Estimation of Intravascular Attenuation by Analyzing Ultrasonic Backscatter to Evaluate Red Blood Cell Aggregation

赤血球集合度評価のための超音波後方散乱特性解析による血管内腔の減衰推定

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1. Introduction

Red blood cell (RBC) aggregation is a reversible phenomenon of RBCs that occurs at a low shear rate in the blood flow. As a non-invasive and quantitative diagnostic method for blood characteristics, we have proposed a method for evaluating the degree of RBC aggregation by analyzing ultrasonic scattering.[1-3] In the method, the RBC aggregation sizes are estimated by fitting the scattering power spectrum of RBCs to the theoretical ones. However, it was assumed that the attenuation of ultrasound propagation in the blood vessel lumen was the same despite the RBCs' conditions that they were aggregated or not aggregated. It causes systematic errors in size estimation. In the present paper, to determine the attenuation of the blood during RBC aggregation and non-aggregation, we derived a method to estimate the attenuation components of ultrasound propagation in the vascular lumen from power spectra obtained from different depths.

2. Measurements and Analysis

2.1 Measurement of ultrasonic backscattering characteristics

When the scatterer size is sufficiently small compared to the wavelength of the transmitted wave, the scattering properties follow Rayleigh scattering, and its power is proportional to the fourth power of the frequency. As the scatterer size increases, the scattering power shows gentle frequency dependence.[4] **Fig. 1** shows a schematic diagram of the scattered wave from an RBC. Eq. (1) shows the power spectrum $P_s(f, d_0)$ scattered from the RBCs in the blood vessel lumen.

$$P_s(f, d_0) = |S(f)G(f)A(f, d_0)H(f, d_0)X(f)|^2 \qquad (1)$$

In addition to the scattering property $S(f)$, $P_s(f, d_0)$ includes the transmission and reception properties of ultrasonic transducer $G(f)$, the sound pressure property $H(f, d_0)$, the frequency dependence of applied signal $X(f)$, and the attenuation property $A(f, d_0)$. f is the frequency, and d_0 is the distance from the probe to the data acquisition position.

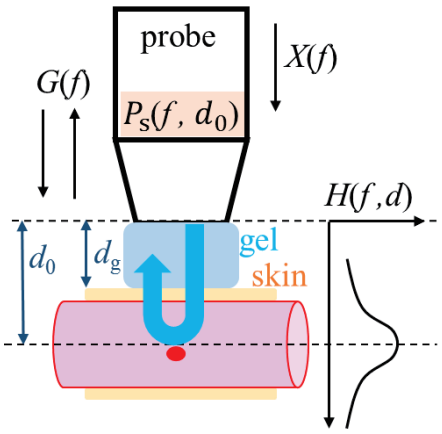

Fig. 1. Schematic diagram of acquisition of RF signals from an RBC.

2.2 Sound pressure characteristics of the probe

In Eq. (1), assuming that the scattering property does not depend on the depth d_0, only the sound pressure property $H(f, d_0)$ and the attenuation property $A(f, d_0)$ depend on the depth d_0. In order to obtain the attenuation component, the power spectrum should be acquired at two positions d_1 and d_2, where the sound pressure properties are equal, that is, $H_1(f, d_1) = H_2(f, d_2)$. Therefore, the sound pressure properties of the probe were measured in water and *in vivo*.

The sound pressure property in water was calculated from the reflection spectrum from the surface of a silicone plate. In *in vivo* measurement, the acquisition position was set at the center of the blood vessel lumen, and the distance from the probe to the center of the lumen was controlled by changing the propagation length in the ultrasonic gel d_g. The attenuation in the gel was corrected by the theoretical value. **Fig. 2** shows the average power in the frequency bandwidth of the experimental system (27-45 MHz). From the

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approximate curves of these characteristics, the positions where the sound pressures are equal were obtained and used for attenuation calculations.

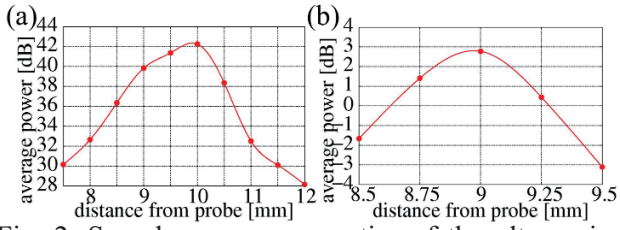

Fig. 2. Sound pressure properties of the ultrasonic probe. (a) water. (b) *in vivo*.

