High Shear Stress and Flow Velocity in Partially Occluded Aneurysms Prone to Recanalization

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Background and Purpose—Hemodynamic factors are thought to play an important role in the initiation, growth, and rupture of cerebral aneurysms. However, the hemodynamic features in the residual neck of the partially embolized aneurysms and their influences on recanalization are rarely reported. In this study, we characterized the hemodynamics of partially occluded aneurysms, which were proven to undergo recanalization during follow-up using computational fluid dynamic analysis.

Methods—From May 2007 to June 2009, we identified 11 partial aneurysms during follow-up, including 5 recanalized cases and 6 stable cases with 3-dimensional digital subtraction angiography. We retrospectively characterized the hemodynamic features around the residual aneurismal pouch using the available postprocedural digital subtraction angiography image data. The occluded part of the aneurysm was regarded as completely separated from the circulation.

Results—The overall blood flow patterns before embolization were almost the same in the recanalized and stable groups. After occlusion, the flow pattern changes, wall shear stress (WSS), and velocity at the remnant neck demonstrated different changes between the 2 groups. Specifically, in the recanalized group, high WSS regions were found near the neck in all 5 cases, with 4 of them being even higher than those before occlusion. Interestingly, in all cases, the high WSS area of the remnant neck coincided with the location where the aneurysm recanalization occurred. In the stable group, 5 out of 6 cases demonstrated lower WSS and velocity at the remnant neck after occlusion.

Conclusions—High WSS and blood flow velocity were consistently observed near the remnant neck of partially embolized aneurysms prone to future recanalization, suggesting that hemodynamic factors may have an important role in aneurismal recurrence after endovascular treatment. The difference in flow pattern could be caused by the incomplete occlusion of the aneurysms. (Stroke. 2011;42:745-753.)

Key Words: cerebral aneurysm ■ endovascular treatment ■ hemodynamics ■ recanalization ■ wall shear stress

Intracranial aneurysms are pathological dilatations of the cerebral arteries that mostly occur at the circle of Willis. A major complication of intracranial aneurysms is rupture, causing subarachnoid hemorrhage, which is associated with high mortality and morbidity.1,2 Cerebral aneurysms can be surgically obliterated by clipping or by endovascular deployment of coils followed by artificial embolization. Because of the difficulties and potential complications of open brain surgery, and because of the improvement of embolic materials, endovascular embolization has been widely used as a safe and effective treatment method. Recurrence of the aneurysms after coil embolization, however, remains a major problem.1 The aneurysms with remnant necks after endovascular occlusion are prone to recanalization, whereas the underlying mechanisms of this phenomenon are not totally clear.3,4 We have a primary interest in the hemodynamic influences in recanalization of partially occluded aneurysms.

Multiple factors have been considered to contribute to the recanalization of embolized aneurysms, including diseases...
congenital vascular defects, hypertension, atherosclerosis, thrombosis), loose packing of the embolic material, location of aneurysm, and presence of a residual neck.\(^5\)\(^-\)\(^7\) There is abundant evidence suggesting that intra-aneurismal hemodynamic patterns may have a profound impact on the development of cerebral aneurysms. Using computational fluid dynamics (CFD) analysis, people have identified that high velocity and high shear stress of the flow impingement may have positive effects on the growth of cerebral aneurysm.\(^8\)\(^-\)\(^10\)

In recent years, the CFD method also has been used to study the flow pattern before and after aneurysmal occlusion.\(^5\)\(^,\)\(^6\)\(^,\)\(^8\)\(^-\)\(^11\)\(^,\)\(^13\)\(^-\)\(^17\) In contrast, few studies have directly examined the relationship between the postprocedural hemodynamic features in the vicinity of the occluded aneurysms and the occurrence of recanalization. Such information might be of special interest in advancing our understanding of the pathogenesis of recanalization and assessing the risks of aneurysm recurrence.

