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Basic study on separation of reflected components in pulse wave propagation using ultrafast ultrasound
超高速超音波撮影による脈波伝搬における反射波分離手法に関する基礎的検討

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1. Introduction

In recent years, a significant number pf mortalities are caused by cardiovascular diseases. Atherosclerosis is known as a main cause of cardiovascular diseases. Plaque inside an arterial wall is formed due to progression of atherosclerosis and an arterial lumen is possibly occluded when plaque ruptures. Therefore, it is important to diagnose atherosclerosis in an early stage. In ultrasound imaging, morphological information is mainly utilized. To diagnose atherosclerosis in an early stage, quantitative diagnostic method is required together with morphological evaluation. In such a situation, an evaluation method of the arterial wall elastic property has been demanded.

In ultrasound imaging, motions and deformations in living tissues are measured for the evaluation of their elastic properties. In such a case, a high frame rate of an imaging system is preferable. For example, a mechanical function of the heart wall could be evaluated from propagation speed of the mechanical wave induced by electrical excitation, and a frame rate of more than 500 Hz is required for such a measurement [1]. Ultrafast ultrasound realizes a frame rate 10-100 times higher than the conventional ultrasound imaging using a focused beam [2].

In the evaluation of mechanical function of the arterial wall, the pulse wave velocity (PWV) is also used [3]. When analyzing the PWV generated by pressure wave inside the carotid artery, the pulse wave includes not only forward components but also reflected components, which occur at areas with different mechanical impedances along a flow path. Such reflected components contain information on the elastic properties of peripheral arteries. In the present study, we investigated a separation method of reflected components in a pulse wave.

For the analysis of pulse wave propagation and evaluation of the PWV estimation method, in this study, the displacement of arterial wall induced by pressure wave was simulated by the fluid-structure interaction (FSI) analysis using a commercial simulation software (COMSOL Multiphysics). Also, the propagation speed of a pulse wave was estimated from the simulated pressure wave with respect to the forward component. The estimated propagation velocity was compared with the true velocity for validation.

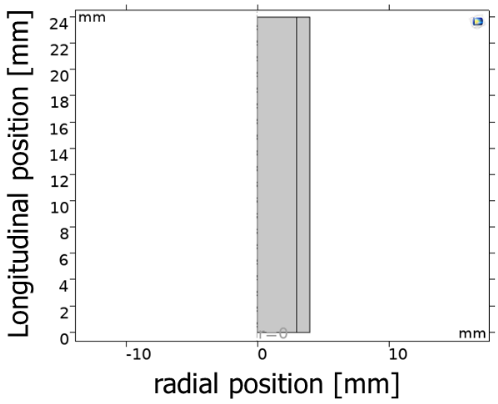

Figure 1 1D Model for simulation of pulse wave propagation.

2. Methods

2.1. Fluid-structure interaction (FSI) simulation

Figure 1 shows a model used in this study. The left and right rectangles (filled with gray color) in Fig. 1 were defined as fluid (blood) and structure (arterial wall) domains, and displacements in the structure domain was simulated by performing the FSI analysis on the boundary between fluid and structure domains. A 1D axisymmetric problem was assumed in this simulation, and the gray dashed line in Fig. 1 represents the axis of the 1D axisymmetric problem. An arterial wall was assumed to be a homogeneous, isotropic, and incompressible Hooke's solid. The fluid is assumed to be incompressible, and the governing equations are the continuity and Navier-Stokes equations. The density and viscosity of the fluid simulating blood were set to 1060 kg/m^3 and 0.004 Pa・s, respectively [4]. The relationship of the pressures at the boundary conditions between the inlet and outlet is given as

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Mechanical Parameters	Values
E (arterial wall)	600 kPa
ρ	1000 kg/m^3
v	0.49

Table I Mechanical properties of the model

$$p_{\mathrm{out}}(t) = p_{\mathrm{in}}\left(t - \frac{D}{c_{\mathrm{PWV}}}\right), \quad (1)$$

where $p_{\mathrm{in}}(t)$ and $p_{\mathrm{out}}(t)$ are inflow and outflow pressures, respectively, and D is the propagation distance. As shown in Eq. (1), the pressure wave at the outlet boundary was delayed from that at the inlet boundary. The pressure wave applied at the inlet boundary was determined using the arterial wall displacement waveform obtained in an *in vivo* measurement of a human carotid artery with ultrasound [5]. The mechanical properties of the model, i.e., elastic modulus E, density ρ, and Poisson's ratio v, are shown in **Table I**.

