FSI analyses on the hemodynamics inside an aneurysm by considering the pressure drop in distal blood vessels

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ABSTRACT

The hemodynamics inside a blood vessel is determined with the complex interaction between the blood flow and vascular deformation, because the blood in a human body is delivered through the compliant blood vessel. Therefore, an analysis of fluid-structure interaction (FSI) is necessary to predict the accurate and realistic hemodynamic characteristics. In the present study, the hemodynamics inside an aneurysm was investigated numerically by using an iterative coupling method. From the results with various levels of arterial compliance, it was observed that the blood flow inside a dilated artery is affected substantially by movement of the arterial wall due to variation of the blood pressure. Therefore, a FSI analysis must be performed to predict the hemodynamics inside an aneurysm accurately. The numerical results of blood flow and arterial movement are also affected by the pressure conditions applied to the outlet of the computational domain. From the results with various models for the pressure drop through the distal blood vessels, it was found that the distal vascular resistance and capacitance must be considered to make realistic prediction of the arterial hemodynamics.

1. INTRODUCTION

Recently, a rapid evolution of numerical methodologies has made it possible to simulate the arterial hemodynamics related closely to a vascular disease. To simulate the arterial hemodynamics accurately, a numerical approach for fluid-structure interaction (FSI) should be employed, because the blood in a human body is delivered through the compliant artery. To obtain the accurate and realistic results of hemodynamic characteristics, a combination of proper boundary conditions has to be applied to the inlet and outlet of the computational domain. The inlet boundary condition based on the blood flow rate was generally used for the proximal faces of the
computational domain and the pressure boundary conditions based on the blood pressure for the distal faces. Although various distal vascular models such as the constant pressure model, resistance model and Windkessel model have been proposed to consider the pressure drop through the distal blood vessels (Vignon-Clementel et al. 2010), it is necessary to understand the effect of distal vascular models on the FSI simulation of arterial hemodynamics. In the present study, a FSI simulation of the hemodynamics inside an aneurysm was performed by using various distal vascular resistances and capacitances based on the Windkessel model.

2. NUMERICAL METHODS

The hemodynamics inside an aneurysm was numerically investigated by coupling a CFD analysis of the blood flow and a structural analysis of arterial wall movement iteratively (Lee et al. 2012).

2.1 Governing Equations

For the CFD analysis of the blood flow in the present study, the governing equations of mass and momentum conservation for an incompressible flow were used:

\[
\frac{\partial u'_i}{\partial x'_j} = 0, \quad \rho'_f \frac{\partial u'_j}{\partial t} + \rho'_f u'_j \frac{\partial (u'_i - u'_{i,q})}{\partial x'_j} = -\frac{\partial p}{\partial x'_i} + \frac{\partial \tau'_{ij}}{\partial x'_j}
\]

where \( t \) denotes the time, \( \rho'_f \) is the fluid density, \( \mu'_f \) is the fluid viscosity, \( u'_i \) is the velocity vector, \( u'_{i,q} \) is the grid velocity vector, \( p \) is the pressure, and \( \tau'_{ij} \) is the shear stress tensor. In the governing equations, the viscous stress tensor for an incompressible flow was calculated as:

\[
\tau'_{ij} = 2\mu'_f s'_{ij} = \mu'_f \left( \frac{\partial u'_i}{\partial x'_j} + \frac{\partial u'_j}{\partial x'_i} \right)
\]

In the present study, these governing equations for a blood flow were discretized using unstructured polyhedral grids for the complex arterial geometry and the fractional step method for the pulsatile blood flow conditions.

For the structural analysis of the arterial wall movement, the following equation of force balance was used:

\[
\frac{\partial \sigma'^s_{ij}}{\partial x'_j} = 0
\]

where, \( \sigma'^s_{ij} \) denotes the solid stress tensor. By assuming the blood vessel as the hyperelastic material, the stress tensor was calculated using the strain energy density function \( U \) as:
where $\mathbf{B}_{ij}$ denotes the left Cauchy-Green deformation tensor, $I_1$ and $I_2$ are the deviatoric strain invariants, $J$ is the determinant of elastic deformation gradient tensor, and $\mathbf{I}$ is the identity tensor. In the present study, the Mooney-Rivlin model for the strain energy density function was used as:

$$U = \sum_{i=1}^{N_u} C_i (J_i - 3)^i (J_2 - 3)^i + \sum_{i=1}^{N_d} D_i (J_3 - 1)^{2i}$$

where $C_i$ and $D_i$ denote the material coefficients, respectively.

