Blood Flow Into Basilar Tip Aneurysms
A Predictor for Recanalization After Coil Embolization

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Background and Purpose—Hemodynamic forces may play a role in the recanalization of coiled aneurysms. The purpose of this study was to investigate the influence of presurgical hemodynamics on the efficacy of coil embolization for basilar tip aneurysms.

Methods—We identified 82 patients who underwent endovascular coil embolization for basilar tip aneurysms with a follow-up of >1 year. Presurgical hemodynamics were investigated using computational fluid dynamics with 3-dimensional data derived from rotational angiography. During postprocessing, we quantified the rate of net flow entering the aneurysm through its neck and calculated the proportion of the aneurysmal inflow rate to the basilar artery flow rate. In addition, we investigated the correlation between the basilar bifurcation configuration and the hemodynamics.

Results—Twenty-five of the 82 patients were excluded because of difficult vascular geometry reconstruction. Among the 57 examined patients, angiographic recanalization was observed in 19 patients (33.3%). The proportion of the aneurysmal inflow rate to the basilar artery flow rate and a coil packing density <30% were independent and significant predictors for the recanalization of coiled aneurysms. Additional investigation revealed that a small branch angle formed by the basilar artery and the posterior cerebral artery increased blood flow into the aneurysm.

Conclusions—The proportion of the aneurysmal inflow rate to the basilar artery flow rate, influenced by the basilar bifurcation configuration, was an independent and significant predictor for recanalization after coil embolization in basilar tip aneurysms. (Stroke. 2016;47:2541-2547. DOI: 10.1161/STROKEAHA.116.013555.)

Key Words: hemodynamics ■ intracranial aneurysm ■ recurrence ■ rest ■ risk factor

Endovascular coil embolization is an established treatment for intracranial aneurysms.1–4 The efficacy of coil embolization has been proven for the prevention of rebleeding in the acute phase of aneurysmal subarachnoid hemorrhage.2,3 Endovascular coil embolization is occasionally preferred in the management of unruptured intracranial aneurysms because it is less invasive than surgical clipping.4–8 However, the long-term risk and durability of coil embolization are unknown.9,10 The frequencies of aneurysm rests or recurrences are higher after coil embolization than after surgical clipping.11,12 Recent studies have revealed that recanalization after coil embolization occurs not only in the short term (typically within 1 year) but also in the long term (after several years).1,13–16 Repeated angiographic examinations or treatments because of the recanalization of coiled aneurysms result in a significant reduction in patient quality of life.

Several risk factors for recanalization after coil embolization have been proposed: ruptured aneurysms, large size, wide neck, posterior circulation, and small embolization volume rate.13–15,17,18 These risk factors were identified on the basis of statistical analyses of certain cohorts. However, causal relationships based on pathophysiology or biomechanics remain unclear.

We speculated that hemodynamic forces cause the recanalization of coiled aneurysms. Recent advances in computational fluid dynamics (CFD) have enabled us to evaluate the hemodynamics of intracranial aneurysms with increasing reliability and accuracy.19–23 Using state-of-the-art techniques, several studies have reported the influence of blood flow on the results of coil embolization for intracranial aneurysms.24–29 In this study, we investigated the hemodynamics of basilar tip aneurysms with special attention to the volume of blood flow into aneurysms through the neck. In addition, we examined the correlation between the configuration of the parent arteries and the proportion of blood flow entering into the aneurysms.

Methods

We retrospectively investigated the clinical and radiological data from 111 consecutive patients who underwent endovascular treatment...
for basilar tip aneurysms during the 7 years from January 2008 to December 2014.

The inclusion criteria of this study were as follows: (1) saccular aneurysms at the basilar tip, (2) observation period for 1 year after endovascular coiling, and (3) the availability of 3-dimensional rotational angiography.

The patients were regularly followed up with magnetic resonance imaging examinations every 6 months after treatment. Follow-up conventional angiography was performed immediately when recanalization was suspected using magnetic resonance imaging, and additional endovascular treatment was administered if needed.

