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Development of numerical vessel wall model based on fluid-structure interaction analysis for local pulse wave velocity estimation

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1. Introduction

Pulse wave velocity (PWV) is used for early diagnosis of atherosclerosis because progress of atherosclerosis results in the increased elasticity of the arterial wall, and the pulse wave which propagate through the arterial wall becomes faster[1,2]. However, brachial-ankle PWV (baPWV) is measured in a long segment of the artery and, it is difficult to obtain regional elasticity to diagnose focal atherosclerotic lesions. In our previous study, an estimation method of regional PWV in a carotid artery by ultrasound was proposed[3]. In the cited study, regional PWV was measured in vivo, but the propagation characteristic of PWV has not been analyzed in detail. Another research group has performed numerical simulations for the detailed analysis of the regional PWV.

In this study, a vessel wall model simulating a carotid artery was developed for evaluating the accuracy of regional PWV estimation, and the radial displacement of the vessel wall model due to changes in blood flow velocity and blood pressure was analyzed[4].

2. Methods

2.1 Simulation conditions

In this study, a three-dimensional (3D) fluid-structure interaction (FSI) analysis is performed using COMSOL Multiphysics 6.0. To simulate a realistic human common carotid artery geometry and blood flow, a 3D vessel wall model is created using the parameters in **Table 1**. The vessel wall is prepared as an isotropic, linear elastic material. The fluid flowing in the vessel wall model is assumed to be an incompressible and Newtonian fluid described by the Navier-Stokes equations and the continuity equations. A laminar flow was assumed.

Table 1 Blood and Vascular Simulation Parameters

Vessel inner diameter	6.0 mm
Vessel wall thickness	0.6 mm
Vessel length	100 mm
Young’s modulus	500, 1000 kPa
Poisson’s ratio	0.495
Blood density	1060 kg/m^3
Blood viscosity	0.005 Pa·s

The vessel wall model developed is shown in **Fig. 1**. The radial displacement at the wall on the plane indicated by the red line in in Fig. 1 is obtained. The time step is 0.001 seconds, the number of frames is 1000, and the total time is 1 second.

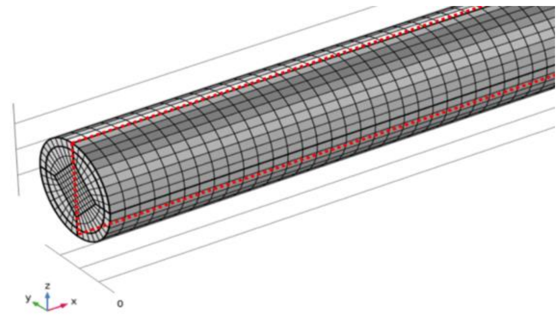

Fig. 2 Vessel wall model and wall displacement acquisition position (red line).

The boundary conditions given from the inlet and outlet of the vessel wall model are the flow velocity and blood pressure waveforms shown in **Fig. 2**, respectively[5]. The reason why those boundary conditions, i.e., flow velocity and blood pressure, are set at zero in the initial frame is to avoid step-like rapid changes in blood pressure and flow velocity. Then, in the 400th frame, the flow velocity and blood pressure were set to gradual upward curves increasing by approximately 50 cm/s and 70 mmHg, respectively.

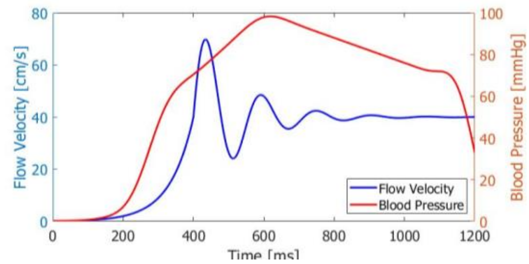

Fig. 1 Boundary conditions.

