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Hemodynamics investigation for a giant aneurysm treated by a flow diverter implantation

Shengzhang Wang [a], Jianjun Li [a], Chao Wang [b], Xinjian Yang [b,*], Shiqing Mu [b] and Wuqing Wang [c,*]

[a] *Department of Mechanics and Engineering Science, Fudan University, 220 Handan Road, Shanghai 200433, China*

[b] *Beijing Neurosurgery Institute, 6 Tiantan Xili, Beijing 100050, China*

[c] *Department of Dermatology, Minghang District Central Hospital, 170 Xinsong Road, Shanghai 201199, China*

Abstract. Flow diverter is a kind of stent-like devices with higher metal coverage rate, and it is deployed endovascularly to treat cerebral aneurysms, especially to treat giant aneurysms. However, there exist some arguments about its safety and efficacy. Hemodynamics is considered to play very important role during the initiation, growth and rupture of cerebral aneurysms. In this study, the models of a giant cerebral aneurysm involved a small branch at the aneurysmal sac before and after flow diverter implantation were constructed by virtual deployment, the blood flows in the models were simulated by computational fluid dynamics method. Analyzing the variations of the hemodynamics, the following conclusions were summarized. The flow diverter is very effective device to occlude the aneurysm, the flow rate at the small branch was rarely changed when the flow diverter deployed and the flow diverter.

Keywords: Cerebral aneurysm, hemodynamics, flow diverter, virtual deployment, numerical simulation

1. Introduction

Cerebral aneurysms are pathologic dilations of the cerebral arteries generally occurred in the anterior and posterior regions of the circle of Willis. Rupture of a cerebral aneurysm causes subarachnoid hemorrhage with an associated high mortality and morbidity rate. The mechanisms responsible for the initiation, evolution and rupture of cerebral aneurysms are not well understood until now. However, it is widely accepted that hemodynamics plays a very important role in the initiation, growth and rupture of

*Address for co-corresponding authors: Xinjian Yang, Beijing Neurosurgery Institute, 6 Tiantan Xili, Beijing 100050, China. Tel.: +86-1-67098852; Fax: +86-21-67018349; E-mail: yang-xj@163.com. Wuqing Wang, Department of Dermatology, Minghang District Central Hospital, 170 Xinsong Road, Shanghai 201199, China. Tel.: +86-21-64923400; Fax: +86-21-64923400-4406, E-mail: wuqingw2006@sina.com.

cerebral aneurysms [1]. Coils is the most common used device to occlude the aneurysms endovascularly, but it has the disadvantage that coiled aneurysms, the giant aneurysms especially, have higher recanalization risk than the surgery clipping [2]. Flow diverter is a new endovascular device to occlude the aneurysm and it is a metal stent-like device with lower porosity. Aneurysm occluded by a flow diverter is considered much lower recanalization risk than coils embolization [3]. But it was reported that some aneurysms after flow diverter implantation ruptured [4] and the related research proposed that the rupture aneurysm after flow diverter implantation had a higher pressure increment, but this conclusion was argued by others. In addition, when the giant aneurysm involves a small branch at the aneurysmal sac, the influence to flow rate at the small branch when the flow diverter deployed has never been discussed. In this study, the model of a giant cerebral aneurysm involved a small branch was selected to be treated by the virtual flow diverter deployment technique, the blood flows in the aneurysm before and after the treatment were simulated numerically by computational fluid dynamics method, and the variations of the hemodynamics factors related to the regrowth and rupture such as velocity, flow rate, wall shear stress etc. were investigated.

2. Materials and methods

2.1. Patient-specific model of cerebral aneurysm

A giant cerebral aneurysm located at the right internal carotid artery was selected to study. The 3D geometry of the cerebral vessel was constructed from the patient undergoing clinically indicated conventional angiography with rotational data acquisition. The reconstructed 3D geometry of the cerebral vessel was exported into STL (Stereo Lithography format) format file. The geometry was imported into Geomagic studio 11.0 (Geomagic Inc., NC, USA) to segment, repair and smooth. After these stages, the geometrical model of the aneurysm was constructed. In Figure 1, the left is the geometrical model of the giant aneurysm. The diameter of the inlet artery in the aneurysm model is 4.4 mm, the diameters of the outlet and the small branch are 3.8 mm and 1.8 mm, respectively. The maximum diameter of the giant aneurysm is 25 mm and the AR (aspect ratio, Depth/Width) is about 0.82.

