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Characteristic Analysis of PA Signals Depending on Size of Optical Absorber Using an AR-PAM System

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1. Introduction

Photoacoustic (PA) imaging is an imaging technique that is based on the PA effect, which is the thermal expansion of a light-absorbing material irradiated with a short pulse of light, generating a pressure wave. To achieve high-definition images of microvessels with diameters ranging from 10 to 200 µm, which are reported to be grown by angiogenesis in inflammatory diseases, our research group has developed a high-frequency annular array transducer and reported an algorithm for enhancing image quality based on signal phase information between the transducer elements[1)]. For further high-precision functional imaging, identification of the morphological structure of microvessels is required.

Recently, "PA spectral analysis (PASA)" has reported that the PA signal's power spectrum contains tissue microstructural information[2,3)]. PASA is based on the fact that the frequency components of the PA signal are closely correlated with morphological properties such as the size, shape, and density of the optically absorbing objects in the tissue[2)]. For example, small objects have a broader power spectrum with more high-frequency components than PA signals from larger objects.

However, previous studies on PASA have mostly focused on the evaluation of tissue[3)] or microsphere absorber[2)], and there are fewer reports on spectral analysis in line structures such as blood vessels or on spectral analysis of PA signals received by annular array transducer.

In this study, to investigate whether PASA with a high-frequency annular array transducer can identify morphological information of microvessels, we analyzed the PA spectrum from several tungsten wires with different diameters and investigated whether there is a relationship between the line structure source and frequency. Six tungsten wires of different diameters (20, 30, 50, 100, 150, and 200 µm) were measured, and the slope and intercept of the regression line obtained by spectral analysis of the PA signal received at the central element of the annular array were calculated.

2. Material and Methods

2.1 Experiment setup and data acquisition

The PA micro-imaging system used in this study has been reported in a previous paper[1)]. The annular array transducer had a concave surface with a geometric focus of 6 mm from the surface of its and a center hole (ϕ 1 mm) for the laser outlet. The concave geometry was divided into four ring-shaped PZT elements (a center frequency of 60 MHz and a detection bandwidth of 24 MHz) with a minimum diameter of 1 mm and a maximum diameter of 6 mm. Our previous report calculated the theoretical axial and lateral resolutions as 56.1 and 36.2 µm, respectively.

The Nd:YAG laser was selected to irradiate 532 nm pulsed beams at a repetition rate of 1 kHz and a pulse duration of 1.2 ns. The PA transmitter/receiver unit was raster-scanned with an XY stage while repeatedly emitting a laser pulse and receiving PA signals. In each receiving event, the PA waves generated at the object by the laser irradiation were received by each element of the annular array transducer and recorded at a sampling frequency of 500 MHz. All signal processing and visualization were performed on MATLAB (Ver. 2023a, Mathworks).

2.2 PA Spectrum Analysis

Tungsten wires of six different diameters (20, 30, 50, 100, 150, and 200 µm) were measured 10 times at the geometric focal point and averaged to reduce noise. The obtained signals were visualized in C-mode by applying the maximum amplitude projection (MAP) method[1)], and the A-lines at points above -6 dB were obtained. For each A-line, only signals between 15 µm shallow and 120 µm deeper than the peak signal were extracted and processed with a 1.42 µs hamming slide window with 30% overlapping[3)]. The power spectral density (PSD) in dB of the obtained signals was calculated as defined by the following equation,

$$\mathrm{PSD} = 10\log_{10}\frac{|F(\omega)|^2}{\Delta f}$$

where $F(\omega)$ represents the spectrum obtained by fast Fourier transform of the acquired signal, and Δf is the bandwidth to be analyzed, $\Delta f = 500\ (\mathrm{MHz})\ /\ 1024\ (\mathrm{sampling\ point}) \fallingdotseq 0.488$ (MHz). These processes were performed for 50 locations above -6 dB in C-mode image, and the PSDs were averaged. In the acquired spectrum, considering that photoacoustic waves are mainly low-frequency and broadband, and the bandwidth of the annular array transducer, the regression line of the PSD for frequencies from 1 to 72 MHz was calculated, and the slope and intercept of the regression line equation were obtained.