We think that not only the retreatment of major recanalization but also the observation of minor recanalization in the long term reduces patient quality of life. Therefore, we defined the recanalized group as the patients with angiographic recanalization after coil embolization and the nonrecanalized group as those without. We examined the patient profiles in the 2 groups, including the mean age, the proportion of male sex, the proportion of ruptured aneurysms, and the observation period after coil embolization. With regard to the technique or the results of coiling, we collected information on the usage of stent-assisted technique or data on the packing density. The Raymond–Roy Occlusion classification, also known as the Montreal Scale, Modified Montreal Scale, or the Raymond Montreal Scale, was used for evaluating the occlusion class after coil embolization. In this system, class 1 is defined as complete obliteration, class 2 as residual neck, and class 3 as residual aneurysm.9

**Computational Fluid Dynamics**

CFD allowed us to study blood flow in the cerebral aneurysms. CFD inputs (1) the vascular geometry, (2) physical properties of blood, and (3) boundary conditions and outputs 3-dimensional or 4-dimensional pressure and velocity data according to the specified boundary conditions, which are visualized by setting appropriate flow parameters. CFD was performed using a commercial package (hemoscope v1.4; EBM Corp, Tokyo, Japan). The inlet and outlet boundary conditions were determined in accordance with a constant wall shear stress theory.30 Detailed information is described in online-only Data Supplement.

**Postprocessing**

Computed velocity information allowed us to visualize aneurysmal flow structures by streamlines, and the inflow environment was characterized by the aneurysmal inflow rate, which was the net flow rate entering the aneurysm through an aneurysmal neck. To quantify the strength of the inflow, the aneurysmal inflow rate coefficient was defined as $\Phi = Q_a/Q_b$, where $Q_a$ and $Q_b$ were the aneurysmal inflow rate and the basilar artery flow rate, respectively (Figure 1). In addition, we examined other CFD parameters correlated with those studied in previous reports, including the maximum and average inflow velocity at the neck plane, the maximum and average flow velocity inside the aneurysms, and the maximum and average wall shear stress on the aneurysmal wall.34,27,29

**Calculation of Morphological Parameters**

Three vascular geometry–based parameters—neck size, aneurysmal height, and aspect ratio—were calculated from 3-dimensional reconstructed images from the rotational angiography as described previously.

**Parent Artery Configuration**

The current hemodynamic study revealed that the proportion of the aneurysmal inflow rate to the basilar artery flow rate (aneurysmal inflow rate coefficient) was significantly related to recanalization. Because we speculated that the configuration of the parent arteries strongly influences the aneurysmal inflow rate coefficient, we conducted further investigations as follows. To assess the configuration of the basilar bifurcation, we created 3 center lines for the basilar artery and bilateral posterior cerebral arteries. Then, we measured the branch angles formed by the junction between the center line of the basilar artery and that of the right or left posterior cerebral arteries (Figure 1). According to this branch angle, we classified the configuration formed by the basilar artery and the unilateral posterior cerebral artery into 3 types: (1) hand-up-type configuration with the angle >100°, (2) hand-horizontal-type configuration with the angle 80°–100°, and (3) hand-down-type configuration with the angle <80°. Each of the bilateral posterior cerebral arteries belongs to one of these 3 types. Therefore, there are 6 types of basilar bifurcation configuration: (1) both-hands-up type (UU), (2) both-hands-horizontal type (HH), (3) both-hands-down type (DD), (4) hand-up/hand-horizontal type (UH), (5) hand-up/hand-down type (UD), and (6) hand-horizontal/hand-down type (HD). We created 3 groups from these 6 types: UU (upward tendency), UH/HH/UD (horizontal tendency), and HD/DD (downward tendency) and examined the correlation between the type of basilar bifurcation configuration and the aneurysmal inflow rate coefficient and also investigated the relationships between the type of basilar bifurcation and the treatment outcome.

