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THE EFFECT OF 3D VISUALIZATION ON OPTIMAL DESIGN FOR STRUT POSITION OF INTRACRANIAL STENT

Hitomi Anzai
Graduate School of Engineering, Tohoku University
Sendai, Miyagi, Japan

Toshio Nakayama
Graduate School of Biomedical Engineering, Tohoku University
Sendai, Miyagi, Japan

Yuriko Takeshima
Institute of Fluid Science, Tohoku University
Sendai, Miyagi, Japan

Makoto Ohta
Institute of Fluid Science, Tohoku University
Sendai, Miyagi, Japan

ABSTRACT

Cerebral aneurysms generally occur at arterial bifurcations and arterial curves in or near the circle of Willis. For the treatment of this disorder, stent placement has been valued as a minimal invasive therapy. The effect of stents on flow reduction in cerebral aneurysms has been examined in several computed fluid dynamics (CFD) studies, suggesting that the stent position or the strut shape may affect flow reduction. However, the position of the stent with the best effect on flow reduction is still unknown because of the flow complexity. Three-dimensional visualization may help to easily specify the inflow zone from the parent artery to the aneurysm and to find the relationship between the effective strut position and the flow pattern. However, confirmation of the ability of 3D visualization to determine the effective position of a stent has not been achieved. In this study, we simulated blood flow with several aneurysm geometries to confirm the effect of 3D visualization on determination of optimal stent position.

First, flow simulation using real aneurysm geometries without a stent was performed as a “pre-stenting situation.” Meshes were generated using a commercial code (Gambit 2.3, Fluent Inc., NH). CFD was carried out using a commercial code (Fluent 6.3, Fluent Inc., NH) based on steady flow. The streamlines around an aneurysm were visualized using a 3D visualization system (EnSight Gold 8.2, Comuputational Engineering Inc., NC) in Realization Workspace (RWS) to visualize the inflow zone.

Secondly, a rectangular solid as a strut model was set in the inflow zone using computer-aided design (CAD) techniques. CFD was then performed as a “post-stenting situation” under the same conditions as the pre-stenting situation using the same mesh generator and CFD code.

Three-dimensional visualization showed an inflow zone in the aneurysm. A bundle of flow streamlines hit the wall of the neck of the aneurysm and entered it. The inflow zone was a narrow local part in contrast to the outflow.

After setting a strut, a change of flow pattern could be observed. The flow speed and the wall shear stress (WSS) were both reduced. When the strut position was moved away from the original position, the flow speed and the WSS were not reduced.

These results may suggest that 3D visualization can provide information useful for strut positioning to realize effective reduction of flow into an aneurysm, especially a side wall aneurysm.

INTRODUCTION

Cardiovascular disease, including heart disease and cerebral vascular disease, is one of the greatest causes of death in developed countries. Cerebral aneurysm is a cerebral vascular disorder that distends the vascular wall, and subarachnoid hemorrhage from a ruptured intracranial aneurysm impairs the quality of life (QOL) of patients in most cases. Therefore, treatment prior to rupture and just after rupture is very important.

There are two types of treatment for aneurysms. One is the surgical approach such as the clipping method, and the other is the endovascular approach such as coil embolization or stent placement. Endovascular treatments have attracted much attention in recent years due to their minimal invasiveness and good prognosis of patients.

The aim of endovascular treatments is to reduce the blood flow in an aneurysm by placement of a device on or in the aneurysm. Embolization by clot formation in an aneurysm is thought to be caused by treatment of the aneurysm. Therefore, it is necessary to investigate the flow pattern around an aneurysm and the distribution of wall shear stress.

The coil embolization method is the most common endovascular treatment for intracranial aneurysms. A stent is used to maintain coils in an aneurysm. However, Aenis et al. reported that the stent itself can reduce the flow in an aneurysm [1], and subsequent studies of sole stenting to reduce the flow more as a "flow diverter" rather than a "support for coiling" have been performed [2-4, 7]. These studies have revealed that the effect of a stent on flow is not only dependent on porosity but also on the design of stent. Stent is a tube with mesh and the mesh consists of member of wire termed strut. Then, the strut position is a base of design of stent. Our previous study has reported that position of one strut affects on flow reduction in aneurysm [9]. This finding suggests the importance of design and position of a strut.

The inflow into an aneurysm is termed secondary flow and is thought to require a 3D viewpoint of the flow structure [5-6]. Three-dimensional visualization is used in several fields to elucidate characteristics of complexity. For example, chemists visualize molecular structure and understand the relationship between atoms. Builders construct a model of a town to help customers understand architectural planning. On the other hand, 3D visualization is thought to be useful for prediction, which is termed "mental simulation." Therefore, we were inspired to use 3D visualization to determine the optimum strut position. In order to validate this method using 3D visualization, the numerical results of blood flow on aneurysm geometry obtained from a human brain were visualized three-dimensionally. Then the position of the strut was decided under observation of the flow.

