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Novel Imaging Method of Continuous Shear Wave by Ultrasonic Color Flow Mapping

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Abstract

Shear wave velocity measurement is a promising method in evaluation of tissue stiffness. Several methods have been developed to measure the shear wave velocity, however, it is difficult to obtain quantitative shear wave image in real-time by low cost system. In this paper, a novel shear wave imaging method for continuous shear wave is proposed. This method uses a color flow imaging which is used in ultrasonic imaging system to obtain shear wave’s wavefront map. Two conditions, shear wave frequency condition and shear wave displacement amplitude condition, are required, however, these conditions are not severe restrictions in most applications. Using the proposed method, shear wave velocity of trapezius muscle is measured. The result is consistent with the velocity which is calculated from shear elastic modulus measured by ARFI method.

Keywords: Shear wave; Real-time imaging; Elastography; Color flow imaging; Trapezius muscle

1. Introduction

Tissue stiffness is a useful parameter in medical diagnosis, because the change of tissue stiffness is a good index for diseases, such as liver fibrosis and breast cancer. Several imaging methods have been proposed in order to estimate the tissue stiffness. Among them, acoustic radiation force impulse (ARFI) imaging is a quantitative method, however, a high frame-rate imaging system is needed in order to detect the tissue displacement which is produced by an impulsive shear wave. Transient elastography, which uses impulsive 50 Hz shear wave applied from tissue

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is a method to measure the shear wave velocity, however, it is difficult to obtain two-dimensional shear wave maps.

In this paper, a novel real-time imaging method of continuous shear wave which propagates in soft tissue is proposed. Feature of the method is that shear wave’s wavefront is observed directly from an ultrasonic color flow image (CFI) used in an ultrasonic imaging system without adding any functions to the system. Quantitative shear wave maps are derived from the observed shear wave’s wavefront map.

2. Method

In CFI, quadrature detector output signals are acquired for \( N + 1 \) successive irradiated ultrasonic waves, and the flow velocity is estimated as \([1]\)

\[
v = \frac{c}{4\pi f_0 \Delta t} \arctan \left( \frac{E_U}{E_L} \right),
\]

where

\[
E_U = \sum_{i=1}^{N} l_i Q_{i+1} - l_{i+1} Q_i,
\]

\[
E_L = \sum_{i=1}^{N} l_{i+1} l_i + Q_{i+1} Q_i,
\]

and \( l_i \) and \( Q_i \) are the quadrature detector output signals, \( f_0 \) is center frequency of the ultrasonic wave, \( c \) is sound velocity, and \( \Delta t \) is time duration between successive ultrasonic pulses that are irradiated in the same direction.

We assume that the shear wave displacement \( \xi \) is:

\[
\xi = \xi_0 \sin (\omega_b t + \phi_b),
\]

where \( \xi_0 \), \( \omega_b \) and \( \phi_b \) are displacement amplitude, angular frequency and initial phase of the sinusoidal displacement, respectively.

Then, the phase of the received ultrasonic wave is:

\[
\phi_i = \phi_0 + \frac{2\pi f_0}{c} \cdot 2\xi.
\]

The quadrature detector output signals are:

\[
l_i = a \cos \left( \phi_0 + \frac{4\pi f_0}{c} \xi \right),
\]

\[
Q_i = a \sin \left( \phi_0 + \frac{4\pi f_0}{c} \xi \right).
\]

If we assume that the shear wave vibration frequency satisfies the following equation:

\[
f_b = \frac{1}{4 \Delta t},
\]

it is derived that \( E_U \) in Eq. (2) is always zero if \( N \) is a multiple of 4.\([2]\) Then, the estimated flow velocity is zero when \( E_L \) is positive. If \( E_L \) is negative, the estimated flow velocity is the maximum, \( v_{\text{max}} \):

\[
v_{\text{max}} = \frac{c}{4 f_0 \Delta t}.
\]

Condition that \( E_L \) is negative is derived under \( \phi_b = 0 \) as:
\[ \frac{1}{8} \lambda < \xi_0 < \frac{3}{8} \lambda , \]  
\[ \text{(10)} \]

where \( \lambda \) is the wavelength of ultrasonic wave. We call Eq. (10) a shear wave displacement amplitude condition. A similar argument of Eq. (8) can be followed when the following equation is satisfied:

\[ f_b = \frac{1}{2} \left( m + \frac{1}{2} \right) \frac{1}{\Delta t} , \]
\[ \text{(11)} \]

where \( m \) is zero or an integer value. We call Eq. (11) a shear wave frequency condition. Under these two conditions, a stripe-like binary pattern consisting of zero and maximum flow velocities appears in CFI. This pattern corresponds to the shear wave’s wavefront that propagates inside the medium.

