Japanese Journal of Applied Physics **53**, 07KF05 (2014) **BRIEF NOTE**
http://dx.doi.org/10.7567/JJAP.53.07KF05

Measurement of elastic wave propagation velocity near tissue surface by optical coherence tomography and laser Doppler velocimetry

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Received November 29, 2013; accepted March 24, 2014; published online June 6, 2014

We demonstrate a new technique for measuring the velocity of elastic waves propagating near a tissue surface by swept-source optical coherence tomography (OCT). We establish a theory for estimating the elastic wave velocity from the OCT images taken with a slow mechanical scanning, which is experimentally verified using agar and tissue samples. The elastic wave velocity measured by this technique agrees well with previous results and that measured with a laser Doppler velocimeter. We also carry out some trial measurements of the elastic wave velocities of several tissue samples by this method. © 2014 The Japan Society of Applied Physics

Although the endoscope is a powerful tool for detecting incipient tumors, it is still difficult to detect small tumors efficiently from optical images of the surface. Tumors are known to be generally harder than that of normal tissues. According to previous studies, it is expected that small tumors can be detected on the basis of their elastic properties.[1,2] However, endoscopic elastography requires deformation measurement with a high spatial resolution. A principle for estimating the elastic properties of tissues by displacement measurement is also essential.

Ultrasonic elastography has been intensively studied and partly used in practice for nonendoscopic fields.[3–10] Optical coherence tomography (OCT) has a higher spatial resolution[11] than ultrasound-based techniques, and has already been put to practical use in eye clinics. The spatial resolution of standard OCT systems in the B-mode image is from several to 10 μm for the depth and from several to 20 μm for the lateral direction.[12] The penetration depth reaches approximately 3 mm. Elastography based on OCT has increasingly become attractive,[13–15] as it takes advantage of the high spatial resolution of the OCT. In the meantime, the displacements with compression provided by applying an external static force or using an acoustic radiation force have been measured. However, the absolute value of an elastic constant cannot be estimated, since it is difficult to determine the absolute value of stress. To date, the elastic properties of tissues have been estimated from various viewpoints.[16,17] If the elastic wave velocity is measured, the elastic constant can be estimated quantitatively, since the velocity is determined by the elastic nature and the density of the media.

In this work, we carry out a trial to detect the velocity of the elastic wave propagation using a swept-source (SS-) OCT. The depth scanning in SS-OCT is sufficiently fast with the use of a high-speed frequency-swept light source, the scanning rate of which is as fast as 20 to 100 kHz. However, the lateral scanning is performed using a mechanical moving mirror and is relatively slow (less than 1 m/s). Shear waves and surface acoustic waves travel in tissues at the velocity ranging from 1 to 20 m/s, which is much slower than that of longitudinal waves. A method for estimating the velocity of such slower waves using a low-speed imaging system is discussed.

One point on the surface of a tissue sample is continuously vibrated with a small stick (a pick) connected to the corn of a small loudspeaker, and the sample is observed by SS-OCT (OCT optics: Santec IV-2000; swept light source: Santec HSL-2000) as illustrated in Fig. 1. We put the samples into a container of 36 mm width, 65 mm length, and 11.5 mm depth. The measurements were carried out from 500 to 1000 Hz at 50 Hz intervals. The lowest frequency is determined by the scanning width (5 mm in this experiment), since the wavelength of the elastic wave should be much shorter than the scanning width. The highest frequency is limited by the displacement resolution of the OCT, because the vibration displacement decreases with increasing frequency. Figure 2 shows an example of the OCT image of the sample. A periodical waveform is clearly observed on the surface, the period of which is defined as Λ. In the OCT image, Λ is not the real wavelength of the elastic wave, because of the difference between the scanning velocity v of the OCT and the elastic wave velocity c. There is a mathematical relation among Λ, v, and c.

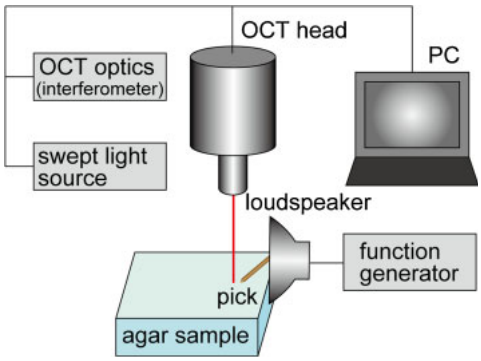


Fig. 1. (Color online) Setup for wave generation and detection.