To address this question, we retrospectively reviewed the preprocedural and postprocedural 3-dimensional (3D) digital subtraction angiography (DSA) data. Eleven cases of coil-embolized aneurysms with residual necks were collected, of which 5 were found recanalized and the other 6 kept angiographically stable in the follow-up. The aim of the present study was to characterize the hemodynamic changes of the partially embolized aneurysms that were predisposed to recanalization. Importantly, in previous studies on the hemodynamics of postembolization aneurysms, the embolization process was mimicked by arbitrarily cutting-off the pouch on the computer screen or the occluded aneurismal part was simulated by a type of computational model;\(^5\)\(^,\)\(^6\)\(^,\)\(^8\)\(^-\)\(^11\)\(^,\)\(^13\)\(^-\)\(^17\) therefore, the geometric data were not from the patient-based image information. To overcome these, all of the pretreatment and posttreatment data used in the present study were obtained from the original DSA images, which would more accurately reflect the real situation.

### Patients and Methods

Patient-specific 3D-DSA data (LCV+; GE Medical Systems) were obtained from rotational series consisting of 2 rotations. The first rotation provided the subtraction mask. The second rotation was

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**Table 1. Patient Population**

<table>
<thead>
<tr>
<th>N</th>
<th>Sex</th>
<th>Age (y)</th>
<th>Size</th>
<th>Site</th>
<th>Operation</th>
<th>Follow-Up Results and Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recanalization case 1</td>
<td>F</td>
<td>59</td>
<td>6.7×7.2 mm</td>
<td>Right ophthalmic segment</td>
<td>Subtotal occlusion</td>
<td>Recanalized at 3 mo</td>
</tr>
<tr>
<td>Recanalization case 2</td>
<td>F</td>
<td>44</td>
<td>2.5×4.3 mm</td>
<td>Left anterior communicating</td>
<td>Subtotal occlusion</td>
<td>Recanalized at 6 mo</td>
</tr>
<tr>
<td>Recanalization case 3</td>
<td>M</td>
<td>38</td>
<td>6.7×7.3 mm</td>
<td>Basilar tip aneurysm</td>
<td>Subtotal occlusion</td>
<td>Recanalized at 2 y</td>
</tr>
<tr>
<td>Recanalization case 4</td>
<td>M</td>
<td>68</td>
<td>8.8×10.0 mm</td>
<td>Left internal carotid artery (C2)</td>
<td>Subtotal occlusion</td>
<td>Recanalized at 2 mo</td>
</tr>
<tr>
<td>Recanalization case 5</td>
<td>F</td>
<td>67</td>
<td>9.1×10.2 mm</td>
<td>Right ophthalmic segment</td>
<td>Subtotal occlusion</td>
<td>Recanalized at 6 mo</td>
</tr>
<tr>
<td>Stable case 1</td>
<td>F</td>
<td>56</td>
<td>4.4×3.5 mm</td>
<td>Left posterior communicating</td>
<td>Subtotal occlusion</td>
<td>Stable at 3 mo</td>
</tr>
<tr>
<td>Stable case 2</td>
<td>F</td>
<td>53</td>
<td>4.1×4.8 mm</td>
<td>Left internal carotid artery (C2)</td>
<td>Subtotal occlusion</td>
<td>Stable at 6 mo</td>
</tr>
<tr>
<td>Stable case 3</td>
<td>M</td>
<td>43</td>
<td>7.0×3.7 mm</td>
<td>Left ophthalmic segment</td>
<td>Subtotal occlusion</td>
<td>Stable at 6 mo</td>
</tr>
<tr>
<td>Stable case 4</td>
<td>M</td>
<td>46</td>
<td>2.0×2.0 mm</td>
<td>Left posterior communicating</td>
<td>Subtotal occlusion</td>
<td>Stable at 3 mo</td>
</tr>
<tr>
<td>Stable case 5</td>
<td>F</td>
<td>46</td>
<td>4.4×3.1 mm</td>
<td>Left anterior communicating</td>
<td>Subtotal occlusion</td>
<td>Stable at 6 mo</td>
</tr>
<tr>
<td>Stable case 6</td>
<td>F</td>
<td>38</td>
<td>5.6×3.0 mm</td>
<td>Left internal carotid artery bifurcating aneurysm</td>
<td>Subtotal occlusion</td>
<td>Stable at 10 mo</td>
</tr>
</tbody>
</table>

F indicates female; M, male.

