Effect of stent porosity on hemodynamics within cerebral aneurysm models: Numerical study

Dai Thanh Phan, Minh Tuan Nguyen, and Sang-Wook Lee

Abstract—In this study, numerical simulations have been carried out to investigate the effects of stent porosity on blood flow characteristics inside stented saccular aneurysm models on variously curved vessels, i.e., vessels with constant and realistic curvatures. Four different stent porosities of 100%, 80%, 74%, and 64% were considered. A finite element method (FEM) solver was employed on unsteady incompressible Navier–Stokes equations of laminar flow. Results were presented in terms of the flow velocity vector fields, the volume inflow rates into the aneurysm, and the wall shear stress (WSS) in the aneurysm sac. It was shown that a stent with porosity of 80%, which is highest in the present study, was found effectively reducing flow into the aneurysm and that stents with lower porosities have only small increase of flow reducing effect. The geometry of aneurysm also has significant effects on stent performance. Further extensive simulations with patient-specific geometry will be necessary.

Keywords—cerebral aneurysm, hemodynamics, stent, porosity, velocity reduction ratio, computational fluid dynamics

I. INTRODUCTION

Cerebral aneurysm is an abnormal widening or bulging of a portion of an intracranial artery due to weakness in the wall of the blood vessel. When the size of an aneurysm increases, there is a significant risk of rupture, resulting in subarachnoid hemorrhage (SAH), other complications or death. SAH is a common and frequently devastating condition, accounting for 5% of all strokes and affecting as many as 30,000 Americans each year [1].

In order to treat aneurysm, endovascular techniques using stents have been more popular. A stent is a flexible cylindrical tube made of a mesh of stainless steel or alloys. Due to its limited permeability, the stent modifies the blood flow into the aneurysm. The resulting stagnant flow normally promotes the formation of a stable thrombus (coagulation) in the aneurysm sac leading to its eventual occlusion [2]. The performance of stent in the respect of hemodynamics depends on its dimension and shape and many studies have been carried out to investigate the effect of stent design on the intra-aneurysmal flow structure. Lieber et al. [3] investigated the effect of the stent strut size on the intra-aneurysmal flow in a sidewall aneurysm model using particle image velocimetry. Liou et al. [4] investigated the effect of stent shapes (helix stent vs. mesh stent) on intra-aneurysmal flow using particle tracking velocimetry measurements and flow visualization. It is expected that the porosity of a stent is the most important parameter that affects its ability to impede or modify the aneurysmal flow [5], [6]. A lower porosity results in more flow blockage, but if the porosity is too low, the stent might inadvertently block perforating vessels or become too rigid for deployment [7], [8]. Because of these constraints, the neurovascular stents currently in use are high-porosity stents. However, there is a lack of study of realistic stent for cerebral aneurysm in scientific literature. In this paper, we will systematically evaluate the influence of the relatively thin strut and high porosity stents.

Recently, computational fluid dynamics (CFD) becomes a valuable tool to investigate blood flow dynamics implicated in vascular disease in a non-invasive manner. In this article, we present a study on the use of CFD to examine changes in local hemodynamic inside aneurysm models with virtual implantation of stent. The finite element method was employed under incompressible, unsteady, Newtonian conditions. Stents with four different porosities ($C_a = 100\%, 80\%, 74\%,$ and $64\%$) are considered for comparing the effect of stent porosity. This study demonstrates the capability of CFD tools for evaluating flow characteristics by stenting in aneurysm and understanding hemodynamic phenomena.

II. METHOD

A. Model Geometry

The idealized cerebral aneurysm model was constructed with
Table 1 The dimension of three stent samples

<table>
<thead>
<tr>
<th>Stent</th>
<th>H (mm)</th>
<th>B (mm)</th>
<th>t (mm)</th>
<th>$C_a$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>w/o</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>1</td>
<td>0.64</td>
<td>0.36</td>
<td>0.038</td>
<td>80</td>
</tr>
<tr>
<td>2</td>
<td>0.65</td>
<td>0.27</td>
<td>0.038</td>
<td>74</td>
</tr>
<tr>
<td>3</td>
<td>0.54</td>
<td>0.16</td>
<td>0.038</td>
<td>64</td>
</tr>
</tbody>
</table>

Fig. 2 A schematic geometry of a rhombus stent

15 mm curvature of radius vessel and a sphere attached to center of the baseline as shown in Fig. 1. The diameters of the aneurysm and parent vessel are 10 mm and 4 mm respectively. Four rhombus shaped-stents with porosities of 100% (no stent), 80%, 74%, and 64% [9] were examined in unsteady pulsatile inflow condition. Stent was deformed to fit into the curved parent vessel.

Detailed shape of the stent design and dimensions are described in Fig. 2 and Table 1, respectively.

