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Effect of blood vessel viscoelasticity on the pulse waveform
血管の粘弾性的性質と脈波波形に関する実験的検討

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1. Introduction

The increase of blood vessel stiffness constitutes risk factors for various disorders such as cardiovascular disease. Therefore, diagnosis of the stiffness has become dramatically important for early detection and intervention of these diseases [1].

In previous research, we focused on the pulse wave to evaluate the viscoelastic property of blood vessel wall and suggested a simple technique to analyze the wave. In this process, we considered the blood vessel as elastic tube and estimated pressure wave caused by the blood flow using continuity equation and the elastic model. In this study, we introduce viscoelastic model considering viscosity of the blood vessel. Then, we investigate the difference between "elastic model" and "viscoelastic model".

2. Methods

2.1. Pulse Wave and Estimation of Reflected Wave

The evaluation of a pulse wave has become important for screening arteriosclerosis, because the wave reflects the characteristics of blood vessel. The pulse wave arises from displacement changes of the surface skin caused by pressure in the blood vessel. The pressure wave is composed of a forward wave and a backward wave. The forward wave is caused by blood flow coming from the constriction of the heart. The backward wave is generated by the reflection of the forward wave at the peripheral arteries. Therefore, the pulse wave is a wave synthesized from the displacement component due to the forward wave and backward wave. In this study, we call the observed displacement component due to the forward wave, "the incident wave" and that due to the backward wave, "the reflected wave". Because the reflected wave is generated by the backward wave which propagates to the peripheral artery, it depends strongly on the viscoelastic properties of the vessel wall. Therefore, the evaluation of blood vessels may be possible by investigating this reflected waveform.

In the previous research, we suggested the separation techniques of the pulse wave. An outline of the techniques is as follows. At first, changes in the cross section of the blood vessel were estimated from the blood flow velocity waveform using the one-dimensional continuity equations.

The forward pressure wave was estimated by substituting the cross section changes into elastic model [2] , which needs to be further explored:

$$P(t) = \frac{1}{Cs}\left(A(t) - A_0\right), \tag{1}$$

where $A(t)$ and $p(t)$ are changes in the cross section of the blood vessel and the pressure, respectively. Cs is the compliance. A_0 is the initial values of cross section. Next, a Voigt model was used to estimate the incident wave from the forward pressure wave. We adopted the relaxation time as a parameter to estimate the optimal incident wave. Here, we focused on the initial upstroke of the pulse wave to decide the parameter, because the upstroke of the pulse wave is composed only of the incident wave. Finally, the estimated reflected wave was obtained by deleting the incident wave from the pulse wave.

2.2. Forward wave estimated by viscoelastic tube

In the proposed technique, the forward wave was estimated by the elastic tube with few viscous effects. However, viscoelastic model is actually necessary to express the behavior of complex viscoelastic body such as the blood vessel. Therefore, we derived a new model considering viscosity of the vessel wall:

$$P(t) = \frac{1}{Cs}\left[\left(A(t) - A_0\right) + \int_0^{\infty}\int_0^{t} \frac{1}{\tau} H(\tau) \exp\left(\frac{u-t}{\tau}\right) \frac{dA(t)}{dt}\, du\, d\tau\right], \tag{2}$$

where τ and $H(\tau)$ is relaxation time and relaxation spectrum. Then, the viscoelastic property of the tube wall is shown in second term of eq. (2). Here, the relaxation spectrum needed in eq. (2) is obtained from the result of actually measured bovine blood vessel. The relaxation spectrum is calculated by means of the first approximation equation[3]:

$$H(\tau) \approx \left| G'(\omega) \frac{d \ln G'(\omega)}{d \ln \omega} \right|_{\omega = 1/\tau}, \tag{3}$$

3. Experiments

3.1. Materials and measurement of viscoelastic property of the blood vessel

The aorta was obtained from a 29–month-old female bovine. The part of the blood vessel which

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was located 15 cm from the aortic valve was used. Prismatic specimen (10.0 x 1.0 x 1.0 mm) was obtained from the vessel wall. Here, we defined the longitudinal axis of the specimen as the circumference direction of the blood vessel.

We measured the dynamic viscoelasitc property of the specimen by a viscoelastic spectrometer (SII Nano Technology Inc. DMS6100). The experiment was conducted by shear mode. Vibration frequency ranged from 0.1 Hz to 20.0 Hz.

