Numerical simulation techniques to predict aneurysm recanalization after coil embolization and their problems

Soichiro Fujimura1,2,* Masaaki Shojima3, Shigeru Nemoto4, Yasuyuki Umeda5, Tomohiro Yamada6, Takumi Ishii1,2, Fuki Wakabayashi7, on behalf of CFD-BIO

1Graduate School of Mechanical Engineering, Tokyo University of Science, 6-3-1 Niijuku, Katsushika-ku, Tokyo 125-8585, Japan
2Department of Innovation for Medical Information Technology, The Jikei University School of Medicine, 3-25-8 Nishi-shinbashi, Minato-ku, Tokyo 105-8461, Japan
3Department of Neurosurgery, Saitama Medical Center, 1981 Kamoda, Kawagoe-shi, Saitama 350-8550, Japan
4Department of Endovascular Surgery, Tokyo Medical and Dental University, 1-5-45 Yushima, Bunkyo-ku, Tokyo 113-8510, Japan
5Department of Neurosurgery, Mie University Graduate School of Medicine, 2-174 Edobashi, Tsu-shi, Mie 514-8507, Japan
6Graduate School of Electrical and Mechanical Engineering, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya, Aichi 466-8555, Japan
7Department of Mechanical Engineering, Tokyo University of Science, 6-3-1 Niijuku, Katsushika-ku, Tokyo 125-8585, Japan

Received: 31 October 2019 / Accepted: 21 January 2020
© Japanese Society of Biorheology 2019

Abstract Various coil modeling techniques have been applied for computational fluid dynamics (CFD) analysis to predict recanalization after aneurysm coil embolization. Investigation on the technical difficulties and the effects on CFD analysis results when using the four main coil modeling methods (solid model, porous model, Dynamic Path Planning, finite element method (FEM) structural analysis) revealed that the expertise required for the analysis as well as the time needed for the analysis increased the more the results were realistic. In addition, by applying the four coil modeling methods to cases that actually underwent coil embolization surgery, hemodynamic factors such as blood flow velocity or mass flow rate were reported to have an effect on the occurrence of recanalization. It was also reported that the consideration of hemodynamic factors is useful for predicting recanalization. Although various validations are required, CFD analysis may be a useful tool for predicting recanalization of aneurysms after coil embolization in the future.

Keywords cerebral aneurysm, coil embolization, recanalization, computational fluid dynamics (CFD), structural analysis

1. Introduction

Currently, coil embolization is frequently used to treat aneurysms. In coil embolization, several to tens of coils are deployed in an aneurysm so that blood flow does not enter the aneurysm. In some cases, blood flow re-enters the aneurysm and re-treatment is required [1, 2]. This phenomenon is called recanalization.

Due to the improvement of computational technology and improvement of image resolution from the development of diagnostic imaging equipment such as computed tomography (CT), magnetic resonance imaging (MRI), and digital subtraction angiography (DSA), an increasing amount of blood flow analysis using computational fluid dynamics (CFD) based on medical images have been performed [3–5]. This technique has also been introduced to investigate aneurysm recanalization, and multiple studies have been conducted so far [6–12]. CFD analysis were conducted on cases where coil embolization were performed, and it has been suggested that recanalization may be predicted by derived hemodynamic factors [8, 10, 12]. The method in which the coil is modeled and deployed in an aneurysm is a major issue when performing CFD analysis to predict recanalization. Many coils are densely inserted into the aneurysm during coil embolization leaving very little space among the coils. In addition, because of the metal artifacts caused by metals such as platinum alloy, which is the main component of the coils, it is extremely
difficult to depict the explicit shape of the coils placed in
the aneurysm from images acquired from a normal diagnostic
imaging device. For this reason, coil modeling has been
carried out by several different methods in previous studies.
In this review article, we discuss the effects on the CFD
analysis results using different coil modeling methods and
the technical issues, and also examine the role of CFD
analysis in predicting recanalization of aneurysms.

2. Methods
A PubMed search was conducted using the keywords,
“aneurysm/intracranial aneurysm” and “CFD/computa-
tional fluid dynamics/computational fluid dynamic/hemo-
dynamic wall shear stress/computational hemodynamics”,
for the period of Jan 1st 2000 through Dec 31st 2018,
yielding a total of 588 studies without overlap. The studies
were then categorized into 16 sections permitting overlap.
English-written full articles were selected and the others
such as abstracts and comments were not categorized. 50
studies in the section “Coil embolization” were included in
this review.

3. Results
(1) Cerebral Artery Model Generation
Many studies investigating recanalization after coil
embolization performed CFD analysis on patients who had
undergone coil embolization and subsequently recanalized.
In order to perform CFD analysis, it is necessary to recon-
struct the aneurysm and the nearby cerebral arteries from
medical images in three dimensions. Many of the studies
have reconstructed the cerebral vascular system based on
images taken by 3D rotational angiography (RA), but some
studies used 3D computed tomography angiography (CTA)
or 3D magnetic resonance angiography (MRA) images [13,
14]. The artery geometries were reconstructed using data
taken before or after coil embolization.

