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Forward Propagated Shear Wave Imaging using CD SWI Elastography

CD SWIエラストグラフィを用いた前方伝播するせん断波の映像系

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1. Introduction

Shear wave elastography (SWE) is an effective method to evaluate tissue stiffness and ARFI(Acoustic Radiation Force Impulse), which is one of SWE, is widely applied to various tissues, such as breast, liver and skeletal muscles. In ARFI, an impulsive shear wave is produced by relatively high intensity ultrasonic wave and the tissue stiffness is measured from the velocity of shear wave which propagates in soft tissue. SWE is also constructed by using continuous shear wave which is excited by mechanical vibrator attached to the tissue surface. We have proposed a novel imaging method (Color Doppler Shear Wave Imaging: CD SWI) for SWE using continuous shear wave[1,2]. CD SWI uses signal processing unit in conventional ultrasound color flow imaging instrument in order to reconstruct the wavefront of shear wave which propagates in soft tissue. Shear wave wavefront appears on color flow image (CFI) as a binary pattern which consists of zero and the maximum flow velocities without adding any extra function to CFI. In CD SWI, two conditions, those are shear wave frequency condition and shear wave displacement amplitude condition, are needed to obtain shear wave wavefront on CFI, but these conditions are not severe restrictions in actual imaging.

A problem of SWE by CD SWI is the reflection of shear wave at the tissue boundary. Reflected shear wave in conjunction with the incident shear wave produces shear wave's standing wave, which degrades the accuracy of shear wave velocity estimation. In this paper, a directional filter which extracts forward propagated shear wave from shear wave standing wave field is proposed for CD SWI elastography. Directional filter is already developed in transient shear wave elastography[3]. But, this filter is effective when both the amplitude and the phase of the shear wave are obtained. However, the shear wave amplitude cannot be obtained in CD SWI, which is a restriction when a directional filter is introduced in CD SWI. This paper discusses a directional filter which is suitable for CD SWI elastography.

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2. Directional filter in CD SWI

In directional filter which extracts forward propagated shear wave, first, two-dimensional Fourier transform of the shear wave phase map is derived by assuming that the shear wave amplitude is a constant value as

$$F_\theta(k_x,k_z) = \iint \exp[j\theta(x,z)]\, exp\,[-j(k_x x + k_z z)]dxdz \ , \quad (1)$$

where $\theta(x,z)$ is the shear wave phase which is estimated by CD SWI. Then, directional filter is applied on wave-number vector space as

$$G_\theta(k_x,k_z) = W(k_x,k_z)\ F_\theta(k_x,k_z) \quad , \quad (2)$$

where $W(k_x,k_z)$ is a transfer function of the directional filter. Transfer function which extracts forward propagated shear wave component with wave-length larger than λ_{TH} is

$$W(k_x,k_z) = \begin{cases} 1 & where\ \ k_x > 0\ \ and\ \ |k| < k_{TH} \\ 0 & otherwise\ , \end{cases} \quad (3)$$

where

$$|k| = \sqrt{k_x^2 + k_z^2} \ , \quad (4)$$

$$k_{TH} = \frac{2\pi}{\lambda_{TH}} \ . \quad (5)$$

After applying the transfer function to the two-dimensional spectrum of shear wave phase map, shear wave phase map is derived as

$$\theta_{FLT}(x,z) = \iint G_\theta(k_x,k_z)\ \ exp[j(k_x x + k_z z)]dk_x dk_z \ . \quad (6)$$

The time lag of ultrasound irradiation in lateral direction (x direction) affects shear wave phase shift which is appeared on CFI. The phase shift of shear wave appeared on CFI is

$$\varphi_m = \ k_0 x + 2\pi f_b \mathrm{K} x \ , \quad (7)$$

where k_0 is wavelength of shear wave, f_b is shear

wave frequency and K is the time lag of ultrasound beam irradiation per unit length [s/m].

Then, the pseudo wave number of shear wave appeared on CFI is

$$k_m = \frac{\partial \varphi_m}{\partial x} = k_0 + 2\pi f_b \mathrm{K} \ . \qquad (8)$$

This equation shows that pseudo wave number of shear wave appeared on CFI increases by $2\pi f_b \mathrm{K}$ from the wave number of shear wave. Hence, we have to take into account of the wave number spectrum's being shifted by $2\pi f_b \mathrm{K}$ in the direction of k_x on two dimensional wave number space.