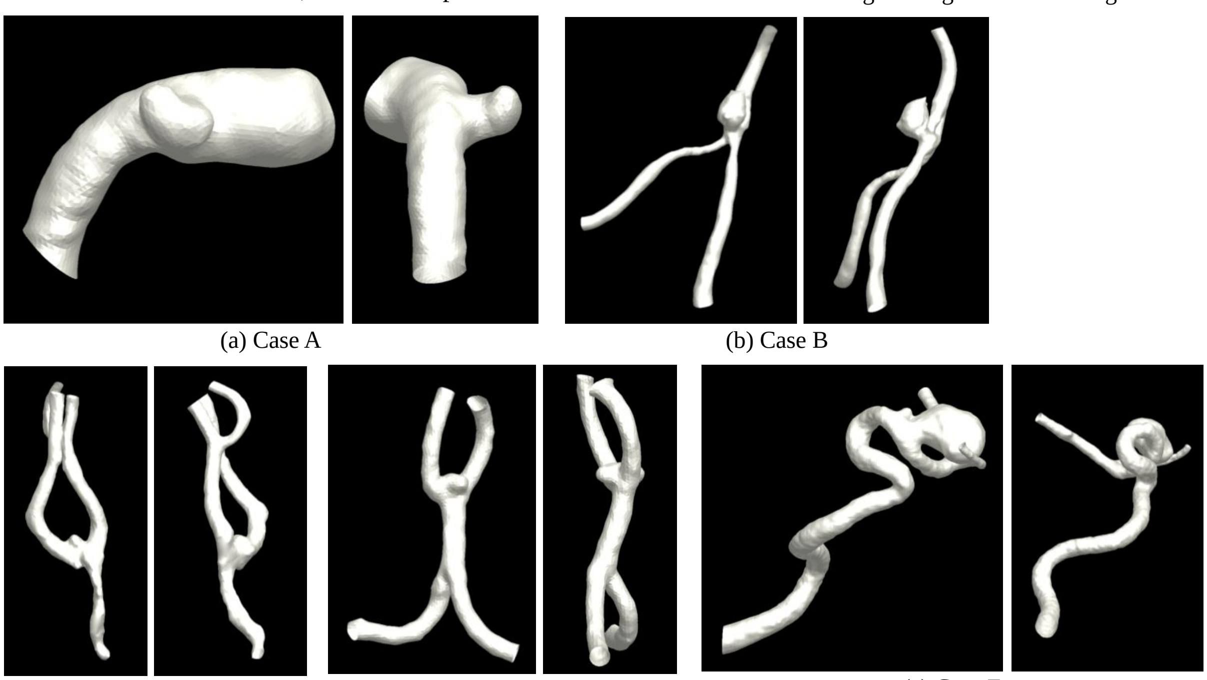
As a result of numerical simulation, the strut at the position determined under the observation of flow had a good effect in reducing flow. This paper describes new methodology for design of a stent using 3D visualization in order to decide the position of a strut.

METHODS

Pre-stenting simulation

Flow simulation using real aneurysm geometries without a stent was performed as a "pre-stenting simulation." In this study, we simulated the flow with 5 types of aneurysm geometry

Fig. 1 Image of sole stenting



(a) Case A
(b) Case B
(c) Case C
(d) Case D
(e) Case E

Fig. 2 Images of aneurysm (left: PA, right: lateral)

Table 1 Source of geometry and location of aneurysm

case	Source	Location
A	Geneva University Hospital	BA
B	VISC09, from Kohnan Hospital	BA
C	VISC09,from Hacettepe Hospital	MCA
D	Fujita Health University	BA tip
E	Fujita Health University	ICPC

provided by four hospitals in STL format (Fig. 2, Table 1). Informed consent was obtained from all patients. Tetrahedron numerical meshes were generated on STL files using Gambit 2.3.

The blood flow was simplified as isothermal, incompressible and laminar Newtonian flow with a density of 1050 [kg/m^3] and a viscosity of 3.5×10^{-3} [Pa s]. Computational fluid dynamics (CFD) were calculated using Fluent 6.3 based on steady flow. The inlet boundary was constant and flow conditions were uniform with a Reynolds number of 200. In case B and D, as they had two inlets, both inlet conditions were set with Reynolds number of 200, the same as for one inlet geometry. All outlets were set with constant pressure condition of 0 Pa.

3D visualization of streamlines

Numerical results were visualized using a 3D visualization system called Realization Workspace (Institute of Fluid Science, Tohoku Univ.). EnSight Gold 8.2 was used as a postprocessor. Streamlines and the arterial wall were projected on the four screens with two different view angles (Fig. 2). A stereoscopic image was observed using shutter-glass (CrystalEyes3, INDYZONE Co., JP). The projected image followed the movement of markers on the glass and the controller shown on the right in Fig. 3, sensed by motion-capture system (VICON MX3+, Crescent Inc., JP). These systems help users to obtain an immersive visualization environment by good view position and simple operation.

From the visualization of streamlines, we were able to choose a strut position which reduced flow.

