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Proceedings of Symposium on Ultrasonic Electronics, Vol. 35 (2014) pp. 193-194
3-5 December, 2014

Shear Elastic Wave Imaging using Ultrasound Color Flow Imaging

超音波カラーフロー画像を用いたずり弾性波映像法

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1. Introduction

To characterize soft tissue by stiffness, several imaging methods have been proposed that differ in terms of their shear wave excitation and detection algorithm. Amoung them, acoustic radiation force impulse (ARFI) imaging is applied for various tissues and its usefulness as an elasticity imaging method has been demonstrated. [1] However, there are two limitations in ARFI method. The first one is that undesirable temperature rise occurs when bone is at the focus of ultrasonic wave.[2] Mmuch attention should be paied when the method is applied to skeletal muscles. The second one is that high frame rate ultrasonic imaging system is required to obtain the image. It is because the Doppler signal frequency which is caused by shear wave tissue motion is usually higher than the pulse repetition frequency of genral-purpose ultrasonic color flow imaging system. Hence, an expensive ultrasonic imaging system of high frame rate is adopted to obtain image.

In this paper, a novel imaging method for a continuous shear wave is proposed. Mechanical vibrator which is attached to the tissue surface excites shear wave into the tissue, that is the same with a transient elastography.[3] But, wavefront of the shear wave that propagates inside the medium is directly reconstructed by the signal processing unit of color flow imaging (CFI) which is adopted in a general-purpose ultrasound imaging system. Neither a special designed shear wave detection unit nor a high frame imaging system is needed to obtain the image. This is because shear wave wave front is directly detected by the characteristic of signal processing unit of color flow imaging under the frequency down-conversion condition of an aliasing effect. In the proposed method, two conditions are needed to obtain image. A frequency condition defines shear wave vibration frequency and a displacement amplitude condition defines minimum displacement amplitude of the shear wave. However, these two conditions are not severe restrictions in most applications. A low-cost, ease-of-use, real-time shear wave imaging system is constructed by this method.

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2. Method

In CFI, quadrature detector output signals I_i and Q_i are acquired for N+1 successive ultrasonic waves and flow velocity is estimated as:

$$v = \frac{c}{4\pi f_0 \Delta t} \arctan\left(\frac{E_U}{E_L}\right), \tag{1}$$

where

$$E_U = \sum_{i=1}^{N} I_i Q_{i+1} - I_{i+1} Q_i$$
$$E_L = \sum_{i=1}^{N} I_{i+1} I_i + Q_{i+1} Q_i \,. \tag{2}$$

When the shear wave which is excited by mechanical vibrator propagates inside a medium, displacement ξ is:

$$\xi = \xi_0 \sin(\omega_b t + \phi_b), \tag{3}$$

where ξ_0, ω_b and ϕ_b are the displacement amplitude, angular frequency and the initial phase of the shear wave.

Then, the output signals of a quadrature detector are:

$$I_i = a\cos\left(\phi_0 + \frac{4\pi f_0}{c}\xi\right)$$
$$Q_i = a\sin\left(\phi_0 + \frac{4\pi f_0}{c}\xi\right). \tag{4}$$

We consider a case that the shear wave frequency satisfies a frequency condition as:

$$f_b = \frac{1}{2}\left(m + \frac{1}{2}\right)\frac{1}{\Delta t}\,. \tag{5}$$

where m is zero or an integer value and Δt is the period of ultrasonic wave pulses in CFI.

In usual, packet size N can be selected by ultrasonic imaging system. If N is chosen as a multiple of 4, it is derived that the E_U in eq. (2) is always zero. Moreover, it is derived that E_L in eq. (2) is negative when $\phi_b=0$ and displacement amplitude satisfies a displacement amplitude condition as:

$$\frac{1}{8}\lambda < \xi_0 < \frac{3}{8}\lambda\,, \tag{6}$$

where λ is the wavelength of ultrasonic wave. Both $E_U=0$ and negative E_L means that the maximum flow velocity appears around vibration phase $\phi_b=0$ in CFI. In usual, the maximum flow velocity appears around every π rad in CFI. Otherwise the estimated flow velocity becomes zero. Hence, a binary pattern which consists of zero and maximum flow velocity appears in CFI, which corresponds to a wavefront of shear wave inside the medium.

