2pBAb6. Measurement of surface acoustic wave in soft material using swept-source optical coherence tomography

Yukako Kato*, Yuji Wada, Yosuke Mizuno and Kentaro Nakamura

*Corresponding author’s address: Tokyo Institute of Technology, Yokohama, 226-8503, Kanagawa, Japan, ykato@sonic.pi.titech.ac.jp

In endoscopic elastography, it is needed to observe small area with high spatial resolution. Optical coherence tomography (OCT) is one of the candidate imaging methods, which has the depth resolution of several~10 μm. In this study, we try to find the propagation velocity of surface acoustic wave (SAW) using a swept-source OCT (SS-OCT). The depth scanning rate in the SS-OCT is rather fast, which is determined by the wavelength sweep of the light source as fast as 20-100 kHz. However, on the other hand, the lateral scanning is limited up to 100 times per second, since it is performed using a mechanical moving mirror. We develop a theory to estimate SAW velocity of tissues ranging from 1 to 20 m/s from data taken by the slow lateral scanning of less than 1 m/s using the OCT. The present method is tested for agar samples with different concentrations and also for several tissue samples. Vibrations are excited on the sample surface using a small stick connected to a loudspeaker. The measurements are carried out at many frequencies from 500 Hz to 1000 Hz. The dependence of the SAW velocity on the concentration successfully agreed the previous results.
INTRODUCTION

Though endoscope is a powerful tool to find incipience tumors, it is difficult so far to discriminate precisely whether it is benignant or malignant. Since it is known that, in many cases, malignant tumor is harder than benignant tumor, elastography is highlighted in this decade. Ultrasonic elastography has been partly used in practical. To realize an endoscopic elastography, deformation measurement with high spatial resolution is required. A principle to estimate the elastic properties of tissue from the displace measurement is also essential.

Optical coherence tomography (OCT) has higher spatial resolution than ultrasound and has already been put to practical use in eye clinic. In general, OCT spatial resolution of B-mode image are several~10 μm for the depth and several~20 μm for the lateral direction. The penetration depth reaches approximately 3 mm. Optical coherence elastography (OCE)\(^2\,^3\), based on OCT, has increasingly become attractive, as it takes advantage of the high spatial resolution of the OCT imaging.\(^3\) Measurements of displacement with giving compression by applying external static force or using acoustic radiation pressure are researched. However, absolute value of elastic constant cannot be estimated, since the absolute value of stress is unknown.\(^4\) If the propagation velocity of surface acoustic wave (SAW) is measured, the elastic constant can be estimated. Li et al.\(^5\) detected surface waves on skin and phantom using a phase-sensitive optical coherence tomography (PhS-OCT) and they has successfully evaluated the Young’s modulus of thick biological phantoms and human skin in vivo.

In this study, we try to detect velocity of SAW using swept-source optical coherence tomography (SS-OCT). The depth scanning in SS-OCT is fast enough with the use of high speed SS light source whose scanning rate is as fast as 20~100 kHz. However, the lateral scanning is performed using a mechanical moving mirrors, and is relatively slow (less than 1 m/s). A method to estimate the SAW velocity (1~20 m/s) using such slow imaging system is discussed in this report.

OPTICAL COHERENCE TOMOGRAPHY

In the early OCT, depth resolution was obtained using a low coherence light which interferes when the optical path difference is almost zero. Thus, depth image is created from mechanical movement of reference mirror. On the other hand, in the SS-OCT, a high coherence laser is used as a light source, and the depth image is obtained from Fourier transform of interference signal.\(^6\) SS-OCT shows better SN ratio. **FIGURE 1** shows a basic setup of the SS-OCT. Light from the source is divided into two beams: one is irradiating the sample and the other is reflected with the reference mirror. Two optical signals from the sample and the mirror are mixed and interfered on a photo detector. The wavelength of light source is swept by time, and depth scanning is done from FFT processing. Wavelength sweep of light source is done by a high speed polygon mirror or MEMS mirror and the rate is 10~100 kHz. On the other hand, horizontal scan is done by a galvanometer mirror and the velocity is slow. The OCT used in this study provides 5-mm scan with the speed of 80 fps. The scanning velocity is calculated to be 0.4 m/s.

**FIGURE 1.** (a) Interference system of SS-OCT. (b) Mechanical scanning system of SS-OCT.
EXPERIMENTAL METHOD

We excite SAW on agar samples with different concentration: 1, 2 and 3%. One point on the agar sample is continuously vibrated with a small stick (a pick) connected to the corn of a small loudspeaker, and the agar samples are examined using the SS-OCT. FIGURE 2 shows the experimental system. We put the samples into a container: width, 36 mm: length, 65 mm and depth, 11.5 mm. The measurement were carried out at every 50 Hz from 500 to 1000 Hz. FIGURE 3 shows an example of agar’s surface tomographic view. From this picture, we measured the pitch $\Lambda$ at each frequency. This pitch $\Lambda$ observed in the OCT image is different from the actual SAW wavelength since the imaging is much slower than the propagation of the SAW.