(2) CFD analysis methods
In CFD analysis, the flow field is simulated by solving
the continuous equation and the Navier-Stokes equation.
\
\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \\
\frac{\partial \mathbf{v}}{\partial t} = -\nabla p + \mu \nabla^2 \mathbf{v}
\]

where \( \rho \) is the density of the fluid, \( \mathbf{v} \) is the velocity, \( p \)
is the pressure, and \( \mu \) is the viscosity coefficient. In most
studies, transient analysis were performed by giving a
pulsatile inflow condition considering pulsation as an
inflow boundary condition. In addition, most studies
assumed the blood vessel wall to be a rigid body, in other
words, fluid structure interaction (FSI) analysis considering
the elasticity of the arterial walls were rarely used. A model
assuming Newtonian fluid is generally used for blood
properties, but there was a study investigating the influence
of non-Newtonian fluid on analysis results [15]. According
to the report, although the use of Newtonian fluids slightly
overestimates the flow velocity, the effects were not large
enough to cause flow changes, so it is reasonable to assume
blood as a Newtonian fluid. Since the Reynolds number of
cerebral circulation is around several hundreds, the flow
field is assumed to be an incompressible laminar flow field.

(3) Methods for modeling coil deployed in aneurysms (virtual
coiling methods)
The following four modeling methods were mainly used
as methods for modeling the coil after embolization.
• Solid Model
Since multiple coils are generally inserted for coil embo-
lization, the inserted coils are deployed inside the aneurysm
in a packed state. The solid model assumes that blood flow
does not enter the region where the coil is inserted and
treats the coil mass as one solid body (see Fig. 1(A)). When
applying the solid model, some studies reconstructed the
coil mass using images taken by diagnostic imaging devices,
other studies artificially reproduced the state in which the coil
mass is deployed by reconstructing the cerebral artery
geometries only at locations where there was blood flow or

![Figure 1](https://example.com/figure1.png)

Figure 1 Diagrams of the modeled coils used in previous studies.
by artificially removing the aneurysm above the aneurysm neck surface from images before coil embolization. [6, 8, 11, 12, 16]. Ten reports have adopted this method.

- Porous Model

The porous model is a type of numerical analysis method used to reproduce a porous medium, which is a state where uniform gaps (pores) are formed inside a structure (see Fig. 1(B)). In the engineering field, it can be used to analyze the permeation of water into a sponge or the flow of air passing through an air filter. The porous model can be applied by giving an external force term to the Navier-Stokes equation. There are various methods for determining the external force term. In previous studies where the porous model was applied to modeling the coil, it was common that the pressure loss was defined by Darcy’s law \( (\nabla p = -K v) \) and the constant of porous resistance \( K \) was determined according to Ergun’s formula as shown below.

\[
K = \alpha |v| + \beta
\]

\[
\alpha = \frac{1.75 \rho (1 - \kappa)}{\kappa^2 D_p}
\]

\[
\beta = \frac{150 \rho (1 - \kappa)^2}{\kappa^2 D_p}
\]

where \( D_p \) is the average particle diameter and \( \kappa \) is the porosity. The methods of Kozeny Carman’s equation \( (K_{\text{perm}} = \phi^3/cS^3 \) (where \( \phi \) is the porosity of the medium, \( S \) is the specific surface area of coils, and \( c \) is the Kozeny coefficient)), and the rule of thumb of Jackson and James has been used in determining coefficients \([10, 17–19]\]. When determining these coefficients, adjustments such as changing the size of the particles to be equivalent to the coil diameter or determining the porosity from the embolization rate were made, to make the model realistic. There were 12 reports that adopted this method.

- Dynamic Path Planning

Dynamic Path Planning (DPP) developed by Morales et al. is a model that imitates the shape of each coil \([20, 21]\). This method simulates the coil shape after embolization based on the shape of the aneurysm and the lengths and diameters of the coils to be inserted (see Fig. 1(C)). DPP defines a formula that takes into account the straightness of the coils, interference with other coils and aneurysm walls, and the local packing densities of the coils in the aneurysm. Weights are determined based on the above formula at the candidate points where the coil may travel, and a curve is created by continuously connecting the candidate points in the direction in which the coil travels easily (the direction with less weight). Then, the coil paths are swept with the coil diameter to obtain the coil shapes after embolization. In this method, only the direction in which the coil easily travels is determined, therefore, material characteristics such as the stiffness of the coils are not taken into consideration. There were three reports that adopted this method.

- FEM-based Structural Analysis

Structural analysis is intended to clarify mechanical changes such as stress and deformation that occur in every part of the structure by numerical analysis. In the engineering field, it is used for various fields such as analysis of metal press work and aircraft wing strength design, etc. In this method, the insertion of the coil into the aneurysm during coil embolization is reproduced by numerical analysis based on the structural analysis adopting the finite element method (FEM) (see Fig. 1(D)) \([22–24]\). Since the shapes of the inserted coils are used in the numerical analysis, it is possible to reproduce the geometry of each coil. It is also possible to consider the material properties and contact of the coils. Eight reports have adopted this method.