Porosity, one of the most important parameters of stent design, is defined as the proportion of open area to total area of the stent as follows:

$$C_a = A_{abcd}/A_{1234} \quad (1)$$

B. Computational Fluid Dynamics (CFD)

Three-dimensional unsteady incompressible momentum and mass conservation equations for Newtonian fluid flow were solved as

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \mu \nabla^2 \mathbf{u} \quad (2)$$

$$\nabla \cdot \mathbf{u} = 0 \quad (3)$$

where, $\mathbf{u}$ and $p$ is fluid velocity vector and pressure, respectively. CFD simulations were carried out using a well-validated, in-house finite-element-based solver employing a sufficient density of quadratic tetrahedral elements. Rigid walls and Newtonian rheology were assumed. Pulsatile inflow boundary conditions were prescribed based on representative waveform shapes in basilar artery. Each simulation was run for four cardiac cycles to damp initial transients; the data from simulation of the forth cardiac cycle were used for analysis.

III. RESULTS AND DISCUSSION

A. Intra-aneurysmal flow structure

Fig. 3 shows comparison of intra-aneurysmal flow patterns by stent porosity. Stents produce significant flow modifications. The inflow into the aneurysm sac is shifted from the distal side of the neck in the unstented model to the proximal side in the stented model. The flow reversal adjacent to the bottom wall of the parent vessel is also greatly reduced after stenting.

For the unstented case, there is a counter-clockwise vortex inside the aneurysm sac which is driven directly by the flow in the parent vessel. After stenting, the vortex is reduced due to the blockage effect of the stents. In the case of $C_a = 64\%$, counter-clockwise rotating vortex was disappeared, but only weak clockwise rotating vortex present. This is similar observations made by Yu et al. [9], Liou et al. [10], and Kim et al. [11] in numerical and experimental studies.

B. Velocity Reduction Ratio

The mean velocity in the midplane in the unstented case is much larger than stented model. The mean velocity lowered

Fig. 3 Comparison of intra-aneurysmal flow structures

Fig. 5 Comparison of velocity reduction ratio
with decrement of stent porosity. In order to assess a quantitative comparison on the flow reduction rate related to the stent efficiency, the variation of the flow pattern in the stented aneurysm was investigated. A global measure of the effect of the stent, i.e., mean velocity reduction [9], [12] is defined as

\[
V_{RR} = (\bar{V}_{ns} - \bar{V}_{st}) / \bar{V}_{ns}
\]  

(4)

where, \( \bar{V}_{ns} \) and \( \bar{V}_{st} \) are the mean unstented and stented velocities in the aneurysm sac, respectively. The reduction of the mean velocity can be interpreted as the increase of the respective flow characteristics due to the effects of stent strut porosity.

Fig. 5 shows the velocity reduction rate within aneurysm sac for different porosity of stents. As expected, the lower stent porosity has a higher velocity reduction rate. At peak systolic phase, the velocity reduction rate for \( C_a = 80\% \), 74\% and 64\% is approximately 90\%, 95\% and 96\% respectively. We may expect this reduction of mean velocity promotes the occurrence of the hemostasis inside the aneurysm which lower the risk of the growth or possible rupture.

C. Wall shear stress

The WSS is known as an important factor that influences aneurysm growth and rupture. The effect of WSS in vascular biology had been studied intensively earlier in the literature. According to the experimental and the CFD study, a high WSS (> 40.0 Pa) is regarded as a major factor in initiation of cerebral aneurysm [13], [14] while a low WSS (< 2.0 Pa) might be a major factor for its growth and rupture [15].

Fig. 6 shows the WSS distribution in both unstented and stented aneurysms. The stents reduced significantly the WSS on the aneurysm wall. Even \( C_a = 80\% \) case decrease WSS up to ten times lower than unstented model. In particular, around the dome of aneurysm the magnitude of WSS value is considerably low, which may associated with the risk of rupture.[15]

D. Cerebral Aneurysm model with realistic curvature

We may expect the curvature of the parent vessel has great effect on the effectiveness of stent. Thus, an elliptic shaped aneurysm on a parent vessel with more realistic curvature which mimics in vivo arterial morphology [16] was considered. Two different porosities of stent, i.e., \( C_a = 100\% \) (no stent) and \( C_a = 80\% \) were applied, but with the same rhombus shaped mesh design.

Fig. 7 compares the streamtraces within the aneurysm sac. Evidently, the vortex strength in the stented aneurysm is lower compared to the unstented aneurysm model. However, the reduction of velocity is much lower than the case of constant curvature vessel by the stent with the same porosity.

IV. CONCLUSION

We demonstrated the CFD simulations of stented aneurysm flow by various stent porosity and parent vessel geometry.

The results showed the stent porosity affects the intra-aneurysmal flow patterns. The implantation of stents reduced the strength of vortex and velocity in the aneurysm sac. A stent with porosity of 80\%, which is highest in the present study, was found effectively reducing flow into the aneurysm and stents with lower porosities have only small increase of flow reducing effect.

The vorticity and velocity reduction rates are strongly correlated to the blood clotting, according to the clotting fraction prediction [17], [18]. The characteristics of flow are also affected by aneurysm and parent vessel geometry. When the geometry changes from an ideal model to a realistic model,
the performance of stent was reduced significantly.

In conclusion, the present numerical study helps better understand about effect of stent porosity on hemodynamics in cerebral aneurysm. Although rather simple rigid models have been used, we could observe fundamental characteristics of stented cerebral aneurysm flow. However, to understand more detailed and accurate performance of stent, more extensive studies with patient-specific geometry based on medical images will be necessary.

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REFERENCES