ORIGINAL PAPER

Assessment of endovascular coil configuration for embolization of intracranial aneurysms using computational fluid dynamics

Tomotaka Ohshima[1], Shigeru Miyachi[2], Ichiro Takahashi[3] and Katsuya Ishii[3]

[1]Department of Neurosurgery, Kariya Toyota General Hospital, Kariya, Japan
[2]Department of Neurosurgery, Osaka Medical College, Takatsuki, Japan
[3]Department of Computational Science and Engineering, Nagoya University Graduate School of Engineering, Nagoya, Japan

ABSTRACT

Endovascular coil embolization of arterial aneurysms is often complicated by reduced blood flow to branching arteries. To determine the optimal coil configuration for safe embolization of endovascular aneurysms without compromising blood flow in branching arteries. A 3-dimensional voxel model, built based on an unruptured vertebral artery–posterior inferior cerebellar artery (VA–PICA) aneurysm, predicted to show impairment of flow in the PICA during endovascular coil embolization (Case 0). Six different models of final coil configuration were generated and applied to this aneurysm. Case 1 was a round coil mass. Case 2 was designed with a stent assist. Cases 3, and 4 were designed with a neck remnant and Cases 5 and 6 incorporated a balloon neck remodeling technique. Computational fluid dynamics was used to analyze the flow in the PICA in each model. The average outflow to the PICA was highest in Case 0 and lowest in Case 2 (in descending order, Case 0, 5, 4, 6, 1, 3, and 2). There was better preservation of outflow to the PICA in the balloon neck remodeling models than in the neck remnant models. In a model of endovascular coil embolization, we found considerable differences in outflow to the branching artery with small changes in coil configuration. Careful preoperative planning is important to minimize the risk of thromboembolic events during and after endovascular coil embolization.

Key Words: coil embolization, computational fluid dynamics, intracranial aneurysms

INTRODUCTION

Despite recent advances in endovascular techniques and technology for coil embolization of intracranial aneurysms, thromboembolic complications intra- and post-procedure are not uncommon, particularly in branches originating from the dome of the aneurysm.[1-2] Surgeons often face the dilemma of achieving complete coil obliteration of an arterial aneurysm while preserving blood flow to the branches. Management decisions require a precise assessment of the risks of thromboembolic events tailored to individual aneurysms. The use of computational fluid dynamics (CFD) has helped to clarify patient-specific intra-aneurysmal flow patterns.[3-4]

Here, we attempt to clarify the optimal coil configuration for endovascular embolization without compromising blood flow in the branching arteries, using CFD and a model based on

an unruptured vertebral artery–posterior inferior cerebellar artery (VA–PICA) aneurysm.

MATERIAL AND METHODS

Computational Models

We selected a patient with an unruptured VA–PICA aneurysm predicted to show impairment of flow in the PICA during endovascular coil embolization. Three-dimensional CT angiography was performed using an Aquilion 64 CT scanner (Toshiba Medical Systems, Tokyo, Japan), and a patient-specific model was built using Digital Imaging and Communications in Medicine (DICOM) data. Next, a 3-dimensional voxel model was built (Case 0; Figure 1). This method is less time consuming compared with the method using an unstructured body-fitted grid, and aneurysm models, with or without modifications, can be easily built. We then built 6 models (Cases 1–6) of various idealized final coil configurations in the modeled aneurysm (Figure 2). Case 1 represented a round coil mass. Case 2 was designed with a stent assist. Cases 3, and 4 were designed with a neck remnant. Cases 5 and 6 incorporated balloon neck remodeling techniques. Case 5 incorporated antegrade neck remodeling with a hyper-compliant balloon, and Case 6 incorporated retrograde neck remodeling with a compliant balloon entering the PICA from the VA. Finally, the outflow to the PICA in each of the models was analyzed using CFD.