**Statistical Analysis**

Unpaired t tests were used for parametric statistical analysis except for the coil packing density. The packing density was not normally distributed, and Wilcoxon rank-sum test was applied for this non-parametric analysis. In addition, the patients were categorized by the threshold of the packing density for recanalization derived from the receiver-operating characteristic curve. Categorical variables were analyzed by Fisher exact test or the $\chi^2$ test. Results with $P$ values <0.05 were considered statistically significant. Then, multivariate analysis was performed to find independent predictors for the recanalization using binary logistic regression analysis and to find confounding factors between potentially independent predictors. Variables with significant $P$ values from the univariate analyses of
the embolization results and flow analyses and morphological parameters including neck size were considered potentially independent variables in the multivariate analysis. A forward stepwise method was used to construct multivariate logistic regression models with the inclusion criterion of $P<0.05$. To evaluate the relationship between the aneurysmal inflow rate coefficient and the basilar bifurcation configuration, the data obtained from each configuration were compared with 1-way ANOVA, followed by a Tukey–Kramer honest significant difference post hoc analysis. All calculations were performed with standard commercial software (JMP Pro Version 11.2; SAS Institute Inc, Cary, NC).

**Results**

Eighty-two patients fulfilled the inclusion criteria. Among them, 25 patients were excluded because of difficulty in reconstructing the vascular geometry from the rotational angiography data. The specific reasons for the exclusions are described in online-only Data Supplement.

Therefore, 57 patients (14 men and 43 women) were included in this study (Table 1). The mean age of the patients was 60.0 years (range, 30–80 years). Angiographic recanalization was observed in 19 patients (33.3%, recanalized group), whereas coiled aneurysms in 38 patients were stable (66.7%, nonrecanalized group). Nine out of the 19 patients with angiographic recanalization underwent additional treatments. Whether additional treatments should be administered was determined through comprehensive consideration of the patient’s age, the extent of recanalization, and the clinical time course.

**Differences Between the Recanalized and Nonrecanalized Groups From the Univariate Analyses**

There was no significant difference in the clinical profiles between the recanalized and nonrecanalized groups (Table 1). Stent-assisted coil embolization was performed in 12 of the 57 cases (21.1%). Stent-assisted technique tended to decrease recanalization rate, but we found no statistical significance in this variable between the 2 groups. Whether additional treatments should be administered was determined through comprehensive consideration of the patient’s age, the extent of recanalization, and the clinical time course.

**Table 1. Patient Characteristics**

<table>
<thead>
<tr>
<th></th>
<th>Recanalized Group (n=19)</th>
<th>Nonrecanalized Group (n=38)</th>
<th>$P$ Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>58.5 (34–77)</td>
<td>60.7 (30–80)</td>
<td>0.4917</td>
</tr>
<tr>
<td>Male sex</td>
<td>3 (15.8%)</td>
<td>11 (28.9%)</td>
<td>0.2766</td>
</tr>
<tr>
<td>Ruptured aneurysms</td>
<td>7 (36.8%)</td>
<td>14 (36.8%)</td>
<td>1.0000</td>
</tr>
<tr>
<td>Mean observation period, d</td>
<td>1765.4 (436–2598)</td>
<td>1553.6 (367–2776)</td>
<td>0.2927</td>
</tr>
<tr>
<td>Stent-assisted coil embolization</td>
<td>2 (10.5%)</td>
<td>10 (26.3%)</td>
<td>0.1681</td>
</tr>
<tr>
<td>Median packing density, %</td>
<td>24.2 (17.5–38.4)*</td>
<td>32.1 (24.8–41.5)*</td>
<td>0.0536</td>
</tr>
<tr>
<td>Packing density &lt;30%</td>
<td>14 (73.7%)</td>
<td>16 (42.1%)</td>
<td>0.0244†</td>
</tr>
<tr>
<td>Raymond–Roy class 1</td>
<td>2 (10.5%)</td>
<td>10 (26.3%)</td>
<td>0.1681</td>
</tr>
<tr>
<td>Raymond–Roy class 3</td>
<td>9 (47.4%)</td>
<td>10 (26.3%)</td>
<td>0.1120</td>
</tr>
</tbody>
</table>

IQR indicates interquartile range.  
*IQR: 25% to 75%.  
†$P<0.05$.