4. Discussion

(1) The effects on the analysis due to differences in coil modeling

CFD analysis for aneurysms after coil embolization has been performed since around 2004. The solid model which does not allow blood flow to enter the aneurysm has been analyzed at a relatively early stage \([25]\). The solid model is simple therefore there is the advantage of being able to perform analysis relatively easily. On the other hand, blood flow that passes through the gaps between the coils cannot be reproduced restricting discussions of blood flow analysis to locations near the neck of the aneurysm \([6, 8, 12, 20]\).

For the method of reconstructing the shape of the inserted coil mass based on the images taken by the diagnostic imaging devices and handling it as a solid model, the reproducibility of the coil shape is limited due to the influence of metal artifacts \([8]\). The solid model can be considered to have been adopted on the assumption that the inside of the aneurysm has completely occluded due to thrombosis around the inserted coils, however, it is a problem that this model does not take into account the influence on blood flow due to the differences in embolization rates. Moreover, this method that treats the entire aneurysm as a solid model is closer to modeling an aneurysm after clipping rather than coil embolization.

If it is before thrombosis, even after coil embolization, blood flows into the aneurysm through the gaps between the coils. This is apparent from angiographic images during coil embolization. The porous model is a technique that started to be applied to consider the inflow of blood inside the aneurysm after coil embolization. In this method, the porous model is applied to the inside of an aneurysm, that is, the region where the coils are inserted. The porous model is also relatively easy to apply, and it is generally incorporated as a default function in commercial analysis software. On the other hand, when applying the porous model, it is essential to define the coefficient such as the
constant of porous resistance $K$ in Darcy’s law that determines the degree of pressure loss. As described in section 3, there are various methods for determining this coefficient, however, the methods used in studies are not unified. Since this coefficient directly affects the analysis results, it is necessary to pay attention to the method of coefficient determination when using the porous model for aneurysms after coil embolization. The effect on the analysis results due to the difference in the determination of coefficients have not been investigated enough. More importantly, the porous model is applied on the assumption that the coil distribution is isotropic and uniform. This is because the porous model assumes a uniform state, but it is difficult to say that the coil distribution in the aneurysm is uniform. In particular, when the embolization rate is low, a large difference occurs in the coil packing densities at different locations within the aneurysm. In addition, since the coils tend to be deployed from the walls of the aneurysm, it is known that there is a difference in the distribution and the packing density of the coils near the walls and towards the center of the aneurysm. For this reason, it is necessary to pay sufficient attention to the interpretation of the analysis results using the porous model for recanalized cases with relatively low embolization rates. Levitt et al. showed an interesting report on the effect of the simplification when using the porous model to represent the state after coil embolization. The effect on the analysis results due to the difference in the determination of coefficients have not been investigated enough. More importantly, the porous model is applied on the assumption that the coil distribution is isotropic and uniform. This is because the porous model assumes a uniform state, but it is difficult to say that the coil distribution in the aneurysm is uniform. In particular, when the embolization rate is low, a large difference occurs in the coil packing densities at different locations within the aneurysm. In addition, since the coils tend to be deployed from the walls of the aneurysm, it is known that there is a difference in the distribution and the packing density of the coils near the walls and towards the center of the aneurysm [20, 22]. For this reason, it is necessary to pay sufficient attention to the interpretation of the analysis results using the porous model for recanalized cases with relatively low embolization rates. Levitt et al. showed an interesting report on the effect of the simplification when using the porous model to represent the state after coil embolization [26]. They succeeded in reconstructing a detailed three-dimensional coil shape of each coil based on the image of the coil after embolization using a high-resolution micro CT. CFD analysis was performed using this reconstructed coil shape and compared with the analysis results using the porous model. When using the porous model, the analysis overestimated the inflow rate inside the aneurysm ranging from tens to hundred-tens of percent, underestimated the oscillatory shear index (OSI) and viscous dissipation, and the wall shear stress (WSS) and wall shear stress gradient (WSSG) had both chances of being underestimated or overestimated. When applying the porous model for the analysis, it is important that the above-mentioned characteristics of the porous model are well understood and that the purposes for blood flow analysis on aneurysms after coil embolization are firmly grasped.

Both the solid model and porous model had the problem that the shape of each coil could not be reproduced, but DPP developed by Morales et al. is a useful solution to overcome this problem [20, 21]. DPP cannot take into account mechanical factors such as the stiffness of the coils and the friction with the walls of the aneurysm, but if the lengths and diameters of the coils to be inserted inside the aneurysm are determined, it is possible to reproduce a coil mass that expresses the geometries of each coil. Since the gap between the coils are also reproduced, it can be used for investigation of hemodynamic factors within the aneurysm after insertion of the coils, and it also allows investigation on the influence of different embolization rates. In addition, the straightness, interference, and the local packing densities of the coils are taken into account in the calculation formula although the material characteristics of the coil cannot be reproduced with DPP. Thereby, DPP succeeds in imitating the basic characteristics of the coils, specifically, the coil deployment distributes more densely near walls and at regions with relatively more space. In fact, the distribution of coils reproduced by DPP has been shown to be similar to that of coils in actual coil embolization [20]. On the other hand, because DPP is an original developed method, programming skills are required to implement it. The calculation cost is higher than that of a solid model or porous model, but the calculation cost is considerably lower than that of a method using structural analysis by FEM.

