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Modeling and Simulation of Blood Flow Analysis on Simplified Aneurysm Models

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Abstract. Nowadays, the cerebral aneurysm is an abnormal focal dilation of a brain artery which is considered as a serious and potentially life-threatening condition. The rupture of an aneurysm causes subarachnoid hemorrhage (SAH) and is associated with high rates of morbidity and mortality. A better understanding of the mechanisms underlying aneurysm pathophysiology is crucial for the development of new preventive procedures and therapeutic strategies. This study focuses on the modeling and simulation of the blood flow analysis using simplified aneurysm models to perform early prediction on the geometrical effects of hemodynamics. The investigation involves three simplified models of aneurysms reconstructed using *Solidworks 2019*, in which the aneurysms are developed at the bifurcation. The qualitative comparison of the hemodynamics between three models was obtained and the geometrical effects were evaluated. The results show that the differences in shape and geometry on aneurysms affect the hemodynamics trend and are capable to apply for further understanding of problems regarding hemodynamics in the patient.

1. Introduction

An aneurysm is an illness that influences the blood vessels and makes the artery walls turn out to be exposed. It causes thinning and swelling in the blood vessel walls. The majority of aneurysms are not dangerous. However, some can break up in their most serious stage leading to life-threatening internal bleeding. Cerebral aneurysms that occur in the head normally can be divided into two symptoms which are ruptured and unruptured aneurysms [1]. Most of the patients did not realize they suffer from the cerebral aneurysms because there is no sign shown until the aneurysms either become bigger or burst. Small aneurysms that produce in the brain normally will not give any effect to the person as well. Besides, the rupture of cerebral aneurysm is one of the main causes of stroke [2]. Due to these issues, many researchers involved their studies with modeling and simulation methods to indeed understand the aneurysm rupture.



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Computational fluid dynamics (CFD) is one of the methods uses to simulate and analyze the aneurysm flow because it can combine the result from the medical imaginary methods and give almost specific hemodynamic conditions for the patients. The CFD is turning into a standard tool for the study of hemodynamics in cerebral aneurysms [3]. The advanced CFD as a result of improvements in computer software first used in fluid engineering and applied to biomechanics has revolutionized studies in the last two decades. The use of CFD explains the increasing number of investigations in this field. The CFD studies apply mathematical models to simulate blood flow conditions based on the shapes of vessels and aneurysms, velocity, and forces such as tension or shear stress [4]. It can assist physicians to quantify in the greater element for some phenomena that are difficult to capture within vivo imaging techniques through the use of CFD to simulate the flow via patient-particular geometries. Image-primarily based CFD can offer specific data at the flow fields and hemodynamic elements affecting blood vessels with temporal and spatial resolutions exceeding the ones of the in vivo techniques. A better understanding of hemodynamics can improve diagnosis and treatment. In the last decade, the CFD simulations have been employed to observe the connection between hemodynamics [2], [5], rupture, and the hemodynamic impact of endovascular treatment.

Hemodynamics modeling in the CFD relies upon the accuracy and underlying assumptions of the tool, for instance, treating blood as a Newtonian fluid with constant viscosity which is a simplification of blood rheology. Generally, blood consists of a way of red and white cells, and platelets floating in plasma that make it a non-Newtonian fluid with a shear-thinning behavior [6]. Hemodynamic factors such as wall shear stress (WSS) elicited by the flow, intra-aneurysmal pressure is spotted because of the jet impingement and blood residence times are recognized to play a serious role in aneurysm rupture [1]. The aneurysm rupture will cause subarachnoid hemorrhage (SAH) with presumably extreme medical specialty complications. The WSS, pressure, molecule home time and stream impingement play imperative elements at intervals in the event of aneurysm rupture. Regarding these, this paper tends to develop the simplified models of aneurysms and extend the investigation to the effect of geometry on the hemodynamics factor.

2. Method

2.1 Design and Modelling

The design and modeling of aneurysm models were developed by using *SolidWorks 2019*. Each model of the aneurysms has been drawn with precise dimensions as the actual size. The 3-dimensional (3D) aneurysms models, models A, B, and C with full dimensions in millimeters are shown in Error! Reference source not found.. Some details of the geometry on simplified aneurysm models are listed in Table 1.

