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Experimental study on the pulse wave propagation in a human artery model

人血管モデル中の脈波伝搬に関する実験的検討

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1. Introduction

Arteriosclerosis causes severe diseases, which are cardiac infarction or cerebral infarction. Diagnosis of arteriosclerosis is effective for reducing the incidence of these diseases[1].

The pulse wave consists of incident and reflected waves, which reflects the pressure wave in the blood vessel. Because attenuation of the reflected wave changes markedly due to the arterial stiffness, wave properties of this reflected wave give us information of arterial stiffness. In previous study, we have proposed a simple method to extract the reflected wave from the observed pulse wave[2,3], and pointed that the amplitudes of the reflected wave increased owing to age. However, the propagation properties of the reflected wave were not perfectly investigated.

In this study, we construct a simple human artery model, and investigate propagation properties of the estimated reflected wave obtained from the measured inner pressure wave and flow velocity waveform.

2. Estimation of reflected wave

The procedure for estimation of reflected wave is shown in **Fig. 1**. By assuming the model artery to be an elastic tube, we estimated the pressure wave from the measured flow velocity waveform using a one-dimensional continuity equation and an elastic model[2,3].

$$\frac{\partial A}{\partial t}+\frac{\partial (Au)}{\partial x}=0 \qquad (1)$$

$$P(t)-P_0=\frac{1}{Cs}(A(t)-A_0) \qquad (2)$$

where, x and t are space and time variables. A and u are the cross-section and flow velocity. Here, we assumed the changes of flow velocity waveform are small between the near point. Cs is compliance. After normalizing amplitude, the reflected wave was obtained by subtracting the estimated incident wave from the measured inner pressure wave.

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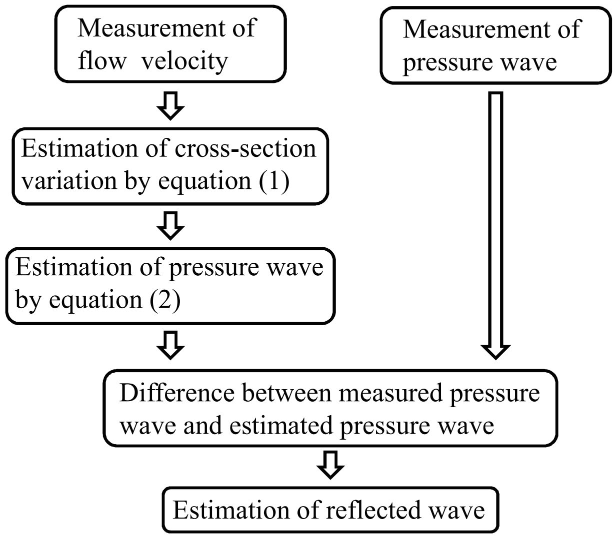

Fig. 1 Procedure for estimation of reflected wave.

3. Experiments

3.1 Construction of a human artery model

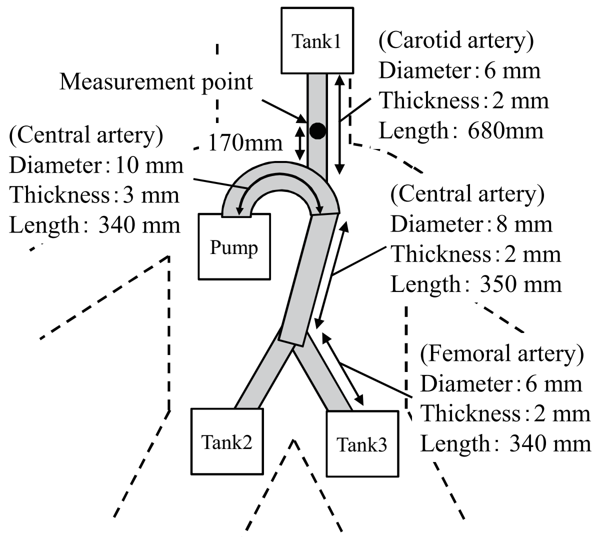

Fig. 2 Details of the simple human artery model.

Figure 2 shows the details of simple human artery model, with central artery, femoral artery and carotid artery. Viscoelastic tubes (Custom made, Polyurethane) are used for each artery. The elastic modulus of the polyurethane was about 70 kPa by the tensile test. Propagation velocity of the intravascular pressure wave in this tube was near the pulse wave velocity *in vivo*. Diameter of the tube changes from 10 to 6 mm from the pump to the tank. Total length is based on the length of a man. Measurement point is set at 170 mm from first bifurcation to tank 1. This point is assumed as the carotid artery of neck in an actual human body.