The method using the structural analysis by FEM takes into consideration the mechanical properties of the coil, which could not be taken into account for DPP. This method tries to reproduce the deployment process of the coils using structural analysis, and it takes into account the material characteristics of the coils and reproduces the shapes of each individual coil. Therefore, it is possible to investigate the influence of factors such as the stiffness and lengths of the coils on the distribution of the coils in the aneurysm. The reproducibility when structural analysis is used for coil insertion has also been investigated, and relatively good results have been obtained [27]. By performing CFD analysis using the coil shape after insertion into the aneurysm, it is possible to investigate the influence on blood flow with varying coil distributions which depends on the type of coils inserted. Furthermore, it is theoretically possible to investigate the effect of blood flow on the behavior of the coil during the deployment process by FSI analysis, but so far, no reports have been confirmed. In order to carry out the structural analysis of coil insertion, it is necessary to use commercial software for structural analysis, or to create or develop new software for structural analysis. When simulating the behavior of coil deployment by structural analysis, it is necessary to perform dynamic analysis on a model with large-scale deformation and non-linearity. In particular, when structural analysis is performed together with CFD analysis, a large amount of calculation cost is required compared with the other methods raised so far.

Of the above methods, in FEM structural analysis, it is not a necessity to define the neck surface separating the aneurysm and the parent artery when modeling the coil. For the method of artificially deleting the aneurysm above the neck surface, the porous model, and DPP, it is necessary to define the neck surface of the aneurysm in order to model the coil. In many studies reported so far, the neck surface has been arbitrarily defined by the analysts themselves or by the software created by the analysts. In many cases, the neck surface is defined as a flat surface, however, in reality the boundary surface of an aneurysm inserted with coils is not likely to be flat, therefore being insufficiently expressed. When the definition of the neck surface changes due to the
difference of analysts, it is necessary to pay close attention to the fact that the analysis results may be affected.

(2) Expertise and analysis time required for each method

Based on previous studies, Table 1 summarizes the required engineering expertise, software expertise, analysis time, and the reality of the results, when implementing each method to model coils. The solid model is simple, so it does not require engineering and software expertise, and the analysis time is only a few hours, but the reality is not high compared to other methods. The porous model does not require much software expertise, since the default function analysis software can be used in most cases. In addition, the analysis time is only a few hours, but depending on the size of the coils inserted, it may take several days. Structural analysis by FEM requires not only understanding of fluid mechanics but also high expertise in computational solid mechanics while also requiring skills in handling specialized software. In addition, since the calculation cost for performing the structural analysis is high, it takes several days to several weeks from the insertion of the coil to the completion of the CFD analysis. However, it can be said that it is the most realistic model among the other methods. Overall, the more the results are realistic, the more expertise is required, and at the same time the required analysis time will be longer.

(3) Hemodynamic factors that affect the occurrence of recanalization

There have been many reports on the recanalization factors of aneurysms using the coil modeling methods described above [6–12]. Studies investigating the hemodynamic aspects of recanalization of aneurysms after coil embolization from CFD analysis of both recanalized cases and stable cases has been conducted since around 2011. The report by Luo et al., which adopted the solid model, was a pioneer study to investigate the recanalization factors from results of CFD analysis, and they examined the effects of WSS and flow velocity at the residual neck [6]. There have been several reports using the solid model in their study to clarify the recanalization factors using CFD after Luo et al., but due to the limitations of solid models described in 3. (1), only hemodynamic factors on the surface of the coil near the neck of the aneurysm or on the neck are investigated. Misaki et al. conducted a CFD analysis with the method of artificially deleting the aneurysm for patients who had recanalized and on stable patients, focusing on Pcom aneurysms. They reported a statistically significant difference in the flow velocities and flow rates in Pcom between the two groups [11]. In addition, in a report that adopted the method of reconstructing the shape of the coil and treating it as a solid model based on the image taken by diagnostic imaging devices, it was reported that the rate of decrease in the flow velocity near the neck of the aneurysm and the rate of increase in pressure before and after coil insertion have a significant effect on recanalization of the aneurysms.

On the other hand, Umeda et al. conducted a CFD analysis using the porous model for recanalized cases and stable cases and found statistical significance in a parameter named residual flow volume (RFV) that evaluates the volume of blood flow that surpasses a certain threshold velocity at the inlet region of an aneurysm after coil embolization [10]. Similarly, Zhang et al. conducted CFD analysis using a porous model for a total of 283 cases and reported that the rate of decrease in flow velocity near the neck of the aneurysm was an important factor for recanalization [9].