Significant because of the $P$ value of 0.0536. We analyzed the receiver-operating characteristic curve and determined a threshold value of 30% of the packing density for recanalization. There were more patients with a packing density <30% in the recanalized group than in the nonrecanalized group ($P=0.0244$).

The aneurysmal inflow rate coefficient was significantly higher in the recanalized group than that in the nonrecanalized group ($P=0.0189$; Table 2 and Figure 2). The cutoff value was 0.5 in the receiver-operating characteristic curve (Table 2). On the contrary, neither the aneurysmal inflow rate nor the basilar artery flow rate was significantly different between the 2 groups. In addition, the maximum and average inflow velocity at the neck plane, maximum and average flow velocity inside aneurysms, and maximum and average wall shear stress on the aneurysmal wall were not significantly different between the 2 groups (Table 2).

In the examination of the morphological parameters, we found that neck size ($P=0.0437$), aneurysmal height ($P=0.0102$), and aspect ratio ($P=0.0458$) were significantly larger in the recanalized group compared with those in the nonrecanalized group (Table 2).

**Results of the Multivariate Analysis**

To identify the independent risk factors that were significantly correlated with the recurrence of coiled aneurysms, multivariate logistic regression analysis was performed on the significant factors from the univariate analyses. Because the morphological parameters, such as neck size, height, and aspect ratio, correlated with themselves, neck size, which is widely considered as a risk factor for recanalization, was selected for the multivariate analysis. The aneurysmal inflow rate coefficient ($P=0.0143$) and the packing density <30% ($P=0.0275$) remained significant for the prediction of recanalization.

**Parent Artery Configuration**

Figure 3 shows the correlation between the type of basilar bifurcation configuration and the aneurysmal inflow rate coefficient. Aneurysms at basilar bifurcations of the UU...
(upward tendency) type had significantly lower aneurysmal inflow rate coefficients than the UH/HH/UD (horizontal tendency) types (mean, 0.25 versus 0.58; \(P=0.0010\)) and DD/HD (downward tendency) types (mean, 0.25 versus 0.73; \(P=0.0005\); Figure 3A). The basilar bifurcation configuration also correlated with the recanalization rate. Aneurysms at HD/DD (downward tendency) type bifurcations had significantly higher rates of recanalization after coil embolization than the other configurations (\(P=0.0021\); Figure 3B).

Qualitative observation using streamlines revealed that in the UU type basilar bifurcation configuration, blood flow from the basilar artery was divided into 3 directions: one entered into the aneurysm, and the others flowed directly out toward the bilateral posterior cerebral arteries (Figure 4A), which resulted in low aneurysmal inflow rate coefficients. On the contrary, in the DD type basilar bifurcation configuration, almost all the blood in the basilar artery entered into the aneurysm (Figure 4B), which resulted in high aneurysmal inflow rate coefficients.

### Discussion

This study demonstrated the correlation between the hemodynamics before coil embolization and the outcome after treatment for basilar tip aneurysms. The proportion of the aneurysmal inflow rate to the basilar artery flow rate (aneurysmal inflow rate coefficient) was an independent and significant predictor for the recanalization of coiled aneurysms. In addition, we demonstrated that the aneurysmal inflow rate coefficient depended on the configuration of the parent arteries.

Previous CFD studies demonstrated the possibility that the fast blood flow at the neck of coiled aneurysm, which exerted high shear stress on the aneurysmal neck, caused future recanalization.\(^{26,27,29}\) The results of those studies suggested the role of blood inflow on recanalization after coil embolization, as did the results of the current study. When blood flow affects the coil mass with thrombus, the velocity of the blood flow decreases, and the pressure increases based on the basic principle of fluid dynamics known as Bernoulli theorem. The strength of the blood flow is calculated by multiplying the pressure with the surface area of the impact site. We hypothesize that this hemodynamic force plays an important role in the recanalization of coiled aneurysms.