Post-stenting simulation

A rectangular solid as a strut model was set in a bundle of inflow streamlines based on a decision using computer-aided design (CAD) techniques (Pro/ENGINEER Wildfire 4.0,

Fig. 3 Realization Workspace
(right: screens, left: glasses and controller)

Table 2 Size of strut

case	Size of strut
A	1.5×0.15×0.15[mm]
B	2.0×0.20×0.20[mm]
C	1.0×0.15×0.15[mm]
D	1.0×0.10×0.10[mm]
E	1.0×0.10×0.10[mm]

Parametric Technology Co., MA). The strut size is shown in Table 2 and this strut was termed the “first strut.” To confirm the effect of this strut position, the strut was placed outside the bundle of inflow and calculations were performed again.

Mesh size around the strut became smaller than around the arterial wall using function of the commercial code Gambit 2.3. In Fig. 4, the image on the left shows the mesh structure at the aneurysm neck without a strut, and the image on the right shows the structure with a strut.

CFD was performed under the same condition as that before stenting simulation using the same CFD code.

Then, numerical results were visualized and the effect of strut on flow was confirmed in the same way as before stenting cases.

Second strut simulation

Based on visualization of the results of the first strut, the next position as the “second strut” was decided. Then, aneurysms with two struts were calculated under the same conditions.

RESULTS

Pre-stenting simulation

The calculation results of all samples before stenting are visualized in Realization Workspace (RWS). Figure 5 shows streamlines through only the neck of the aneurysm. The streamlines make a bundle gradually through parent artery. Then the bundle of streamlines splits from the flow in parent artery and enters the aneurysm sacks along the walls of the neck. The bundle of inflow (BOI) streamlines into the aneurysm can be observed as a local, narrow zone in the neck. The bundle of outflow can be also observed as a zone in the neck; however, it is larger than the inlet zone.

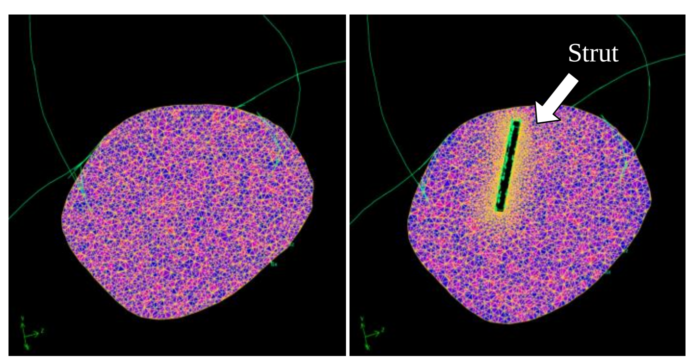


Fig. 4 Image of fine mesh around the strut from the view of cross section of strut (right: pre-stenting case, left: post-stenting case)