Since the DPP and FEM structural analysis methods require more expertise and time for analysis, the reports using these methods for investigations of recanalization factors using CFD blood flow analysis on multiple aneurysm cases number only a few. In particular, for the method using structural analysis, there have been reports on the coil insertion and CFD analysis by structural analysis for basic geometrical models or on specific single case, but a report applying this method to many cases could not be confirmed [22–24].

| Coil Model                  | Solid Model | Porous Model | Dynamic Path Planning | FEM-based Structural Analysis |
|-----------------------------|-------------|--------------|-----------------------|-------------------------------|
| Engineering Expertise       | Low         | Medium       | Low                   | High                          |
| Software Expertise          | Low         | Low          | Medium                | High                          |
| Analysis Time               | A Few Hours | A Few Hours  | A Few Hours–A Few Days| A Few Days–A Few Weeks        |
| Reality                     | Low         | Low          | Medium                | High                          |

FEM, finite element method
All of the above methods were reported to reveal hemodynamic factors affecting the occurrence of recanalization by performing blood flow analysis after coil insertion by expressing the coil with a model. There are also reports in which hemodynamic factors involved in recanalization were investigated using only aneurysms and artery shapes before coil insertion without the modeling of coils. Fujimura et al. conducted CFD analysis on the artery geometries of before and after coil deployment in a total of 100 cases, in which 26 patients were re-treated due to recanalization and 74 cases that remained stable. They reported that in terms of hemodynamic factors before coil deployment, there were no factors that had a statistically significant effect. However, Sugiyama et al. conducted a CFD analysis on basilar tip aneurysms for 57 cases (recanalized: 19 cases, stable: 38 cases) on the diagnostic images before coil insertion and they reported that the mass flow rate (inflow rate coefficient) flowing into the aneurysm with respect to the parent artery was statistically significant [7]. From previous studies, it seems that the CFD analysis was more successful in identifying statistically significant factors related to recanalization after coil embolization when the coil was modeled using some technique rather than CFD analysis performed only for aneurysms prior to coil embolization without modeling the coil. Considering that the modeled coil is determined by the shape of the aneurysm before coil embolization, factors such as embolization rate and coil distribution cannot be considered, however, by finding the appropriate parameters, it is possible that a simple coil model with CFD analysis may be able to predict recanalization after coil embolization at low cost.

In addition to hemodynamic factors, other factors such as aneurysm rupture status, aneurysm size, and coil embolization rate are also thought to be involved in the recanalization of aneurysms. Many of the studies that have investigated the hemodynamic factors related to recanalization after coil embolization so far, have been comparisons made between recanalized cases and stable cases in the presence of statistically significant differences in aneurysm rupture status, aneurysm size, coil embolization rate, and aspect ratio (AR), etc. In order to clarify the hemodynamic factors that affect the occurrence of recanalization, it would be desirable to conduct CFD analysis and statistical comparisons on a large number of cases, stratified by size and embolization rate.

Although many studies have reported that flow velocity and mass flow rate are related to the recanalization of aneurysms after coil embolization, it is a problem that it is difficult to compare these results due to the differences in coil modeling methods, hemodynamic parameters, and boundary conditions.

(4) The possibilities of CFD as a tool for the prediction of recanalization

From clinical research results, there are many factors such as the morphological factor of aneurysm size, the treatment technique factor of embolization rate, and the patient history factors such as hypertension, and rupture status have been reported to be related to recanalization. Considering that it has been speculated that hemodynamic stress is greatly involved in the recanalization of aneurysms after coil embolization from when coil embolization began to be used in clinical practice, it is expected that recanalization can be predicted with higher accuracy by taking into account the hemodynamic factors from CFD together with the clinical research factors said to be related to recanalization. Fujimura et al. reported that simultaneous consideration of hemodynamic factors, morphological factors, and patient information of aneurysms is important for predicting recanalization of aneurysms [8]. They considered the hemodynamic factors from CFD analysis, aneurysm morphological factors, and patient clinical information, and using the statistical method of multivariate analysis obtained a comprehensive parameter (RP: re-treatment predictor) built for predicting recanalization. As a result of receiver operating characteristic (ROC) analysis, the sensitivity was 0.885, the specificity was 0.716, and the area under curve (AUC) was 0.833 when classified by the cutoff value derived from RP. On the other hand, when ROC analysis was performed using only the volume embolization ratio (VER), which has been reported to be involved in recanalization in many studies so far, the cut-off value was embolization rate = 20.2%, with the sensitivity = 0.500, the specificity = 0.784, the AUC = 0.631. In addition, when ROC analysis was performed only with the flow velocity reduction rate inside the aneurysms (Ane.V * reduction rate), which was considered to be the hemodynamic factor that had the most significant effect in the same report, the sensitivity = 0.654, the specificity = 0.581, and the AUC = 0.640. When these three patterns of ROC analysis results were statistically compared using ROC contrast, considering all three factors yielded a statistically significantly higher prediction accuracy than that of the patterns where only one factor was considered.