### 2.2 Simulation Conditions

For the fusiform aneurysm, a simplified computational domain was modeled by the dilated artery with the diameter of 20.0 mm located at the center of parent artery with the diameter of 10.0 mm and the length of 150.0 mm. For the non-Newtonian characteristics of blood, the Carreau model (Johnston et al. 2004) widely used for non-Newtonian blood viscosity was applied as shown in Fig. 1. For the arterial compliance, the arterial wall having the arterial properties used in Torii et al. (2009) was modeling with the thickness of 2.0 mm. For the FSI simulation of blood flow and arterial wall movement, not only the blood flow velocity but also the blood pressure has to be defined. For the pulsatile flow conditions in the parent artery, the velocity and pressure waveforms of abdominal aorta (Scotti et al. 2005) was used as shown in Fig. 2. Based on the velocity waveform with the peak systolic velocity of 118.7 cm/s and diastolic velocity of 11.6 cm/s, the inlet boundary condition was applied to the proximal parent artery. For the pressure waveform with the systolic blood pressure of 117 mmHg and diastolic blood pressure of 70 mmHg, the pressure boundary condition using the following Windkessel model was applied to the distal parent artery.

$$p(t) = p_0 e^{-\tau R_C} + \frac{e^{-\tau R_C}}{C} \int_0^t e^{\tau R_C} Q(t) dt, \quad \tau = R_C C$$
where, $p_0$ denotes the downstream pressure, $R$ the proximal vascular resistance, $R_d$ the distal vascular resistance and $C$ the distal vascular capacitance. With these simulation conditions, the FSI simulation was performed during 5 cardiac cycles. Using 12 CPUs on a Linux server with a 2.4 GHz AMD Opteron 64 bit processor, it took about 50 hours to obtain the periodic patterns.

3. RESULTS AND DISCUSSIONS

In the present study, the FSI simulations on the hemodynamics inside a simplified model of fusiform aneurysm were performed as shown in Fig. 3. From the results, it was observed that the hemodynamics inside the parent artery is highly affected by the
pulsatile blood flow. In the systolic phase, the parent artery is exposed to high wall shear stress with the increase the flow rate through the parent artery. However, the hemodynamics inside the dilated aneurysmal region is affected by the complex interaction of blood flow and arterial wall movement. Not only the arterial wall movement but also the blood flow was highly influenced by the blood pressure closely related to the pressure boundary condition applied to the distal region of computational domain.

To obtain the effect of the pressure boundary condition for modeling the pressure drop through the distal blood vessels, the numerical results of the hemodynamics inside the fusiform aneurysm were compared with various distal vascular resistances and capacitances based on the Windkessel model. Fig. 4 shows the pressure drop through the distal blood vessels obtained from blood flow simulation without considering the arterial wall movement. From the results, it was observed that the pressure drop through the distal blood vessels linearly increases with the increase of distal vascular resistance, and the difference between systolic and diastolic blood pressure decreases with the increase of distal vascular capacitance. To match the numerical results of FSI simulation with the systolic and diastolic blood pressure of 117 and 70 mmHg, the coefficients of Windkessel model were obtained as follows:

\[
R = 2581.2 \text{ dyne} \cdot \text{s} / \text{cm}^5, \quad p_0 = 9637.5 \text{ kPa}, \\
R_d = 25166.2 \text{ dyne} \cdot \text{s} / \text{cm}^5, \quad C = 2.544 \times 10^{-5} \text{ cm}^5 / \text{dyne} 
\]  

(6)

From the FSI simulation using these coefficients of Windkessel model, the arterial hemodynamics inside the fusiform aneurysm was predicted as shown in Fig. 5. The numerical results of blood flow rate and blood pressure at the distal parent artery show the similar patterns compared to the velocity and pressure waveforms as shown in Fig. 2. Therefore, the distal vascular model including the distal vascular resistance and capacitance has to be considered for the realistic blood flow and blood pressure.

4. CONCLUSIONS

A fluid-structure interaction (FSI) simulation is necessary to predict arterial hemodynamics accurately, because the blood flow is related closely to movement of the arterial wall. From FSI simulations of arterial hemodynamics inside a fusiform aneurysm, it was observed that the boundary conditions related to both the blood flow and blood pressure are equally important to predict realistic arterial hemodynamics. To model the pressure drop through the distal blood vessel, both the distal vascular resistance and capacitance have to be considered.

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