2.2. Virtual implantation of the flow diverter

The giant cerebral aneurysm was treated virtually by a flow diverter (Tubridge, produced by Shanghai MicroPort Medical Co., Ltd.) implantation. The diameter and the metal coverage rate of the flow diverter are 4.5 mm and 22%. The flow diverter was deployed into the aneurysm by the simplex mesh method [5]. In Figure 1, the right is the model of the giant aneurysm with the flow diverter implantation.

2.3. Mesh generation

The computational meshes of the aneurysm models were generated by Ansys ICEM-CFD 13.0, and the unstructured meshes composed by tetra elements were specified as follows: 0.28 mm was set to the max element size in the aneurysm, 0.03 mm was set to the max element size near the metal struts of the flow diverter in order to capture the boundary. The numbers of elements in the computational meshes for the aneurysm model and the model of the aneurysm with flow diverter implantation were demonstrated in Table 1. Because the element number of per cubic millimeter in the models before and after flow diverter implantation was more than 1,800, it can be believed that the computational results did not depend on the meshes [6].

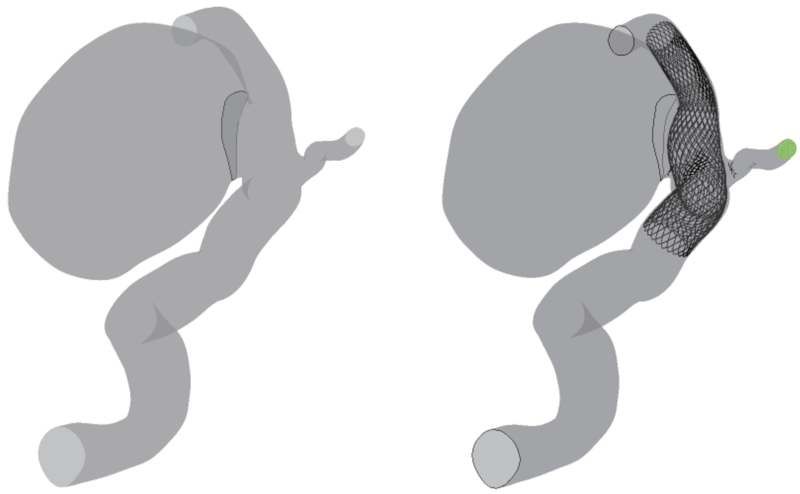

Fig. 1. A giant cerebral aneurysm before and after a flow diverter deployed virtually

Table 1
Computational meshes before and after flow diverter implantation

	Number of nodes	Number of elements	Number of elements in per mm^3
before	1,282,662	7,611,281	1,823
after	2,164,973	12,012,340	2,850

2.4. *Boundary conditions*

The artery wall was assumed to be rigid because the material properties and the thickness of the artery is very difficult to obtain. Steady flow simulation can accurately approximate the wall shear stress on the aneurysm wall but the computation time is much smaller [7] though the blood flow is pulsatile. A parabolic velocity profile was imposed at the inlet. 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. The boundary condition was traction-free with 10000 Pa reference pressure at the outlets. The wall of the artery and the struts of the flow diverter had no-slip condition.

2.5. *Numerical scheme*

The computational meshes were imported into the commercial CFD package ANSYS CFX 13.0 (Ansys, Inc., Canonsburg, PA, USA) to simulate the blood flow in the aneurysm before and after flow diverter implantation. The finite volume method is employed to solve the Navier-Stokes equations in Ansys CFX 13.0 to obtain both the pressures and the velocities. The convergence criteria of the simulations was the residuals of velocity and mass less than 1×10^{-5}. Because the diameter of the parent artery in the aneurysm is larger than 1 mm, blood can be treated as incompressible Newtonian fluid with density 1050 kg/m^3 and viscosity 0.0035 Pa·s [8]. It should be noted that the Reynolds numbers in the inflow pipe was about 200, and thus the laminar flow was reasonable.