Comparisons of ROC analysis results have been done in other studies as well. According to the report of Nambu et al., pressure difference (PD) was reported as the hemodynamic factor that had the most significant effect on recanalization, and the sensitivity obtained as a result of ROC analysis for PD reported the sensitivity = 1.000, the specificity = 0.907, the AUC = 0.967 was better than the results of ROC analysis for Neck area (AUC = 0.767) and ROC analysis for Maximum size (AUC = 0.807). According to Umeda et al., The results of ROC analysis (sensitivity = 0.77, specificity = 0.79, AUC = 0.86) for RFV, which is a hemodynamic factor, were not particularly superior in
sensitivity compared to other morphological factors, however, it had the highest AUC value (see Table 2). These results indicate that it may be useful to consider hemodynamic factors obtained by CFD analysis when trying to predict recanalization in future works. In particular, the value of VER has been frequently used so far in the field of coil embolization. Takao et al. reported that the VER cut-off value for recanalization of aneurysms after coil embolization is 19.2%, so it seems to be quite frequent that the clinical target for coil embolization is a VER of 20% or more. The previous study by Umeda et al. reported a VER cut-off value of 27.4%, and the results of ROC analysis on the hemodynamic parameter RFV (AUC = 0.86, 95% CI: 0.74–0.98) was not particularly superior to the results of ROC analysis on VER (AUC = 0.81, 5% CI: 0.65–0.97). On the other hand, Fujimura et al. reported a VER cut-off value of 20.1%, and the results of ROC analysis for RP which includes hemodynamic parameters (AUC = 0.833, 95% CI: 0.741–0.925) had a statistically significantly higher prediction ability than the results of ROC analysis of VER (AUC=0.631, 95%CI: 0.499–0.762). These results show the possibility that the use of CFD will be effective in predicting recanalization of aneurysms, replacing the existing method of using VER.

Here, Fig. 2 is an example of coil modeling and CFD analysis by DPP for a case where coil embolization was performed. In this analysis example, it was confirmed that there was a high velocity region on the neck surface in the recanalized case, and recanalization and coil compaction occurred from this region. However, such analyses were conducted by experienced analysts over a period of about half to several days per case under sufficient facilities. In order to clinically use CFD as a tool for predicting recanalization, it is necessary for doctors to easily handle it in a clinical setting, however, as of now it is extremely difficult for an inexperienced person to obtain these results immediately.

Also, as described in 3. (2), there is the dilemma that the expertise and time required for analysis increases as the current coil modeling method increases its reality in its results. When performing CFD analysis for the purpose of recanalization prediction, it is necessary to establish a practical balance on, how much reality of the model is required, whether the prediction accuracy in that case is

Table 2 Results reported in previous studies of receiver operating characteristic (ROC) analysis for factors related to recanalization

| Author         | Parameter       | Sensitivity | Specificity | AUC   | 95% CI         | Cut-off point |
|----------------|-----------------|-------------|-------------|-------|----------------|---------------|
| Fujimura et al. [8] | RP              | 0.885       | 0.716       | 0.833 | 0.741–0.925    | 0.218         |
|                | Anc.V* reduction rate | 0.654       | 0.581       | 0.640 | 0.512–0.768    | 0.993         |
|                | VER             | 0.5         | 0.784       | 0.631 | 0.499–0.762    | 20.2%         |
| Nambu et al. [12] | Maximum Size    | —           | —           | 0.807 | 0.639–0.976    | —             |
|                | Inflow Area     | —           | —           | 0.787 | 0.560–1.000    | —             |
|                | Neck Area       | —           | —           | 0.767 | 0.543–0.992    | —             |
|                | Inflow Rate     | —           | —           | 0.761 | 0.531–0.990    | —             |
|                | Infow Rate Ratio | —           | —           | 0.761 | 0.531–0.990    | —             |
|                | PD              | 1           | 0.907       | 0.967 | 0.920–1.000    | 2.83          |
| Umeda et al. [10] | Maximum Size    | 0.69        | 0.71        | 0.74  | 0.57–0.90      | 6.8mm         |
|                | Dome Volume     | 0.77        | 0.71        | 0.80  | 0.65–0.94      | 79.5mm³       |
|                | Neck Width      | 0.85        | 0.75        | 0.77  | 0.62–0.93      | 4.3mm         |
|                | Neck Area       | 0.84        | 0.79        | 0.83  | 0.70–0.96      | 13.1mm²       |
|                | VER             | 0.77        | 0.71        | 0.81  | 0.65–0.97      | 27.4%         |
|                | Inflow Area     | 0.77        | 0.75        | 0.77  | 0.61–0.92      | 5.3mm²        |
|                | Outflow Area    | 0.85        | 0.75        | 0.79  | 0.63–0.94      | 7.9mm²        |
|                | RFV             | 0.77        | 0.79        | 0.86  | 0.74–0.98      | 20.4mm³       |

AUC, area under curve; CI, confidence interval; RP, re-treatment predictor; Anc., aneurysm; V, velocity; VER, volume embolization ratio; PD, pressure difference; RFV, residual flow volume
sufficient, whether it can be easily handled in clinical settings, and how much time is required for analysis.