3.2 Measurement of inner pressure wave and flow velocity in the model

A measurement system was constructed by a pump (Custom made, Tomita engineering Co., Ltd), and the simple human artery model. A pulsatile flow was input into the human artery model using the pump. The input liquid (water) flow waveform to the tube was a half cycle of a sinusoidal wave. The period was 0.3 sec, and the total flow volume was 4.5 ml. We measured the inner pressure wave and flow velocity in the human artery model. We used a pressure sensor (Keyence AP-10S) to measure inner pressure wave. We used ultrasonic Doppler system (Toshiba Medical Systems Aplio SSA-700A) to measure flow velocity. The center frequency of the ultrasonic pulse used (Toshiba Medical Systems Probe PLT-1204AT) was 12 MHz.

4. Results and discussion

Figure 3 shows measured results of normalized inner pressure wave and flow velocity. Following the procedure in Fig. 1, we estimated the reflected wave in **Fig. 4** by subtracting the estimated pressure wave from the pressure wave. The arrival time difference between observed pressure wave and estimated reflected wave is 0.19 sec. From Moens-Korteweg equation[1], the estimated inner pressure propagation velocity is 4.9 m/s for soft tube with 70 kPa. Considering the velocity, the first peak of estimated reflected wave then corresponds to the wave reflected at tank 1. In addition, the second peak of estimated reflected wave also corresponds to the wave which reflected twice in this model. The first was the reflection at tank 2 or 3. The second was the reflection at tank 1. Here, one should notice the interesting difference between the flow velocity waveform and estimated reflected wave. The negative peak of flow velocity corresponds to the positive peak of reflected wave. The actual blood flow velocity is more complex than the experimental wave; however, we find several negative peaks, which show a possibility of similar mechanism.

5. Conclusion

We estimated reflected wave from the measured inner pressure wave and flow velocity waveform in a simple human model. In consequence, reflected wave that propagates in carotid artery of the model showed large amplitude by the method we proposed. The results tell us the possibility of cardiac artery evaluation using this method.

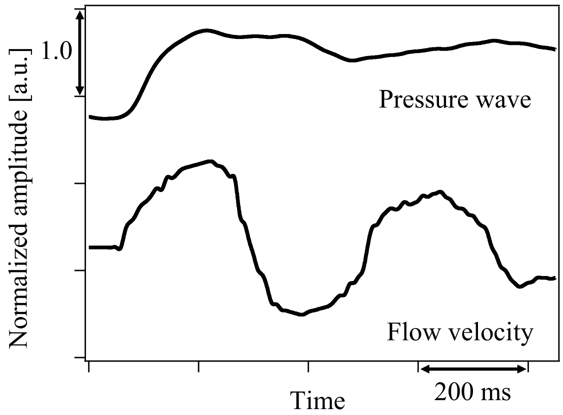

Fig. 3 Observed inner pressure wave and flow velocity.

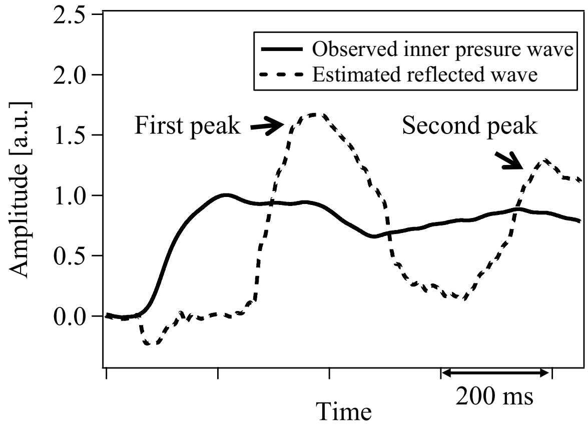

Fig. 4 Estimated reflected wave after separation.

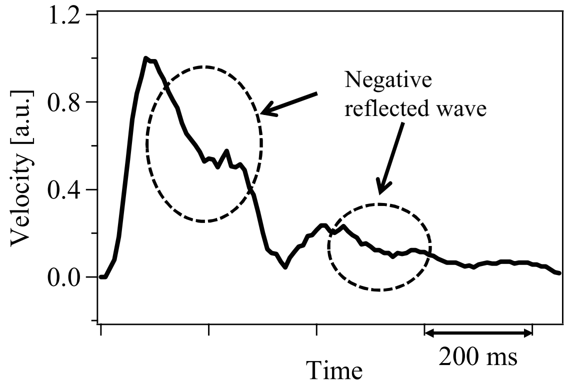

Fig. 5 Composition of blood flow velocity waveform.

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