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In Vivo Measurement of Ultrasound Attenuation in Dorsal Hand Vein Considering Blood Flow

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1. Introduction

Red blood cell (RBC) aggregation is a reversible adhesion phenomenon occurring under low-shear-rate conditions in blood flow.[1)] We proposed a method for estimating the size of RBC aggregates based on ultrasound measurements,[2)] which requires compensation for attenuation differences between propagation media by measuring the attenuation coefficients of the blood and skin.

In our previous study,[3)] the attenuation coefficient of blood was estimated from the depth-dependence of the power spectra after compensating for the sound pressure distribution. However, the result was higher than the published values.[4)] This difference could be due to the non-uniform scattering and attenuation properties within the vascular lumen, caused by the radial distribution of the shear rate under laminar flow conditions. To estimate the radially averaged attenuation coefficient, considering the effect of blood flow, the analysis region must be expanded possibly in the radial direction.

In this study, we investigated a substitution method to estimate the radially averaged attenuation coefficient within the vascular lumen. The conventional sound pressure compensation method and substitution method were applied to the attenuation coefficient measurement of a blood-mimicking phantom and the dorsal hand vein of a healthy subject, and the results were compared.

2. Principle and method

2.1 Estimation of the attenuation coefficient using sound pressure compensation

The RF signals acquired with the ultrasound beam focused at the vessel center were used to compute the backscatter power spectrum $P(f, z_i)$ using an analysis window at depth z_i. To compensate for sound pressure variations, $P(f, z_i)$ was multiplied by the squared ratio of the sound pressures at the reference depth z_0 and the target depth z_i, yielding the corrected spectrum $P'(f, z_i)$.[3)] The attenuation coefficient of blood, $\alpha_b(f)$, was estimated from its depth dependence.

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2.2 Estimation of the attenuation coefficient by substitution of the propagation medium

As shown in **Fig. 1**, the focal depth z_F was set to the shallow and deep regions of the vascular lumen by changing the propagation distance in water, while keeping the skin thickness z_{sk} constant. The backscatter power spectra $P_s(f, z_F)$ and $P_d(f, z_F)$ were measured in the shallow and deep regions, respectively. Using these, along with the attenuation coefficient of water, $\alpha_w(f)$,[5)] and the difference in the water path length, z_d, the attenuation coefficient of blood, $\alpha_b(f)$, was calculated as follows:

$$\alpha_b(f) = \frac{-1}{2z_d}\left\{10\log_{10}\frac{P_d(f, z_F)}{P_s(f, z_F)} - 2z_d\alpha_w(f)\right\}. \quad (1)$$

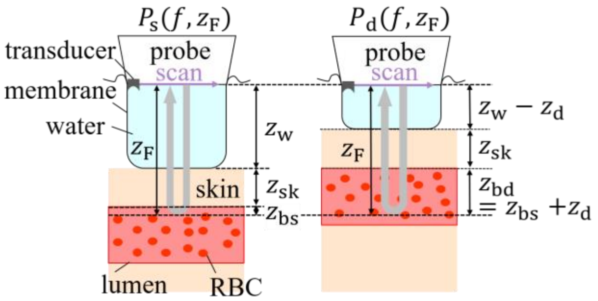

Fig. 1 Schematic of ultrasound measurements focusing on shallow and deep regions of the vascular lumen.

2.3 Measurement of a blood-mimicking phantom

A blood-mimicking phantom was prepared by suspending polyamide particles with a diameter of approximately 19 µm in water at 1 vol%. A mechanical linear probe equipped with a single concave transducer (center frequency: 40 MHz; focal depth: 9.1 mm) and an ultrasound diagnostic system (UD-8000; Tomey Corporation, sampling frequency: 240 MHz) were used for the measurements. In the conventional method,[3)] the attenuation coefficient was calculated from the power spectra obtained by placing analysis windows at 0.1-mm intervals within a ±0.5 mm centered at the focal depth. In the substitution method, the water propagation path was varied by approximately 0.8 mm. Each measurement (113 beams × 10 frames) was repeated ten times.

