Computational Hemodynamics for a Pair of Intracranial Aneurysms Treated with Flow Diverting Stents

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Abstract

Flow diverting stent is a stent-like device with higher metal coverage rate to occlude the intracranial aneurysms. Comparing to coils, flow diverting stent is considered more effective and lower recanalization rate. In this article, a pair of intracranial aneurysms, both located at the two sides of the parent artery and one aneurysm sac involving a branch artery, were treated virtually with two kinds of flow diverting stents: LVIS and Pipeline by rapid deployment method. Blood flows in the pair of aneurysms before and after treatment were simulated by computational fluid dynamics and the hemodynamic parameters such as velocity, wall shear stress were calculated. Analyzing the numerical results, it was observed that velocity reduction of the treated aneurysms with Pipeline was much larger than with LVIS, wall shear stress on the treated aneurysm with Pipeline is much smaller than with LVIS, and the increment of flow rate at the branch artery when the aneurysm treated with Pipeline was larger than that with LVIS. The following conclusions can be summarized that Pipeline is more effective to occlude the aneurysm than LVIS, but the aneurysm treated with Pipeline has more rupture risk than with LVIS. The branch artery located at the aneurysm sac has suction effect when the aneurysm is treated with flow diverting stent, which reduces velocity further inside the aneurysm sac and benefits embolization formation.

Keywords: Hemodynamics, Intracranial aneurysm, Flow diverting stent, Computational fluid dynamics

Introduction

Intracranial aneurysms are pathologic dilations of the intracranial arteries, generally located at the circle of Willis. Rupture of intracranial aneurysms causes subarachnoid hemorrhage with an associated high mortality and morbidity rate [1]. Endovascular treatment is a minimally invasive surgery which releases coils or stent-assisted coils to occlude aneurysms in order to prevent blood flowing into the aneurysmal sacs and promote thrombus formation. However the aneurysms occluded with coils have high recanalization rate comparing to surgery clipping [2]. Flow diverting stent is a new endovascular device to occlude the aneurysm and it is a braided stent with higher metal coverage rate. An intracranial aneurysm occluded by a flow diverting stent is considered much lower recanalization risk than coils embolization [2]. Many investigators have studies the relationship between hemodynamics and intracranial aneurysms and it is widely agreed that hemodynamics plays a very important role in the initiation, growth and rupture of intracranial aneurysms. The change of hemodynamics when flow diverting stents deployed to treat intracranial aneurysms has been studies by many research groups [3-7]. However, when intracranial aneurysms involving branch arteries, the aneurysms treated with flow diverting stents may occlude branch arteries to induce cerebral ischemia. Hence change of hemodynamics when the aneurysm involved branch vessel treated with flow diverting stent is very complicated but has rarely been discussed. In this study, a pair of intracranial aneurysms involving a branch artery at one aneurysm sac will be treated virtually with two kinds of flow diverting stents by Rapid deployment technique. Blood flows in the aneurysms before and after treatment will be simulated by computational fluid dynamics, and the hemodynamic parameters such as velocity, flow rate, and wall shear stress will be calculated. By analyzing the changes of these parameters after the aneurysms treated with flow diverting stents, the effects of the different stents will be discussed and compared from the hemodynamic viewpoint.

Methodology

A 53 year-old female patient was suffering from a pair of aneurysm sacs located two sides of the left internal carotid artery. The patient-specific geometrical model was constructed from the medical image data. The two kinds of flow diverting stents were deployed into the parent artery across the orifices of both aneurysms by rapid virtual deployment technique. Blood flows in the aneurysms before and after treatment were simulated by computational fluid dynamics. This section introduces the details of these methods.

Vascular Models

A pair of intracranial aneurysm sacs located at the left internal carotid artery were selected to study. The two aneurysm sacs located at the two sides of the parent artery and a branch artery locates at the upper sac of the aneurysm model, see the left figure of Figure 1. The 3D geometry of the artery was constructed from the patient undergoing clinically indicated conventional angiography with rotational data acquisition. The reconstructed 3D geometry of the artery was exported into STL (Stereo Lithography format) format file. The geometry was imported into the reverse engineering software Geomagic studio 11.0 to segment, repair and smooth. After these stages, the geometrical model of the aneurysm was constructed. The diameters of the inlet and the outlet at the artery are 4.8 mm and 4.4 mm, respectively, and the diameter of branch artery is 1.8 mm.

