1J3-4

Application of continuous shear wave elastography method for liver viscoelasticity measurement

Ren Koda[1†*], Takato Kuwabara[1], Naoki Tano[2], Marie Tabaru[2], Shunichiro Tanigawa[3], Naohisa Kamiyama[3] and Yoshiki Yamakoshi[1] ([1]Grad. School of Science and Technology, Gunma Univ.; [2] IIR, Tokyo Tech; [3]GE HealthCare)

1. Introduction

Transient elastography, which measures the average elastic modulus on the axis of the ultrasonic beam by applying mechanical vibration from the body surface, is a currently practical method for measuring the elasticity of the liver. However, a wide elastic distribution cannot be obtained. On the other hand, in shear wave elastography method, which uses focused ultrasound to generate shear waves inside the tissue and obtains elastic distribution in the region of interest, shear waves with sufficient amplitude cannot be obtained due to transmission limitations such as the voltage of the focused ultrasound. Also, since the generated shear wave is an impulse, there are problems such as a change in the center frequency as it propagates.

Yamakoshi et al. have proposed a continuous shear wave elastography (C-SWE) method, which uses an external vibrator to generate the shear wave with a fixed frequency for elastic visualization of internal tissue.[1,2]

Living tissue has not only elasticity but also viscosity. Therefore, shear waves propagating in the body have different velocities (velocity dispersion) depending on the frequency. In other words, if the shear wave velocity for each frequency is known, the viscoelasticity of the tissue can be evaluated. In this paper, the C-SWE method, in which the frequency of the shear wave can be arbitrarily selected, was applied to the viscoelasticity measurement of the liver *in vivo.*

2. Viscoelastic measurements by changing frequencies for C-SWE

The shear wave velocity is independent of the shear wave frequency in elastic media, but it depends on the frequency in viscoelastic media. Viscosity shows dispersion characteristics in the propagating shear waves, which means that the resultant shear wave velocity is dependent on the frequency of the shear wave, with the higher frequency components of the shear wave propagating faster than the lower frequency components. When a soft tissue is modeled as a viscoelastic medium, H. L. Oestreicher[3] showed that 1) most parts of the energy radiated from the surface propagates as a transversal wave in the tissue-like medium when the frequency of low-frequency vibration is less than about 1 kHz, and 2) the velocity of the transversal wave in infinite uniform medium is given by[4,5]

$$v_{sh}=\sqrt{\frac{2}{\rho}\frac{{\mu_1}^2+\omega^2{\mu_2}^2}{\mu_1+\sqrt{{\mu_1}^2+\omega^2{\mu_2}^2}}} \quad (1)$$

where ρ is the density of the medium, ω is the angular frequency of vibration, and μ_1 and μ_2 are the coefficients of shear elasticity and shear viscosity, respectively. Using Voigt model, shear wave velocity at different frequencies can be calculated. From above, we see that low-frequency wave velocity is related closely to the shear viscoelastic properties of the medium.

We assume that the shear wave frequency satisfies the following condition: If the repetition frequency (PRF) of ultrasonic waves is f_{PRF}, the selection condition for the shear wave frequency f is

$$f=f_{PRF}/N \quad (2)$$

where N is any integer. In this study N=16 is used. Here, we consider the case where the shear wave is recorded for 2 to 4 cycles during the data collection time width ($T=N/f_{PRF}$) in one packet (N data). When two cycles of shear waves are recorded in T, $f_0=1/(T/2)=f_{PRF}/8$, where f_0 is the fundamental frequency. $f_1=1/(T/3)=(3f_{PRF})/16=1.5f_0$ when the

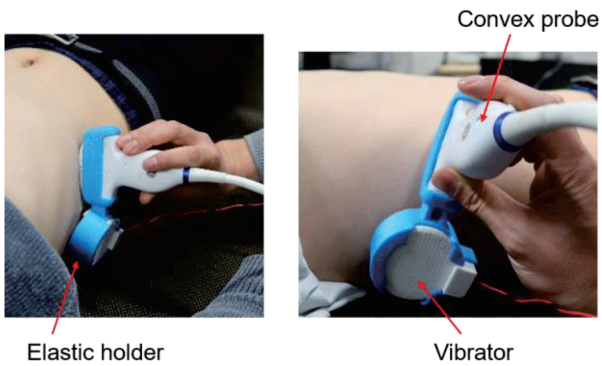

Fig. 1 Experimental setup for *in vivo* liver measurement.

E-mail: †*koda@gunma-u.ac.jp

shear wave is recorded for 3 cycles during T, $f_2=1/(T/4)=(4f_{PRF})=2f_0$ when the shear wave is recorded for 4 cycles during T. Since f_{PRF}=623.3 Hz in this study, f_0=77.9 Hz, f_1=116.9 Hz, and f_2=155.8 Hz.