2.4 In vivo measurement of human blood

The dorsal hand vein of a healthy subject in his

20s was measured with a focus on the shallow, central, and deep regions. The measurement and analysis conditions of the in vivo measurements, such as the window interval, analysis range, and water path adjustment, were the same as those of the phantom experiments. Each measurement (113 beams × 10 frames) was repeated seven times.

3. Results

3.1 Phantom experiment

Figure 2 shows the mean and standard deviation of the backscatter power spectra $P_s(f, z_F)$ and $P_d(f, z_F)$ over ten measurements. Owing to attenuation, $P_d(f, z_F)$ exhibited lower power.

Figure 3 shows the mean and standard deviation of the attenuation coefficients $\alpha_p(f)$ of the blood-mimicking phantom obtained using both methods over ten measurements. The results were similar, confirming that the substitution method can properly estimate the attenuation coefficient.

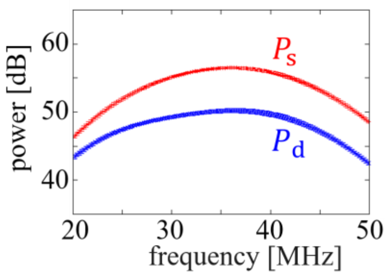

Fig. 2 Backscattered power spectra measured in the shallow and deep regions of the phantom.

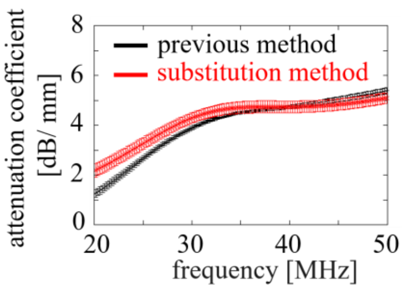

Fig. 3 Attenuation coefficient of phantom measured using the conventional and substitution methods.

3.2 In vivo experiment

Figure 4 shows the mean and standard deviation of the backscatter power spectra $P_s(f, z_F)$, $P_c(f, z_F)$, and $P_d(f, z_F)$, measured seven times in the shallow, central, and deep regions of the vessel, with the analysis window placed at the focal depth z_F. The central spectrum $P_c(f, z_F)$ was higher than the shallow spectrum $P_s(f, z_F)$, possibly due to the enhanced RBC aggregation in the low-shear central region under laminar flow or the hematocrit elevation caused by “axial migration” of RBCs.[6)]

Figure 5 shows the mean and standard deviation of the attenuation coefficients of the blood, $\alpha_b(f)$, measured using both methods over seven measurements. The attenuation coefficient obtained by the substitution method was lower than that obtained by the conventional method and closer to the published value[4)]. One possible reason for the overestimation in the conventional method is the excessive sound pressure compensation. The exact cause of this will be investigated in future studies.

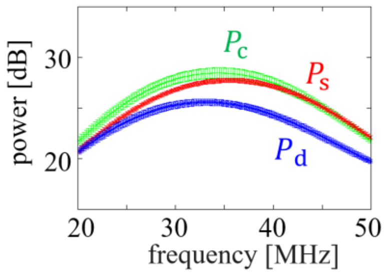

Fig. 4 Backscattered power spectra measured in the shallow, central, and deep regions of the vascular lumen.

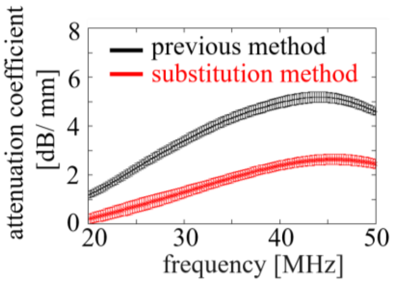

Fig. 5 Attenuation coefficient of blood calculated using the substitution and conventional methods.

4. Conclusion

In this study, the substitution method was applied to estimate the radially averaged attenuation coefficient of the blood under blood flow. The phantom experiment confirmed its applicability, and *in vivo* experiment yielded value close to the published value.[4)]

In future studies, we will increase the number of subjects and evaluate the accuracy and reproducibility of the substitution method.

References

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