3.2. *Measurement of the blood flow velocity*

The blood flow velocity was obtained by a Doppler blood flow measurement using ultrasonic diagnostic equipment (Toshiba Medical Systems Aplio SSA-700A). The center frequency of the ultrasonic pulse used (Toshiba Medical Systems Probe PLT-1204AT) was 12 MHz. The experimental subject was a healthy man in their twenties. The subjects refrained from meal, exercise, and smoking for more than two hours before the experiment. The measurement was started after the subjects lay down for ten minutes in a room at 25℃.

4. Results and Discussion

Figure 1 shows the measured complex modulus. Both values increased with the frequency. Next, we normalized storage elastic modulus by the value at 0.1 Hz and calculated the relaxation spectrum by eq. (3). The result is shown in Fig. 2. Estimated forward waveforms using eq. (1) and eq. (2) with the relaxation spectrum are shown in Fig. 3. Here, waveforms were normalized by the maximum values of each waveform. Both waveforms are similar, especially at the wave front, telling that the effect of viscosity of the vessel wall seems small. Since we use the initial upstroke of the forward wave to estimate the incident wave in our technique, the estimation results using a Voigt model does not change dramatically due to the model.

5. Conclusion

In this study, we focused on the estimation technique of the forward wave. We derived viscoelasitic model assuming viscosity of the bovine blood vessel. As a result, there is a little difference between forward waveforms calculated by the elastic model and viscoelastic model. Therefore, the simple elastic model seems acceptable and useful for the estimation of "incident wave".

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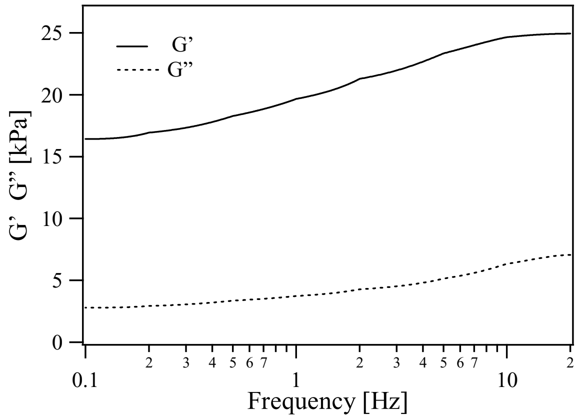

Fig. 1 The measured complex modulus of a bovine blood vessel.

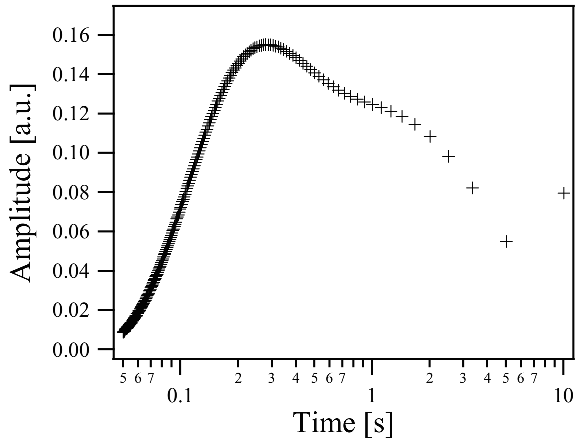

Fig. 2 Calculated relaxation spectrum of bovine blood vessel walls.

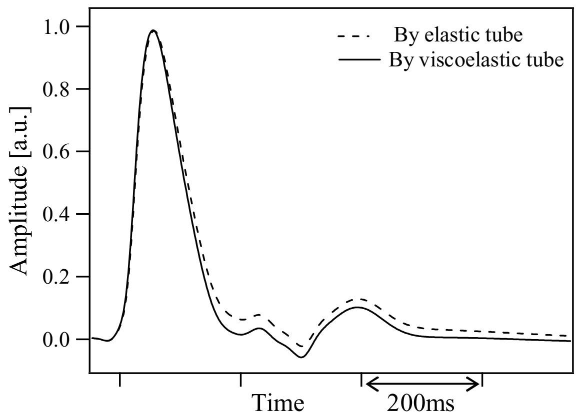

Fig. 3 Relationships between forward waves estimated by elastic and viscoelastic models.

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