2.3 Measurement method

The Tomey ultrasound diagnostic apparatus UD-8000 (sampling frequency: 240 MHz) and mechanical probe with a center frequency of 40 MHz were used for B-mode measurement. Microparticles and human dorsal veins were used for objects. In the phantom experiment, aqueous solutions of 10.0 g/l were prepared using microparticles with diameters of 5, 20, 30, and 40 μm. 19 frames were acquired every 5 s, and the attenuation coefficient was calculated at each frame. The average attenuation of all flames was treated as the attenuation coefficient of the corresponding microparticle size. In *in vivo* experiment, 19 frames were acquired for the center of the vascular lumen every 10 s. After 6 frames were measured at rest, the blood flow was stopped by pushing the blood vessels by a rod-like device to make the RBCs easily aggregate. The attenuation coefficient was calculated for 19 frames. The subjects were two healthy men in their 20s.

3. Results

3.1 Experiments for microparticles

From Fig. 2(a), two depths were set as 9.24 and 10.25 mm, and the power spectra were obtained. **Fig. 3(a)** shows the attenuation coefficient for 5 and 40 μm particles. **Fig. 3(b)** shows the attenuation coefficient for each particle size. Error bars are the standard deviations between 19 frames. This confirms that the attenuation coefficient of the aqueous solution increases as the particle size increases.

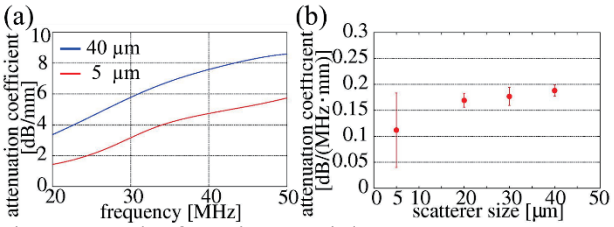

Fig. 3. Results for microparticles.
(a) Frequency dependence of attenuation coefficient.
(b) The relation between attenuation coefficient and scatterer size.

3.2 *in vivo* experiments for human dorsal veins

From Fig. 2(b), two depths were set as 8.61 and 9.29 mm, and the power spectra were obtained. **Fig. 4(a)** shows the average attenuation coefficient for subject A. To calculate the attenuation coefficient, the first 6 frames (1-6 frames) were used for at rest and the last 6 frames (13-18 frames) were used for during avascularization to avoid transient condition from rest to avascularization. From these results, we confirmed that the attenuation was large during avascularization. **Fig. 4(b)** shows the temporal change of the attenuation coefficients. The RBCs gathered and the particle size increased during avascularization. As the result, the attenuation of the blood vessel lumen increased. **Table 1** shows the results of the attenuation coefficient. The attenuation coefficient at rest almost corresponds to the published value of approximately 0.02 [dB/(MHz·mm)].[5] Therefore, the attenuation coefficient obtained in the present paper is appropriate.

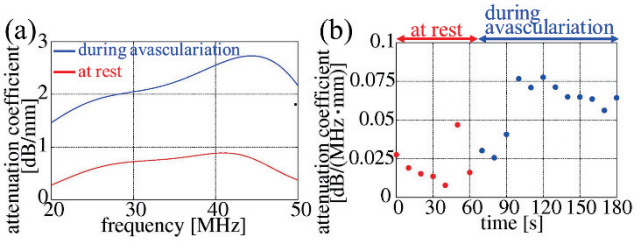

Fig. 4. Results of *in vivo* measurements.
(a) Frequency dependence of attenuation coefficient.
(b) Temporal change of attenuation coefficients.

Table 1. Attenuation coefficient.
[Unit: dB/(MHz·mm)]

	At rest	During ava
Subject A	0.022	0.064
Subject B	0.035	0.061

4. Conclusion

We proposed a method to calculate attenuation from the spectra obtained at two different positions with equal sound pressure in the vascular lumen. From the experiment using microparticles, it was found that the attenuation coefficient increases as the particle size increases. In *in vivo* experiments with human dorsal hand veins, the attenuation coefficient during avascularization was greater than that at rest. From these findings, it was suggested that RBC aggregation occurred during avascularization and attenuation of the blood vessel increased. In future, we aim to improve the size estimation accuracy by calculating the attenuation component by this method and applying the conventional size estimation method to the corrected spectra.[1-3)]

References

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