Virtual Deployment

To treat a pair of aneurysm sacs located at two sides of the same position of the parent artery, comparing to coils embolization, flow diverting stent has lower money cost and simpler procedure. Assuming that the pair of aneurysm sacs are treated with two kinds of flow diverting stents: LVIS and Pipeline, both are widely employed in clinic. The difficulty of the virtual treatments is to deploy flow diverting stent into the aneurysm model reasonably. Finite element method is capable to deploy flow diverting stents virtually but it is very complicated for modeling and time consuming for simulation [8-9]. Rapid virtual deployment technique based on simplex mesh method or spring theory has been applied to deploy flow diverting stents virtually by many groups and it has been proved acceptable from the geometry and the artery wall attaching [10-12]. Both flow diverting stents are deployed virtually into the parent artery across the aneurysms orbits by rapid virtual deployment technique. Actually, both flow diverting stents have the different geometric parameters such as the number of struts, the diameter of the strut and the metal coverage rate, presented in Table 1.

Table 1. Geometric parameters of LVIS and Pipeline

	LVIS	Pipeline
Number of the struts	16	48
Diameter of the strut (μm)	61	48
Metal coverage rate	20%	29%

Figure 1: The models of a pair of aneurysm sacs before (Left) and after treated with LVIS (Middle) and Pipeline (Right)

Numerical Simulations

The computational meshes of the aneurysm models were generated by Ansys ICEM-CFD 15.0, and the unstructured meshes composed of tetra elements were specified as follows: the max element size in the artery was 0.3 mm, the max element sizes near the metal struts of LVIS and Pipeline were 0.03 mm and 0.02 mm, respectively, in order to capture the strut wires. Blood was assumed as Newtonian flow with density 1050 kg/m^3 and dynamic viscosity 0.0035 Pa•s. The steady laminar flows in the models were simulated by the commercial CFD package ANSYS CFX 15.0. A parabolic velocity profile was imposed at the inlet and the average velocity at the inlet was calculated by Poiseuille law to guarantee the average wall shear stress at the inlet artery to be 1.5 Pa [4-7]. The boundary condition was traction-free with 10000 Pa reference pressure at the outlets. The walls of the artery and the struts of the flow diverting stents had no-slip condition.

Results and Discussion

Figure 2 demonstrates velocity contours on the center plane cross the pair of aneurysm sacs before and after treated with LVIS and Pipeline. It is observed that the velocity in the pair of aneurysm sacs, especially in the upper sac, is reduced remarkably after treated with Pipeline, but LVIS is not so effective to reduce the velocity inside the aneurysm sacs. Figure 3 demonstrates wall shear stress on the pair of aneurysms before and after treated with LVIS and Pipeline. It is observed that wall shear stress on the aneurysm sacs is reduced remarkably after treated with Pipeline, but the reduction on the aneurysm sacs after treated with LVIS is small. Moreover, no obvious change can be observed on the parent artery after treated with flow diverting stents. In order to occlude the aneurysm by flow diverting stents, the more velocity reduction is expected and therefore Pipeline is more effective to occlude aneurysms than LVIS. On the other hand, lower wall shear stress is considered to be a high risk factor related to the aneurysm rupture [3-4], therefore the aneurysm treated with Pipeline has higher risk to rupture than treated with LVIS. Table 2 demonstrates the variation of flow rat at the inlet, outlet and small branch artery before and after treatment. It is observed that the flow rate at the branch artery increases when Pipeline or LVIS is deployed to occlude the aneurysm sacs and the increment with Pipeline is larger than that with LVIS. Actually, Pipeline has higher metal coverage rate than LVIS, therefore it is understood easily that Pipeline is more effective to reduce the velocity inside the aneurysm sacs than LVIS. However, the branch artery located at the upper aneurysm sac has the suction effect when a flow diverting stent is deployed to occlude the aneurysms, that is why the flow rate at the branch artery is increased after treatment, and the suction effect of branch artery can reduce the velocity inside the aneurysm sac further.