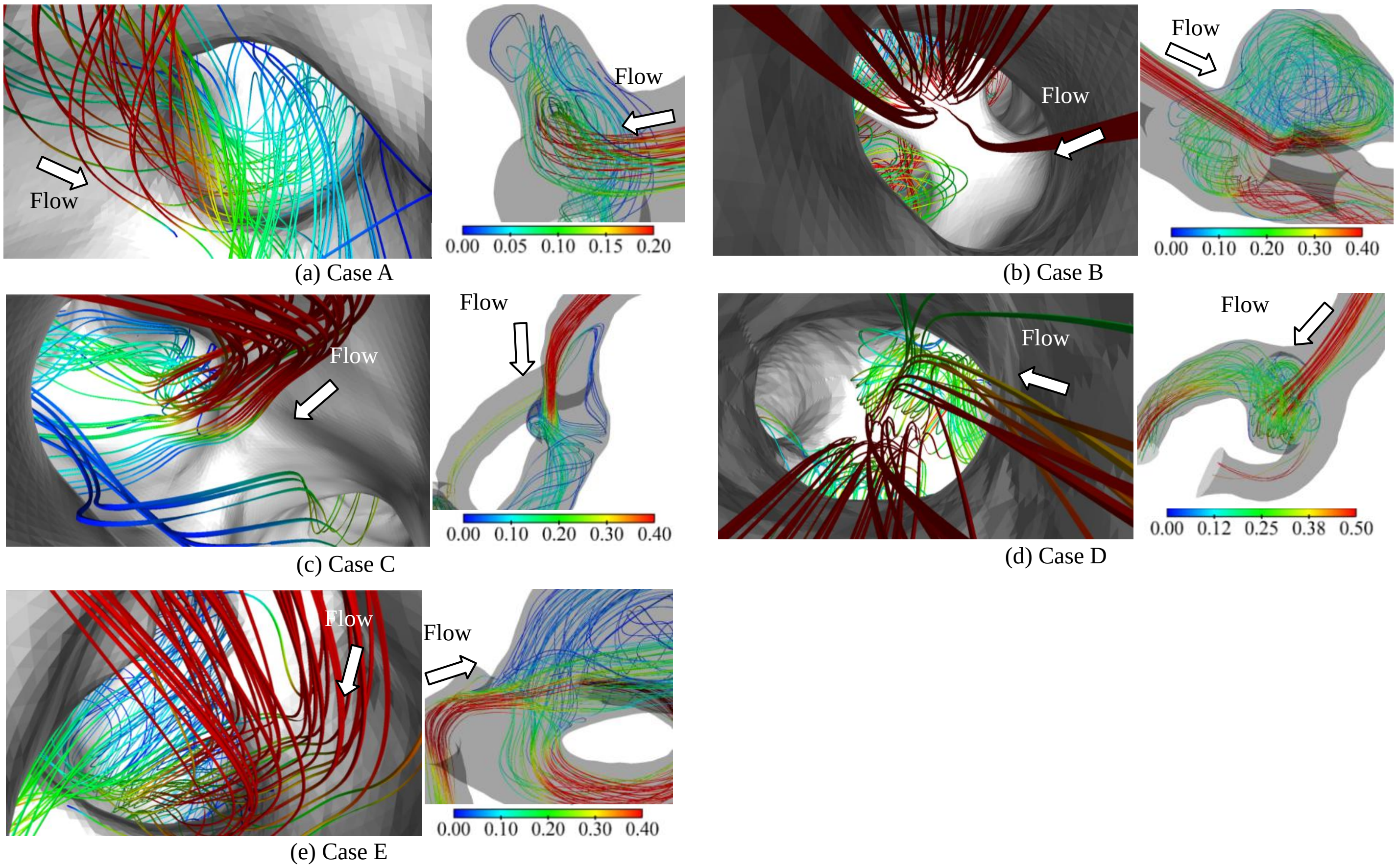


Fig. 5 Images of streamlines through neck (left: from inside of artery, right: from outside of artery)

These results of 3D visualization enable a decision on strut position. The position of strut predicted from 3D visualization is the split point of BOI from the flow in parent artery and seems to be the best position.

Post-stenting simulation – first trial

We put a strut in the BOI as the first trial and compared the resulting flow and the effect of the strut position with those of the stent outside the BOI. The strut of A-1, B-1, C-1, D-1, or E-1 was put in the BOI of each case, respectively. The strut of A-2, B-2, C-2, D-2, or E-2 was placed outside the BOI of each case. Figure 6 shows the position of struts of all cases. The streamlines visualized in Fig. 6 are the results of a "pre-stenting case." The upper-left image of Fig. 6 is the view from outside the parent artery to show the long axis of the struts. The upper-right image is a view from outside of the artery, to show the cross section of the struts. The bottom image is the view inside an artery termed flying through. The area ratio of the strut to the cross section of the parent artery is around 2% in all cases.

After setting of the first strut, the flow pattern in the artery changed (Fig. 7, Fig. 8). Note that the starting point of the streamline is at the same position in each geometry to observe the change of flow. The mean velocity in the aneurysm and the mean wall shear stress (WSS) of post-stenting simulation are lower than the results of pre-stenting simulation. This result indicates that the stent in the BOI reduces the velocity and WSS (Table 3). The mean velocity and the mean WSS of the strut position outside the BOI are higher than the results of strut position in the BOI. This result suggests that the strut outside the BOI does not play a role in the reduction of flow.

The bundle of streamlines splits on the strut in case A-1. The bundle under the strut goes through the parent artery. The bundle above the strut joins the bundle which hits the wall of the neck and leaves to the parent artery without rotating in the sack. This confluence is attributed to the fact that flow speed is reduced by the strut. The streamline with low speed is easily diverted by another streamline.

In case B, the BOI hits the wall of the arterial bifurcation and is significantly diverted. The strut was set on the diverting point of the BOI. As a result, the direction of the BOI is not so changed but velocity is reduced on the strut. Then rotation in the sack ceases.

The aneurysm in case C is still small and the BOI is narrow. The bundle is split by the strut. Then, the colliding point of the bundle on the wall is changed.

Case D has a dumbbell-shaped aneurysm. In this case, one strut was set in each aneurysm. The BOI hits the wall of the bifurcation and is significantly diverted. Due to the struts, velocities of the streamlines are reduced. Then rotation in the sack ceases and WSS is reduced.