Table 1. Details of geometry on simplified aneurysm models.

| No. | Types | Model A | Model B | Model C |
|-----|---------------------|---------|---------|---------|
| 1. | Number of inlets | 1 | 1 | 1 |
| 2. | Number of outlets | 1 | 2 | 2 |
| 3. | Number of aneurysms | 1 | 1 | 1 |
| 4. | Size of aneurysm | 1.6 | 3.7 | 1.3 |
| 5. | Size of artery | 2.1 | 2.4 | 1.0 |

Notes: Size of the aneurysms and arteries is indicated in the unit millimeter (mm)

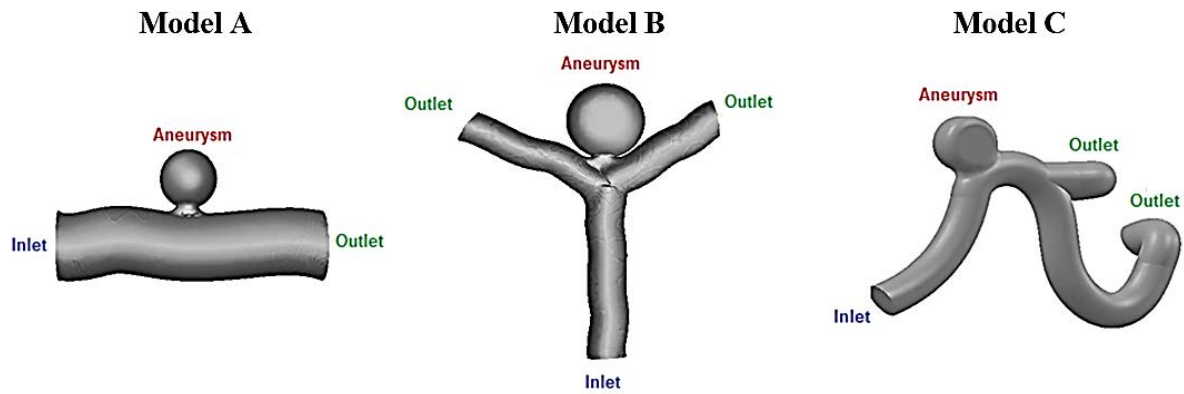


Figure 1. 3D simplified aneurysm models with full dimension [unit: mm].

2.2 Meshing

The meshing process of the geometry was conducted purposely to build a grid system and calculate the flow domain for the whole model. The mesh edge function is used to manage the mesh density of a particular part, while mesh face is intended to display the mesh edge effect. The details and information about the number of elements and nodes for all three aneurysm models are shown in Table 2 and Figure 2.

Table 2. Total number of nodes and elements

| No. | Properties | Model A | Model B | Model C |
|-----|------------|---------|---------|---------|
| 1. | Nodes | 16427 | 26751 | 31978 |
| 2. | Elements | 149342 | 205778 | 293344 |

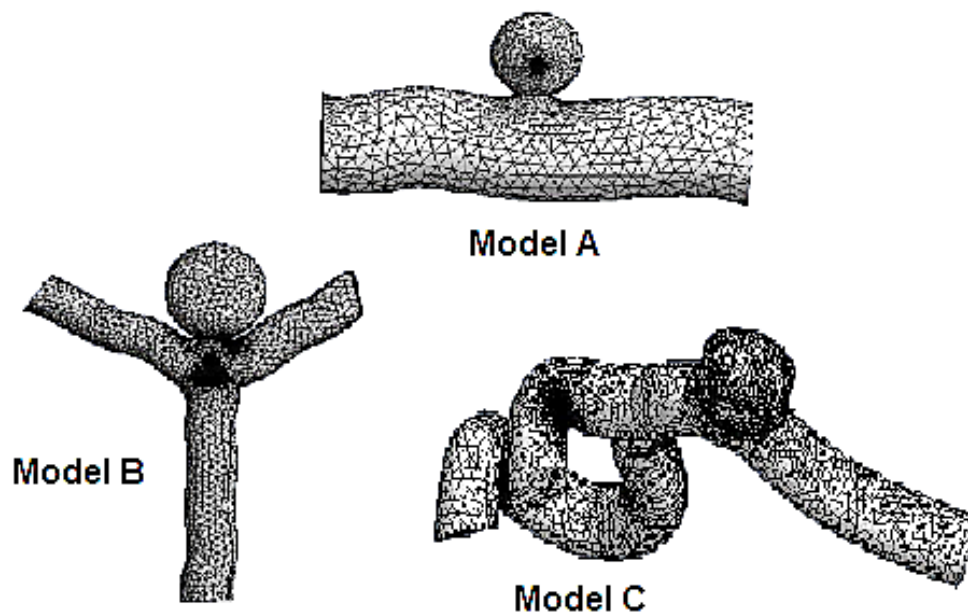


Figure 2. Representation of tetrahedral mesh for three aneurysm models.

