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Binary Pattern Color Doppler Shear Wave Elastography*

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***Abstract*— Some studies suggested a correlation between tissue elasticity and diseases, such as Adhesive Capsulitis (AC) of the shoulder. One category of method to measure elasticity is by utilizing Doppler imaging. This paper discusses color Doppler shear wave elastography methods and demonstrated an experiment with biological tissue mimicking phantom. A simulation with binary pattern color Doppler shear wave elastography shows that wavelength of a shear wave with suggested magnitude is equal to four multiple of pitch strip in a color flow image. However, the larger amplitude changes the duty ratio and frequency of the pattern. An experiment with biological tissue mimicking Polyvinyl Alcohol (PVA) phantoms has shown that the binary pattern color Doppler method has successfully recovered shear wave velocity map and calculate the elasticity.**

***Clinical Relevance*— The result of experiments presents a possibility of using the method for quantitatively access the stage of tissue stiffness related disease.**

I. Introduction

Tissue elasticity is often used as a heath state indicator of biological tissue in many situations. Different methods have been developed to measure this mechanical property [1]. In a medium with neglectable viscosity, elasticity is obtained from the square of shear wave velocity times medium density [2]. In the Acoustic Radiation Force Impulse (ARFI) Imaging method [3], the shear wave is induced in a tissue by high-intensity ultrasonic wave from an ultrasonic wave transducer. This shear wave is then measured by the same transducer with a high pulse repetition frequency and frame rate. Color Doppler shear wave elastography in contrast requires low pulse repetition frequency (PRF) of an ultrasound imaging system. Shear wave velocity and wave propagation direction map are reconstructed from a sequence of binary color flow images. However, the shear wave displacement amplitude, frequency and packet size must be controlled to a certain condition [4].

In this paper, the basis for shear wave elastography and the displacement amplitude requirement of the binary pattern color Doppler method are discussed. In addition, an experiment result to image a biological tissue mimicking phantoms is presented.

II. Methods

A. Color Doppler Method in Shear Wave Elastography

The early technique to analyze tissue stiffness is based on a method called vibrational sono-elastography [5] which in principles map the maximum displacement of a local particle motion at low frequency vibration by Doppler variance analysis. In this method, shear wavelength could not display since the phase data are not available.

Color Doppler shear wave elastography in contrast, successfully estimates the phase of internal vibration by ultrasound array [2]. When a mechanical vibration is induced to a medium, a propagating shear wave is produced. An ultrasound transducer array detected vertical tissue motion as a pattern of flow velocity along spatial dimension for any given time. The phase of the shear wave phase is estimated by analyzing the spectrum of Doppler signal. The velocity map can be reconstructed by repeating the process to all elements.

By current technology of the ultrasound imaging system, imaging resolution, Pulse Repetition Frequency (PRF) and imaging frame rate are high enough in respect to the commonly used shear wave frequency (100-400 Hz). When the system is applied to image a propagating shear wave, produced color flow image is a sinusoid interference pattern of the shear wave and the scanning process of transducer. After compensation by transducer scanning delay, phase map of the shear wave can be directly reconstructed, and the shear wave wavelength is estimated from the pattern pitch along propagation direction. Since the vibration is externally induced, the propagation velocity and direction can be determined accordingly.

B. Binary Pattern of Shear Wave Wavefront

In the binary pattern shear wave elastography [4], the same hardware configuration is employed, which is a mechanical vibration source assembled near an ultrasound array transducer as shown in Figure 1. A shear wave is externally induced and propagated in the medium. When a color flow imaging system is used, a sequence of ultrasonic pulses is radiated to the medium. The phase of reflected signal by this medium is shifted proportionally to the sinusoidal displacement of the shear wave.

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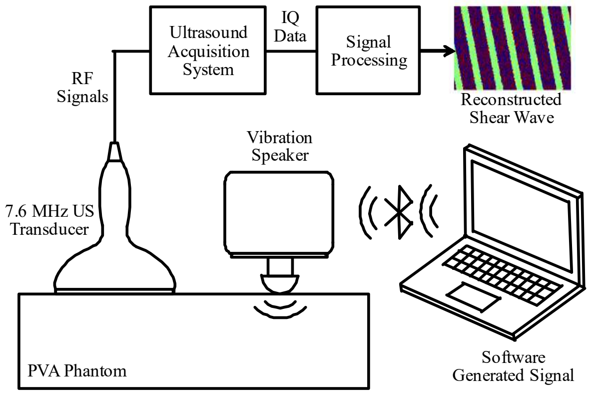


Figure 1. Hardware setup in color Doppler elastography.