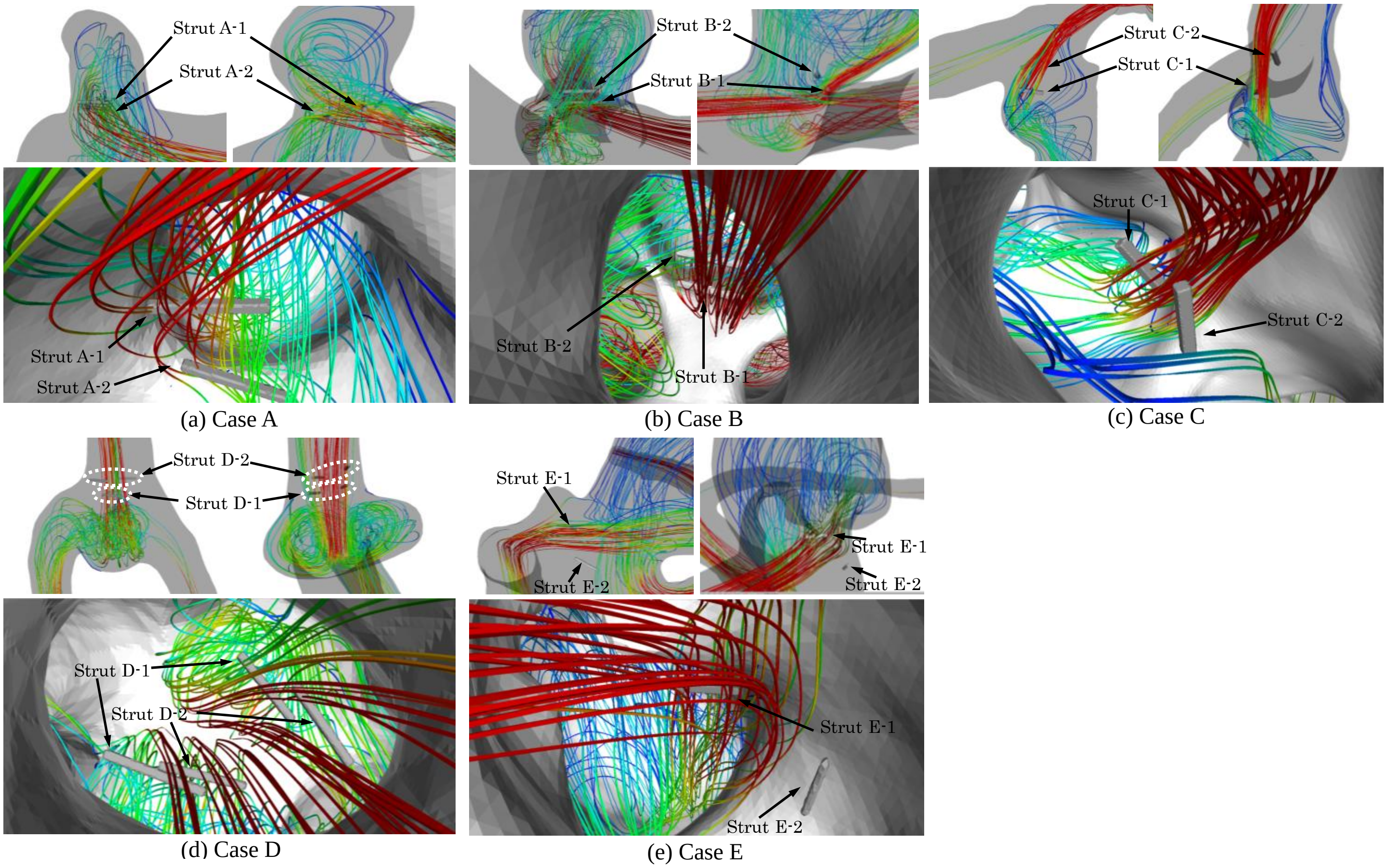


Fig. 6 position of strut (upper-left: PA view from outside of artery, upper-right: lateral view from outside of artery, bottom: from inside of artery)

Table 3 Values of mean velocity in first trial

Case		mean velocity [m/s]	mean WSS [Pa s]	reduction rate of velocity [%]	reduction rate of WSS [%]
A	pre-stenting	4.228×10^{-2}	4.307×10^{-1}		
	strut in the BOI	3.107×10^{-2}	2.076×10^{-1}	26.5	51.8
	strut outside of the BOI	4.021×10^{-2}	4.051×10^{-1}	4.89	5.95
B	pre-stenting	1.020×10^{-1}	1.879		
	strut in the BOI	8.161×10^{-2}	1.111	20.0	40.9
	strut outside of the BOI	1.010×10^{-1}	1.829	1.00	2.89
C	pre-stenting	1.460×10^{-1}	3.909		
	strut in the BOI	1.228×10^{-1}	3.465	15.9	11.4
	strut outside of the BOI	1.366×10^{-1}	3.695	6.46	5.47
D	pre-stenting	2.006×10^{-1}	5.963		
	strut in the BOI	1.772×10^{-1}	4.894	11.7	17.9
	strut outside of the BOI	1.946×10^{-1}	5.688	2.97	4.62
E	pre-stenting	5.560×10^{-1}	4.875×10^{-1}		
	strut in the BOI	4.415×10^{-1}	3.206×10^{-1}	20.6	34.2
	strut outside of the BOI	5.531×10^{-1}	4.881×10^{-1}	0.52	-0.13

