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Novel Estimation Method of Shear Wave Displacement Amplitude excited by Vibrator

加振により励起されたせん断波振幅の新たな推定法

Yoshiki Yamakoshi†, Mayuko Yamazaki, Yoshino Ishimori and Kana Taniuchi
(Grad. School of Science and Technology, Gunma Univ.)
山越芳樹†，山崎真有子，石森愛乃，谷内華菜（群馬大学大院理工学府）

1. Introduction

Shear wave elastography (SWE) is a quantitative method in order to measure the viscoelastic properties of tissue. Among shear wave elastography, ARFI(Acoustic Radiation Force Impulse), which uses an impulsive shear wave excited by relatively high intensity focused ultrasonic wave, is widely used. We have proposed a novel shear wave elastography: Color Doppler Shear Wave Imaging (CD SWI)[1,2]. CD SWI uses signal processing unit in conventional ultrasound color flow imaging instrument in order to reconstruct the wavefront of continuous shear wave which is excited from the tissue surface by a small vibrator. Shear wave wavefront appears on the color flow image(CFI) as a binary pattern which consists of zero and the maximum flow velocities without adding any extra function to CFI. Although two conditions; shear wave frequency condition and shear wave displacement amplitude condition, are needed in order to obtain shear wave wavefront, these conditions are not severe restrictions in actual imaging.

CD SWI is an imaging system of shear wave phase map. From the shear wave phase map, shear wave velocity map and shear wave propagation direction map are reconstructed. However, if the shear wave amplitude map is obtained by CD SWI, absorption of shear wave and the penetration of shear wave into stiff lesions give useful information about tissue mechanical properties. In this paper, a novel method which estimates the relative displacement amplitude of shear wave from CFI is proposed.

2. Method

Vibration amplitude which is produced by shear wave is written as follows ;

$$\xi = \xi_0 \sin(\omega_b t + \Delta\phi) \ , \tag{1}$$

where $\omega_b (= 2\pi f_b)$ is the angular frequency of shear wave and $\Delta\phi$ is the phase of shear wave.

If ultrasonic wave irradiates every Δt, the quadrature output signals of the received ultrasonic wave I_i, Q_i (i=1,4) are given by

$$I_1 = K \cos\left[\frac{4\pi f_0}{c}\xi_0 \sin(\Delta\phi)\right] \tag{2}$$

$$Q_1 = K \sin\left[\frac{4\pi f_0}{c}\xi_0 \sin(\Delta\phi)\right] \ , \tag{3}$$

$$I_2 = K \cos\left[\frac{4\pi f_0}{c}\xi_0 \cos(\Delta\phi)\right] \tag{4}$$

$$Q_2 = K \sin\left[\frac{4\pi f_0}{c}\xi_0 \cos(\Delta\phi)\right] \ , \tag{5}$$

$$I_3 = I_1 \tag{6}$$

$$Q_3 = -Q_1 \ , \tag{7}$$

and

$$I_4 = I_2 \tag{8}$$

$$Q_4 = -Q_2 \ . \tag{9}$$

In CFI, flow velocity is estimated as follows ;

$$v = \frac{c f_{PRF}}{4\pi f_0} \tan^{-1}\left(\frac{E_U}{E_L}\right) \ , \tag{10}$$

where

$$E_U = \sum_i^N (I_i Q_{i+1} - I_{i+1} Q_i) \ , \tag{11}$$

$$E_L = \sum_i^N \left(I_i I_{i+1} + Q_i Q_{i+1}\right) \ . \tag{12}$$

By substitution of eqs.(1)-(9)into eq.(11), we obtain $E_U = 0$. On the other hand, E_L is derived by assuming $\Delta\phi \cong 0$ as

$$E_L \cong NK^2 \cos\left[\frac{4\pi f_0}{c}\xi_0 \cos(\Delta\phi)\right] \ . \tag{13}$$

Hence, shear wave displacement amplitude condition of CD SWI, which shows minimum displacement amplitude of the shear wave, is given by

$$\xi_{\mathrm{TH}} = \frac{\lambda}{8\cos(\Delta\phi)} \ . \tag{14}$$

The range of shear wave phase $\Delta\phi_w$ which shows the maximum flow velocity is

$$\Delta\phi_w = 2\cos^{-1}\left(\frac{\lambda}{8\xi_0}\right) \ . \tag{15}$$

Since the maximum flow velocity appears ever π[rad] on CFI, duty ratio of $\Delta\phi_w$ gives

$$d_r = \frac{\Delta\phi_w}{\pi} = \frac{2}{\pi}\cos^{-1}\left(\frac{\lambda}{8\xi_0}\right) . \qquad (16)$$

Eq.(16) shows that duty ratio d_r changes depending on the shear wave displacement amplitude ξ_0 . This implies that shear wave displacement amplitude ξ_0 is measured from the duty ratio d_r. However, d_r also changes by MTI filter and color Doppler gain of ultrasound imaging system. Hence, if d_r is measured in advance for a phantom by changing the displacement amplitude of the vibrator and a calibration curve between d_r and the displacement amplitude, the relative value of shear wave displacement amplitude is estimated from d_r by the calibration curve.