To derive the shear wave’s velocity and the propagation direction, CFI is acquired during the time period \( T_{CFI} \) and the Fourier analysis is applied. The shear wave velocity and shear wave propagation direction maps are derived by differentiation the phase of Fourier spectrum followed by shear wave’s wave number estimation.

3. Experimental result

Experimental setup is shown in Fig.1. Shear wave was excited by a small linear vibration actuator (35mm in length). This actuator produced a sinusoidal vibration of 1 mm in amplitude at frequency of around 300 Hz. An ultrasonic imaging system with 6.5 MHz linear probe (Hitachi Aloka Medical, EUB-7500, Japan) was adopted. Pulse repetition frequency of ultrasonic pulses was set to 365 Hz. Shear wave’s wavefront that was appeared on CFI was acquired via a video capture (Epiphan, DVI2USB, USA) and the shear wave velocity and shear wave direction maps were reconstructed in PC.

Figure 2 shows shear wave maps which are reconstructed by the proposed method. Figures 2 (a)-(d) are CFI, shear wave phase map, shear wave velocity map, and shear wave propagation direction map, respectively. Shear wave frequency was 276.3 Hz, which corresponded to \( m=1 \) under the shear wave frequency condition. Although the frequency which satisfied the shear wave frequency condition was 273.75 Hz for PRF of 365 Hz, the same shear wave’s wavefront map was observed around this frequency. If the frequency was shifted slightly from the integer multiple of the frame rate of CFI, the shear wave’s wavefront was displayed as a motion picture on CFI. From Fig.2 (a), it was found that the shear wave’s wave front was shown as a binary pattern consisting of...
zero and the maximum flow velocities. From the quantitative shear wave maps shown in Figs.2 (b)-(d), the shear wave propagation in the phantom was clearly seen.

In vivo experiment was carried out for trapezius muscle under the approval of IRB. Figure 3 shows the experimental result. Figures 3 (a)-(d) are the photograph of experiment, CFI, shear wave phase map, velocity map, and propagation direction map, respectively. Frequency was set to 276.5 Hz. Shear wave velocity on ROI in Fig.3 (e) was 4.22 m/s. This result was consistent with the velocity which was derived from the shear elastic modulus measured by ARFI method. [3]

4. Conclusion

Problem of continuous shear wave excitation is that it is difficult to estimate shear wave velocity because the shear wave tends to produce the standing wave. But, if shear wave propagation is visualized in real-time, the continuous shear wave excitation becomes a powerful tool because the generation of the standing wave is suppressed effectively by optimizing the shear wave excitation position and by selection of the shear wave frequency. The accuracy of shear wave velocity measurement is improved by using the real-time visualization of shear wave propagation because the shear wave velocity can be measured by considering the shear wave propagation direction. In this paper, we propose a novel real-time visualization method for continuous shear wave excitation. This method uses color flow imaging in general purpose ultrasonic imaging system to detect the shear wave's wavefront. Feature of the method is that the shear wave’s wavefront is reconstructed directly without adding any functions to the ultrasonic imaging system. Although two conditions, those are the shear wave frequency condition and the shear wave displacement amplitude condition, are required to obtain map, these conditions are not severe restrictions in most applications. To obtain high spatial resolution map, the shear wave frequency is chosen among several frequencies, but there is no upper limit of the frequency. Quantitative shear wave maps, such as shear wave velocity map and shear wave propagation direction map, are reconstructed from the observed shear wave’s wavefront map. The proposed imaging system might be suitable for tissues in the vicinity of the skin because of large attenuation of shear wave. However, this extremely low-cost real-time shear imaging system is useful in characterization of tissue mechanical properties.

References