Computational Simulation

CFD of these models was carried out using the incompressible fluid analysis module in Fujitsu α-Flow software (Fujitsu, Tokyo, Japan). We assumed that a non-Newtonian fluid property for blood and an elastic property of the vessel walls could be neglected. The simulations were performed with the material constants for blood density = 1055 kg/m^3 and blood dynamics viscosity = 0.0049 Pa·s. The governing equations were 3-dimensional incompressible unsteady Navier–Stokes equations. Each simulation was performed for 8 s. The boundary condition "velocity-inlet" was based on data from the patient with the aneurysm selected for modeling, acquired using a 3.0-Tesla MR scanner (Signa Infinity TwinSpeed with Excite [version 12]; GE Healthcare, Milwaukee, WI, USA) with a commercially available 8-channel head array coil. The pressure at the outlets was assumed to be zero at each time step. The grid points in the blood vessel and the aneurysm numbered about 500,000 in each simulation. The calculations were performed with the Fujitsu HPC2500 at the Information Technology Center of Nagoya University.

RESULTS

Imaging and analysis of flow dynamics were successfully obtained for all models (e.g., Case 0; Figure 3). The results of the outflow to the PICA for each model are shown in the Figure 4 and 5. The average outflow to the PICA was highest in Case 0 and lowest in Case 2 (in descending order, Case 0, 5, 4, 6, 1, 3, and 2). There was better preservation of outflow to the PICA in the balloon neck remodeling models than in the neck remnant models. Therefore, a linear coil configuration did not necessarily improve preservation of outflow to the PICA compared with a round coil configuration.
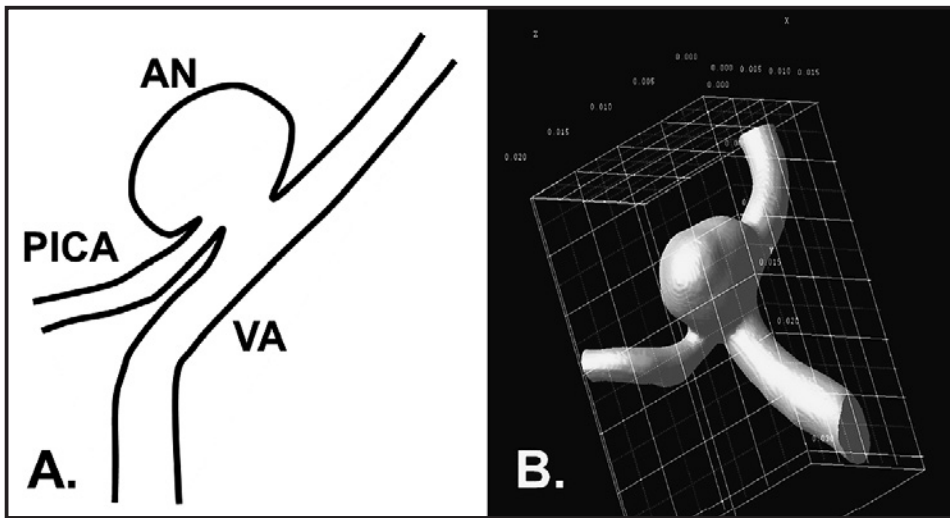
Fig. 1 Patient-specific model (Case 0). **A**: Schema of a vertebral artery (VA)–posterior inferior cerebellar artery (PICA) aneurysm (AN). **B**: Computational 3-dimensional model built from clinical data.
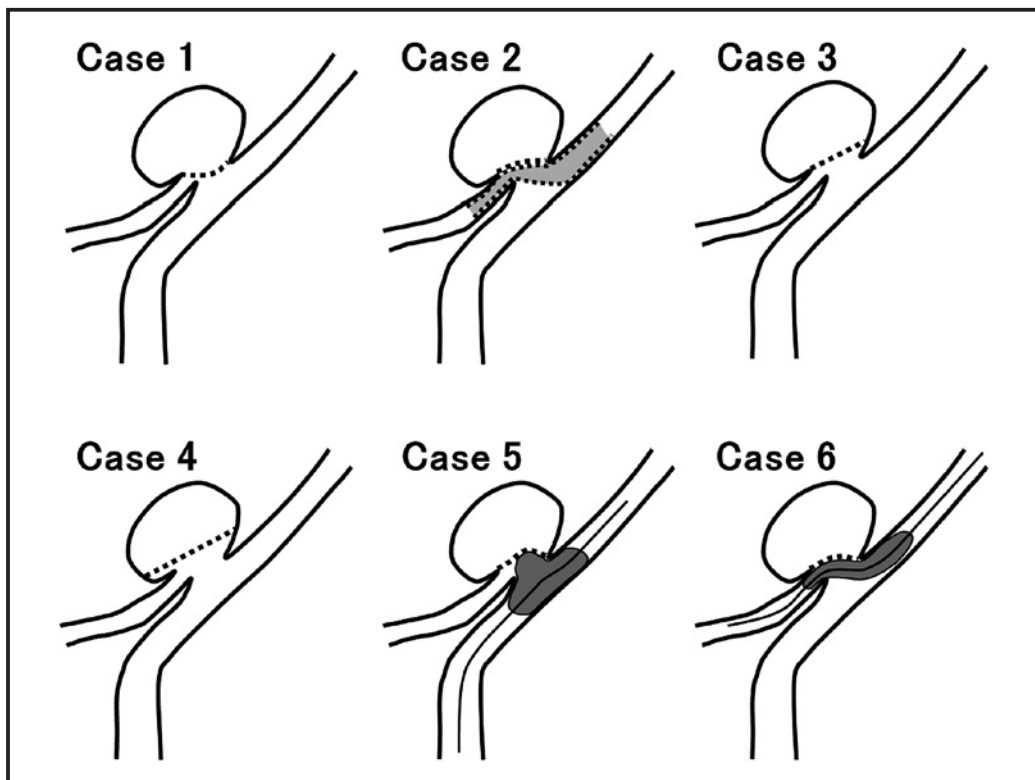

