^{-jkx}, the phase $\angle\{\tilde{v}(t_0; x, f) \cdot e^{-jkx}\}$ of $\tilde{v}(t_0; x, f) \cdot e^{-jkx}$ becomes constant regardless of x.

In this report, in order to consider the shear wave propagation in the two-dimensional cross section of a liver, i.e., the transverse (x) and axial (z) directions, the mean squared error between the phase of the complex vibration velocity and its linear model (shear wave is locally approximated to a plane wave) is simultaneously calculated in two directions. The model of two-dimensional complex vibration velocity distribution at the time t_0 is expressed as follows:

$$\hat{v}(t_0;\ x,\ z) = v_0 \cdot e^{-j(k_x x + k_z z)}, \qquad (2)$$

where v_0 indicates complex velocity amplitude.

The mean squared error α between the phase $\angle v(t_0,;x,\ z)$ of the measured complex vibration velocity and its model $\{-(k_x x + k_z z)\}$ is expressed as follows:

$$\alpha = \sum_R \{\angle\hat{v}(t_0; x,\ z) + (k_x x + k_z z)\}^2, \quad (3)$$

where R indicates a region of interest where α is calculated.

In order to determine $\hat{k}_x$ and $\hat{k}_z$ which minimizes the error α, α is partially differentiated by k_x and k_z and zeroed. Then, least square solutions $\hat{k}_x$ and $\hat{k}_z$ are obtained by solving the simultaneous equation given by

$$\frac{\partial\alpha}{\partial k_x} = 0, \qquad \frac{\partial\alpha}{\partial k_z} = 0. \qquad (4)$$

As described above, in this report, shear wave propagation speed was estimated by estimating $\hat{k}_x$ and $\hat{k}_z$ simultaneously using the phases of vibration velocity waveforms.

3. Experimental Results

Figures 1(a) and (b) show propagation speed maps of soft and hard agar phantoms, respectively. The soft and hard agar phantoms were made from 5% and 10% agar. Also, both phantoms contain graphite powder of 3 g as scatterers. As shown in Fig. 1, the shear wave propagation speed in the hard agar phantom is much higher than that in the soft agar phantom. These results show that the proposed method can distinguish the difference in the tissue elastic property.

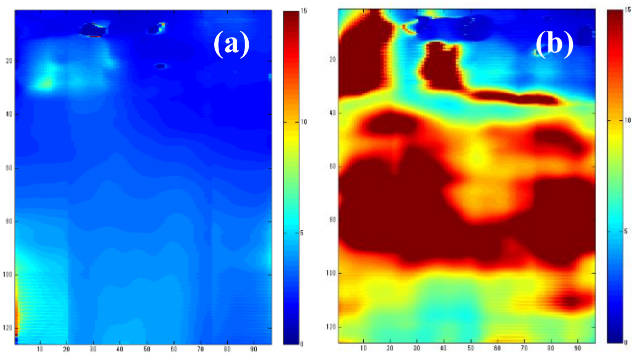

Fig. 1: Propagation speed maps of soft agar (a) and hard agar (b).

Figures 2(a) and (b) show a B-mode image of the liver of a 42 years old healthy male and shear wave propagation speed map, respectively. There is a heart in the lower right side and it is difficult to estimate propagation speed there because that region is too close to the source of vibration. However, in the other regions, shear wave propagation speed was estimated to be about 1 m/s, and this result agreed well with those reported in literature [7].

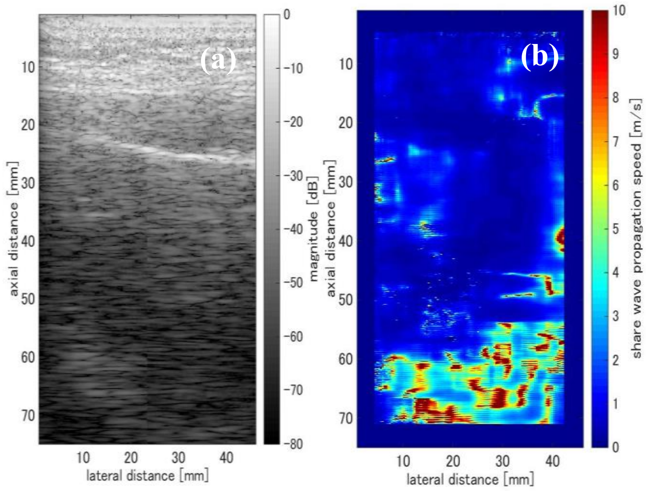

Fig. 2: (a) Ultrasonic B-mode image of the liver of a 42-year-old healthy male. (b) Shear wave propagation speed.

4. Conclusion

In this report, the validation experimental results show that the difference in tissue elasticity can be detected by the proposed method. Two dimensional estimation of wave numbers of the shear wave occurred by heartbeat in the liver was conducted for estimation of propagation speed.

References

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