NUMERICAL INVESTIGATION OF GEOMETRIC EFFECTS ON HEMODYNAMCS OF CEREBRAL ARTERY USING DEFORMABLE MODEL

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INTRODUCTION

A subarachnoid hemorrhage is mainly caused by rapture of an intracranial aneurysm[1]. However, it is reported that the rate of rupture of aneurysms is less than 1.0 % [2]. Since Japanese have a high ratio of subarachnoid hemorrhage [1], it is important to evaluate risk factors for subsequent aneurysmal rupture in order to determine an appropriate treatment.

The cerebral aneurysm has the distinctive characteristics such that it tends to be created at preferential locations among preferential age groups [1]. Since vascular geometry varies with an age, the paper aims to investigate the relationship between cerebrovascular geometry and hemodynamics. The authors have been developing an image-based simulation and database system, which consists of medical image–based geometric modeling, grid generation, finite element fluid simulation, and scientific visualization [3]. The database system is designed so as to organize and analyze medical imaging, physiological, and numerical data.

In order to conduct parametric study to evaluate the effects of vascular geometry on hemodynamics, the paper focuses on three-dimensional image-based modeling. In the paper, the cerebrovascular model is constructed using the level set method as a geometric image segmentation technique followed by B-Spline surface reconstruction. The present construction technique is compared with the conventional one, in which segmentation is conducted using methods based on intensity thresholding and then reconstruction is done by Marching Cubes method. Since the geometric parameters of cerebral artery can be derived from the present geometric model construction, the vascular geometry can be varied. The numerical simulations are conducted for the deformed geometric models and the results are compared with those of the original model.

CONSTRUCTION OF GEOMETRIC MODEL

Segmentation from the CT images

Since the CT values of bones and arteries are close, it is difficult to distinguish the boundarry. The level set method is an implicit boundary-tracking technique and can handle arbitrary topological changes. The geometry's evolution is described as the level set function ϕ with the following partial differential equation [4]:

$$\frac{\partial \phi}{\partial t} + v\left|\nabla \phi\right| = 0 \tag{1}$$

$$v = \frac{1}{1 + \nabla G(x,y) * \left(I(x,y)\right)} \tag{2}$$

$$G(x,y) = \frac{A}{2\pi\sigma} \exp\left\{-\frac{x^2+y^2}{2\sigma^2}\right\} \tag{3}$$

where v is the velocity function, I is image intensity, and A and σ are control parameters.

Figure 1. (1)-(4) show the original image (1) and comparison of segmentations between a intensity threshold (2) and the level set method (3 and 4).

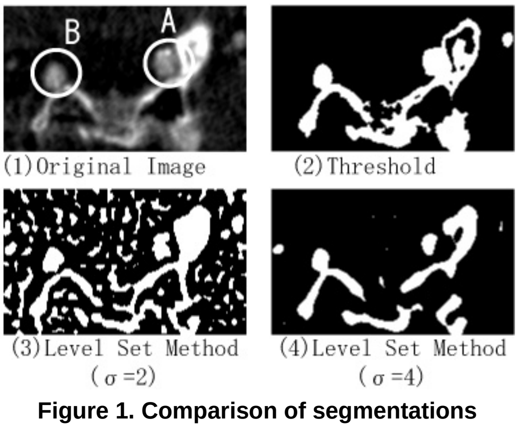


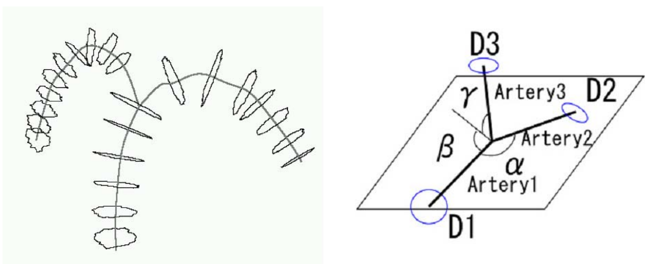
Figure 1. Comparison of segmentations

The arteries in the images are marked as A and B in Fig. 1(I). As shown in the results of an intensity threshold (Fig. 1 (2)), the boundary between the bone and the artery is not tracked. On the contrary, the level set method can distinguish the boundary clearly as shown in Figs. 1 (3) and (4), where the control parameters are A=5, and σ=2 for (3) and σ=4 for (4). However, if σ becomes large, the smoothness of the boundary becomes excessive as shown in Fig. 1(4).

