RULE-BASED SIMULATION OF AORTIC ANEURYSMAL GROWTH INDUCED BY HEMODYNAMICS

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INTRODUCTION

An aneurysm is a vascular disease characterized by local ballooning of an arterial wall. The etiology of aneurysm formation is thought to be due to long-term remodeling of blood vessel wall in response to hemodynamics [1]. Changes in vessel geometry and mechanical properties of blood vessel wall induce alteration in the pattern of hemodynamics which then provides new mechanical stimuli to the vessel wall to cause further wall remodeling. However this repeated process has not been included in the past studies [2, 3]. In this study, the influence of hemodynamics on the wall is expressed by a remodeling model that provides growth and degeneration of the arterial wall depending on wall shear stress (WSS). The objective of this study is to see how the aortic geometry changes when the wall grows and mechanical properties change, and to find out the remodeling rule to represent anatomically realistic aneurysm by computer simulation.

METHODS

The geometry of the aortic trunk was made from MR images of a human aorta that does not have an aneurysm.

The mesh model for CFD analysis of blood flow was generated by dividing the lumen of the aorta into hexagonal elements. Blood flow was assumed to be an incompressible Newtonian fluid. We solve the equation of Navier-Stokes along with the equation of continuity to gain fluid velocities within the aorta and whereby WSS at the aortic wall.

The arterial wall model was constructed by dividing the luminal surface of the aorta into triangular elements using the nodal points of CFD mesh. The thickness of the wall was assumed to be constant. The deformation of the wall was depicted as a combination of continuum model and discrete elements model. Namely, plane-strain continuum model of an isotropic material was used to represent an in-plane deformation, whereas bending-spring model was adopted to express an out-plane deformation. The total elastic energy of the arterial wall can be expressed as a function of the position vectors of nodal points. We determined the nodal positions in the framework of the minimum energy concept and consequently obtained the geometry of the aorta. The CFD mesh was also deformed along with the movement of the nodal points at the wall.

Remodeling of the aortic wall was expressed by altering mechanical properties and providing growth of the arterial wall. Numerically, growth of the wall was expressed by adding growth strain $\Delta\varepsilon'$ to wall, whereas weakening and hardening of the vessel wall were expressed by decreasing and increasing Young's modulus. We related the occurrence of those events to WSS. Thresholds for WSS τ_h and τ_l are set to define high and low WSS regions. Growth and weakening of the wall were considered in the high WSS region and hardening of the wall in the low WSS region.

A simulation procedure was summarized as follows. A transmural pressure was firstly imposed to obtain the initial geometry of the aorta. Given the geometry, the blood flow was calculated to gain WSS. Followed by updating wall properties and growth according to remodeling model based on WSS, the aortic geometry was calculated by a quasi-static approach until an elastic energy in the aorta reached minimal. The calculation was returned to the analysis of blood flow to see if there were any regions where WSS exceeds the thresholds.

RESULTS AND DISCUSSION

Figure 1 (a) and (b) show contour plots of WSS at the initial and the maximum of the total growth strain $\Delta\varepsilon_{max}$ =0.33. Initially, high WSS is found from the end of ascending aorta to the proximal side of the aortic arch as seen in Fig 1 (a). High and low WSS induce hardening and weakening of the wall as vascular remodeling, widening a gap of mechanical properties. In addition, the wall grows in high WSS regions. A combination of these causes a local dilation of the aorta. Although WSS at the proximal side of the aortic arch tends to decrease, remodeling progresses further. As a result, the aortic dilation at the proximal side of the aortic arch develops into fusiform aneurysm as shown in Fig. 1 (b). Compared with other results which were obtained by computer simulations based on a single remodeling rule, it was found that the combined factor of wall growth and mechanical property change plays important role in localized expansion of artery as seen in the actual aorta.

REFERENCES

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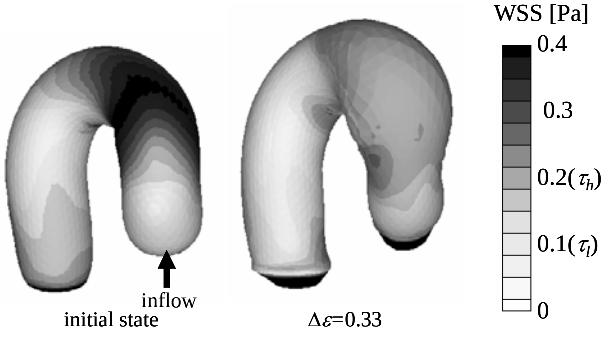

(a)Initial geometry (b) $\Delta\varepsilon$ =0.33

Fig. 1 Geometry of the aorta and contour plots of the WSS at initial (a) and advanced state (b).