The difference in methodology between previous studies and our current study should be emphasized. In the present study, the geometries before coil embolization—not after—were used to evaluate the presurgical hemodynamics. We suggest that presurgical hemodynamic simulation can provide useful information for predicting the outcome after coil embolization; that is, we can determine whether coil embolization or clipping surgery are suitable for individual cases in terms of the risk of recurrence. The results of this study also suggest that a tight packing density should be achieved when treating basilar tip aneurysms with a high aneurysmal inflow rate coefficient.

### Table 2. Hemodynamic and Morphological Factors

<table>
<thead>
<tr>
<th></th>
<th>Recanalized Group (n=19)</th>
<th>Nonrecanalized group (n=38)</th>
<th>(P) Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basilar artery flow rate, Qb (mL/min)</td>
<td>70.16 (27.32–184.14)</td>
<td>64.81 (25.57–129.94)</td>
<td>0.5279</td>
</tr>
<tr>
<td>Aneurysmal inflow rate, Qa (mL/min)</td>
<td>46.12 (5.26–127.33)</td>
<td>30.03 (4.13–118.80)</td>
<td>0.0542</td>
</tr>
<tr>
<td>Aneurysmal inflow rate coefficient, Qa/Qb</td>
<td>0.64 (0.1–1.25)</td>
<td>0.45 (0.07–1.08)</td>
<td>0.0189</td>
</tr>
<tr>
<td>Maximum neck inflow velocity, m/s</td>
<td>0.236 (0.086–0.746)</td>
<td>0.171 (0.079–0.400)</td>
<td>0.0706</td>
</tr>
<tr>
<td>Average neck inflow velocity, m/s</td>
<td>0.106 (0.046–0.354)</td>
<td>0.083 (0.040–0.170)</td>
<td>0.1420</td>
</tr>
<tr>
<td>Maximum aneurysmal flow velocity, m/s</td>
<td>0.240 (0.109–0.746)</td>
<td>0.181 (0.079–0.395)</td>
<td>0.0917</td>
</tr>
<tr>
<td>Average aneurysmal flow velocity, m/s</td>
<td>0.047 (0.014–0.156)</td>
<td>0.038 (0.006–0.099)</td>
<td>0.3124</td>
</tr>
<tr>
<td>Maximum wall shear stress, Pa</td>
<td>7.506 (1.654–24.540)</td>
<td>6.691 (1.953–15.741)</td>
<td>0.4991</td>
</tr>
<tr>
<td>Average wall shear stress, Pa</td>
<td>0.675 (0.101–2.668)</td>
<td>0.607 (0.070–2.233)</td>
<td>0.6828</td>
</tr>
<tr>
<td>Neck size, mm</td>
<td>6.13 (2.45–11.13)</td>
<td>5.05 (2.32–8.52)</td>
<td>0.0437*</td>
</tr>
<tr>
<td>Height, mm</td>
<td>6.30 (1.33–12.85)</td>
<td>4.24 (0.91–11.24)</td>
<td>0.0102*</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>0.99 (0.54–1.72)</td>
<td>0.84 (0.33–1.37)</td>
<td>0.0458*</td>
</tr>
</tbody>
</table>

\(^*P<0.05\).

Figure 2. The difference in the aneurysmal inflow rate coefficient between the recanalized and nonrecanalized groups. The aneurysmal inflow rate coefficient was significantly higher in the recanalized group than in the nonrecanalized group (\(P=0.0189\)).
We did not find a statistically significant correlation between the velocity or wall shear stress and the recanalization rate as reported previously. We speculated that there are 2 reasons for this. One is the difference in methodology described above. Postsurgical hemodynamics were examined in the previous studies; conversely, presurgical hemodynamics were examined in the present study. The other reason is the robustness of the parameters. The aneurysmal inflow rate coefficient, which was significantly correlated with recanalization, converges at a certain value even if there are a variety of inlet conditions. On the contrary, the velocity, wall shear stress, and inflow volume strongly depend on the inlet conditions. In the present study, we adopted the inlet conditions predicted from the diameter of the parent vessels (please see Methods section in the online-only Data Supplement). If we had used patient-specific inlet conditions measured by phase-contrast magnetic resonance, parameters such as the velocity and wall shear stress might have been significantly correlated with the recanalization rate.