2.3 Computational Fluid Dynamics (CFD)

The function of CFD is to analyze the blood flow inside the aneurysm. The CFD gives a very important part of this analysis and will be used to calculate the maximum WSS, velocity profile, inlet area, and pressure distribution. The CFD provides numerous information on blood vessel hemodynamics after convergence. The CFD analysis was performed by solving steady Navier-Stokes equations (1) and continuity equation (2) using fluid analysis software, *ANSYS 15.0*. The following governing equations were discretized using the finite volume method.

$$\rho(\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla p + \mu \nabla^2 \mathbf{u} \quad (1)$$

$$\nabla \cdot \mathbf{u} = 0 \quad (2)$$

where \mathbf{u} is the velocity vector, p is the pressure, ρ is the density. The blood was assumed to be incompressible Newtonian fluids with a density of 1050 kg/m^3 and viscosity of $3.5 \times 10^{-3} \text{ Pa.s}$ [3]. Arterial walls were expected to be rigid with no-slip. The inlet boundary condition was set to 0.348 m/s in systole condition. In the outlet boundary condition, the P -fixed approach [7] was performed.

2.4 Pressure-fixed (P -fixed) approach [7]

We defined the outlet $i \in [1, I]$, where I is the total number of outlets and corresponding outlet pressures, $p^{(i)}$. In the P -fixed approach, we set all the outlet pressures to zero, i.e., $p^{(i)} = 0$ for $i \in [1, I]$.

3. Results and Discussion

In this section, the results of the blood flow analysis are shown and compared. The effect of three different simplified models on hemodynamics was first investigated. Second, we studied the effect of flow velocity on the aneurysm region, and then finally as additional, the trend of velocity fields on the cutting region was observed.

3.1 Effect of different shape on hemodynamics

Based on the simulation results of the aneurysm models as shown in Figure 3, the WSS distributions along the blood vessels or arteries are varied with locations. The maximum WSS was found at the edge of the artery outlet, the neck of the aneurysm and parent artery for Model A, Model B, and Model C, respectively. The values of maximum WSS at the mentioned locations for Model A, Model B, and Model C are 28.7 Pa , 29.5 Pa , and 15.8 Pa , respectively. However, in the aneurysm region, the dome showed the least WSS distribution for all the models. Some researchers have reported that 45% of the maximum WSS has been found at the neck of the aneurysm, followed by 40% at the bifurcation, 10% at the aneurysm dome, and 5% at the parent artery [8]–[10]. Besides, the researchers claimed that the indication of different maximum WSS location would be due to the aneurysm models which were constructed under unspecified and non-systematic conditions. The aneurysm models were replicated without compromising the realistic aneurysm models which would affect the mesh quality [11]. Furthermore, the shape of aneurysm models strongly depends on the reconstruction technique especially through medical images and this technology affects the WSS distribution and hemodynamics at the aneurysm models [12], [13]. Therefore, a systematic procedure is vital for the building and reconstruction of aneurysm models.