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2.2 PWV estimation using waveforms rise time

In this study, the segments of lengths of 30 mm at both ends of a 100 mm length vessel wall model are excluded in consideration of the influence of boundary conditions, and waveforms' peak rise times in the central segment of a length of 40 mm are calculated from the waveform at both ends. The peak of the waveforms is obtained between 400 ms and 450 ms, when the flow velocity waveforms peak. PWV is estimated as

$$PWV_{td} = \frac{L}{t_{out} - t_{in}}, \qquad (1)$$

where L, t_{out}, and t_{in} are the analyzed vessel length, outlet side waveform rise time, and inlet side waveform rise time, respectively.

2.3 Modified Moens-Korteweg equation

The relationship between PWV and the incremental elastic modulus of the arterial wall can be expressed using the Moens-Korteweg equation as follows:

$$PWV_{MK} = \sqrt{\frac{Eh}{2\rho_f R_0}}, \qquad (2)$$

where E, h, ρ_f, and R_0 are the vessel wall Young's modulus, vessel wall thickness, blood density and vessel radius, respectively[6]. Also, Eq. (2) can be expressed using Poisson's ratio ν as follows[7]:

$$PWV_{ref} = \sqrt{\frac{Eh}{2\rho_f R_0(1-\nu^2)}}. \qquad (3)$$

In this study, a reference PWV was calculated using each of the parameters shown in Table 1.

3. Results

The radial displacements obtained by simulation for two different Young's modulus values are shown in **Fig. 3**. The velocity waveforms obtained by differentiating each are shown in **Fig. 4**.

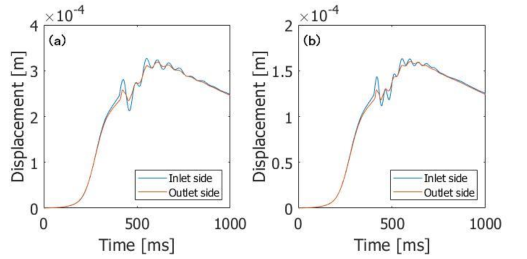

Fig. 3 Radial displacements at Young's moduli (a) 500 kPa and (b) 1000 kPa.

In Fig. 4(a), the peak rise times at the inlet side and outlet side were 0.409 s and 0.415 s, respectively. The PWV obtained from the rise time difference was calculated to be PWV_{td} = 6.67 m/s, and the PWV was obtained from the modified Moens-Korteweg

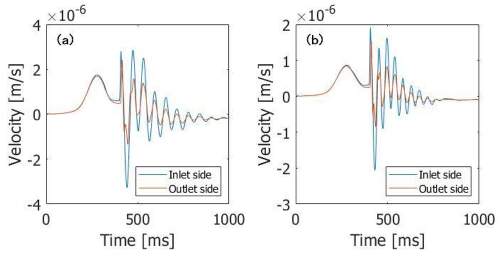

Fig. 3 Velocity waveforms at Young's moduli (a) 500 kPa and (b) 1000 kPa.

equation as PWV_{ref} = 7.90 m/s. In Fig. 4(b), the respective peak rise times were 0.407 s and 0.412 s, and PWVs were obtained as PWV_{td} = 8.00 m/s and PWV_{ref} = 11.17 m/s.

The error between the reference PWV and the estimated PWV was -1.23 m/s at a Young's modulus of 500 kPa and -3.17 m/s at 1000 kPa.

There is an error of about 2 m/s under each condition. The PWV was analyzed under the conditions, i.e., a vessel length of 40 mm and a time step of 0.001 s. Under such conditions, the estimated PWV is changed by about 1~2 m/s from 1-point shift in the peak-tracking step.

4. Conclusion

In this study, we developed a model for local PWV estimation and examined the validity of the propagation velocity. The estimated propagation velocity was similar to that derived from the Moens-Korteweg equation and was shown to be reasonable. In our future work, regional PWV estimation will be performed with ultrasonic simulation using the displacements obtained from the model developed in this study.

References

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