We demonstrated the influence of the parent artery configuration on aneurysmal hemodynamics: a small branch angle formed by the basilar artery and the posterior cerebral artery resulted in the concentration of blood flow into the aneurysm, which was associated with a high aneurysmal inflow rate coefficient and high recanalization rate. On the contrary, a large branch angle resulted in the diversion of blood flow, which was associated with a low aneurysmal inflow rate coefficient and low recanalization rate. Using the results from the morphological assessment of the basilar bifurcation configurations, we may be able to identify aneurysms with a high risk of future recanalization after coil embolization and recognize the need of tight coil packing without CFD analysis.

Limitations
The retrospective design is a major limitation of this study. A prospective study with a larger cohort including all types of...
an aneurysm is needed for sufficient statistical power to prove the usefulness of hemodynamic simulation for predicting the recanalization of coiled aneurysms.

Furthermore, the study cohort consisted of only Japanese patients. The Japanese race has been reported as being at low risk of aneurysmal growth.32 Recent reports have suggested that the enlargement of the aneurysmal dome and the deformation of the coil mass are the main causes for the recanalization of coiled aneurysms.33,34 Therefore, it needs to be recognized that ethnicity might play a role in the recanalization rate.

We cannot overlook the limitation about CFD studies. Typical simplifications were made during the model generation, the setting of the boundary conditions related to wall compliance and outflow conditions, and the numeric technique used to solve the governing equations. However, these effects are considered to be negligible if the vascular geometry is correctly modeled.35 We should also mention the relatively large number of patients who were excluded because of difficulty reconstructing the geometries (please see online-only Data Supplement). In the present study, we used a simple threshold method with minimal manual operation to reconstruct the geometries of the aneurysms with the parent arteries to minimize the effect of manual segmentation on CFD simulation, resulting in the increased reproducibility and robustness of the CFD simulation. As a result, we excluded 25 of the 82 patients because of the difficulty of reconstructing the geometries. In particular, large or giant aneurysms presenting with size-related insufficient filling of the contrast agent in the aneurysms themselves or in the posterior cerebral artery were excluded, because we did not use a state-of-the-art segmentation technique. Therefore, the findings of this study should apply to small aneurysms rather than large or giant ones.

We did not use patient-specific inlet conditions; instead, predicted flow rates from the vessel diameter were substituted for the inlet boundary condition. We randomly selected 15 from 57 cases in this study and checked the robustness of the simulations under the pulsatile inlet conditions in which the basilar artery flow rate fluctuated from −35% to +65% compared with the predicted flow rates. We found that the aneurysmal inflow rates fluctuated from −35% to +65% in phase with the basilar artery flow rate, and the differences in the aneurysmal inflow rate coefficient converged to <10% in each phase. Patient-specific inlet conditions are not always available in clinical situation. In addition, steady-state simulation has an advantage in sparing calculation time.36,37 Therefore, the methodology in this study, steady-state simulation under the predicted flow rates, is suitable for clinical practice. However, further investigation is necessary to validate the results of steady-state simulation under the predicted value by comparing these results with those of transient simulation under patient-derived pulsatile flow rates as measured by phase-contrast magnetic resonance or ultrasound Doppler.

Conclusions

The proportion of the aneurysmal inflow rate to the basilar artery flow rate, which was calculated by CFD using presurgical vascular geometry, was an independent and significant predictor for recanalization after coil embolization. It may be sensible to apply those findings to rather small aneurysms, because the large or giant aneurysms presenting with size-related insufficient angiography were excluded in this CFD study.

Acknowledgments

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Disclosures

None.