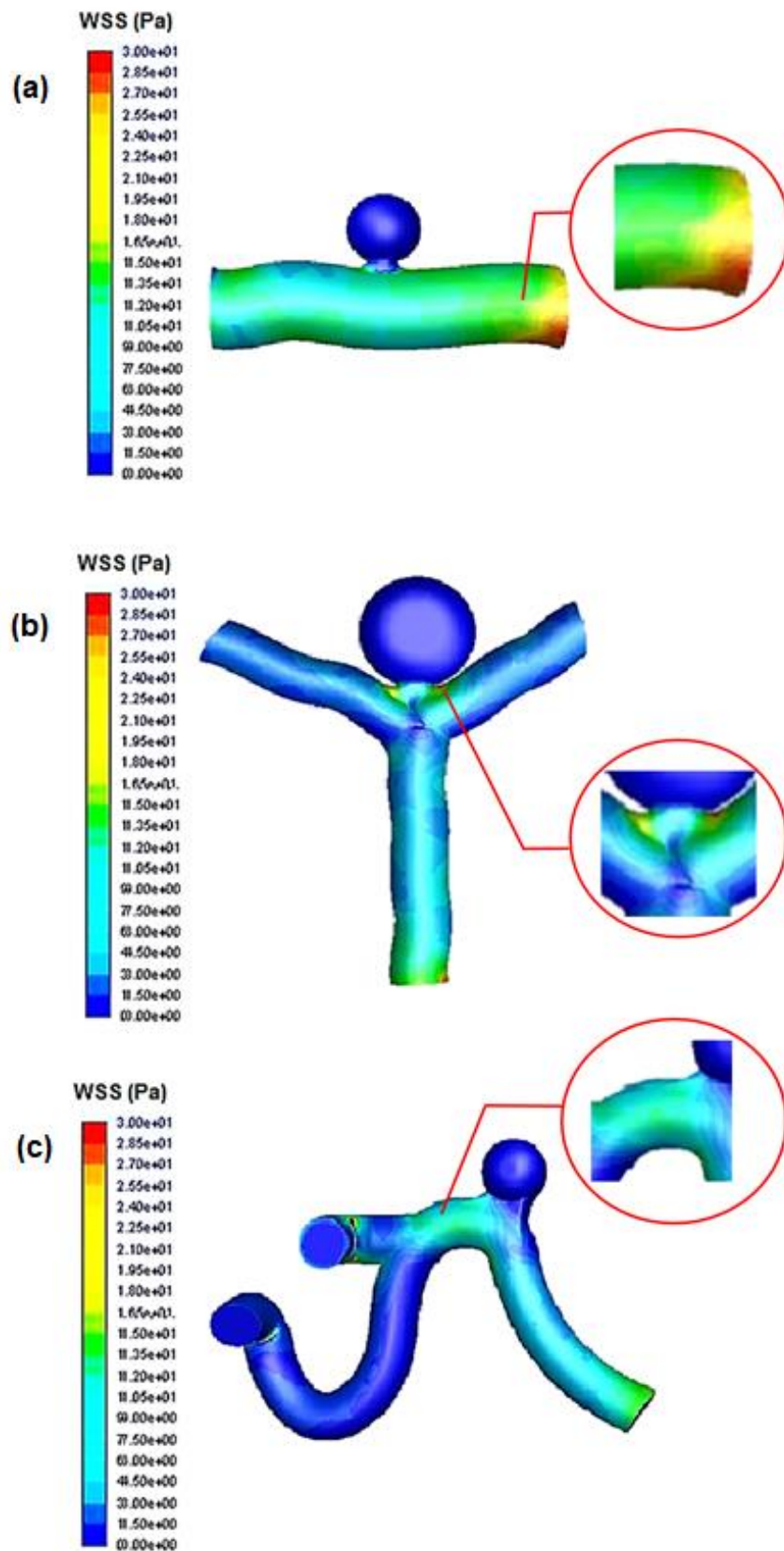


Figure 3. Distribution of WSS for a) Model A, b) Model B; and c) Model C. Red circle represented the location of maximum WSS of the simplified aneurysm models.

3.2 Wall Shear Stress versus Velocity

There is a close relationship between WSS and velocity. The present simulation results are illustrated in Figure 5. As for this simulation, the blood was assumed as a laminar and Newtonian fluid. The WSS is directly proportional to the velocity profile which adheres to the fluid mechanics' behavior [14]. The WSS equation (3) is shown below

$$\tau = \mu \frac{du}{dz} \quad (3)$$

where μ is the dynamic viscosity, u is the velocity of the fluid along the boundary, and z is the distance above the boundary. The WSS acting along the boundary is shown in Figure 4. As the velocity across the boundary or the blood artery increases, the WSS acting towards the wall also increases in which the maximum WSS is obtained between the boundary or blood artery. However, the WSS distribution would be different in shape and beyond fluid behavior. It was reported that the velocity profile showed an inversed relationship with the WSS distribution [15], [16] due to the boundary condition setup and physical model construction [12].