Fig. 2 Schema of 6 models with various final coil configurations in the modeled aneurysm (Case 0). Case 1 represented a round coil mass. Case 2 was designed with a stent assist. Cases 3, and 4 were designed with a neck remnant. Cases 5 and 6 incorporated balloon neck remodeling techniques. Dotted lines: idealized coil margin.
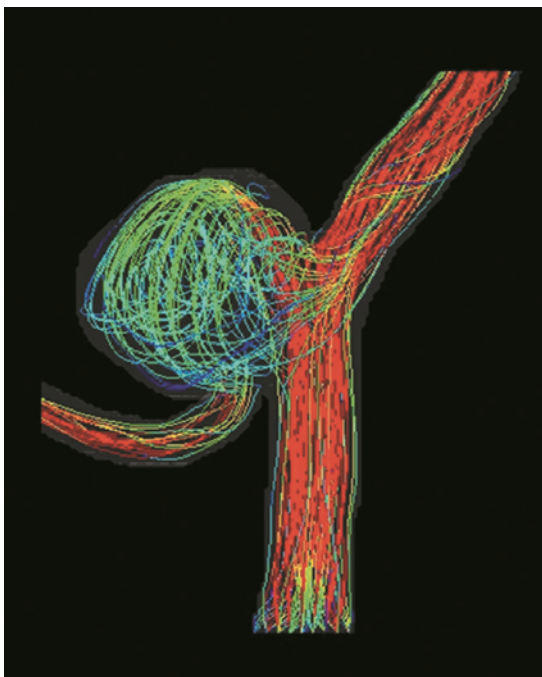
Tomotaka Ohshima *et al.*