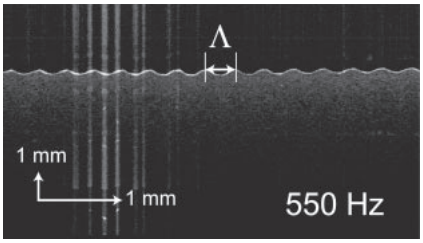


Fig. 2. Example of OCT image for agar surface.

Here, let us explain how to calculate the elastic wave velocity v from the OCT images. Using the lateral scanning velocity v in the OCT, the observed position x can be expressed as

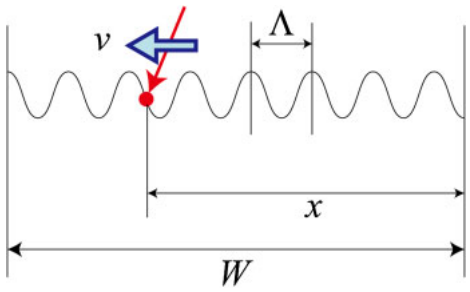


Fig. 3. (Color online) Sample surface observed by OCT.

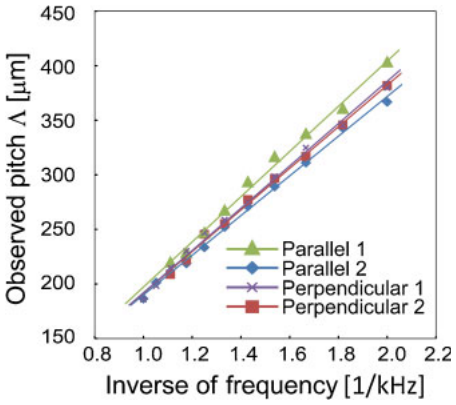


Fig. 4. (Color online) Observed pitch vs inverse of frequency. A 2% agar sample was used. Four trends indicate measured points and their linear approximation in each scanning direction (to and fro): parallel and perpendicular to the elastic wave propagation.

$$x = vt, \tag{1}$$

where t is time. The vertical displacement of the elastic wave is then expressed as

$$y = A\cos(kx - 2\pi ft), \tag{2}$$

where f is the frequency and k is the wave number of the wave. In our experiment, the elastic wave velocity c is approximately 10 times higher than the lateral scanning velocity v of the OCT. In such a case, a waveform with a pitch Λ is observed as shown in Fig. 3. Note that the observed pitch Λ is different from the wavelength of the wave as explained above. By eliminating the time from Eq. (2) using Eq. (1), we obtain

$$y = A\cos 2\pi f\left(\frac{1}{c} - \frac{1}{v}\right)x. \tag{3}$$

Here, considering that Λ is the pitch,

$$f\left|\frac{1}{c} - \frac{1}{v}\right|\Lambda = 1 \tag{4}$$

is satisfied. Thus, from Eq. (4), we can calculate the elastic wave velocity c using the experimentally obtained Λ as follows. The pitch Λ is measured at many different frequencies and plotted as a function of the inverse of the frequency, as shown in Fig. 4; the elastic wave velocity is then obtained from its slope. To derive the scanning velocity v, the same procedure is performed by scanning perpendicularly to the propagating direction of the elastic waves, in which the elastic wave velocity can be regarded as ∞. In this

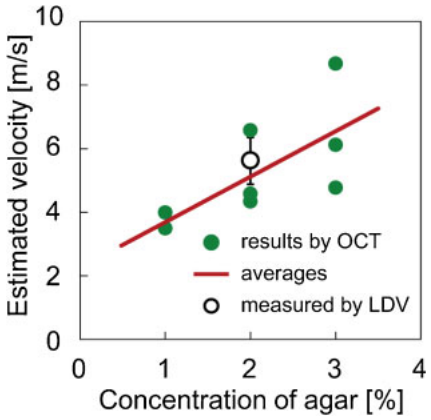


Fig. 5. (Color online) Elastic wave velocity for 1, 2, and 3% agar measured by OCT and LDV.