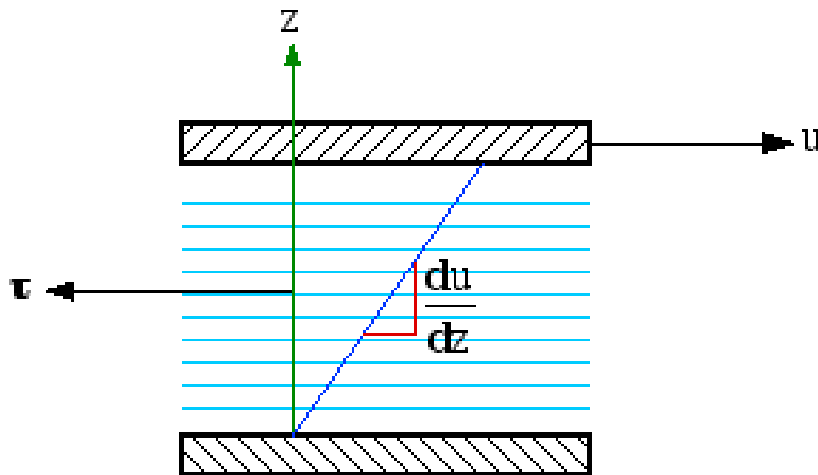


Figure 4. Illustration of WSS acting along the boundary

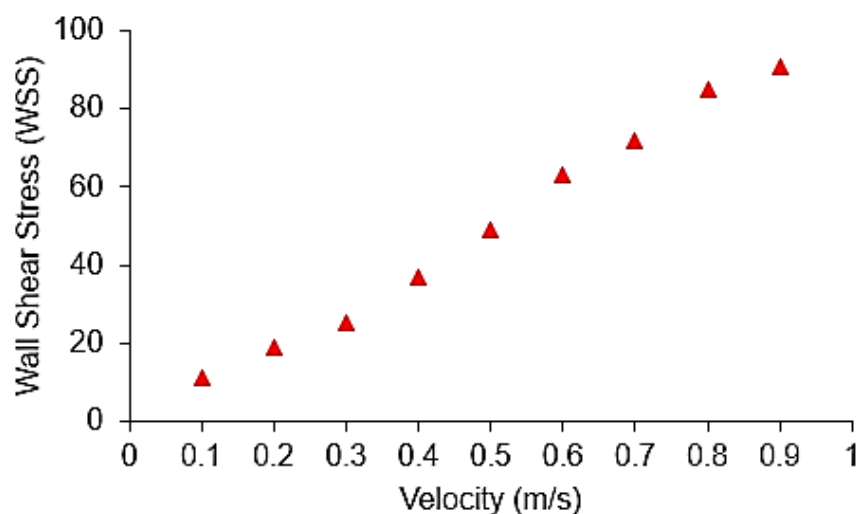


Figure 5. Maximum WSS versus inlet velocity

3.3 Effect of flow velocity on the aneurysm region

The aneurysm regions for all three models have shown the least WSS distribution except for the artery parts with varying WSS distribution and high possibility of rupture. This condition same goes to the velocity vector. It can be observed in Figure 6 that the velocity vector appeared to be less dense in the aneurysm region but high dense along the artery. The simulated blood flow towards the aneurysm region (less dense) and exited along both sides of the aneurysm neck (high dense) towards the artery. Furthermore, there is research reported that the application of a high volume of mesh density has contributed to an underestimation of WSS distribution and affected the velocity vector. The high volume of mesh density, tetrahedral mesh might have shown accurate estimation for certain cases but somehow the application of low volume of mesh density, the polyhedral mesh has shown better convergence and good agreement towards WSS distribution and velocity vector with less computing time [17], [18].

