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Characterization of elastic thin tube through laser-diode-based photoacoustic measurement

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1. Introduction

Arteriosclerotic diseases have been increasing in recent years, and as they progress, they are more likely to cause myocardial infarction and cerebral infarction [1]. Although several diagnostic methods have been studied for relatively large blood vessels, hardening also occurs in small blood vessels. Micro arteriosclerosis in the brain and kidneys occurs in arteries with a diameter of 0.5 to 1 mm. In case that arterial inner diameter is narrowed, it will induce serious diseases such as acute myocardial infarction and cerebral infarction [2]. Current non-invasive measurement methods can only observe the vessels of 2-6 mm in diameter, and it is difficult to estimate the stiffness of sub-millimeter vessels.

The authors have reported the photoacoustic measurements of glass capillaries and silicon tubes 1 mm in outer diameter containing liquids using a semiconductor laser [3]-[5]. Influence of the acoustic modes in the tubes and elastic properties of the tube wall on the frequency response and directivity of the photoacoustic signal were clarified. In this report, to investigate the effect of the composition of the liquid in the microtubule on the photoacoustic signal, we fabricated a phantom model of a small artery filled with a mixture of red ink and cooking oil in a silicon tube with an outer diameter of less than 1 mm, and investigated a method to estimate the oil concentration through photoacoustic measurement.

2. Mixed liquid sample and photoacoustic spectroscopy

The optical absorption spectra of LDL, which is oil, and the main component of blood (hemoglobin) are different. Therefore, by comparing the magnitudes of the photoacoustic signals for multiple optical wavelengths, photoacoustic spectroscopy is used to estimate the composition of the measured object. In this report, we present the results of a simple spectroscopic experiment using only two wavelengths. For the light source, we chose an easily available semiconductor laser with an appropriate optical wavelength.

3. Experimental setup

As shown in Fig. 1, a silicone tube of 1.0 mm in outer diameter and 0.5 mm in inner diameter was embedded in a cubic phantom (EXSEAL, H00-600J). Red ink was used for the experiments instead of blood, while olive oil instead of LDL. Their material constants are summarized in Table 1 [7]. 40 kHz strong ultrasound was used to mix the ink and oil, and the mixture was filled into the silicone tubes. Two semiconductor lasers with different wavelengths were used: 405 nm (Thorlabs, L405G1); 520 nm (Thorlabs, L520P50). As shown in Fig. 2, Oil exhibits higher absorbance at 405 nm, while red ink has higher absorbance at 520 nm. The light was focused at the silicon tube from the outside of the phantom into using a biconvex spherical lens. To receive the photoacoustic signals, a planar transducer (JAPAN PROBE, 2K10I) with a center frequency of 2 MHz and a diameter of 14 mm was pressed against the side wall of the phantom. Output signal was amplified by 40 dB and observed with an oscilloscope. Angle between the transducer axis and the laser beam can be set arbitrarily since the photoacoustic signal from the silicone tube exhibits little directivity [6], In this experiment, the angle was set to 90°. The pulse width of the excitation pulse was fixed at 340 ns.

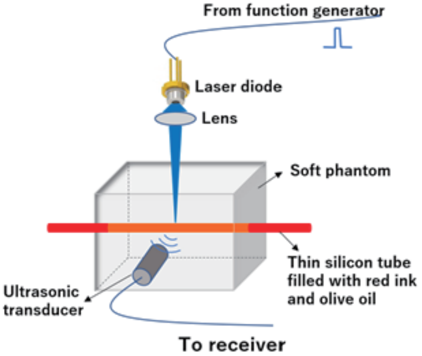


Fig. 1 Experimental setup for measuring the photoacoustic signals.

Table 1 Material constants of red ink and olive oil.

	Red ink	Olive oil (25°)
Density [kg/m^3]	1000	918[7]
Sound velocity [m/s]	1500	1440[7]
Acoustics Impedance [MRayl]	1.5	1.32[7]

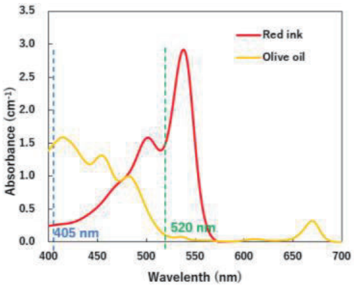
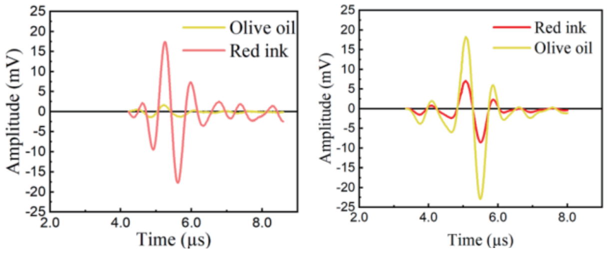


Fig. 2 Optical absorption spectra of red ink and olive oil.