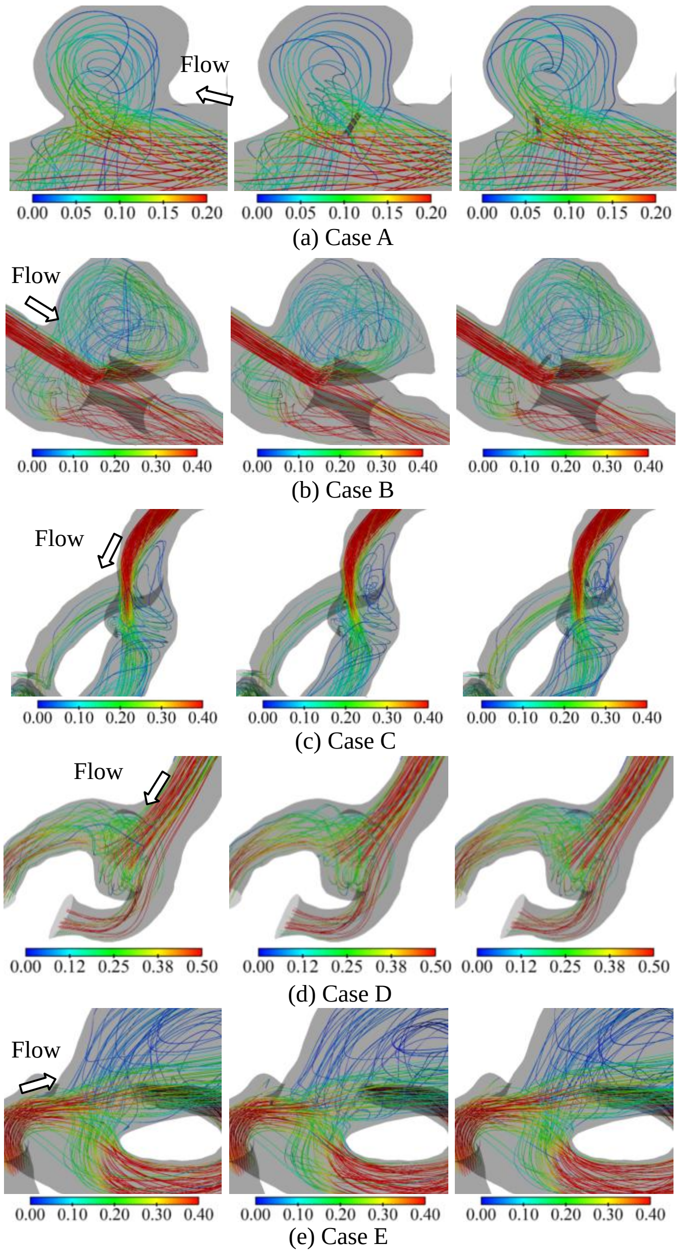


Fig. 7 Image of streamlines through neck (left: w/o strut, center: with strut in BOI, right: with strut outside the BOI)

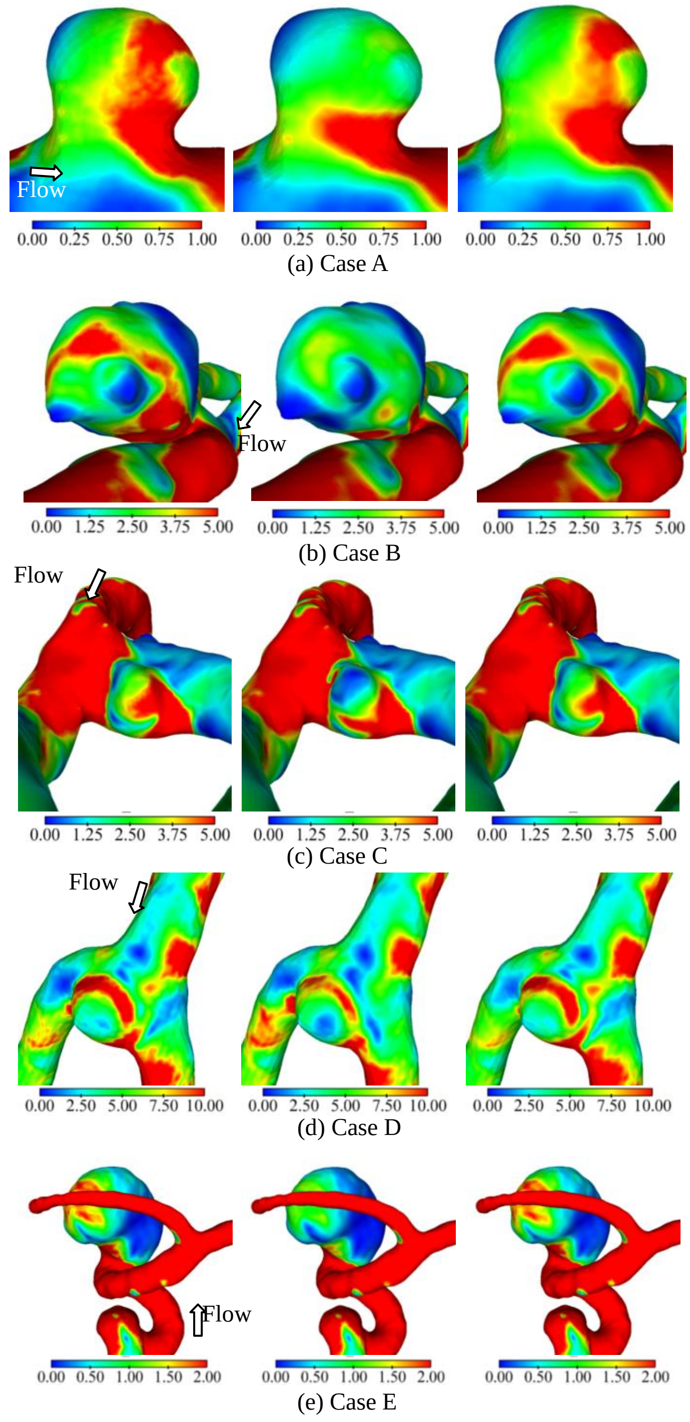


Fig. 8 Image of WSS of aneurysm (left: w/o strut, center: with strut in the BOI, right: with strut outoffside the BOI)

The BOI is split by the strut and a part of bundle goes along the wall of the neck in case E-1. In addition, shear stress on the top of the aneurysm becomes lower due to the reduction of flow speed.