A structural computational grid was designed by defining 28 and 8 elements in the longitudinal and radial directions, respectively. The PWV was estimated from the simulated pressure waveform in the fluid domain. The time-step in the FSI simulation was set at 0.0001 second.

2.2. Estimation of PWV

The pressure wave simulated using the FSI was obtained along lateral and time (frame) directions. The PWV was estimated using the phase of the pressure wave. First, the analytic signal $a_m(t)$ at the m-th position along the model was obtained by applying Hilbert transform to the pressure waveform in the frame direction. To estimate the PWV, the evaluation function $A(k)$ was calculated as [6]

$$A(k) = \frac{|\mathrm{E}[a_m(t)]|^2}{\mathrm{V}[\angle\{a_m(t) \cdot (a_0(t) \cdot e^{i(2\pi f t - k \cdot d_m)})\}]}, \quad (2)$$

where $\mathrm{E}[\cdot]$ and $\mathrm{V}[\cdot]$ denote expectation and variance, respectively, $\angle\{\cdot\}$ denotes the phase term of a complex signal, and $a_0(t)$ is the pressure wave at the 0-th position. The evaluation function $A(k)$ becomes maximum when the propagation speed of the simulated wave $a_m(t)$ is equal to the propagation speed of the model $e^{i(2\pi f t - k \cdot d_m)}$. The PWV at a time (frame) of interest was obtained from wave number k and dominant frequency f as

$$c_{\mathrm{pwv}} = \frac{2\pi f}{k}. \quad (3)$$

In this study, the time of interest was set at the time when the pressure wave at the center of the model was maximum.

3. Results

Figure 2 shows the image of the simulated pulse wave propagation. In Fig. 2, the first derivative

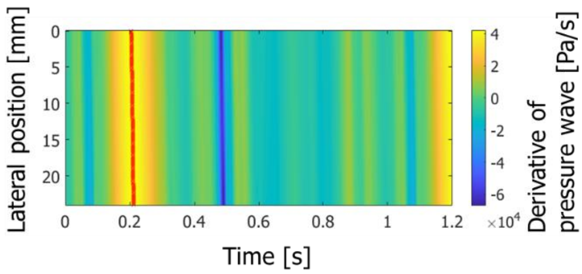

Fig. 2 Spatiotemporal map of derivative of pressure wave. Red line shows peak positions.

of the pressure wave in the fluid domain, which has a linear relationship with velocity of the arterial wall, was displayed. The red line shows peak positions in the pressure waveforms. The PWV of the simulated wave was 3.05 m/s. Bias error $\varepsilon_{\mathrm{bias}}$ of the estimated elastic moduli was evaluated as

$$\varepsilon_{\mathrm{bias}} = \frac{E_e - E_r}{E_r}, \quad (4)$$

where E_e and E_r were the estimated and true elastic moduli, which were estimated using Moens-Korteweg equation [6] from the PWVs. The bias error of the elastic modulus was -12.0%.

4. Conclusion

The PWV is used for evaluation of mechanical function of the arterial wall. For the analysis of the pulse wave propagation and evaluation of the PWV estimation, a basic study using a FSI simulation was performed. In this simulation, the displacement of the arterial wall induced by the pressure wave was simulated by the FSI simulation. Also, the propagation speed of the pulse wave was estimated from the simulated pressure wave. In our future work, we will simulate pulse wave propagation containing the reflected components for an investigation of a separation method of the forward and reflected wave components.

References

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