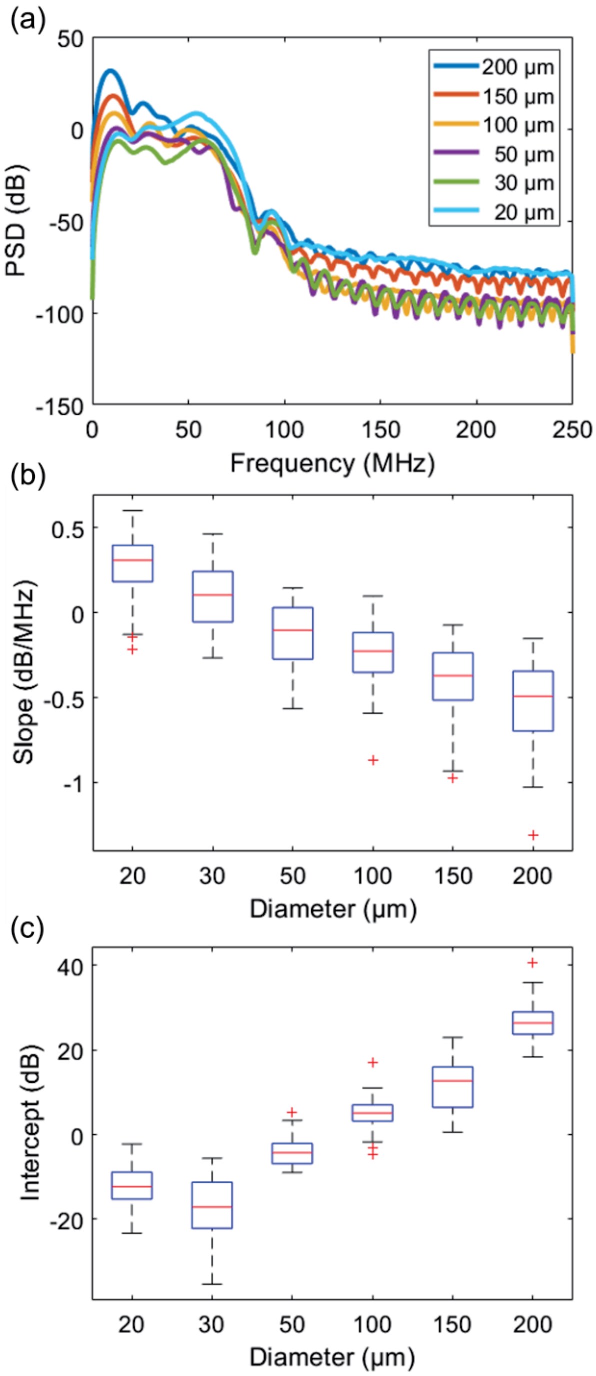

Fig. 1 (a) Results of spectral analysis. (b) (c) The boxplot showing the slope and the intercept value of the regression line for each spectrum, respectively. The red line in each box is the median of the sample; the upper and lower ends of each box indicate the upper quartile and lower quartile; The '+' mark indicates outliers.

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3. Results and discussion

Fig. 1 shows the results of the spectrum analysis. As shown in Fig. 1(a), the larger the diameter of the tungsten wire, the stronger the low-frequency component, and the smaller the diameter, the stronger the high-frequency component around 60 MHz. As a result of calculating a regression line for each spectrum, as shown in Fig. 1(b), the smaller the diameter of the wire, the larger the slope value. As shown in Fig. 1(c), the intercept value of the regression line increased with wire diameter.

The reason why the intercept value at 20 μm was calculated larger than that at 30 μm is that the measured wire diameter was less than half the resolution of the system as described in section 2.1 and the PSD was calculated larger around 60 MHz, which is the center frequency of the annular array transducer. This suggests that when performing spectral analysis using a high-frequency transducer, the slope and intercept values for optical absorbers smaller than half the resolution may not vary uniformly with diameter as well as those for diameters larger than the system resolution.

In summary, these results suggested the possibility of obtaining morphological information on line optical absorbers by spectral analysis in wires measured with a high-frequency annular array transducer.

4. Conclusion

In this study, we analyzed the PA spectrum from several tungsten wires with different diameters to investigate whether line structure sources are related to the frequency and whether it is possible to identify morphological information of optical absorbers using a high-frequency annular array transducer. As a result, spectral analysis of wires measured with a high-frequency annular array transducer indicated a relationship between the diameter and frequency of the line absorber, suggesting the possibility of obtaining morphological information on the line optical absorber by using information on the slope and intercept of the regression line. In the future, we will examine the effectiveness of this method in actual human skin microvessels.

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References

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