Fig. 3 Computational flow dynamic analysis of Case 0. Red lines show the highest velocity, blue lines show the lowest velocity.
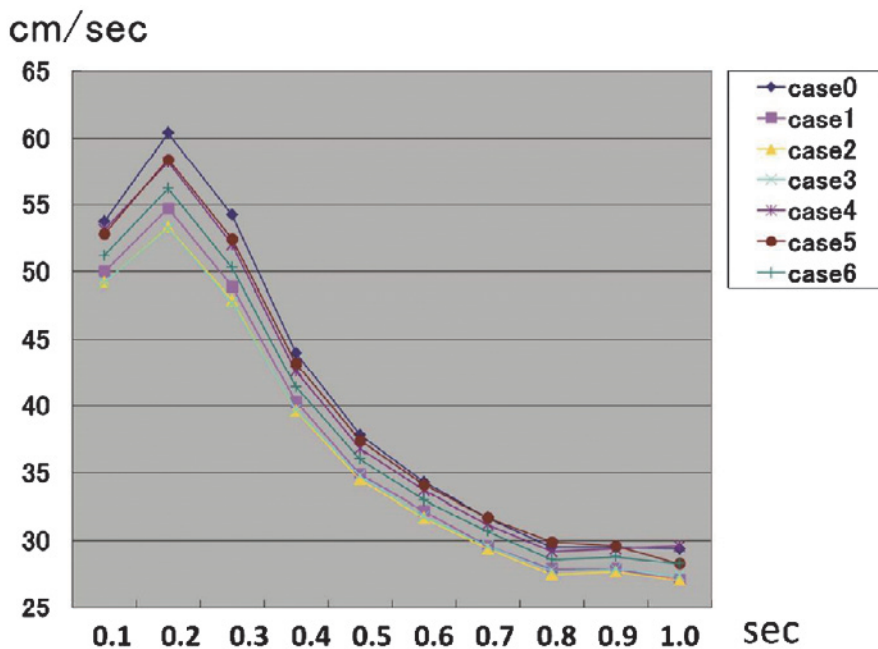

Fig. 4 The results of the outflow velocity to the posterior inferior cerebellar artery. The horizontal and vertical axis shows time (second) and the outflow velocity (m/sec), respectively.

Outflow velocity (m/s)

Time (sec)	case0	case1	case2	case3	case4	case5	case6
0.1s	53.7	50.0	49.2	49.2	53.1	52.8	51.2
0.2s	60.4	54.7	53.3	53.2	58.2	58.4	56.2
0.3s	54.2	48.9	47.9	47.7	52.0	52.4	50.3
0.4s	44.0	40.3	39.6	39.7	42.6	43.2	41.4
0.5s	37.8	34.9	34.5	34.8	36.8	37.4	36.0
0.6s	34.3	32.2	31.7	31.8	33.7	34.1	33.0
0.7s	31.7	29.6	29.4	29.6	31.2	31.7	30.7
0.8s	29.5	27.9	27.5	27.8	29.2	29.9	28.6
0.9s	29.5	27.9	27.7	27.9	29.4	29.6	28.8
1.0s	29.4	27.1	27.1	27.4	29.6	28.3	28.3

Fig. 5   The results of determine the quantity of the outflow velocity in each case.

DISCUSSION

This study reveals that the risk of thromboembolic complications in endovascular-treated aneurysms may be affected by subtle differences in the coil configuration around the aneurysmal neck. The geometry of some PICA aneurysms precludes selective endovascular occlusion of the aneurysm with preservation of flow to the branch. However, direct surgery for these aneurysms is also challenging because of their location and close proximity to the medulla and lower cranial nerves. We used CFD in a modeled VA–PICA aneurysm to determine outflow to the PICA under a number of conditions. The findings could facilitate safety management decisions for coil embolization in PICA aneurysms.