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**Figure 1.** The magnitude of velocity (m/s).
performed simultaneously with the administration of contrast material. All the images acquired were immediately transferred via network to a workstation (Advantage Unix; GE Medical Systems) for volume analysis. A 3D reconstruction algorithm based on the algebraic reconstruction technique was used to digitally produce 3D-DSA images on the workstation within 8 minutes. Algorithms were maximum intensity projection and surface-shaded display at an isosurface with a mean threshold value of 1300 Hounsfield unit (H). The threshold values before and after coagulation were approximately similar for every patient. The 3D-DSA image displayed on the monitor was subjected to reformatting into transverse regularly spaced sections and saved as secondary DICOM format. For the existence of the coils in the aneurysmal sac after endovascular treatment, the contrast material cannot enter the coiling space of the aneurysm again. The coils were eliminated from the aneurysmal sac automatically in the 3D reconstruction process. Large series of secondary data in DICOM format containing the images and other relevant information were imported into in-house software developed by the Capital Medical University to create 1 patient medical information image in stereolithography format that included blood vessel luminal surface data. The stereolithography format file was then imported into ICEM CFD software (ANSYS, Inc, Canonsburg, PA) to create the volume grids used for fluid dynamics calculation. The volume grid numbers used in this study varied from 1,300,000 to 1,800,000. After meshing, we used ANSYS CFX 11.0 software (ANSYS, Inc, Canonsburg, PA) to generate the configuration files that specified the settings of blood properties, boundary conditions, and the time step for fluid field computation. Eight hundred time steps per cardiac cycle were used, and time step was 0.001 seconds. The governing equations underlying the calculation were the Navier–Stokes formulations, with an assumption of a laminar, homogenous, and incompressible blood flow. The blood vessel wall was assumed to be rigid with no-slip boundary condition. The average Reynolds number was within the range of normal blood flow in human cerebral arteries, indicating a laminar flow condition. A Newtonian flow condition was used to perform the calculation. In fact, some researchers have provided evidence that overall blood flow pattern and shear stress distribution are relatively independent of the setting of either a Newtonian or a non-Newtonian viscosity. The density and dynamic viscosity of blood were specified as 1060 kg/m³ and 0.004 Newton-second/m². The inflow boundary condition was a pulsatile period velocity profile that was obtained by transcerebral Doppler, and the pulsatile velocity boundary conditions were imposed at the model inlet by using a superposition of Womersley velocity profiles for each mode. A traction-free boundary condition was applied to the outlets. The initial pressure and velocity were set to zero.

Data Source

All medical data were acquired for diagnostic purposes, and consent was obtained from the patients or their closest relatives before the study. Inclusion criteria were: (1) cases were selected from the aneurysms that we embolized between May 2007 and June 2009; (2) aneurysms selected were partially occluded by coiling and were followed-up by angiography within 2 years; and (3) clinical 3D-DSA images were of adequate resolution for the purpose of CFD analysis in the treatment, after the treatment, and also during follow-up. The exclusion criteria were: (1) aneurysms were totally occluded in the initial treatment; (2) aneurysms were treated by the assistance of stents; (3) clinical 3D-DSA images were not of adequate resolution for the purpose of CFD analysis in the treatment or after the treatment; and (4) patients and their relatives did not consent to CFD analysis.

Eleven cases of coil-embolized aneurysms with residual necks were collected, with all of the DSA images meeting the quality requirements for CFD purposes, of which 5 were found recanalized in the follow-up, whereas the other 6 were angiographically stable. The general information of the patients and the characteristics of the aneurysms are summarized in Table 1. The computed velocity and WSS were synchronized with the pulsatile flow of the systemic circulation and the values at peak systole were analyzed (Figures 1 and 2).