A quadrature detector catches this signal and produces complex valued output. A typical signal processing flow is shown on the Figure 2. First, IQ data are decomposed, and the spectrum of the moving images are analyzed. The flow velocity reconstruction follows the pulse Doppler method which is derived from the autocorrelation techniques [6]. By repeating the process to all area, the shear wave velocity map is recovered.

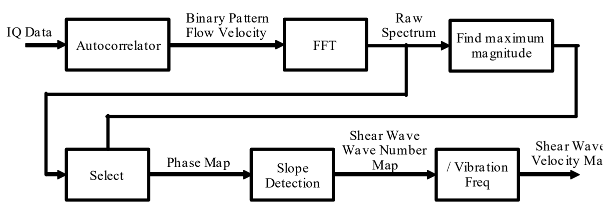


Figure 2. Signal processing framework of color Doppler elastography.

The differencing factor of binary pattern elastography from direct Doppler reconstruction is on the imaging procedure which requires a special condition of vibration frequency and amplitude. Under the given condition, the flow velocity appears as binary pattern on the color Doppler image.

According to the reference, the shear wave frequency condition f_b is given by

$$f_b = \frac{1}{2}\left(m - \frac{1}{2}\right)\frac{1}{\Delta t} \quad , \tag{1}$$

where Δt is successive ultrasonic pulses repetition interval of color flow velocity estimation, and m is a non-negative integer value. The displacement amplitude requirement is derived from a condition when the estimated flow velocity is the maximum, leading to

$$\frac{1}{8}\lambda < \xi_0 < \frac{3}{8}\lambda \quad . \tag{2}$$

Under the two conditions the shear wave map is reconstructed from repeating pattern of zero and maximum flow velocities in Color Flow Image (CFI) system. Since shear wave displacement is assumed as a sinusoid, the output signal of quadrature detector become

$$I_i = a\cos\left(\phi_0 + \frac{4\pi f_0}{c}\xi_0\sin(\omega_b t + \phi_b)\right) \quad \text{and}$$
$$Q_i = a\sin\left(\phi_0 + \frac{4\pi f_0}{c}\xi_0\sin(\omega_b t + \phi_b)\right) \quad . \tag{3}$$

By the autocorrelation, the value of velocity can be calculated for the given vibration frequency by

$$\hat{v} = \frac{c}{4\pi f_0 \Delta t}\tan^{-1}\frac{E_U}{E_L} \quad , \tag{4}$$

where

$$E_U = \sum_{i=-\frac{N}{2}}^{\frac{N}{2}} I_i Q_{i+1} - I_{i+1} Q_i \quad \text{and}$$
$$E_L = \sum_{i=-\frac{N}{2}}^{\frac{N}{2}} I_{i+1} I_i + Q_{i+1} Q_i \quad . \tag{5}$$

It can be seen from the formula that the pattern of binary flow velocity can be simulated as a function of maximum displacement ξ_0 and vibration phase $\omega_b t + \phi_b$. The value of maximum velocity

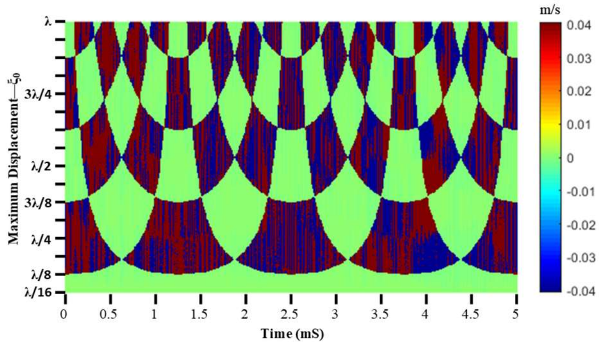
$$v_{max} = \frac{c}{4 f_0 \Delta t} \quad . \tag{6}$$

was derived when E_L is negative and E_U is zero. This is correct when $E_U = 0^+$. However, in the case of $E_U = 0^-$, the value of v_{max} becomes negative since calculation of *atan* division move abruptly from quadrant II to the quadrant III. This principle explained the mixture of positive and negative value of binary pattern in the simulation.