FIGURE 2. (a) Setup for surface acoustic wave generation and detection. (b) Size of a sample (agar) and a container.

FIGURE 3. Example of agar OCT image.

ESTIMATION OF SURFACE ACOUSTIC WAVE VELOCITY

Here, let us explain how to figure out the SAW velocity from the OCT images. Lateral scanning velocity $v$ in OCT is expressed as

$$v = nW,$$

using the scanning rate $n$ and the width of scan $W$. The place of observation can be written as

$$x = vt,$$

where $t$ is the time. Surface acoustic wave displacement is expressed as

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

where $c$ is the velocity, $f$ is the frequency and $k$ is the wave number of the SAW. In our experimental setup, the SAW velocity $c$ is approximately 10 times higher than the OCT scan velocity $v$. In such a case, a wave with pitch $\Lambda$ is observed as shown in FIGURE 4. Here, one should be noted that the apparent pitch $\Lambda$ is different from the wavelength of the SAW. If the time is eliminated from eq.(3.3) using eq.(3.2),
Here, considering that \( \Lambda \) is the pitch,

\[
f \left[ \frac{1}{c} - \frac{1}{v} \right] \Lambda = 1
\]

is satisfied. Thus, from eq. (3.5) we can figure out the SAW velocity \( c \) by measuring \( \Lambda \).

When we measured SAW, we scanned two different directions: perpendicular and parallel to the SAW propagation as shown in FIGURE 5. When scan is carried out perpendicularly, the SAW velocity is observed as \( \infty \), then we can find the scan velocity of the OCT from eq.(3.5):

\[
v = f \Lambda.
\]

FIGURE 6 is a plot of the pitch \( \Lambda \) vs. the inverse of the frequencies. From the slope of the results, the SAW velocity is obtained.
MEASUREMENT RESULTS

First, we measured 1, 2 and 3% agar samples. Measurements were made three times for each sample. FIGURE 7 shows the results. A line in the figure represents the averaged value. The averages of SAW velocity were 3.7 m/s, 5.2 m/s and 6.5 m/s, respectively. The SAW velocity increased linearly with the increase in the agar concentration. This tendency agrees with the previous study4).

Next, we measured the SAW velocities of tissue samples: chicken liver and white chicken meat. For white chicken meat, measurements were carried out for both directions: perpendicular and parallel to fiber. FIGURE 8 shows the OCT images of each sample. Attenuation of chicken liver (FIGURE 8(a)) was so large that the wave could be observed until the half place of the image. In the case of the white chicken meat with perpendicular propagation to fiber (FIGURE 8(c)), it was difficult to observe displacement, and it was impossible to estimate the SAW velocity. FIGURE 9 shows the pitch \( \Lambda \) vs. the inverse of the frequencies for the chicken liver and the white chicken meat with perpendicular propagation of SAW to fiber. In this case, we calibrated the scanning velocity from a measurement of a simple piston motion. TABLE 1 summarizes the SAW velocities estimated using the presented method. The SAW velocity of liver was 1.2 m/s, while that of white chicken meat (parallel propagation to fiber) was 8.7 m/s. As is observed in the results for the agar samples (FIGURE 7), with the increase of SAW velocity, deviation of estimation of SAW velocity increased. Consequently, estimated velocity of white chicken meat might include large error.

FIGURE 10 shows the estimated error of SAW velocity when the reading error is \( \pm 1\% \). If the estimated velocity exceeds 6 m/s (30 times larger than the scanning velocity), the error is reaches 50%.

![FIGURE 7. SAW velocity for 1, 2 and 3%](image1)

![FIGURE 9. Slope of calibration, white chicken meat (parallel to fiber) and chicken liver.](image2)

![FIGURE 8. (a) OCT image of chicken liver; (b) OCT image of white chicken meat observed with parallel scan to fiber; (c) OCT image of white chicken meat observed with perpendicular scan to fiber.](image3)

<table>
<thead>
<tr>
<th>Tissue samples</th>
<th>SAW velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>chicken liver</td>
<td>1.2 m/s</td>
</tr>
<tr>
<td>white chicken meat (parallel to fiber)</td>
<td>8.7 m/s</td>
</tr>
<tr>
<td>white chicken meat (perpendicular to fiber)</td>
<td>difficult to find a specific value</td>
</tr>
</tbody>
</table>
We tried to measure SAW velocity using SS-OCT which has slow horizontal scanning system. As a result, the relationship between agar concentration and the SAW velocity agreed qualitatively with the previous study. Using the same methods, we also estimated the SAW velocity of several tissue samples. In this study, since the depth of the sample and the size of container might be comparable with the SAW wavelength, the excited waves might not be real SAW. Also effect of reflection from the container can exist. As future work, we should consider about the size of samples with simulation and we try to figure out the elastic modulus. In addition, a vibration system which can be used for endoscope is necessary.

REFERENCES