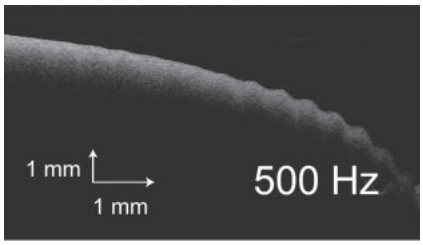
experiment, the scanning velocity of the OCT was calculated to be 0.193 m/s using

$$v = f\Lambda. \tag{5}$$

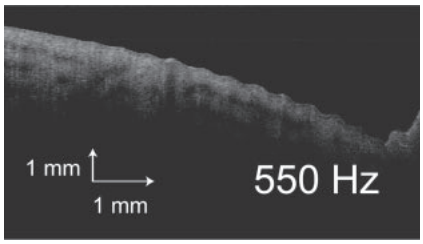
We measured three agar samples with different concentrations of 1, 2, and 3%. Measurements were performed three times for each sample. Figure 5 shows the results, in which a line represents the average value. The averages of the elastic wave velocity were 3.7, 5.2, and 6.5 m/s for the 1, 2, and 3% samples, respectively. The elastic wave velocity was linearly increased with increasing agar concentration. The results almost agree with those shown in Ref. 19, where the elastic wave velocity was about 3.5 m/s in 1% agar and proportional to the agar concentration.[18,19)]

We also measured the elastic wave velocity in the 2% agar sample using a scanning laser Doppler velocimeter (LDV) to verify the results. We scanned 10 points along the wave propagation path with a half-wavelength pitch, and the phase of the vibration velocity was recorded at every point. The elastic wave velocity was calculated from the phase difference between the two adjacent points. The measurements were carried out at 2 kHz. As plotted in the figure, the average of the LDV results was 5.6 m/s, which is close to the results obtained by the above-mentioned method with OCT. As observed in the results for the agar samples (Fig. 5), with the increase in the elastic wave velocity, the deviation of the estimated elastic wave velocity was increased. If the elastic wave velocity exceeded 6 m/s (30 times larger than the scanning velocity), the error reached 50%.

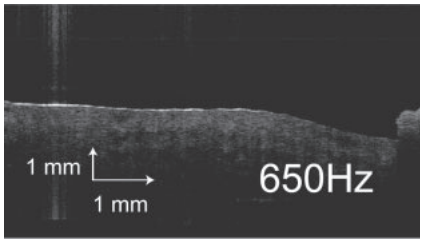
Finally, we measured the elastic wave velocities of tissue samples such as chicken liver and white chicken meat. For the white chicken meat, measurements were performed in both directions: perpendicular and parallel to the fiber. Figure 6 shows the OCT images of the chicken liver and the white chicken meat when the waves were propagated. Attenuation in the chicken liver [Fig. 6(a)] was so high that the wave was observed only for half of the image. In the case of the white chicken meat with the propagation direction perpendicular to the fiber [Fig. 6(c)], it was difficult to observe the displacement, resulting in the failure in estimating the elastic wave velocity. The elastic wave velocity of the liver was 1.2 m/s, while that of the white chicken meat was 8.7 m/s.



(a)



(b)



(c)

Fig. 6. (a) OCT image of chicken liver. (b) OCT image of white chicken meat observed with parallel scan to the fiber. (c) OCT image of white chicken meat observed with perpendicular scan to the fiber.

In conclusion, we tried to measure the elastic wave velocity propagating near the surface of tissue samples by vertical displacement measurement using an SS-OCT with a slow horizontal scanning system. We developed the method for estimating the elastic wave velocity (1–20 m/s) using the slow imaging system (less than 1 m/s). As a result, the relationship between the agar concentration and the elastic wave velocity agreed qualitatively with a previous study a nd with the elastic wave velocity measured with an LDV. By the same method, we also estimated the elastic wave velocity of several tissue samples. Estimating the elastic constants using the elastic wave properties is left for a future study.[20)]

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