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Estimation of Radial Distribution of Ultrasound Scatterer Diameter for Assessment of Red Blood Cell Aggregation
赤血球凝集度評価を目指した超音波散乱体サイズの血管径方向分布の推定

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1. Introduction

Red blood cell (RBC) aggregation is one of the factors that determine the viscosity of the blood and is important to be evaluated for assessment of the blood conditions[1)]. Aggregated RBCs gather near the center of the vessel, the shear stress which activates vascular endothelial function is reduced, and vasodilatory response is less likely occurred. Such degradation of the blood condition leads to cardiovascular diseases such as hypertension, atherosclerosis, obesity, and diabetes. Moreover, inflammation caused by such diseases changes synthesis of plasma proteins and fibrinogen and RBC aggregation is further promoted. Thus, the assessment of RBC aggregation may also detect inflammation. In diagnostic ultrasound imaging, it is known that smoke-like echo can be seen depending on the degree of RBC aggregation[2)].

In this study, we aim to realize a method for non-invasive and quantitative assessment of RBC aggregation by estimating radial distiribution of the scatterer size using the frequency characteristic of ultrasonic backscattering with an assumption that aggregated RBCs are spherical.

2. Principle

2.1 Characteristic of Ultrasonic Backscattering

An RBC, which is about 8 μm in diameter, is small ultrasound scatterer compared with the ultrasonic wavelength of about 40 MHz. In addition, the difference between acoustic impedance of an RBC and that of blood plasma is very small. Consequently, the amplitudes of scattered RF echoes are very small. Therefore, RF echoes are analyzed in the frequency domain to utilize the difference of the frequency characteristic of ultrasonic backscattering which depends on the scatterer size. A small scatterer such as to an RBC exhibits Rayleigh scattering and power spectrum of a scattered echo is proportional to the fourth power of frequency[3)]. In contrast, when the size of a scatterer becomes large, which is regarded as a reflector, power spectrum does not show frequency dependence.

In this study, assuming that an RBC and aggregated RBC are spherical scatterers, the following theoretical formula was used. A scatterer is modeled by placing an infinite number of infinitesimal point sources on the surface of a spherical scatterer. When a plane wave insonifies to the scatterer, the theoretical power spectrum $Q(ka)/4\pi a^2$ of the scattered echo is given by[4)]

$$\frac{Q(ka)}{4\pi a^2} = \sum_{n=0}^{\infty} \sin^2\left[\delta_n^{'}(ka)\right] \quad (1)$$

where $Q(ka)$ is the scattering cross section, k is the wave number, a is the radius of the scatterer, n is the number of point sources on the surface of the scatterer, and $\delta_n'(ka)$ is the differentiated phase difference between the incident wave and scattered wave.

Figure 1 shows logarithmic theoretical power spectra derived from eq. (1) for respective scatterer sizes. In particular, the difference of the spectral slopes in the range from 20 to 40 MHz is large. Therefore, ultrasound pulses at a center frequency of 40 MHz were used in the present study.

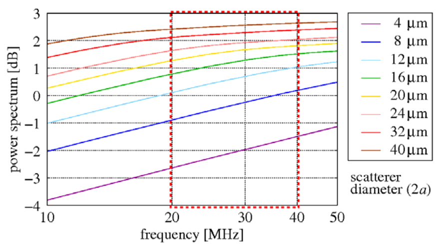

Fig. 1 Logarithmic theoretical power spectrum for each scatterer diameter ($2a$).

2.2 Normalization of Power Spectra

The measured power spectrum $P_s(f)$ from lumen of the vein contains not only the scattering property $S(f)$ from scatterers, but also the frequency response $G(f)$ of transmitting and receiving transducers and attenuation property $A_1(f)$ of the propagation medium. Therefore, the power spectrum $P_r(f)$ of a reflector, vein wall, was used for normalization, as shown in eq. (2), to

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obtain only scattering property.

$$10\log_{10}\frac{P_s(f)}{P_r(f)}=10\log_{10}\frac{|S(f)G(f)A_1(f)X(f)|^2}{|R(f)G(f)A_2(f)X(f)|^2}$$
$$\approx 10\log_{10}\frac{|S(f)|^2}{|R(f)|^2}\quad, \qquad (2)$$

where $A_2(f)$ is the attenuation property of the propagating medium in the measurement of the reflector and $X(f)$ is the spectrum of the signal applied to the transducer. In the present study, $A_2(f)$ is assumed to be same as $A_1(f)$.