3. Experiments

Experimental-set up is shown in Fig.1. Shear wave is excited by large amplitude multilayer

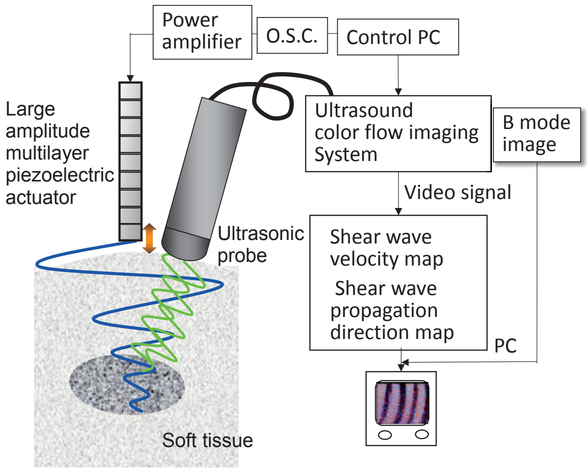

Fig.1 Experimental setup

piezoelectric actuator (AHB800, NEC Tokin, Sendai). An ultrasonic imaging system with 6.5 MHz linear probe (EUB-8500, Hitachi Aloka Medical, Tokyo) is adopted. Pulse repetition frequency is set to 365 Hz.

Fig.2 shows the experimental result for agar gel phantom. Fig.2 (a) shows CFI image for the shear wave frequency of 273.6 Hz. This frequency corresponds to m=1 of frequency condition. It is clearly see a binary pattern which consists of zero and maximum flow velocity in CFI. Fig.2 (b) shows the shear wave phase map which is derived by applying the Fourier analysis to CFI. Fig.2 (c) and (d) are shear wave velocity map and shear wave propagation map, respectively.

Fig.3 shows an experimental result in vivo for trapezius muscle. Fig.3 (a) shows the photograph of experiment. Fig.3 (b) is CFI. Fig. 3 (c), (d) and (e) are shear wave phase, shear wave velocity and shear wave propagation direction map, respectively. Shear wave velocity inside ROI is 6.32 m/s.

4. Discussions

A novel imaging method for a continuous shear wave is proposed. A feature of this method is that shear wave images are obtained without adding an additional function to an ultrasonic wave imaging system. To obtain the image, frequency condition and displacement amplitude condition are required. For example, shear wave frequency must be around 91 Hz, 274 Hz, 456 Hz for ultrasonic wave pulse repetition frequency of 365 Hz. Minimum displacement amplitude is about 29 μm for US frequency of 6.5 MHz. This displacement is easily exited by a small multilayer piezoelectric actuator in most applications. A problem of the method is low signal-to-noise ratio of the reconstructed image. But, an image quality is improved effectively by the Fourier analysis method which is demonstrated in Fig. 3. Using the proposed method, a low-cost, ease-of-use, real-time shear wave imaging system can be constructed.

References

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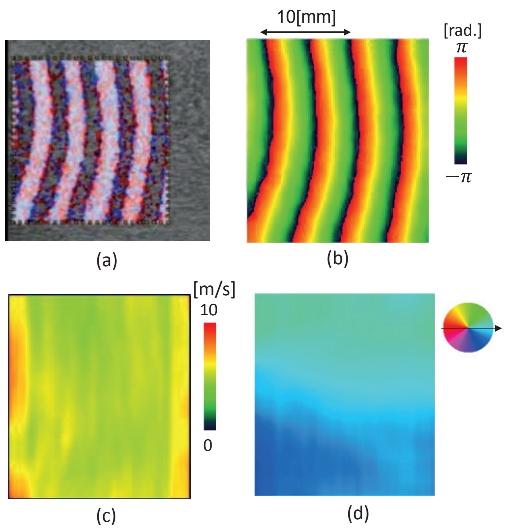

Fig.2 Experimental result (Agar gel phantom)

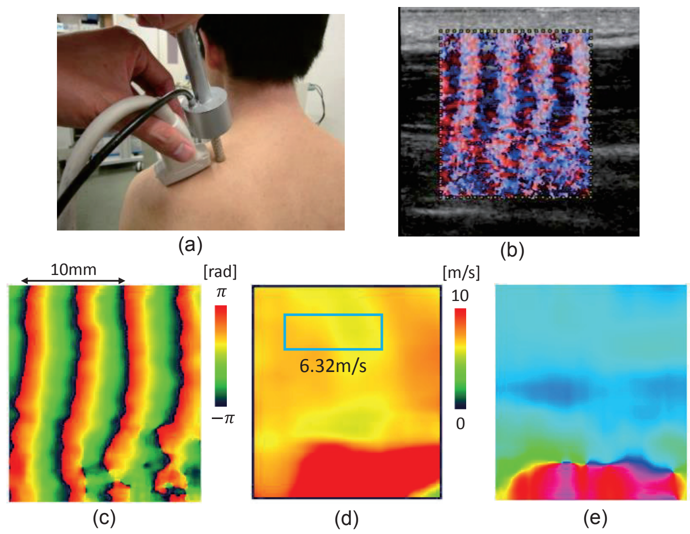

Fig.3 Experimental result in vivo (Trapezius muscle)