Three-dimensional surface reconstruction

To determine geometric parameters followed by deformation of the 3-D models, reconstruction is carried out using B-spline surfaces. After 2-D cross-sectional segmentation operations, the centerline of each extracted artery is determined using the method developed by Saito, et al. [5]. As shown in Fig. 2 (1), perpendicular cross-sections are oriented along the centerline and B-spline surfaces are reconstructed according to the centerline and cross-sectional plane.

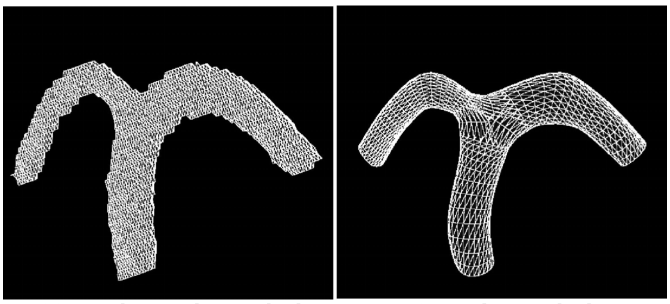
The parameters comprise diameter of arteries 1,2, and 3 and angle between arteries, α, β, and γ as shown in Fig. 2 (2). The model varies by changing the distance from the centerline or the angle of bifurcation from the centerline.



(1) Medial axis and cross section (2) Parameters of geometry

Figure2. Geometric parameters and deformation of model

Figures 3 (1) and (2) compare 3-D surface reconstruction using Marching Cubes and B-Spline methods. The present method can construct smoother surface comparing with Marching Cubes method.

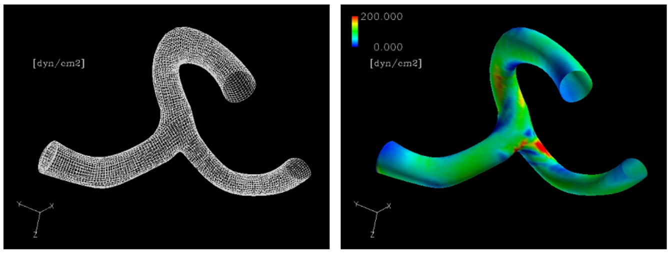


(1) Marching Cubes method (2) B-Spline method

Figure 3. 3-D surface reconstruction

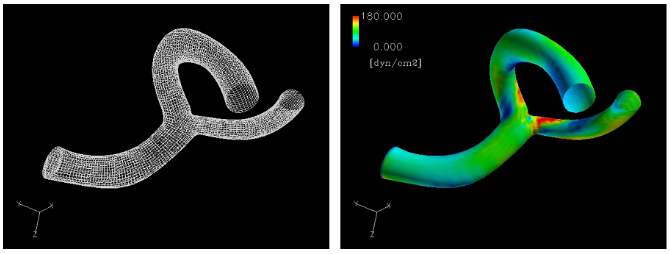
NUMERICAL SIMULATION

Blood is assumed to be Newtonian incompressible flow, whose governing equations are the continuity and Navier-Stokes equations. The simulations are performed for blood flow in the middle cerebral artery (MCA) using the finite element method (FEM). Figure 4 (1) shows the original vascular model of MCA extracted from the CT images with D_1 = 2.41 mm, D_1/D_p = 0.8, and α= 100.4 degrees. On the other hand, Fig. 5 (1) shows the deformed model of original model with the same D_1 and D_1/D_p but α= 150.0 degrees, which is varied from α= 100.4 degrees. Creation and rupture of cerebral aneurysm has a strong correlation with wall shear stress distributions. Thus, Figs. 4 (2) and 5(2) describe the wall shear stress distribution at systole. As shown in the figures, the wall shear stress distribution changes, particularly near the bifurcation area. As the bifurcation angle between the parent artery 1 and the child artery 2 becomes large, the higher wall shear stress appears in the other artery 3 as shown in Fig. 5 (2).



(1) FEM mesh (2) The wall shear stress distribution

Figure 4. CT image-based model of middle cerebral artery



(1) FEM mesh (2) The wall shear stress distribution

Figure 5. Deformed model of middle cerebral artery

CONCLUSIONS

The 3-D vascular geometric construction is presented. The segmentation is carried out by the level set method and the surface reconstruction is done using the B-Spline surfaces. The present method can track the boundary of artery clearly and can obtain smoother surfaces comparing to the conventional method. In addition, the parameters of cerebrovascular geometry are derived and the geometric model are varied by the geometric parameters. The numerical simulation are conducted and the results of the deformed model are compared with those of original model. Further investigation will be carried out using different models in order to evaluate the effects of vascular geometry on hemodynamics and will be presented at the conference.

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