Table 2
Hemodynamics variation in the aneurysmal sac before and after flow diverter implantation

	Average Velocity (m/s)	Average Pressure (Pa)	Average WSS (Pa)
before	0.057	10646	0.69
after	0.023	10723	0.48

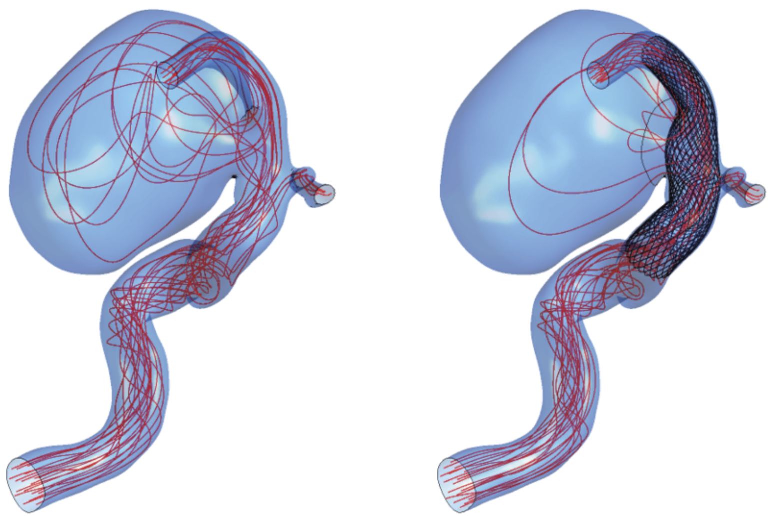

Fig. 2. Streamlines before and after a flow diverter deployed

3. Results and discussion

Figure 2-5 present the distribution of the hemodynamics factors such as streamlines, pressure, velocity and wall shear stress and Table 2 demonstrates the variation of average velocity, pressure and wall shear stress on the aneurysmal sac before and after the flow diverter implantation.

3.1. Streamline and flow pattern

Figure 2 shows the streamlines in the cerebral aneurysm before and after flow diverter implantation. It is observed that the velocity is decreased remarkably and the flow structure becomes simpler after the flow diverter implantation.

3.2. Velocity distribution

Figure 3 shows the velocity distribution on the cross section of the aneurysm before and after flow diverter implantation. It is observed that the velocity inside the aneurysmal sac is reduced remarkably after the flow diverter implantation. The average velocity inside the aneurysmal sac is decreased from 0.057 m/s to 0.023 m/s.

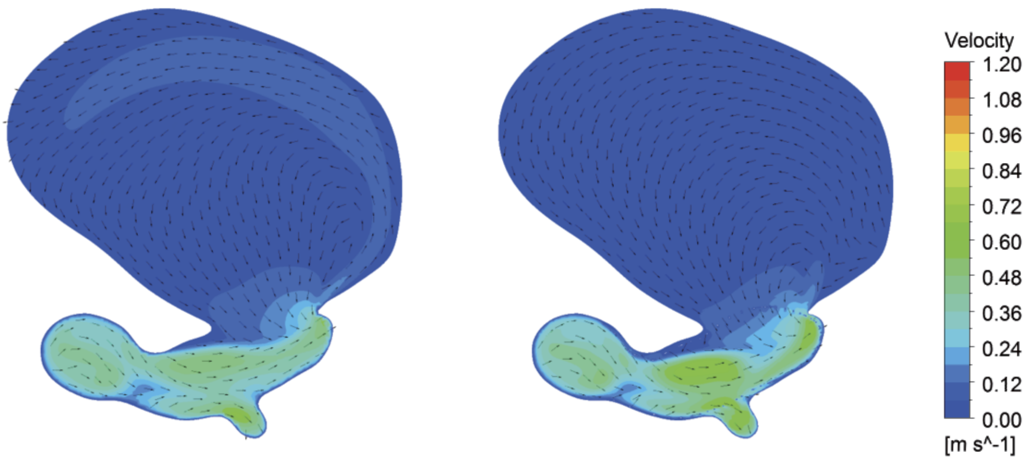

Fig. 3. Velocity contours in a cross section before (left) and after (right) a flow diverter deployed