Fig. 1 shows the experimental setup for *in vivo* liver measurement. A LOGIQ E10x ultrasound diagnostic device (GE HealthCare, Wauwatosa, USA) was modified so that the IQ signal can be saved in the Doppler mode. An ultrasound convex probe (C1-6-D) was placed on along the 9th-10th intercostal space. An elastic holder made with a 3D printer was used to tilt the ultrasonic probe toward the vibrator so that the excitation position and the shear wave image reproduction position were close to each other. The vibrator uses a small audio actuator that can independently set the vibration frequency and amplitude.

Fig. 2 shows an example of setting an entire region of interest (ROI) for *in vivo* liver measurement and small divided ROIs for shear wave velocity analysis. Shear wave velocity measurements were obtained in small ROIs separated by 2.8 mm (Fig.2(b)). Velocity data were selected only for regions where the shear wave velocity was below a threshold. Furthermore, the velocity data only the region on which were selected by taking into account of the index representing the displacement amplitude of the shear wave and the propagation direction of the shear wave. Averages were taken from multiple horizontal ROIs for one depth. Data on the side closer to the oscillator (on the right side of the image) was obtained.

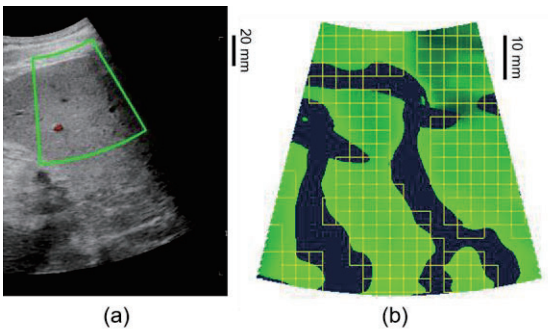

Fig. 2 Example of setting of region of interest: Overall ROI size of C-SWE (a), small divided ROIs for shear wave velocity analysis (b).

3. Results

Fig. 3(a) shows the propagation of shear waves in the liver under vibrations at the fundamental frequency f_0 and the frequency f_1, which is 1.5 times the fundamental frequency. The shear wave propagation map displays wavefronts every π/8. It can be seen that the wavefront interval is narrower at the 1.5 times frequency than at the

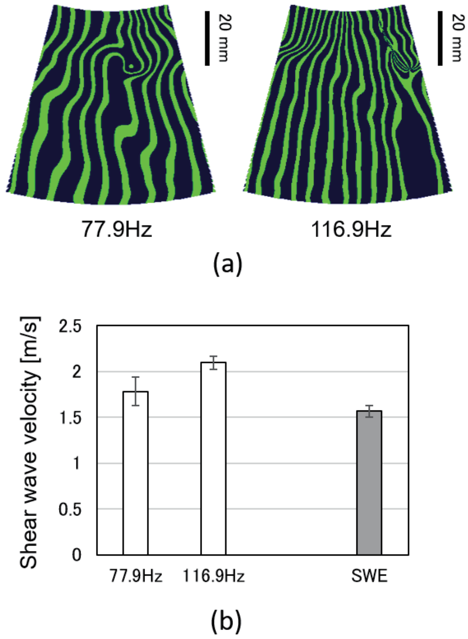

Fig. 3 Frequency dependence of shear wave velocity *in vivo* normal liver. (a) Shear wave propagation map (b) Comparison of shear wave velocity by the proposed method and general SWE.

fundamental frequency. **Fig. 3(b)** shows the measurement results of shear wave velocity at a depth of 8.4 mm from the top of the ROI. Measurement results by general SWE are also shown. The shear wave velocity dispersion obtained by the proposed method is 8.04 m/s/kHz, which is close to the normal liver shear wave velocity dispersion reported under low-frequency excitation below 100 Hz[6].

4. Conclusions

Shear waves propagating in the liver were visualized using a continuous shear wave imaging method using arbitrarily selected frequencies, and it was shown that the frequency dependence of shear wave propagation could be measured.

References

1) Y. Yamakoshi et al. Ultrason Imaging., 37, 323-340 (2015)
2) Y. Yamakoshi et al. IEEE Trans Ultrason. Ferroelectr Freq Control. 64, 340-348.(2017)
3) H. L. Oestreicher, J Acoust Soc Am 23, 707–714 (1951)
4) Y. Yamakoshi, J. Sato, T. Sato, IEEE Trans. Ultrason. Ferroelectr. Freq. Control 17, 45–53 (1990)
5) B. Zhou, X. Zhang, J. Mechanical Behavior of Biomedical Materials 85, 109-116 (2018)
6) D Klatt, et al., Phys Med Biol 52, 7281–7294 (2007)