5. Conclusion

CFD analysis of blood flow for aneurysms after coil embolization has been performed using various coil modeling techniques. Each modeling method has various effects on analysis results, but advanced expertise, skills, and more analysis time are required to improve the reality of the model. The results of investigations using these modeling techniques and CFD analysis indicate that hemodynamic factors such as flow velocity and mass flow rate affect the occurrence of recanalization. It was also reported that consideration of hemodynamic factors is useful for predicting recanalization. Although various verifications are necessary, CFD analysis may be a useful tool for predicting recanalization of aneurysms after coil embolization in future works.

References

1. Kwon SC, Kwon OK. Endovascular coil embolization of unruptured intracranial aneurysms: a Korean multicenter study. Acta Neurochir (Wien). 2014; 156: 847–54.
2. Sluzewski M, van Rooij WJ, Rinkel GJ, Wijnalda D. Endovascular treatment of ruptured intracranial aneurysms with detachable coils: Long-term clinical and serial angiographic results. Radiology. 2003; 227: 720–4.
3. Cebral JR, Mut F, Weir J, Putman C. Quantitative characterization of the hemodynamic environment in ruptured and unruptured brain aneurysms. AJNR Am J Neuroradiol. 2011 Jan; 32(1): 145–51. doi: 10.3174/ajnr.A2419. Epub 2010 Dec 2.
4. Meng H, Tutino VM, Xiang J, Siddiqui A. High WSS or low WSS? Complex interactions of hemodynamics with intracranial aneurysm initiation, growth, and rupture: toward a unifying hypothesis. AJNR Am J Neuroradiol. 2014 Jul; 35(7): 1254–62. doi: 10.3174/ajnr.A3558. Epub 2013 Apr 18.
5. Takao H, Murayama Y, Otsuka S, Qian Y, Mohamed A, Masuda S, Yamamoto M, Abe T. Hemodynamic differences between unruptured and ruptured intracranial aneurysms during observation. Stroke. 2012 May; 43(5): 1436–9. doi: 10.1161/STROKEAHA.111.640995. Epub 2012 Feb 23.
6. Luo B, Yang X, Wang S, Li H, Chen J, Yu H, Zhang Y, Zhang Y, Mu S, Liu Z, Ding G. High shear stress and flow velocity in partially occluded aneurysms prone to recanalization. Stroke. 2011 Mar; 42(3): 745–53. doi: 10.1161/STROKEAHA.110.593517. Epub 2011 Jan 13.
7. Sugiyama S, Niizuma K, Sato K, Rashad S, Kohama M, Endo H, Endo T, Matsumoto Y, Ohta M, Tominaga T. Blood flow into basilar tip aneurysms: a predictor for recanalization after coil embolization. Stroke. 2016 Oct; 47(10): 2541–7. doi: 10.1161/STROKEAHA.116.013555. Epub 2016 Sep 13.
8. Fujimura S, Takao H, Suzuki T, Dahmani C, Ishibashi T, Mamori H, Yamamoto M, Murayama Y. A new combined parameter predicts re-treatment for coil-embolized aneurysms: a computational fluid dynamics multivariable analysis study. J Neurointerv Surg. 2018 Aug; 10(8): 791–6. doi: 10.1136/neurintsurg-2017-013433. Epub 2017 Dec 15.
9. Zhang Q, Jing L, Liu J, Wang K, Zhang Y, Paliwal N, Meng H, Wang Y, Wang S, Yang X. Predisposing factors for recanalization of cerebral aneurysms after endovascular embolization: a multivariate study. J Neurointerv Surg. 2018 Mar; 10(3): 252–7. doi: 10.1136/neurintsurg-2017-013041. Epub 2017 Apr 4.
10. Umeda Y, Ishida F, Tsuji M, Furukawa K, Shiba M, Yasuda R, Toma N, Sakaide H, Suzuki H. Computational fluid dynamics (CFD) using porous media modeling predicts recurrence after coiling of cerebral aneurysms. PLoS One. 2017 Dec 28; 12(12): e0190222. doi: 10.1371/journal.pone.0190222. eCollection 2017.
11. Misaki K, Takao H, Suzuki T, Nishimura K, Kan I, Yuki I, Ishibashi T, Yamamoto M, Murayama Y. Estimated pretreatment hemodynamic prognostic factors of aneurysm recurrence after endovascular embolization. Technol Health Care. 2017 Oct 23; 25(5): 843–50. doi: 10.3233/THC-160495.
12. Nambu I, Misaki K, Uchiyama N, Mohri M, Suzuki T, Takao H, Murayama Y, Futami K, Kawamura T, Inoguchi Y, Matsuzawa T, Nakada M. High pressure in virtual postcoiling model is a predictor of internal carotid artery aneurysm recurrence after coiling. Neurosurgery. 2019 Mar 1; 84(3): 607–15. doi: 10.1093/neuros/nyy073.
13. Otani T, Li S, Shigematsu T, Fujinaka T, Hirata M, Ozaki T, Wada S. Computational study for the effects of coil configuration on blood flow characteristics in coil-embolized cerebral aneurysm. Med Biol Eng Comput. 2017 May; 55(5): 697–710. doi: 10.1007/s11517-016-1541-6. Epub 2016 Jul 21.
14. Irie K, Anzai H, Kojima M, Honjo N, Ohta M, Hirose Y, Negoro M. Computational fluid dynamic analysis following recurrence of cerebral aneurysm after coil embolization. Neurosurgery. 2019 Mar 1; 84(3): 607–15. doi: 10.1093/neuros/nyy073.
15. Morales HG, Larrabide I, Geers AJ, Aguilar ML, Frangi AF. Newtonian and non-Newtonian blood flow in coiled cerebral aneurysms. J Biomech. 2013 Sep 3; 46(13): 2158–64. doi: 10.1016/j.jbiomech.2013.06.034. Epub 2013 Jul 23.
16. Park W, Song Y, Park KJ, Koo HW, Yang K, Suh DC. Hemodynamic characteristics regarding recanalization of completely coiled aneurysms: computational fluid dynamic analysis using...
virtual models comparison. Neurointervention. 2016 Mar; 11(1):30–6. doi: 10.5469/neuroint.2016.11.1.30. Epub 2016 Mar 3.