4. Effect of oil concentration on photoacoustic signals

Figs. 3 (a) and (b) show the temporal waveforms of the photoacoustic signals for red ink and olive oil, respectively, with different excitation light wavelengths.

Since the absorption at 405 nm is higher for olive oil than red ink, the photoacoustic signal for olive oil showed higher amplitude (47 mV) than that for red ink (16 mV). Since red ink absorbs 520 nm laser light better than olive oil, the photoacoustic signal for red ink resulted in higher amplitude (34 mV) than for olive oil (5 mV).



(a) (b)

Fig. 3 Temporal waveforms of photoacoustic signals for different laser wavelengths: (a), 405 nm; (b), 520 nm.

Next, we conducted measurements for ink/oil mixtures. The photoacoustic signal exhibited broad frequency peaks at around 1 MHz and 1.3 MHz regardless of the oil concentration as demonstrated in Fig. 4 because these peaks are caused by the acoustic resonance in the tube. The peak frequencies are determined only by the inner diameter of the tube since the physical properties of red ink and olive oil exhibit close values to each other, resulting in close sound velocity, as listed in Table 1. As shown in Fig. 5, as the oil concentration increases, the photoacoustic signal tends to increase for the 405 nm laser, whereas decreases for the 520 nm laser.

Here, let us define a new index α that represents the light wavelength dependence of photoacoustic sensitivity:

$$\alpha = \frac{NA_{405}}{NA_{405}+NA_{520}}\ . \qquad (1)$$

NA_{405} is the normalized peak-to-peak amplitude of the photoacoustic signal for the 405 nm laser, and NA_{520} is that for the 520 nm laser. Fig. 6 shows the relationship between α and the oil concentration of the mixture. α increases monotonically as the oil concentration. The index α may be used to estimate or compare oil concentrations.

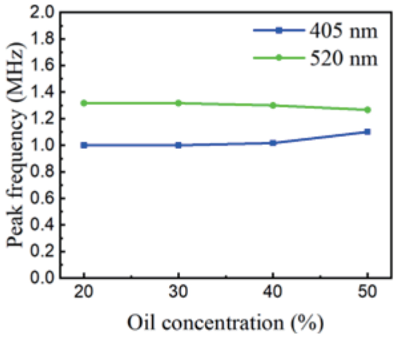


Fig. 4 Peak frequencies of photoacoustic signal vs. oil concentration for two light wavelengths.

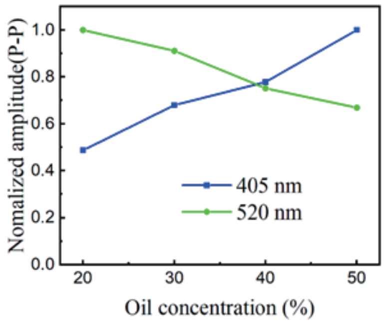


Fig. 5 Photoacoustic signal amplitudes as functions of oil concentration for two light wavelengths.

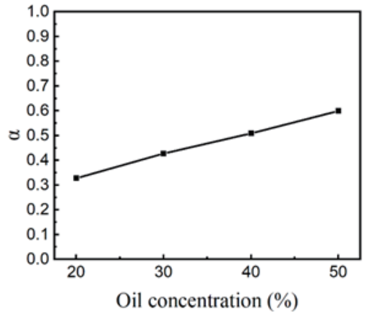


Fig. 6 Wavelength dependence of photoacoustic sensitivity vs. oil concentration.

5. Conclusions

We conducted photoacoustic measurements at two wavelengths, 405 nm and 520 nm, using a phantom model with an embedded silicon tube and ink/oil mixture to simulate blood vessels and arteriosclerotic blood. The 405 nm laser produced a higher photoacoustic signal as the oil concentration in the mixture increased, whereas the 520 nm laser produced lower photoacoustic signal as the oil concentration increased. This result is expected as a method to estimate the oil concentration if the resolution becomes better.

Acknowledgment

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