Numerical Simulation of the Intra-Aneurysmal Flow Dynamics

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Summary

Intra-aneurysmal flow dynamics is analyzed qualitatively and quantitatively with numerical simulation technique, and presented for the future clinical application in embolizing cerebral aneurysms. From the volumetric data obtained by three-dimensional computed tomographic angiography, patient-specific vessel models were created for 16 middle cerebral artery aneurysms. Intra-aneurysmal flow dynamics was visualized and analyzed qualitatively, and the geometrical parameters of vessels and aneurysms that affect the intra-aneurysmal flow dynamics were determined quantitatively by correlation analysis. The flow velocity was delayed in the aneurysm cavity, especially at its tip where the rupture usually occurs.

The intra-aneurysmal flow dynamics was considerably influenced by the geometrical parameters that are related to the width of the neck and the branching angle of larger branch artery. The intra-aneurysmal flow dynamics is complex, and the numerical flow simulations with patient-specific vascular models seems effective in understanding the flow dynamics and planning the endovascular treatment of cerebral aneurysms.

Introduction

Haemodynamics plays a crucial role in the rupture of cerebral aneurysms¹, and the endovascular treatment of cerebral aneurysms in-

tends to change the hemodynamic flow pattern, which may enhance thrombosis and healing within the aneurysms. Preoperative information of the intra-aneurysmal flow dynamics may contribute largely in planning of the optimal treatment of cerebral aneurysms. Previous studies have disclosed the intra-aneurysmal hemodynamics in simple idealized geometries², however, more patient-specific hemodynamic information is desired in order to design a patient-specific therapeutic plan.

Numerical flow simulation provides the visualization and quantification of the haemodynamics in temporal and spatial detail, and this technique has already been applied to predict the complex hemodynamics around the bifurcation of cerebral arteries from the simple geometrical parameters³, and to evaluate the role of wall shear stress in the development and the rupture of cerebral aneurysms⁴. In this paper, the intra-aneurysmal flow dynamics is analyzed qualitatively and quantitatively with numerical simulation technique, and presented for the future clinical application in embolizing cerebral aneurysms.

Methods

The patient population and the methods of this study are partially same as those of our previous paper⁴, and the details are described there.

Figure 1 Geometrical parameters. D_p , D_1 and D_2 are the diameters of parent artery, larger branch artery and smaller branch artery, respectively. D_n is the diameter of the aneurysm inlet, and H is the height of the aneurysm. Alpha (α) is the angle between the axis of parent artery and the normal vector of the aneurysm inlet plane. Alfa 1 (α_1) and 2 (α_2) are the angles between the axis of parent artery and the axis of branch arteries.

From the volumetric data obtained by three-dimensional (3-D) computed tomographic angiography, patient-specific vessel models were created for 16 middle cerebral artery aneurysms. The aneurysm and the 20 mm of vessels were trimmed out for the computational analysis, and intersecting planes dividing the aneurysms from the surrounding arteries were created to measure the flow volume that entered into the aneurysms. Spatial average of the flow velocity in the aneurysm cavity was also calculated.

Table 1 Correlation coefficients between the geometrical parameters and the intra-aneurysmal flow volume and velocity.

Geometrical Parameter	Flow Volume	Flow Velocity
α_1	-0.44	-0.33
$80^\circ - \alpha_1$	-0.61	-0.57
α_2	-0.02	+0.19
α	-0.67	-0.09
D_1/D_p	-0.19	-0.16
D_2/D_p	0.03	0.08
D_n/D_p	0.83	0.34
Aspect ratio	-0.23	-0.55

Numerical simulations of flow dynamics in these models were executed using our original finite-element code³. Blood was assumed an incompressible Newtonian fluid and the vessel wall was assumed rigid. For the inlet of MCA, pulsatile flow with a Womersley velocity profile was simulated with a typical MCA velocity waveform. Traction free boundary condition was applied to the outlets of the vessel models.

Intra-aneurysmal flow dynamics was analyzed qualitatively with the cross-sectional visualization of the velocity field. For quantitative analyses, geometrical parameters of the aneurysm shape and the surrounding arteries were determined as shown in figure 1. Correlation coefficients were calculated between these geometrical parameters and the intra-aneurysmal flow volume and velocity.

Results

Qualitative Analysis

The flow was stagnated in the aneurysm, and the flow velocity in the aneurysm cavity was always slower than that in the arterial lumen. At the bottom of the aneurysm, relatively fast flow was observed. In contrast, at the top of the aneurysm, the flow velocity was markedly slow and the bloodstream recirculated there.

Flow simulation clearly visualized the inflow zone and the outflow zone at the inlet of the aneurysms. The inflow zone was smaller than the outflow zone, and the velocity of the inflow zone was faster than that of the outflow zone in all 16 cases.

Quantitative Analysis

The result of correlation analyses is summarized in the table. Geometrical parameters related to the width of the aneurysm neck (D_n/D_p and Aspect ratio (AR)) related moderately to the intra-aneurysmal flow volume and velocity. There was a tendency that the wider the neck was, the more blood entered in the aneurysm and the faster the intra-aneurysmal flow velocity was.

There was a trend that the parameters of the larger branch had more influences on the intra-aneurysmal flow volume and velocity than those of the smaller branch. The branching angle influenced on the intra-aneurysmal flow than the diameter of the branch artery. The intra-aneurysmal flow volume and velocity became maximum when the branching angle of

Figure 2 Visualization of intra-aneurysmal flow dynamics of three MCA aneurysms. Colored contour reflect the magnitude of velocity and the vectors reflect the direction of flow. A and B, a ruptured case. Flow is delayed at the tip of aneurysm. In-flow zone is smaller than the outflow zone. C and D, an unruptured case. E and F, an ruptured case.

the larger artery was 80 degree. There was a trend that the wider the difference from the 80 degree, the slower and the less flow volume entered into the aneurysm.

Discussion

The present study revealed that the flow velocity is delayed in the aneurysm cavity, especially at its tip where the rupture usually occurs. The intra-aneurysmal flow dynamics was considerably influenced by the geometrical parameters that are related to the width of the neck (D_n/D_p and AR) and the branching angle of larger branch artery.

The slow flow at the upper part of the aneurysm favors the endovascular treatment of the ruptured cerebral aneurysm. Thrombosis could be accelerated with coils at the top of the aneurysm, where the rupture usually occurs. Thus, the goal of the initial treatment of aneurysmal subarachnoid haemorrhage, that is, the prevention of rebleeding, could be achieved with the coil embolization. However, the fast flow at the lower part of the aneurysm may cause the regrowth of the aneurysm, and this can reduce the reliability and the completeness of the endovascular treatment for the unrup-

tured cerebral aneurysm. Preoperative simulation of the intra-aneurysmal flow dynamics may be useful in selecting the candidate for the endovascular treatment and in planning additional intervention like the flow diversion with bypass surgery.

Preoperative flow simulation may be useful in planning the embolization with liquid materials. It is preferable that they are injected in the low velocity area at first. Simulation will be useful in deciding the position of the microcatheter tip, and in deciding the termination of the embolization.

Intra-aneurysmal flow dynamics differs individually, and the fluid dynamic simulation should be done with patient-specific data for the preoperative planning of endovascular therapy. In the near future, magnetic resonance imaging can provide the information of the intra-aneurysmal flow dynamics.

Conclusions

The numerical flow simulations with patient-specific vascular models seems effective in understanding the flow dynamics and planning the endovascular treatment of cerebral aneurysms.

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