References


ONLINE SUPPLEMENT

Supplemental Methods

Computational fluid dynamics

Vascular geometry

At first, 3D vascular geometry of the vascular lumen was constructed by a medical-image-processing package (Ziostation2; Ziosoft, Inc., Japan). Input images from the rotational angiography (Innova 3131; GE Healthcare Japan, Tokyo, Japan) were reconstructed into a 3D dataset with an approximate spatial resolution of 0.2 mm. The region of interest in the posterior circulation included the basilar artery, superior cerebellar arteries, and posterior cerebral arteries. These major arteries and other branches were included in the CFD if the diameter of each artery was >1.0 mm. Henceforth, the diameter denotes the median of the equivalent cross-sectional diameter measured along the center line of each segmented vessel. The vascular lumens were defined as those of a single threshold or greater. The threshold was represented as one-half of the peak intensity in the P1 segment of the posterior cerebral arteries. With the threshold, the software allowed us to obtain polygonized surface geometries using the marching cubes method.

Preprocessing

Then, a hemoscope allowed us to carry out the following processing in an automated fashion. First, these vascular geometries were filled with unstructured cells. The cells were mainly hexahedral and their size was approximately 0.25 mm in the far-wall regions, and 0.125 (width) and 0.05 (height) mm in the near-wall regions. The near-wall meshes consisted of three layers. The inlet and outlet vessels were extended by 5 and 10 times greater than their diameters, respectively. The blood density ($\rho$) and viscosity ($\mu$) were set at $\rho = 1050$ kg/m$^3$ and $\mu = 0.004$ Pa. The boundary conditions were determined in accordance with a constant wall shear stress theory; in other words, the flow rates of the inlet and outlet vessels were calculated using the following equation.

$$Q = \frac{\tau \pi}{32\mu} D^3$$ (1)

where $Q$, $\tau$, $\mu$, and $D$ denote the flow rate, wall shear stress, fluid viscosity, and vascular diameter, respectively. The equation is a well-known theoretical basis of a fully developed laminar pipe flow. Herein, the wall shear stress was set at $\tau = 1.5$ Pa. After calculating the total inflow at an inlet vessel, the amount of inflow was distributed at
each outlet vessel according to equation (1), and the specified velocities were substituted for outlet boundary conditions. The present computation adopted a steady flow rate, and thus, the inlet pressure was set at 100 mmHg.

**Computation**

A finite volume method was used to solve the governing equations: 3D unsteady Navier–Stokes equations and equation of continuity. The blood was assumed to be incompressible and a Newtonian fluid, and the nature of the blood flow was allowed to have transient behaviors. The Euler method and second-order upwind scheme were adopted for discretizing the unsteady and convective acceleration terms. The convergent criteria were set at $10^{-4}$.

**Reference**

**Supplemental Results**

**Specific reasons for exclusions**

Eighty-two patients fulfilled the inclusion criteria in this study. Among them, 25 patients were excluded because of difficulty in reconstructing the vascular geometry from the rotational angiography data. The specific reasons for the exclusions are as follows: artifact caused by body motion (six cases), poor filling of the contrast agent inside the aneurysms (five cases), poor filling of the contrast agent in a basilar artery as a result of blood flow from a contralateral vertebral artery (four cases), poor filling of the contrast agent in a posterior cerebral artery (three cases), low contrast as a result of insufficient infusion of the contrast agent (three cases), narrowing of a posterior cerebral artery because of the junction of a posterior communicating artery (two cases), and adhesion to surrounding vessels (two cases).

Table 1 shows the comparison of aneurysmal size between included and excluded cases. Wilcoxon rank-sum test was applied for the nonparametric analysis. There was no significant difference in neck size and aneurysmal height between the two groups.

<table>
<thead>
<tr>
<th></th>
<th>Included cases</th>
<th>Excluded cases</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(n = 57)</td>
<td>(n = 25)</td>
<td></td>
</tr>
<tr>
<td>Median neck size [mm]</td>
<td>5.32 (4.21–6.39)*</td>
<td>5.10 (3.60–7.60)*</td>
<td>0.896</td>
</tr>
<tr>
<td>Median height [mm]</td>
<td>4.67 (2.90–5.73)*</td>
<td>5.90 (3.50–8.50)*</td>
<td>0.139</td>
</tr>
</tbody>
</table>

* IQR = interquartile range: 25%–75%