3. Results

In order to evaluate the usefulness of digital filter in CD SWI, numerical simulation is carried out. It is assumed that a plane reflector is placed right side of ROI (size 22*22mm) and shear wave is excited by a point source placed at 22mm left upper of the ROI. Shear wave frequency is 275Hz and shear wave velocity is 5.1m/s. Free end reflector is assumed and the reflection coefficient is 0.2. Attenuation of shear wave by the medium is neglected. **Fig. 1** shows the result. Figs. 1(a-1) and (a-2) are the shear wave phase map and its spectrum on wave number space when the reflected shear wave is taking into account. Inherent phase modulation due to the standing wave component is shown. Figs. 1(b-1) and (b-2) are shear wave phase map and its spectrum which are derived after applying the directional filter which extracts the forward propagated wave. It is found that the effect by standing wave is suppressed effectively.

Fig. 2 shows the quantitative evaluation of the

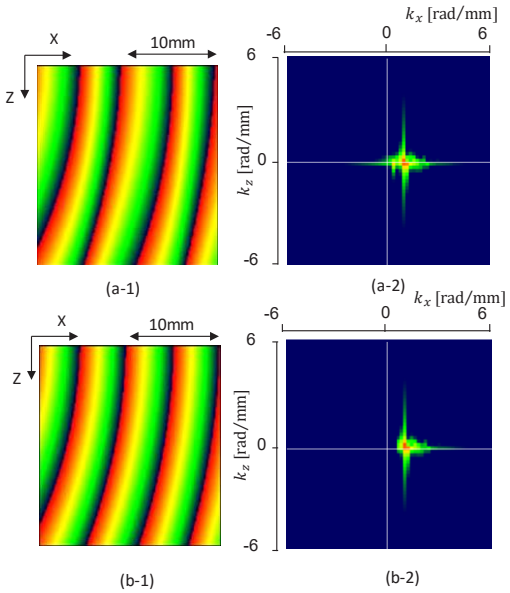

Fig. 1 Effect of directional filter in CD SWI (Numerical simulation result).

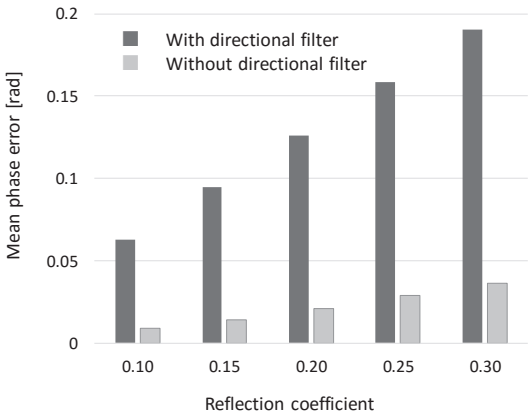

Fig. 2 Mean phase error evaluated for different reflection coefficient

proposed directional filter for different reflection coefficient. Horizontal axis is the reflection coefficient and the vertical axis is the mean phase error of the shear wave phase map after applying the directional filter. Although the error increases with the reflection coefficient, mean phase error decreases effectively by the directional filter.

Fig. 3 shows phantom (konjak) experimental

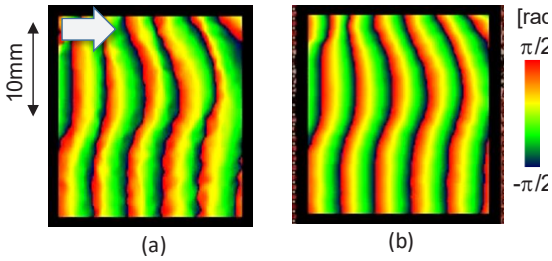

Fig. 3 Phantom experimental result. (a): without directional filter. (b): with directional filter.

result. Figs. 3(a) and (b) are the results without directional filter and that with directional filter. We see the effect of directional filter from this result.

4. Conclusions

Extraction of forward propagated shear wave from shear wave's standing wave field is an important technology in SWE using continuous shear wave. To extract the forward propagated shear wave in CD SWI, we proposed a directional filter and its usefulness is evaluated both by numerical analyses and experiment. CD SWI elastography which includes the directional filter is a tool to obtain quantitative information about tissue stiffness.

References

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