As the result of first trial, the BOI changed especially with struts in the BOI. And the position of second strut with good effect of reduction on flow is predicted.

Post-stenting simulation – second trial

The second strut position is shown in Fig. 9. The size of the "second strut" is the same as that of the "first strut." The streamlines visualized in Fig. 9 are the results of "post-stenting simulation" with struts in the BOI.

After placement of the second strut, the flow pattern in the artery changes. Mean velocity and mean WSS are smaller than those of "post-stenting simulation" (Table 4).

Table 4 Values of mean velocity in second trial

Case	mean velocity [m/s]	mean WSS [Pa s]	reduction rate of velocity [%]	reduction rate of WSS [%]
A	2.495×10^{-2}	1.621×10^{-1}	41.0	62.4
B	7.346×10^{-2}	9.270×10^{-1}	28.0	50.7
C	7.206×10^{-2}	1.423	50.7	63.6
D	1.614×10^{-1}	4.225	19.5	29.1
E	4.116×10^{-2}	2.884×10^{-1}	26.0	40.8

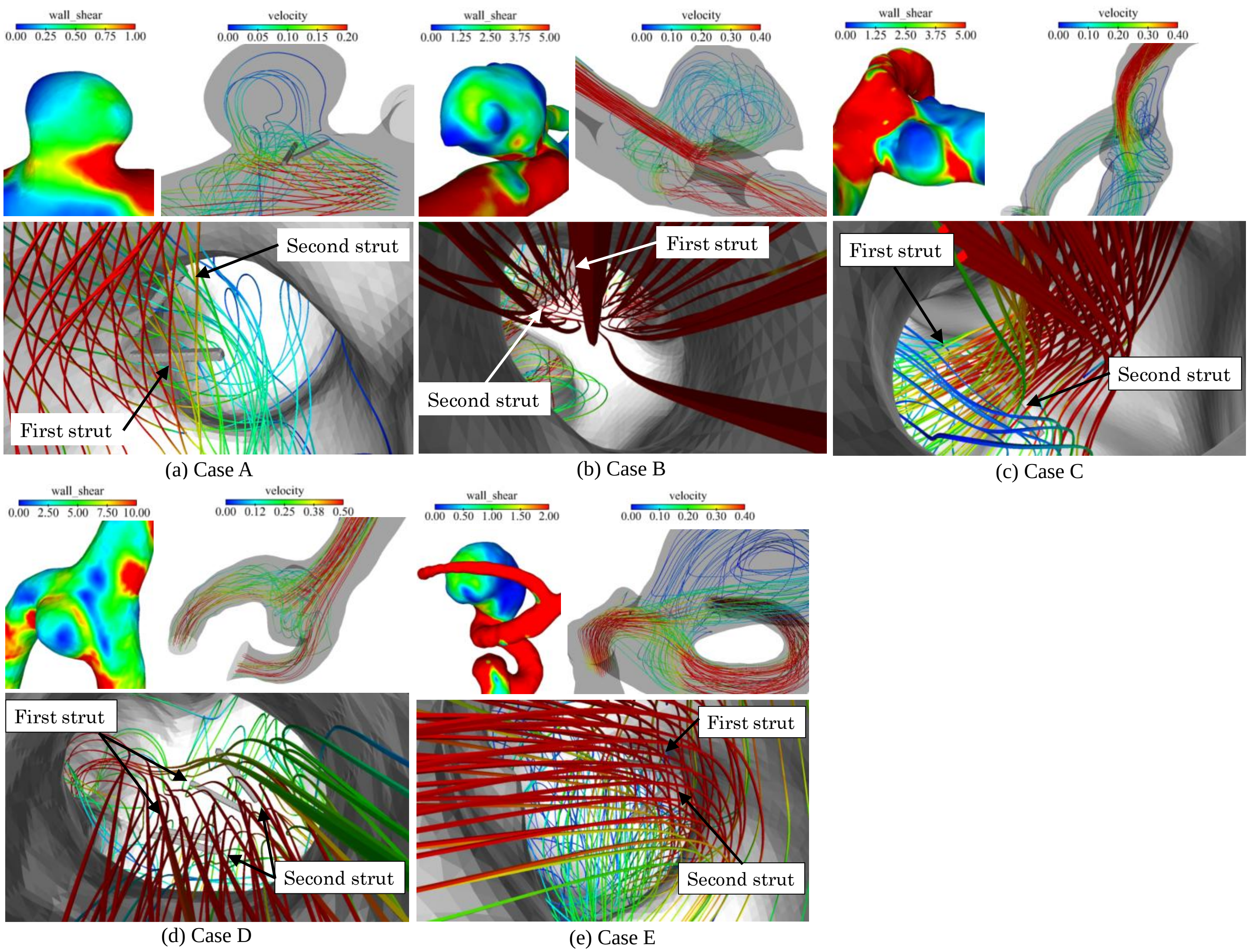


Fig. 9 Images of streamlines after second trial
(upper-left: PA view from outside of artery, upper-right: lateral view from outside of artery, bottom: view from inside of artery)

DISCUSSION

This paper describes the possibility of 3D visualization to understand the flow around an aneurysm, and the possibility of estimation of a strut position with a good effect on flow reduction in an aneurysm.

