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Theoretical Verification on Changes in Ultrasonic Peak Frequency during Measurement of Red Blood Cell Aggregation Degree

赤血球凝集度測定における超音波ピーク周波数変化の理論的検討

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1. Introduction

Measurement of red blood cell aggregation degree using ultrasonic peak frequency has been studied in our laboratory. In the experiments, an ultrasonic wave was transmitted into a blood sample and its reflection wave was received with a transducer. The peak frequency was defined on a spectrum of the obtained signal by analyzing with a FFT (Fast Fourier Transform), was declined according to average diameter of the aggregation. This study was aimed to conduct a theoretical verification of the peak frequency based on losses of the acoustic energy in real blood sample.

2. Method

2.1 Our Previous Measurement

Figure 1 shows the measurement setup designed in our previous study[1)]. A 20-MHz ultrasonic transducer that had an element 6.3 mm in diameter and was not focused was employed. Blood-mimicking suspensions were prepared by dispersing fine acryl particles in water. The reflection spectrum was obtained by waves that were transmitted to the suspensions and received by an ultrasonic transducer. Ultrasonic transmission from the transducer was reflected at a reflection board (glass) through the suspensions, and the reflected wave was received by the transducer. Thus, the power spectrum was formed by an iterative attenuation.

2.2 Calculation of Peak Frequency with Attenuation Coefficients

Blood can be regarded as a suspension composed of solid component mainly occupied with red blood cell (hereafter, RBC) and liquid component, namely, plasma. Ultrasonic transmission from the transducer was reflected at a reflection board through the blood sample, and the reflected wave was received by the transducer. Thus, the power spectrum was formed by an iterative attenuation losses generated by the RBCs dispersed in the plasma.

In the case of the experiments conducted with the setup drawn in Fig.1, the main factors for ultrasonic attenuation were scattering, thermal and viscous losses. Thus, the peak frequency was calculated on the basis of the modeling of the attenuations caused by these losses. In general, the hematocrit value of human body ranges from 35 to 50 %, but the hematocrit was assumed as 5 % according to the suitable experimental condition. To simplify the following calculations, the aggregations of the RBC was approximated as sphere. The calculation method described below can be applied to the suspension with the concentration of less than 10 vol%.

The attenuation coefficient α_s due to the ultrasonic scattering by the RBCs is shown below.

$$\alpha_s = \epsilon k_c \frac{k_c^3 a^3}{6}\left(\gamma_k^2 + \frac{\gamma_p^2}{3}\right) \qquad (1)$$

$$\gamma_K = \frac{K'_* - K}{K} \qquad (2)$$

$$\gamma_\rho = \frac{3\left(p_p - \rho_m\right)}{p_p + \rho_m} \qquad (3)$$

Here, ε is the volume fraction, α is the radius, K is the bulk modulus, ρ is the mass density, λ is the wavelength, and k is the wave number.

The viscous absorption coefficient can be described below.

$$\alpha_v = \epsilon \mathrm{k}_c \frac{(s-1)^2 18 b^2 (b+1)}{81(b+1)^2 + b^2[(4s+2)b+9]^2} \quad [1/\mathrm{m}] \qquad (4)$$

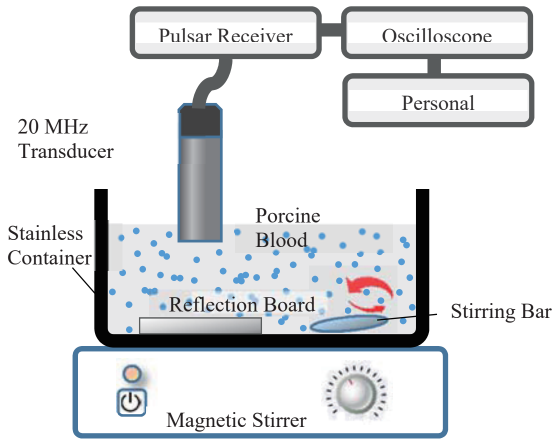


Fig. 1 Experimental setup composed in our previous study.

$$s = \rho_0'/\rho_0 \tag{5}$$

$$b = \rho_0'/\rho_0 b = (\omega/2\nu)^{1/2} \tag{6}$$

Here, ω is the angle frequency, and ν is the kinematic viscosity coefficient. The thermal absorption coefficient can be described as follows.

$$\alpha_T = \frac{3\epsilon \mathrm{T} c_m p_m \tau_m T}{2a^2}\left(\frac{\beta_m}{C_p^m p_m} - \frac{\beta_p}{C_p^p p_p}\right)^2 ReH \tag{7}$$

$$H^{-1} = \frac{1}{1-jz_m} - \frac{\tau_m tanhz_p}{\tau_p tanhz_p - z_p} \tag{8}$$

$$z_{m,p} = a(1+j)\sqrt{\frac{\omega p_{m,p} C_p^{m,p}}{2\tau_{m,p}}} \tag{9}$$

Here, τ is the thermal resistance, β is the thermal diffusivity, is the thermal capacity, c is the sound velocity, and T is the temperature.