Results

**CFD Analysis Before Embolization in Recanalized and Nonrecanalized Aneurysms**

The overall blood flow patterns before embolization were almost the same in recanalized and stable aneurysms. Flow impingement is collision of the in-flow jet with the wall of the aneurysm. Complex flow impingement regions could be observed in all cases before occlusion. The blood flow entered the aneurysm sac through the impingement region and formed a large and complex vortex inside (Figure 3C). The WSS and the velocity were high at the impingement region (Figures 3D and E, 4D and E, 5D and E, arrow).
Figure 3. A 59-year-old woman with sudden subarachnoid hemorrhage. Digital subtraction angiography (DSA) showed an ophthalmic segment aneurysm (A, B). Streamline (C), velocity (D), and (E) wall shear stress (WSS) showed a large and complex vortex inside aneurysm at the systolic peak (t=0.2 seconds). There was an impingement region (with high velocity magnitude and WSS) at the neck of the aneurysm (C–E, arrow). After the aneurysm was partially occluded by coiling (F, G), blood entered the remnant neck and formed a small vortex (H, I). There appeared a new impingement region at the remnant neck, where the velocity and WSS at this region were larger than those before occlusion (I, J, arrow). The occluded aneurysm was verified recanalized by DSA follow-up (K, L). The blood flow formed a new large vortex again (M, N). At the region where the blood flow entered the recurrent aneurysm, large velocity and WSS can be observed (N, O, arrow). The point where the blood entered the aneurismal sac was coincident with the impingement region of the occluded aneurysm.
Case 6, the velocity and WSS at the remnant neck were increased in 5 of 6 cases. In nonrecanalized and WSS at the remnant neck became lower than those before occlusion (Figures 4D and E, 5D and E, arrow). However, the velocity also observed at the remnant neck before occlusion (Figure 4I, J, arrow) compared with the other 5 nonrecanalized cases (Tables 2 and 3).

### CFD Analysis After the Subtotal Embolization in the Recanalized Group

After the partial occlusion, disappearance of the majority of the aneurysmal pouch markedly changed the impingement region. The new impingement regions were formed at the remnant neck of the aneurysms compared to the previous impingement regions at the aneurysmal sidewall. Notably, the blood flow patterns became different after embolization in the recanalized and nonrecanalized groups. In 4 out of 5 recanalized cases (1, 2, 4, and 5), an obvious impingement region can be observed in the remnant neck (Figure 3I, J, arrow); these new impingement regions were at the former high-flow path before occlusion.

An intriguing finding was that in 4 cases (1, 2, 4, and 5), the blood flow velocity and WSS at the remnant necks were larger than those at the original impingement regions of untreated aneurysms (Tables 2 and 3). Interestingly, in all cases, the high WSS area of the remnant neck coincided with the location where the aneurysm recanalization occurred later (Figure 3N, O). In recanalized case 3, the maximum WSS at the remnant neck was not increased as compared to that at the original impingement region (Table 3); this could be attributable to the fact that a new impingement region did not form after occlusion. Nevertheless, a spot of high WSS still could be observed near the remnant neck. In the recanalized aneurysms, high velocity and WSS regions were present in all cases. The impingement region in the residual necks and vortex in cases 1 and 4 were similar to those before embolization (Figure 3C, D, M, N, arrow).

### CFD Analysis After the Partial Embolization in the Nonrecanalized Group

In the nonrecanalized group, impingement regions were also observed at the remnant neck before occlusion (Figures 4D and E, 5D and E, arrow). However, the velocity and WSS at the remnant neck became lower than those before occlusion (figure 4L, J, arrow) in 5 of 6 cases. In nonrecanalized case 6, the velocity and WSS at the remnant neck were increased (Figure 5I, J, arrow) compared with the other 5 nonrecanalized cases (Tables 2 and 3).