Table 2: Flow rate at the branch vessel before and after the aneurysms treated with LVIS and Pipeline

Flow rate (ml/s)	No treatment	LVIS	Pipeline
inlet	4.88	4.88	4.88
outlet	4.65	4.54	4.52
branch	0.23	0.34	0.36

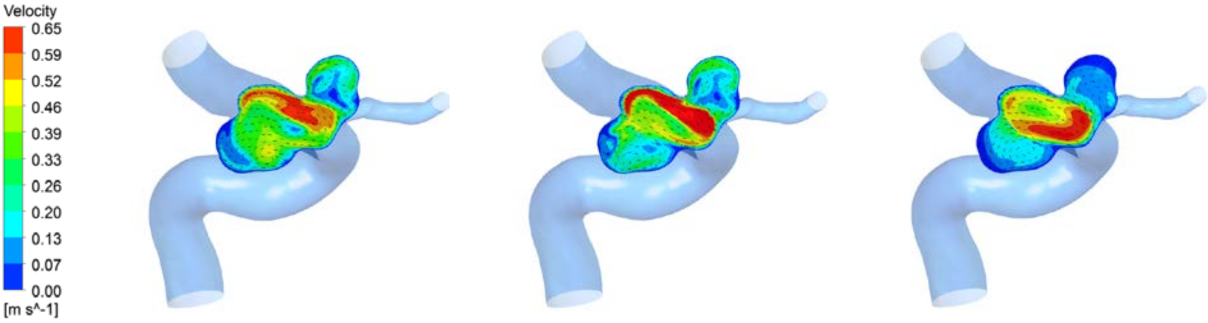

Figure 2: Velocity contours on the cross section of the pair of aneurysms before (Left) and after treated with LVIS (Middle) and Pipeline (Right)

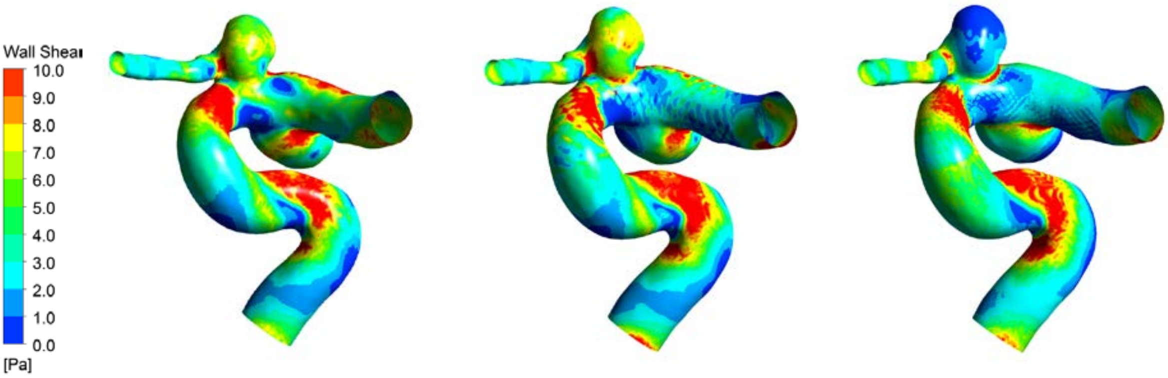

Figure 3: Wall shear stress contours on the aneurysm before (Left) and after treated with LVIS (Middle) and Pipeline (Right)

Conclusions

The following conclusions can be drawn from the numerical results: Pipeline is more effective to occlude the aneurysm than LVIS, but the aneurysm treated with Pipeline has more rupture risk than with LVIS. The branch artery located at the aneurysm sac has the suction effect when the aneurysm sacs are occluded with flow diverting stents, which reduces the velocity inside the aneurysm sac further and benefits embolization formation.

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