To calculate the transmitted waves, the Lambert-Beer law was utilized. The law is generally applied to the relationship between the optical attenuation and the concentration of optical absorber, however, on the basis of the similarity of the sound wave and optical wave, the law was considered to be utilized. When the incident light density is I_0 and the transmitted light density is I, the law is described as:

$$\mathrm{A} = \log\frac{I}{I_o} = \alpha d \tag{10}$$

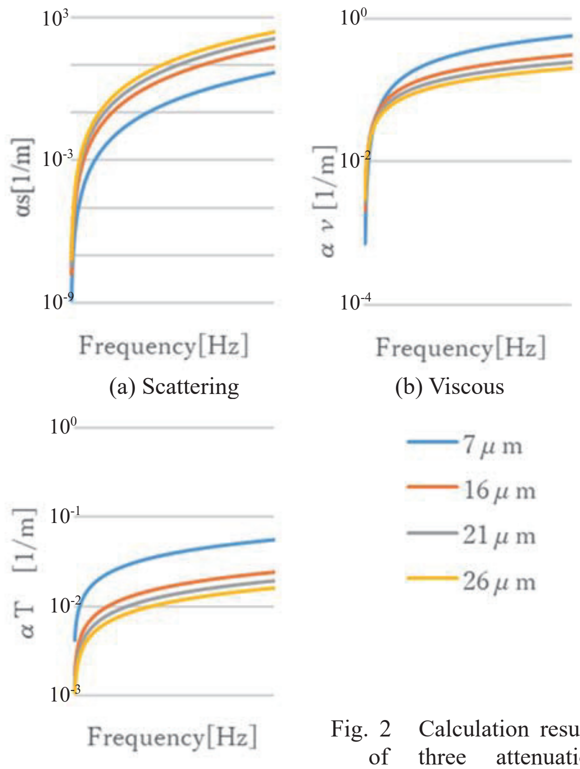
Here, d is the distance

When the three attenuation coefficients mentioned above are substituted to Eq. (10), the transmitted light density is obtained as:

$$\mathrm{I} = I_o \exp(-2d\alpha) \tag{11}$$

3. Results and discussion

Porcine blood was used as the experimental sample and dextran 70 was added to the blood sample to control the aggregation size. The average diameters of the aggregations obtained the experiments were 7, 16, 21 and 26 µm. **Figure 2** shows the frequency characteristics of the scattering attenuation, the viscous attenuation and the thermal attenuation obtained by varying the aggregation diameter from 7 to 26 µm. In all cases in Fig. 2, as the aggregation increased, the peak frequency decreased.



(a) Scattering (b) Viscous

(c) Thermal

Fig. 2 Calculation results of three attenuation coefficients.

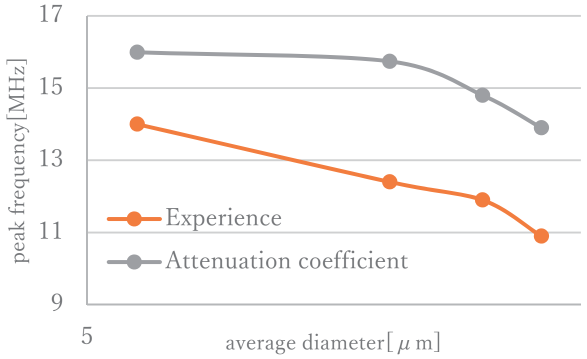


Fig.3 Peak frequency for average aggregation size of red blood cells.

The relationship between the aggregation diameter and the peak frequency is drawn in **Fig. 3**. The calculated results was roughly corresponded to the experimental results. In this study, a possibility of the estimation method for the RBC aggregation degree with the ultrasonic technique. In our future works, a precise model based on ECAH theory will be discussed.

References

1) T. Sato, K. Ikeda, Jpn. J. Appl. Phys. 57, 07LF16 (2018).