2.3 Method for Estimating Scatterer Size

Scatterer size was estimated by determining the theoretical power spectrum which minimized the sum of squares of the difference between the measured normalized power spectrum and the theoretical power spectrum of each scatterer diameter shown in **Fig. 1**. Furthermore, the magnitude-squared coherence function of received RF echoes was used as weighting function to consider the signal-to-noise ratio (SNR).

2.4 Correction of Attenuation due to Depth

In estimation of the radial distribution of ultrasound scatterer diameter, it is necessary to consider the difference in the ultrasonic attenuation depending on the depth. In normalization, since it is assumed that the attenuation of medium in measurement of a scatterer is same as that of a reflector, it is necessary to consider the difference in the attenuation property due to the difference in propagation distance when the analyzed position is different from the position of the vessel wall. Ultrasonic attenuation is expressed by the attenuation coefficient α [dB/MHz/cm]. In the present study, relative attenuation coefficient α' [dB/MHz] was estimated by the slope of the difference between power spectra of echoes from a distance of interest and the distance which is same as the propagation distance in the measurement of the vessel wall.

3. Results

Ultrasound diagnostic equipment (Tomey UD-1000) with a probe at a center frequency of 40 MHz was used for measurement of the dorsal hand vein of a healthy subject. **Figure 2** shows the ultrasound images of lumen and the vessel wall.

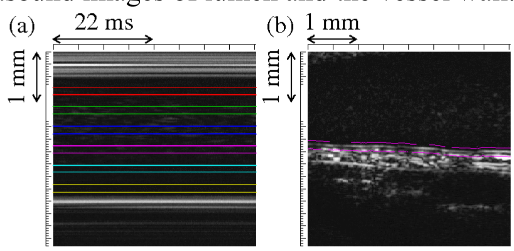

Fig. 2 Ultrasound images of (a) lumen (M-mode) and (b) vessel wall (B-mode).

The power spectra $P_s(f)$ and $P_r(f)$ were obtained from RF echoes from the regions shown by the colored dashed lines in **Fig. 2**. **Figure 3(a)** shows the difference in power spectra of echoes from the depth, which is same as the vessel wall (8.30 mm) and each depth (7.15, 7.53, 7.92, 8.30, 8.69, 9.07 mm). **Figure 3(b)** shows relative attenuation coefficients determined from the slope of the regression lines.

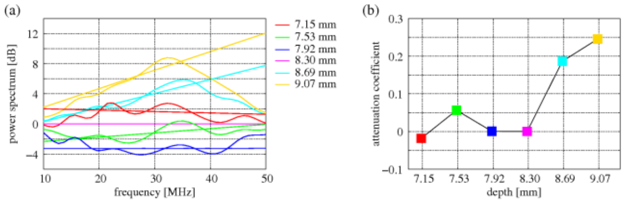

Fig. 3 (a) Difference in power spectra and regression line. (b) Relative attenuation coefficient.

Power spectra were corrected using the estimated relative attenuation coefficient. Measured power spectra and corrected power spectra are shown in **Figure 4**.

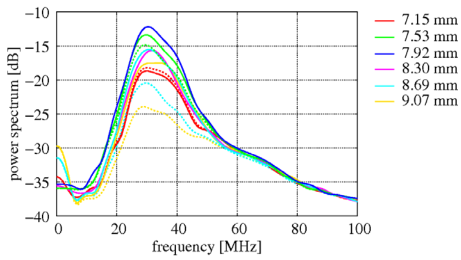

Fig. 4 Measured power spectra (dashed line) and corrected power spectra (solid line).

Table 1 shows estimated scatterer diameter. It was confirmed that similar scatterer size was obtained for every radial position by correcting the effect of attenuation.

Table 1 Estimated scatterer diameter [μm] (before and after correction).

depth [mm]	7.15	7.53	7.92	8.30	8.69	9.07
before	10	26	14	12	40	40
after	10	14	12	12	12	8

4. Conclusion

At rest, it is considered that the scatterer size in lumen should be uniformly distributed. As shown in **Table 1**, effects of attenuation depending on depth are corrected by using relative attenuation coefficient, and an almost uniform size distribution in the radial direction was obtained.

References

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