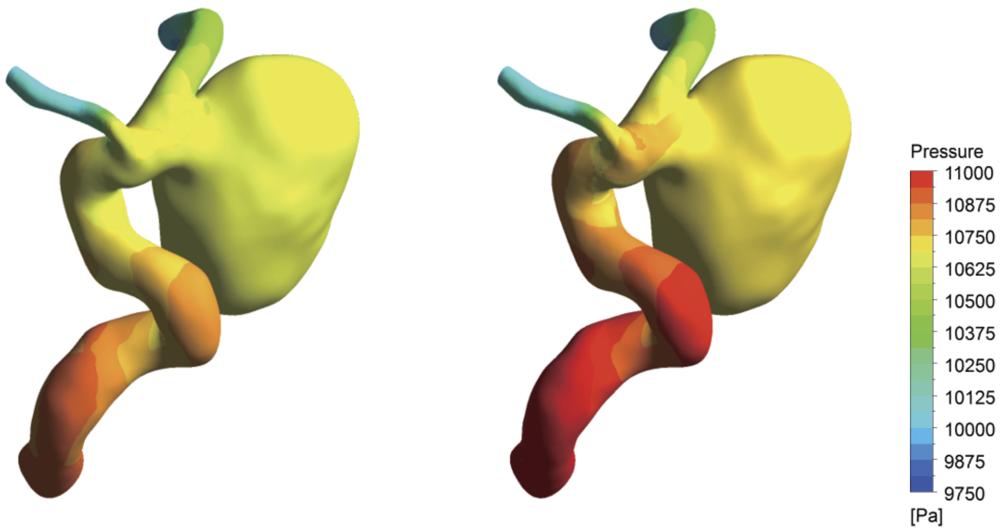

Fig. 4. Pressure contours before (left) and after (right) a flow diverter deployed

3.3. Pressure

Figure 4 shows the pressure distribution on the aneurysm wall before and after the flow diverter implantation. It is observed that the pressure on the aneurysmal sac is increased from 10646 Pa to 11723 Pa. This is due to the resistance increased after the flow diverter implantation, therefore the pressure on the aneurysmal sac increases when the flow rate keeps constant. In fact, the pressure increment is less than 1%.

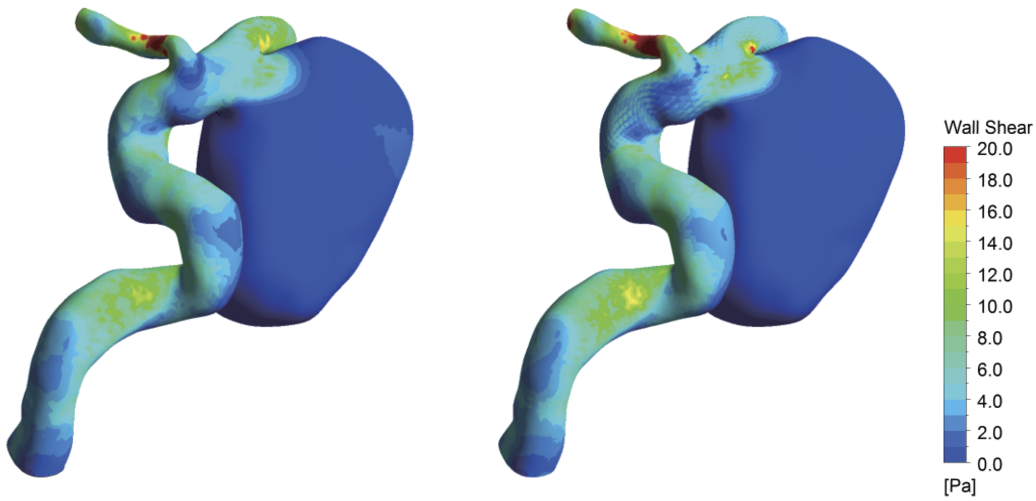

Fig. 5. Wall shear stress contours before (left) and after (right) a flow diverter deployed

Table 3
Flow rate before and after the flow diverter implantation

Flow rate	before (mm^3/s)	after (mm^3/s)	variation rate(%)
inlet	4.86	4.86	0
outlet	3.52	3.62	2.8
branch	1.36	1.26	-7.4

3.4. Wall shear stress

Figure 5 shows the wall shear stress distribution on the aneurysm before and after the flow diverter implantation. It is observed that the wall shear stress on the aneurysmal sac and on the part of the parent artery connecting to the aneurysm is reduced remarkably. The average wall shear stress on the aneurysmal sac is decreased from 0.69 Pa to 0.48 Pa. However, the wall shear stress located at the distal side of the aneurysmal neck is increased to 22 Pa from 15 Pa after the flow diverter implantation.

