대동맥 판막 모델의 유체-구조 상호작용 전산해석: 타당성 연구

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Fluid-structure interaction simulation of aortic valve models: A feasibility study

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Abstract : Transcatheter aortic valve(TAV) implantation has been carried out as an alternative to patients with severe aortic stenosis, who are at high risk for surgical therapy. Fluid-structure interaction(FSI) simulation is important because the biomechanical environment of TAV is closely related to the interaction between the motion of aorta as well as leaflets and the complex aortic hemodynamics. In this study, we performed the feasibility study of FSI simulation for aortic valve model with the aim of extending to TAVI FSI analysis in future work.

1. Introduction

Transcatheter aortic valve(TAV) implantation has been carried out as an alternative to patients with severe aortic stenosis, who are at high risk for surgical therapy.(1) Although TAVI has the advantage of being non-invasive, there are still a number of issues that need to be understood or overcome in order to be more widely applied.

In engineering perspectives, these include paravalvular regurgitation during systolic phase, pressure drop across the valve, complex disturbed flow and vortical structures within the ascending aorta, migration/torsion forces on the TAV, leaflet stresses and deploying force, etc.(2)

The biomechanical environment of TAV and in turn, its clinical prognosis are closely related to the interaction between the motion of aorta as well as leaflets and the complex aortic hemodynamics. Therefore, it is considered that the fluid-structure interaction(FSI) simulation is important, but the approach is generally limited due to numerical difficulties as well as computing cost.(3)

In this study, we performed the feasibility study of FSI simulation for aortic valve model with the aim of extending to TAVI FSI analysis in future work.

2. Numerical Method

2.1. Governing equations

The governing equations of fluid flows are the incompressible Navier-Stokes equations which can be written in the arbitrary Lagrangian-Eulerian (ALE) form as follows:

$$\nabla \cdot \mathbf{v} = 0 \quad \text{in } \Omega^f \qquad (1)$$

$$\rho^f \left[\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} - \mathbf{v}^m) \cdot \nabla \mathbf{v}\right] = \nabla \cdot \boldsymbol{\sigma}^f + \rho^f \mathbf{b}^f, \quad \text{in } \Omega^f \qquad (2)$$

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The governing equation of solid in the Lagrangian form is written as follows:

$$\rho^s \frac{\partial^2 \mathbf{u}}{\partial t^2} = \nabla \cdot \boldsymbol{\sigma}^s + \rho^s \mathbf{b}^s \quad \text{in} \quad \Omega^s, \tag{3}$$

Due to the force equilibrium condition, the traction should be also continued along the fluid-structure interface:

$$\boldsymbol{\sigma}^f \cdot \mathbf{n}^f + \boldsymbol{\sigma}^s \cdot \mathbf{n}^s = 0 \quad \text{on} \quad \Gamma^{fs} \tag{4}$$

2.2. Numerical scheme

The governing equations of fluid flows are discretized by the *P2P1* finite element which allocates the pressure variable only on the vertices and the velocity variable on both vertices and mid-node. In order to describe the large deformation of structure, we employed total Lagrangian formulation. Projection based semi-implicit scheme for the fluid-solid coupling which is highly effective in numerical convergence is applied.[(4)]

2.3. Mooney-Rivlin model for hyperelastic materials

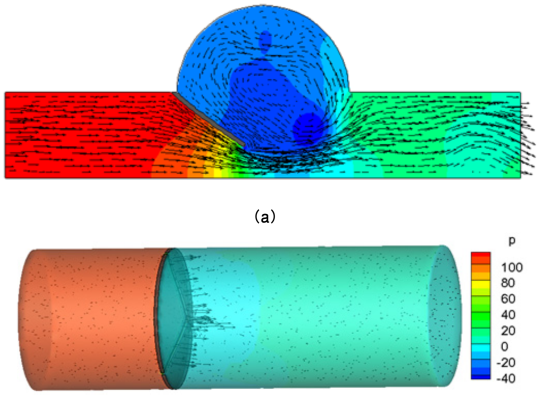
In the study, the Mooney-Rivlin model is used, which is the most common model used to describe material behavior of blood vessel problem. It is known as nonlinear material since the complex relationship of stress and strain of the material.

The Mooney-Rivlin model for compressible material is expressed by[(5)]

$$\psi = \frac{\mu_1}{2}(\bar{I}_1 - 3) + \frac{\mu_2}{2}(\bar{I}_2 - 3) + \frac{k}{2}(J - 1)^2, \tag{5}$$

3. Results

We carried out FSI simulations for 2D and 3D aortic valves in pulsatile flow condition. Pressure and velocity fields are shown in Fig. 1 and 2. Computation time was reduced by more than 10 times compared with a commercial S/W, Ansys Fluent.



(b)

Fig. 1 Pressure and velocity fields (a) 2D valve (b) 3D valve

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