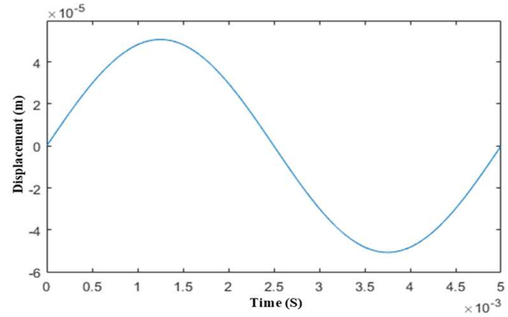
III. Results

A. Simulation

A simulation is performed to visualize the effect of changing shear wave amplitude in the binary pattern color Doppler elastography. An ultrasonic frequency f_0 = 7.6 MHz and sound speed c = 1540 m/s are used. To follow the frequency condition, PRF = 800 Hz, and shear wave frequency f_b =200 Hz are chosen. On the Figure 3, a cycle of shear wave at amplitude of λ/4 (b) is plotted below the simulated binary pattern of different amplitudes (a). It can be seen from the image that each period of shear wave with suggested amplitude produced four cycles of binary pattern in the color flow estimation. However, it possible to expand the range of amplitude such up to ξ_0 = λ. The binary pattern appears more frequent with higher shear wave amplitude and the duty ratio is altering. By calculation from equation 6, the maximum velocity in this simulation is 0.0405 m/s. Figure 4 shows a simulation result of a shear wave with a propagating speed of 5.353 m/s at an angle of 15.524° traveling in a 2 x 4 cm phantom.



(a)



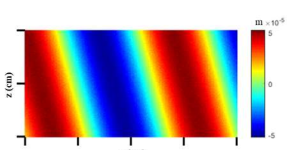
(b)

Figure 3. Binary pattern in color Doppler elastography with variable amplitude of shear wave.

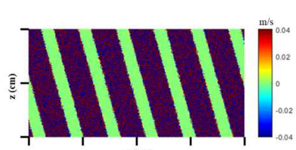
Figure 4 (a) shows the shear wave when ξ_0 is λ/4. Figure 4 (b), (c) and (d) shows the resulting binary pattern by color flow image when the ξ_0 is λ/4, λ/2, and 13λ/16, respectively. It can be clearly seen that the binary pattern changes due to the change of shear wave amplitude.

B. *Phantom Experiment*

An experiment with a setup as in Figure 1 is performed. The shear wave is excited from a 100 Hz software generated sine wave transmitted a vibration speaker (EWA A106 Pro) with a 15 mm × 40 mm hemisphere shaped actuator head. An ultrasonic imaging system with a 7.6 MHz linear probe of 128 channel array (Verasonics, The Vantage 256™) is adopted to observe CFI. The pulse repetition frequency of ultrasonic pulses for color Doppler imaging is set to 400 Hz. Color flow images are acquired in the form of IQ data. Image processing is performed in PC to obtain shear wave velocity and shear wave direction maps. The photograph of experiment is shown on Figure 5.



(a)



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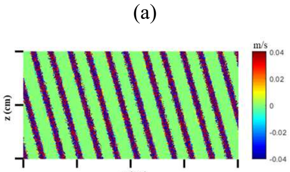
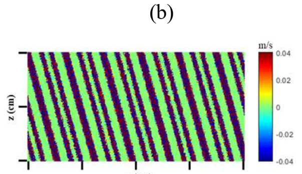


(c)



(d)

Figure 4. Different binary patterns of a same shear wave wavelength caused by different amplitudes.

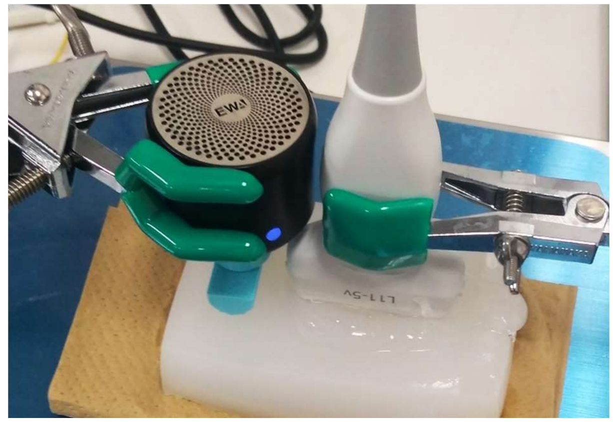
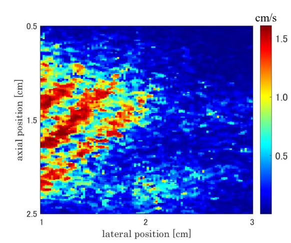
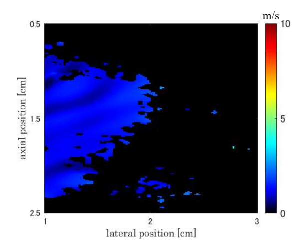


Figure 5. Phantom measurement photograph.

The PVA phantoms are made from mixture of Polyvinyl Alcohol (PVA) granules (JF-17, Japan Vam & Poval Co., Ltd.), water (H_2O) and the Dimethyl Sulfoxide (DMSO) liquid (043-07211, Fujifilm Wako Pure Chemical Industries, Ltd.) by weight ratio of $\frac{w}{100}: 0.2(1-\frac{w}{100}):\ 0.8(1-\frac{w}{100})$. 1 g cellulose powder (036-22225, Fujifilm Wako Pure Chemical Industries, Ltd.) is added for every 100 g of phantom as reflector. The color display obtained by measurement of 4%, 6%, and 8% phantoms are shown on the Figure 6 (a, c, and e). As a comparison, the elastic modulus of the PVA phantoms with the same concentration are measured by compression test (JIS6254 K: 2016， C method). The compression test standard is adopted because PVA phantoms has the crosslinked structure and similar mechanical properties with rubber.