17. Otani T, Nakamura M, Fujinaka T, Hirata M, Kuroda J, Shibano K, Wada S. Computational fluid dynamics of blood flow in coil-embolized aneurysms: effect of packing density on flow stagnation in an idealized geometry. Med Biol Eng Comput. 2013 Aug; 51(8): 901–10. doi: 10.1007/s11517-013-1062-5. Epub 2013 Mar 26.

18. Liu J, Jing L, Wang C, Paliwal N, Wang S, Zhang Y, Xiang J, Siddiqui AH, Meng H, Yang X. Effect of hemodynamics on outcome of subtotally occluded paraclinoid aneurysms after stent-assisted coil embolization. J Neurointerv Surg. 2016 Nov; 8(11): 1140–7. doi: 10.1136/neurintsurg-2015-012050. Epub 2015 Nov 26.

19. Graziano F, Russo VM, Wang W, Khismatullin D, Ulm AJ 3rd. 3D computational fluid dynamics of a treated vertebrobasilar giant aneurysm: a multistage analysis. AJNR Am J Neuroradiol. 2013 Jul; 34(7): 1387–94. doi: 10.3174/ajnr.A3373. Epub 2013 Jan 10.

20. Morales HG, Larrabide I, Geers AJ, San Román L, Blasco J, Macho JM, Frangi AF. A virtual coiling technique for image-based aneurysm models by dynamic path planning. IEEE Trans Med Imaging. 2013 Jan; 32(1): 119–29. doi: 10.1109/TMI.2012.2219626. Epub 2012 Sep 19.

21. Morales HG, Kim M, Vivas EE, Villa-Uriol MC, Larrabide I, Sola T, Guimaraens L, Frangi AF. How do coil configuration and packing density influence intra-aneurysmal hemodynamics? AJNR Am J Neuroradiol. 2011 Nov–Dec; 32(10): 1935–41. doi: 10.3174/ajnr.A2635. Epub 2011 Sep 1.

22. Fujimura S, Takao H, Suzuki T, Daishani C, Ishibashi T, Mamori H, Yamamoto M, Murayama Y. Hemodynamics and coil distribution with changing coil stiffness and length in intracranial aneurysms. J Neurointerv Surg. 2018 Aug; 10(8): 797–801. doi: 10.1136/neurintsurg-2017-013457. Epub 2017 Dec 19.

23. Leng X, Wang Y, Xu J, Jiang Y, Zhang X, Xiang J. Numerical simulation of patient-specific endovascular stenting and coiling for intracranial aneurysm surgical planning. J Transl Med. 2018 Jul 21; 16(1): 208. doi: 10.1186/s12967-018-1573-9.

24. Damiano RJ, Ma D, Xiang J, Siddiqui AH, Snyder KV, Meng H. Finite element modeling of endovascular coiling and flow diversion enables hemodynamic prediction of complex treatment strategies for intracranial aneurysm. J Biomech. 2015 Sep 18; 48(12): 3332–40. doi: 10.1016/j.jbiomech.2015.06.018. Epub 2015 Jun 27.

25. Byun HS, Rhee K. CFD modeling of blood flow following coil embolization of aneurysms. Med Eng Phys. 2004 Nov; 26(9): 755–61.

26. Levitt MR, Barbour MC, Rolland du Roscoat S, Geindreau C, Chivukula VK, McGah PM, Nerva JD, Morton RP, Kim LJ, Aliseda A. Computational fluid dynamics of cerebral aneurysm coiling using high-resolution and high-energy synchrotron X-ray microtomography: comparison with the homogeneous porous medium approach. J Neurointerv Surg. 2017 Aug; 9(8): 0. doi: 10.1136/neurintsurg-2016-012479. Epub 2016 Jul 12.

27. Babiker MH, Chong B, Gonzalez LF, Cheema S, Frakes DH. Finite element modeling of embolic coil deployment: multifactor characterization of treatment effects on cerebral aneurysm hemodynamics. J Biomech. 2013 Nov 15; 46(16): 2809–16. doi: 10.1016/j.jbiomech.2013.08.021. Epub 2013 Sep 18.