### Discussion

In this study we demonstrated that the residual neck of partially embolized aneurysms that underwent subsequent recanalization may be associated with high flow velocity and WSS. An impressive finding is that the high velocity and WSS region coincide with the location of future aneurysm recanalization. Boet et al provided the observational data that paraclinoid/ophthalmic segment artery aneurysms were more susceptible to recanalization after primary treatment and hypothesized that the high shear stress imposed on aneurysms in this particular position might contribute to the recurrence. To our knowledge, the present study provides the first numeric data indicating that the mean WSS at the remnant neck of partially embolized recanalization-prone aneurysms was 3.4-fold higher than the mean maximum WSS on the original aneurysms neck. In the stable group, the WSS at the remnant neck was 3.1-fold lower than that on the original aneurysms.

Several recent studies used CFD methods to examine the changes of hemodynamic patterns after aneurysmal embolization. For example, Ortega et al. performed CFD simulation within a patient-derived basilar aneurysm model. The embolization was mimicked by artificially cutting-off the aneurismal sac from the neck. Consistent with our data, they identified a blood flow impingement adjacent to the remnant neck and found an increase in WSS. Byun and Rhee used a simplified approach by treating the Guglielmi detachable coil as a solid sphere in the aneurismal sac. They studied the effects of endovascular treatment on the hemodynamics in a basilar tip aneurysm model by computer-based modeling of the embolization procedure. Of note, all of these results were derived from online simulation of the coil placement using computer programs,

### Table 2. Magnitude of Velocity

<table>
<thead>
<tr>
<th>N</th>
<th>Follow-Up Station</th>
<th>Before Occlusion</th>
<th>After Occlusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recanalization case 1</td>
<td>Recanalized</td>
<td>1.057</td>
<td>2.606</td>
</tr>
<tr>
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<td>Recanalized</td>
<td>0.595</td>
<td>1.669</td>
</tr>
<tr>
<td>Recanalization case 3</td>
<td>Recanalized</td>
<td>0.711</td>
<td>0.599</td>
</tr>
<tr>
<td>Recanalization case 4</td>
<td>Recanalized</td>
<td>0.985</td>
<td>1.055</td>
</tr>
<tr>
<td>Recanalization case 5</td>
<td>Recanalized</td>
<td>0.574</td>
<td>1.171</td>
</tr>
<tr>
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<td>1.654</td>
<td>0.0722</td>
</tr>
<tr>
<td>Stable case 2</td>
<td>Stable</td>
<td>1.206</td>
<td>0.382</td>
</tr>
<tr>
<td>Stable case 3</td>
<td>Stable</td>
<td>0.821</td>
<td>0.0520</td>
</tr>
<tr>
<td>Stable case 4</td>
<td>Stable</td>
<td>0.898</td>
<td>0.0511</td>
</tr>
<tr>
<td>Stable case 5</td>
<td>Stable</td>
<td>1.359</td>
<td>0.0929</td>
</tr>
<tr>
<td>Stable case 6</td>
<td>Stable</td>
<td>0.430</td>
<td>1.273</td>
</tr>
</tbody>
</table>

Data presented as m/s.

### Table 3. Magnitude of Wall Shear Stress

<table>
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<th>Before Occlusion</th>
<th>After Occlusion</th>
</tr>
</thead>
<tbody>
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<td>Recanalization case 1</td>
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<td>49.285</td>
<td>88.599</td>
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<td>Recanalization case 2</td>
<td>Recanalized</td>
<td>35.878</td>
<td>63.521</td>
</tr>
<tr>
<td>Recanalization case 3</td>
<td>Recanalized</td>
<td>64.486</td>
<td>50.753</td>
</tr>
<tr>
<td>Recanalization case 4</td>
<td>Recanalized</td>
<td>37.061</td>
<td>47.779</td>
</tr>
<tr>
<td>Recanalization case 5</td>
<td>Recanalized</td>
<td>26.537</td>
<td>35.425</td>
</tr>
<tr>
<td>Stable case 1</td>
<td>Stable</td>
<td>73.421</td>
<td>4.545</td>
</tr>
<tr>
<td>Stable case 2</td>
<td>Stable</td>
<td>63.807</td>
<td>7.983</td>
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<td>Stable case 3</td>
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<td>6.371</td>
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<tr>
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<td>47.428</td>
<td>4.495</td>
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<tr>
<td>Stable case 6</td>
<td>Stable</td>
<td>16.581</td>
<td>55.973</td>
</tr>
</tbody>
</table>