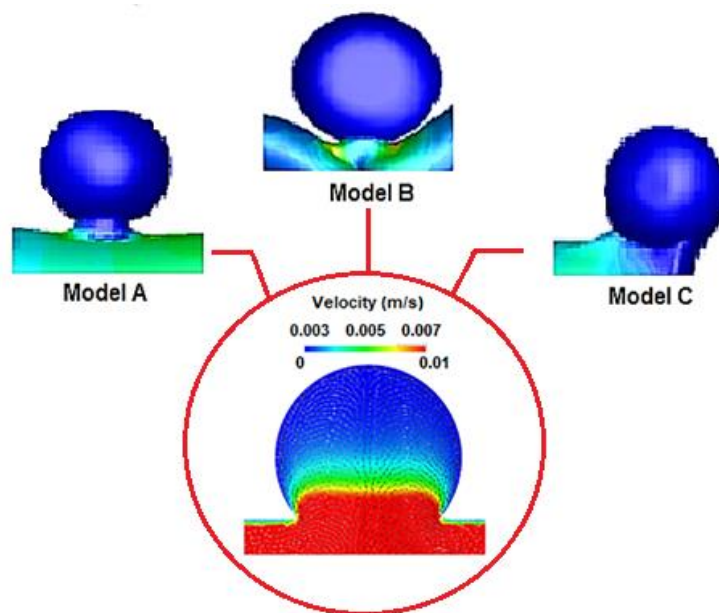


Figure 6. Comparison of WSS between three models of aneurysms region. The red circle illustrated the details of the velocity vector in aneurysm occurred in real condition.

3.4 Effect of velocity field distribution on cutting edge

The different cutting edge has shown to affect velocity field distribution. Figure 7 shows that there is an increase of velocity field distribution at the cutting region with a cutting angle of 90° followed by 45° and 30° . This might be due to the cutting assumption along the artery. When the simulation was performed on the artery cut at 90° with slight alignment to the artery, the velocity field distribution was stable, but when the simulation was performed on the artery cut at 30° with oblique corner to the artery, the velocity field distribution was dense. This might be due to the oblique corner which has created high force and stress concentration towards the area, causing the blood flow to move towards the area with high velocity. It was reported that the rupture of the aneurysm has a close relation to the WSS distribution and velocity flow field, but somehow the rupture at the parent artery is seldom to be occurred [8]–[10], [19]. However, there is an argument on the effect of cutting edge towards the velocity field distribution as there is less research study concerning the cutting effect on aneurysm rupture. Therefore, more studies have to be conducted to progress proper velocity field distribution with different cutting angles.

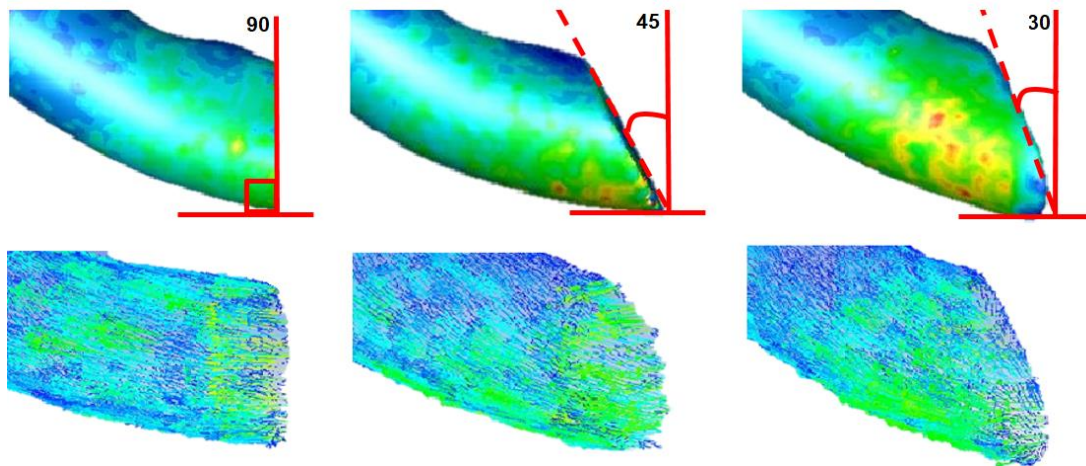


Figure 7. Illustration of velocity field distribution based on different cutting shapes.

4. Conclusion

The advancement in CFD study has contributed to a better understanding of the mechanisms underlying aneurysm pathophysiology which is crucial for the development of new preventive procedures and therapeutic strategies in the medical industry. This paper performs an early prediction of the geometrical effects on hemodynamics. It is found that the difference in shape for model construction has affected the simulation results such as the WSS distribution and velocity flow field due to physical technique in building the aneurysm models. Moreover, the relationship between WSS and velocity is found to adhere to fluid mechanics behavior. The mesh quality is also found to have an effect on the hemodynamics at aneurysm models as well. On the other hand, the effect on cutting edge on velocity field distribution has to be further explored. The differences in shape and geometry on aneurysms can be considered for further understanding of problems regarding hemodynamics in patients.

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