It is also derived that displacement amplitude of shear wave depends on the ratio between first order spectrum and DC component of spectrum of flow velocity recorded on CFI, the relative value of the displacement amplitude of shear wave is measured from the spectral ratio.

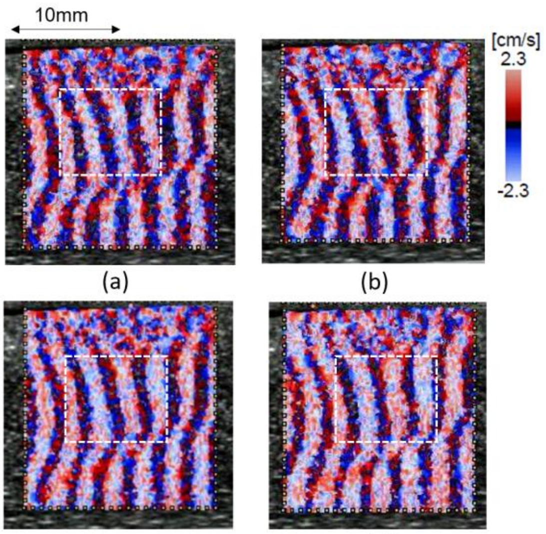

Fig.1 CFI acquired for different amplitude of vibration.(a): 0.5, (b): 1.0, (c): 2.0 and (d): 3.0 (Arb. unit), respectively.

3. Results

In order to evaluate a method to estimate shear wave displacement amplitude, which is discussed above, CFI is observed by changing the amplitude of vibrator. Phantom is agar gel. Shear wave frequency is 276.5Hz. Results are shown in **Fig.1**. It is shown that duty ratio of fringe on CFI, which shows shear wave wavefront, increases with the vibrator amplitude.

Fig.2 shows an example of image for breast phantom (BB-04, OST, Japan). Fig.(a) is B-mode image. Circular hypoechoic area is a model of stiff malignant lesion. Fig.(b) and (c) are shear wave propagation map and shear wave velocity map, which are reconstructed by CD SWI. Fig.(d) is displacement amplitude map which is obtained by the proposed method. Stiff area shows low displacement amplitude area, because displacement amplitude is much lower than that of the surrounding soft area.

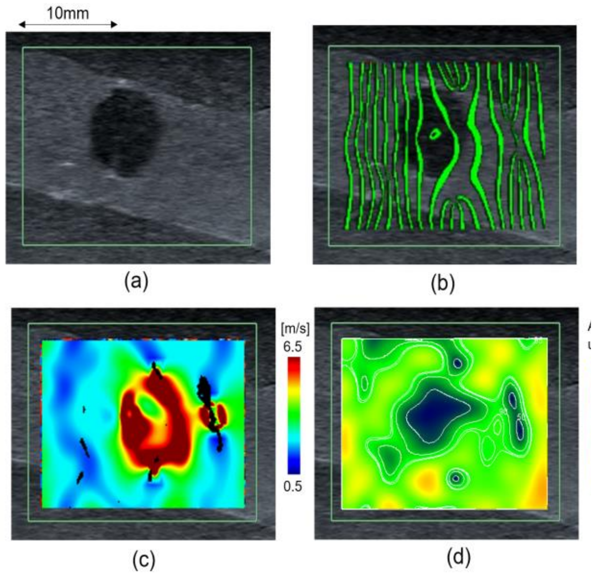

Fig.2 Breast phantom image. (a): B-mode image, (b): shear wave propagation map, (c): shear wave velocity map and (d): shear wave displacement amplitude map which is observed by the proposed method.

4. Conclusion

CD SWI elastography is a novel imaging method which observes shear wave propagation in real-time. This paper proposes a novel method which reconstructs shear wave displacement amplitude map in CD SWI elastography. Both theoretical discussion and basic experimental result show that the proposed method is useful for real-time displacement amplitude estimation which is suitable for CD SWI.

References

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