Data presented as Pa.
Figure 4. A 46-year-old woman with sudden subarachnoid hemorrhage. Digital subtraction angiography (DSA) showed a left anterior communicating aneurysm (A, B). The blood formed a large and complex vortex inside the aneurysm (C). An obvious impingement region can be observed at the side wall of the aneurysm (D, E, arrow). DSA image showed nearly complete occlusion after coiling (F, G). A small vortex can be observed in the remnant neck (H). The velocity and wall shear stress (WSS) at the occluded remnant neck became lower than that before occlusion (I, J, arrow). Six months after the endovascular treatment, the patient returned for follow-up examinations. DSA examination showed the aneurysm had no recanalization (K, L).
Figure 5. A 38-year-old woman with digital subtraction angiography (DSA) examination that showed left internal carotid artery bifurcating aneurysm (A, B). A large vortex was observed in the aneurysm sac (C), but no obvious high velocity and WSS region could be observed at the aneurysmal neck (D, E, arrow). The aneurysm was partially occluded and left a remnant aneurismal neck (F, G). The large and complex vortex became smaller at the remnant neck (H). However, the velocity and WSS became larger than that before endovascular occlusion at the remnant neck (I, J, arrow). Ten months later, the patient returned for follow-up DSA examination and showed no aneurismal recanalization (K, L).
but not from the actual patient-based imaging information. Similar methods also were used by other groups.15–17 In contrast to previous studies, we innovatively used both of the original pretreatment and posttreatment DSA images to derive the input data for CFD simulation, and this eliminated the potential bias introduced by computer-based mock embolization.

Our results and those found by Ortega et al5 indicate that a localized postembolization high WSS at the remnant neck area might contribute to the development of canalization. Although the precise mechanistic link between the 2 is currently unclear, some studies of the pathogenesis of cerebral aneurysms have shed a light on the roles of WSS. First, WSS higher than normal physiological levels is associated with structural changes that may prompt the vessel wall dilatation, such as disruption of the internal elastic lamina, thinning of the media, and wall damage.22,23

Second, high WSS and fast blood flow may hamper the local blood coagulation process and prevent formation of blood clots inside the aneurysms.13,24 Furthermore, the pressure caused by high-speed blood flow may lead to coil compaction, especially in aneurysms with a wide neck, which is thought to be a determining factor in recanalization.3,25 Supporting this, we observed that in the 2 aneurysms with wide necks (recanalized cases 2 and 5), coil compaction occurred.

Conclusion

In summary, we demonstrated that high WSS and high blood flow velocity were consistently observed near the remnant neck of partially embolized aneurysms prone to future recanalization, suggesting that hemodynamic factors may have an important role in aneurysmal recurrence after endovascular treatment. This is in line with the notion that a remnant neck after occlusion is an important risk factor for recanalization.3,4 The results of our study prompt that the hemodynamic factors at the remnant neck, especially the high WSS, could be an attribution to the aneurismatic recanalization. The results also may suggest that the different flow patterns could be secondarily to incompletely blocked aneurysms. Although our data emphasize a role of hemodynamic factors in the recanalization of embolized aneurysms, other factors, such as pathologic factors (congenital defect, hypertension, atherosclerosis),22 and technical strategies (dense packing, use of decorated coils or stents),26–28 are also likely to be involved.

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Disclosures

None.

References


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