Mental simulation using 3D visualization

Recent dramatic developments of 3D visualization techniques can be applied to many fields such as molecular chemistry, medical diagnosis, architecture and so on. The well-known and general purpose of using the 3D function is to support consensus formation. Moreover, a new field called "mental simulation" using 3D visualization has appeared.

In this study, "mental simulation" means a process to simulate physical phenomena mentally without actual action. In other words, it is a process to imagine the possibility in the next condition under currently known information. Studies such as this use "mental simulation" to detect the flow on an aneurysm and to place one or two strut(s) in the flow to reduce it.

We initially tried to grasp several important characteristics such as BOI or direction of flow on/to an aneurism by 3D visualization of streamlines. Then the position of the strut was decided by imagining the flow with a strut.

The results show that 3D visualization is useful for grasping the flow on an aneurysm and placing a strut to reduce the speed of blood flow in the aneurysm.

Effect of stent

A stent strut can have two types of effect on reduction of flow. The first effect is called diversion of flow [4, 7]. This effect reduces the blood flow speed because the flow streamlines jostle each other and balance. The other way is to reduce the flow speed based on the effect of the surface area of the stent on flow. Because the velocity on the wall surface should be equal to zero and the blood has high viscosity, the flow speed is reduced along the surface.

Region of this study

The flow in an aneurysm may affect clotting or rupturing [8] after stenting. On the other hand, the flow on an aneurysm or its neck will affect the flow pattern and lead to a decision of stent position. Therefore, the flow on an aneurysm or its neck is the region of interest in this study.

Pre-stenting simulation

Streamlines of blood flow are bundled gradually when they go through a parent artery with several curves and twists. Then the constructed BOI enters the aneurysm through the neck. The results of characteristics of flow entering an aneurysm and of the construction of BOI indicate that a stent affects a BOI to reduce the flow in aneurysm and that the placement of a strut in BOI is the most effective position for the reduction of flow. Regarding the strut position, the split of BOI from the flow in the parent artery may be the best position. A strut placed perpendicular to the direction of BOI will be more effective. If the strut is placed after the split, it is difficult to prevent the flow entering the aneurysm by the change of BOI direction.

Post-stenting simulation

In cases A, C and E, the streamlines are changed by the strut. Thus, it can be said that the struts act as a "flow diverter." In cases B and D, the change of streamline direction is smaller than in the other cases, although both reduction rates of flow speed and WSS are similar to cases A, C and E. This result indicates that the struts of B and D act as "flow decelerator," described previously. The strut placed in high-speed flow tends to result in reduction of velocity rather than diversion of flow. In the case of flow deceleration, the strut should be placed from a viewpoint different from that of the "flow diverter" strut. In cases B and D, the strut placed in the high-speed flow tends to reduce the velocity rather than diverting the flow. The way to decide the position of the "flow decelerator" strut must be decided in another way differs from the position of the "flow diverter" strut.

The advantage of 3D visualization is that depth can be perceived. This perception is necessary to recognize the relation between the flow and geometry. In the case of 2D visualization, the perception of depth is lost. In order to make 3D reconstruction from 2D visualization, several 2D viewpoints are necessary. In the case of 3D visualization, this process of mental reconstruction can be skipped. Thus, the prediction of flow after stenting can be created directly and easily from the 3D image before stenting. Also, the effects of 3D visualization for BOI may be available to design the stent for the reduction and diversion of flow.

However, the following points should be still discussed. In case of simulation with pulsatile flow, BOI will fluctuate according to the pulsation. In such case, the recognition of BOI may be insufficient and the role of the strut in the BOI under steady flow is too limited. Observing the BOI under pulsation with 3D visualization can further facilitate recognition of the relation of flow and geometry because of flow complexity.

The cases in this study covered bifurcation, side wall and dumbbell aneurysms. However, not all aneurysms were covered and the number of cases should be increased to confirm the effect of 3D visualization on the recognition of flow and on the design of struts.

CONCLUSION

The flow around an aneurysm was observed using a 3D visualization system. As a result of visualization, the bundle of inflow (BOI) into an aneurysm was observed. This characteristic of flow can facilitate prediction that a strut on BOI may reduce the flow in an aneurysm. Regarding strut position, the split of BOI from the flow in the parent artery may be the best position.

After setting of a strut ay the position mentioned above, velocity and WSS were reduced. Strut changed the flow direction and a new BOI appeared on aneurysm. The position of a second strut was decided under observation of the new BOI.

After placement of a second strut, velocity and WSS were further reduced.

Therefore, 3D visualization may be helpful for determining of strut position which will be have a good effect on flow. However, the number of cases should be increased to confirm this effect on recognition of flow and on the design of a strut.

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