We have previously reported a successful method to make patient-specific aneurysmal models using DICOM data in the rectangular coordinate system.[3-4] In the present study, this aneurysm model was modified and various coil-embolized aneurysms were built. Before running the models, we expected that Cases 2 and 3 would have higher outflow than Case 1. Moreover, we expected that Case 2 would have higher flow than the pretreatment condition (Case 0) because of adjusted flow to the PICA. However, it appears that when the branch originates at a sharp angle, as was the case with this aneurysm, the outflow is highest under the pretreatment condition. The finding of better preservation of outflow in the balloon neck remodeling models compared with the neck remnant models suggests that the use of a balloon to lift the coil mass around the aneurysmal neck was effective. In particular, balloon herniation with a hyper-compliant balloon (Case 5) preserved the highest amount of outflow to the PICA. Therefore, a linear coil configuration is not necessary to preserve outflow. Because surgical closure lines are generally linear, surgeons have to pay careful attention to preserve arterial branches.

Despite recent advances in computational flow analysis, modeled flow is very different from in vivo vascular flow systems.[5-6] For example, whole vessels should be built with elasticity and

thickness. The pulsating motion of vessels, peripheral vascular resistance, and differences among individual patients are also important factors in the accurate evaluation of flow patterns. Previous reports have suggested that the effects of vessel wall elasticity and pulsation are not significant in relation to intra-aneurysmal flow.[7] The present study shows a tendency towards different flow patterns in models with subtle changes in coil configuration in the neck of the aneurysm.

Further research, using patient-specific CFD, is needed to properly analyze the relationship between coil configuration in the neck of an arterial aneurysm and the outflow to the branches. In the future, CFD could be used to assess safety and to determine appropriate coil configurations for individual aneurysms.

CONCLUSIONS

We identified considerable differences in the outflow to the branching artery with small changes in coil configuration for endovascular coil embolization. Careful preoperative planning is important to minimize the risk of thromboembolic events during and after endovascular coil embolization. In the future, CFD could be applied to individual cases to determine a safe and adequate coil configuration for endovascular coil embolization.

ACKNOWLEDGEMENTS

REFERENCES

1) Kim BM, Park SI, Kim DJ, Kim DI, Suh SH, Kwon TH, Choi HS, Won YS. Endovascular coil embolization of aneurysms with a branch incorporated into the sac. *AJNR Am J Neuroradiol*, 2010; 31: 145–151.

2) Lubicz B, Lefranc F, Levivier M, Dewitte O, Pirotte B, Brotchi J, Baleriaux D. Endovascular treatment of intracranial aneurysms with a branch arising from the sac. *AJNR Am J Neuroradiol*, 2006; 27: 142–147.

3) Naito T, Miyachi S, Matsubara N, Isoda H, Izumi T, Haraguchi K, Takahashi I, Ishii K, Wakabayashi T. Magnetic resonance fluid dynamics for intracranial aneurysms-comparison with computed fluid dynamics. *Acta Neurochir (Wien)*, 2012; 154: 993–1001.

4) Ohshima T, Miyachi S, Hattori K, Takahashi I, Ishii K, Izumi T, Yoshida J. Risk of aneurysmal rupture: the importance of neck orifice positioning-assessment using computational flow simulation. *Neurosurgery*, 2008; 62: 767–775.

5) Cebral JR, Castro MA, Burgess JE, Pergolizzi RS, Sheridan MJ, Putman CM. Characterization of cerebral aneurysms for assessing risk of rupture by using patient-specific computational hemodynamics models. *AJNR Am J Neuroradiol*, 2005; 26: 2550–2559.

6) Hassan T, Timofeev EV, Saito T, Shimizu H, Ezura M, Matsumoto Y, Takayama K, Tominaga T, Takahashi A. A proposed parent vessel geometry-based categorization of saccular intracranial aneurysms: computational flow dynamics analysis of the risk factors for lesion rupture. *J Neurosurg*, 2005; 103: 662–680.

7) Low M, Perktold K, Raunig R. Hemodynamics in rigid and distensible saccular aneurysms: A numerical study of pulsatile flow characteristics. *Biorheology*, 1993; 30:287–298.