(a)



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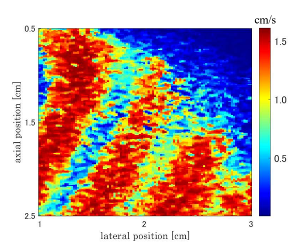

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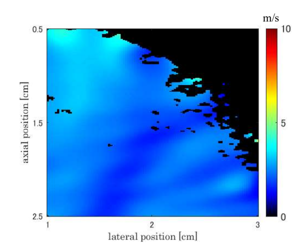

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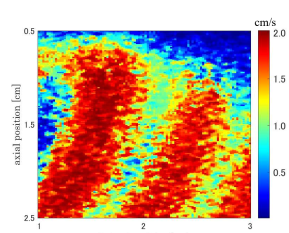
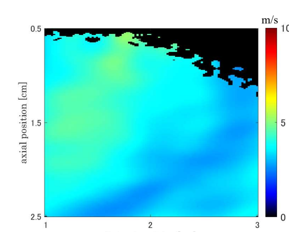


(e)



(f)

Figure 6. Phantom experiment footage.

The tested objects are three cylindric phantoms with diameter 35.6 mm and 50 mm thickness in a laboratory temperature of 21° C. The elastic modulus E is calculated using compressive force F at 10% strain in the 4th cycle by the equation

$$E = \frac{F}{A\varepsilon} \quad , \qquad (7)$$

where

E : Young modulus (Pa),
F : Compressive force (N),
A : Material cross-sectional area before compression (m^2), and
ε : Compression strain.

The measurement results of elasticity by binary pattern color Doppler method and the compression test are presented on the Table I.

TABLE I. ELASTICITY MEASUREMENT RESULTS

PVA Consentration	Young Modulus (kPa)		Relative Error
	Shear Wave Elastography	*Compression Test*	
4%	5.21±0.48	3.53±0.24	47.6%
6%	18.7±1.96	14.1±1.9	32.6%
8%	38.8±3.04	40.67±6.13	4.6%

IV. DISCUSSION

Two methods of color Doppler elastography are described, i.e. direct shear wave elastography with a sufficiently high imaging rate, and the binary pattern shear wave wavefront mapping. The observable binary pattern on the second method is four time denser than the shear wave original wavelength, which means that a lower vibration frequency will give the same number of wave pattern than with a direct Doppler elastography. However, when the amplitude of the shear wave is increased beyond the suggested range [4], the binary pattern appears more frequent with higher shear wave amplitude and the duty ratio is altering as depicted by Figure 4. To the best of author knowledge, this is the first paper that reveals the effect of shear wave amplitude in the resulting binary pattern by simulation.

On the experiment of binary pattern color Doppler elastography, wavelength of the shear wave increases as the phantoms become harder following the PVA concentration increase. The larger the wavelength of the shear wave, the faster the propagation, which means, the higher the elastic modulus. Therefore, this result reflects the difference in the elastic modulus of the phantom. This result is in a good agreement with the compression test, where the higher PVA concentration, the higher is measured elastic modulus. This indicates that the binary pattern color Doppler elastography is able to correctly evaluate the elastic modulus.

The propagation velocity was calculated based on the phase spectrum analysis of the shear wave wavefront. Therefore, variations in the propagation velocity are caused by wavefront change that appeared as spatial slope of the phase spectrum. The propagation velocity cannot be estimated well in some areas where the amplitude of the shear wave does not meet the conditions for detecting the wave surface. After excluding these areas, the propagation velocity was evaluated as shown on the Figure 6 (b, d, and f). By looking at all measurement data, it is demonstrated that imaging the stiffness of the phantom is possible. However, it seems that the shear wave is more difficult to propagate in lower elasticity phantom. As seen in the Figure 6 (a), the shear wave could not be imaged on the right side of the ROI for the 4% phantom, because of the insufficient amplitude of the shear wave. This also explained the high error in the measurement of low elasticity phantom as given by Table I.

Measurement of ligament elasticity by Shear-wave elastography (SWE) [7] has shown an insight on distinct elasticity on the Adhesive Capsulitis (AC). Since color Doppler elastography induces a shear wave externally by a mechanical vibrator, the estimation of the shear wave velocity and thus the tissue elasticity is considered more accurate. In clinical application, the method may be combined with ligament velocity difference method to obtain a better presentation of AC [8].

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