3.5. Flow rate

The flow rates in the inlet, outlet and the branch are demonstrated in Table 3. The flow rate in the inlet has no variation after the flow diverter implantation, the flow rate in the outlet has 2.8% increment and the flow rate in the small branch has 7.4% drop. On the other hand, when the flow diverter is implanted into the parent artery to occlude the aneurysm, it may occlude the small branch located at the aneurysmal sac because the struts cover the aneurysmal orifice. However, the flow rates in the small branch decreases less than 10% and the flow diverter does not occlude the small branch.

4. Conclusions

The following conclusions are summarized by analyzing the hemodynamics factors distributions in the cerebral aneurysm before and after the flow diverter implantation:

1) The flow pattern is simplified and the velocity inside the aneurysmal sac is reduced remarkably after the flow diverter implantation, therefore the flow diverter is very effective device to occlude the cerebral aneurysm.
2) The averaged wall shear stress on the aneurysmal sac is decreased from 0.69 Pa to 0.48 Pa, thus the regrowth risk of the aneurysm will be reduced after flow diverter implantation [9–13].
3) The flow rates of the small branch outlet have a little change after the flow diverter implantation, hence it can be believed that the flow diverter changes the flow rate very little at the small branch.

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References

[1] M. Sforza, C.M. Putman and J.R. Cebral, Hemodynamics of cerebral aneurysms, Annual Review of Fluid Mechanics **41** (2009), 91-107.
[2] B. Seibert, R.P. Tummala, R. Chow, A. Faridar, S.A. Mousavi and A.A. Divani, Intracranial Aneurysms: Review of Current Treatment Options and Outcomes, Frontiers in Neurology **2** (2011), 1-10.
[3] F. Mut, E. Scrivano, C. Bleise, P. Lylyk and J. Cebral, Hemodynamics in two tandem aneurysms with flow diverters, Int J Numer Meth Biomed Engng **30** (2014), 517-524.
[4] J.R. Cebral, F. Mut, M. Raschi, E. Scrivano, R. Ceratto, P. Lylyk and C.M. Putman, Aneurysm Rupture Following Treatment with Flow-Diverting Stents: Computational Hemodynamics Analysis of Treatment, American Journal of Neuroradiology **32** (2011), 27-33.
[5] I. Larrabide, M. Kim, L. Augsburger, M.C. Villa-Uriol, D. Rüfenacht, A.F. Frangi. Fast Virtual Deployment of Self-Expandable Stents: Method and in vitro Evaluation for Intracranial Aneurysmal Stenting. Medical Image Analysis **16** (2012), 721-30.
[6] A. Valencia, J. Munizaga, R. Rivera, et al., Numerical investigation of the hemodynamics in anatomically realistic lateral cerebral aneurysms. Conf Proc IEEE Eng Med Biol Soc 2010, 2616-2621.
[7] A.J. Geers, I. Larrabide, H.G. Morales, A.F. Frangi, Approximating hemodynamics of cerebral aneurysms with steady flow simulations, Journal of Biomechanics **47** (2014), 178-185.
[8] F.J. Gijsen, F.N. van de Vosse, J.D. Janssen, The infuence of the non-Newtonian properties of blood on the ?ow in large arteries: steady flow in a carotid bifurcation model, Journal of Biomechanics **32** (1999), 601-608.
[9] I. Chatziprodromou, A. Tricoli, D. Poulikakos, et al., Haemodynamics and wall remodeling of a growing cerebral aneurysm: a computational model, Journal of Biomechanics **40** (2007), 412-426.
[10] J.R. Cebral, M.J. Sheridan and C.M. Putman, Hemodynamics and bleb formation in intracranial aneurysms, American Journal of Neuroradiology **31** (2010), 304-310.
[11] M. Shojima, M. Oshima, K. Takagi K et al., Magnitude and role of wall shear stress on cerebral aneurysm: computational fluid dynamic study of 20 middle cerebral artery aneurysms, Stroke **35** (2004), 2500-2505.
[12] M. Shojima, S. Nemoto, A. Morita, et al., Role of shear stress in the blister formation of cerebral aneurysms. Neurosurgery, **67** (2010), 1268-1274.
[13] B. Luo, X. Yang, S. Wang, et al., High shear stress and low velocity in partially occluded aneurysms prone to recanalization, Stroke **42** (2011), 745-753.