IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

Modeling and Simulation of Blood Flow Analysis on Simplified Aneurysm Models

To cite this article: Lim Sheh Hong *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **917** 012067

IOP Conf. Series: Materials Science and Engineering **917** (2020) 012067 doi:10.1088/1757-899X/917/1/012067

Modeling and Simulation of Blood Flow Analysis on Simplified Aneurysm Models

Lim Sheh Hong[1*], Mohd Azrul Hisham Mohd Adib[1*], Muhammad Uzair Matalif[1], Mohd Shafie Abdullah[2], Nur Hartini Mohd Taib[2], Radhiana Hassan[3]

[1]Medical Engineering & Health Intervention Team (MedEHiT), Department of Mechanical Engineering, College of Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia
[2]Department of Radiology, School of Medical Sciences, Health Campus, Universiti Sains Malaysia, 16150 Kubang Kerian, Kelantan, Malaysia
[3]Department of Radiology, Kulliyyah of Medicine, International Islamic University Malaysia, 25200 Kuantan, Pahang, Malaysia

*Email: shehhong.lim@gmail.com; azrul@ump.edu.my

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.

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)*

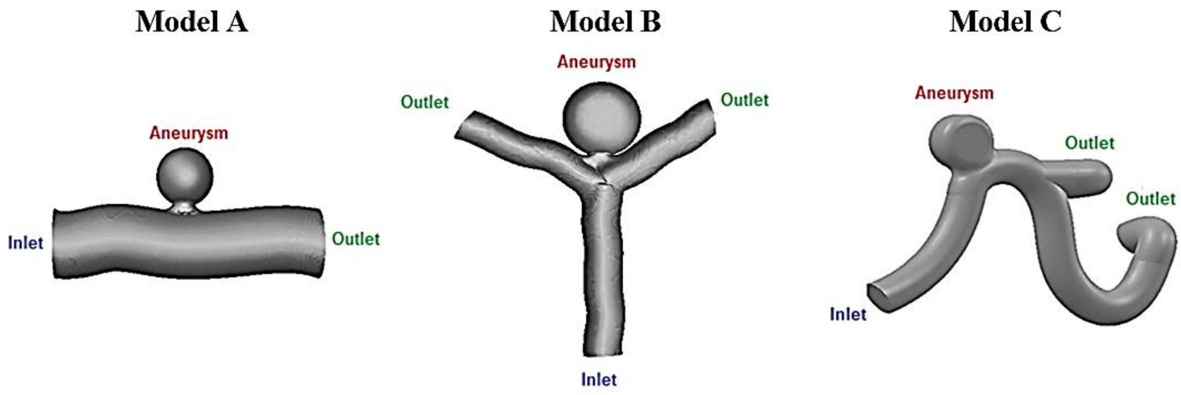

Figure 1. 3D simplified aneurysm models with full dimension [unit: mm].

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

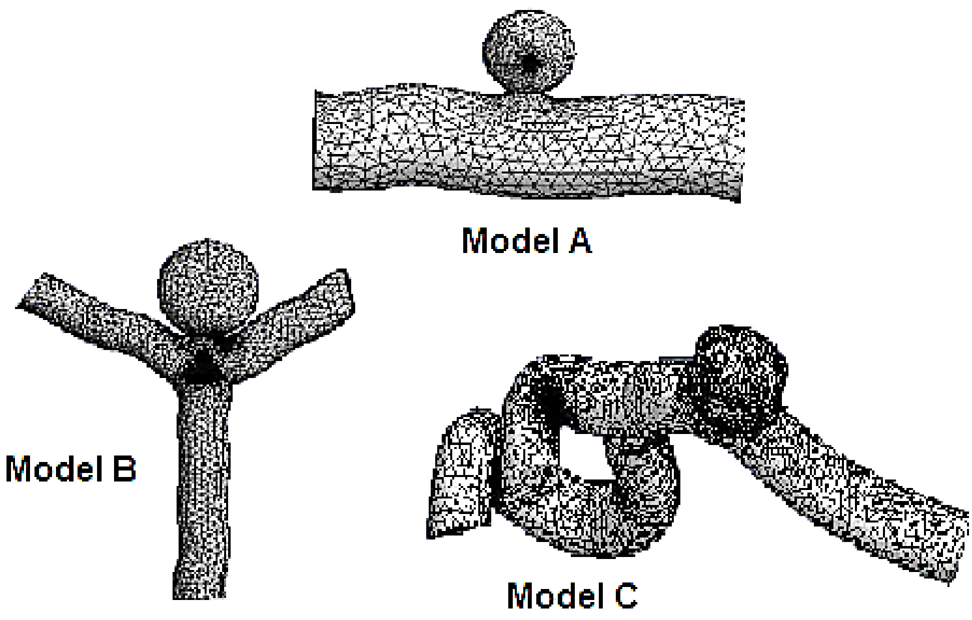

Figure 2. Representation of tetrahedral mesh for three aneurysm models.

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.

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

$$\nabla\cdot\mathbf{u} = 0 \tag{2}$$

where **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 x 10^{-3} Pa.s [3]. Arterial walls were expected to be rigid with no-slip. The inlet boundary condition was set to 0.348m/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.

IOP Conf. Series: Materials Science and Engineering **917** (2020) 012067 doi:10.1088/1757-899X/917/1/012067

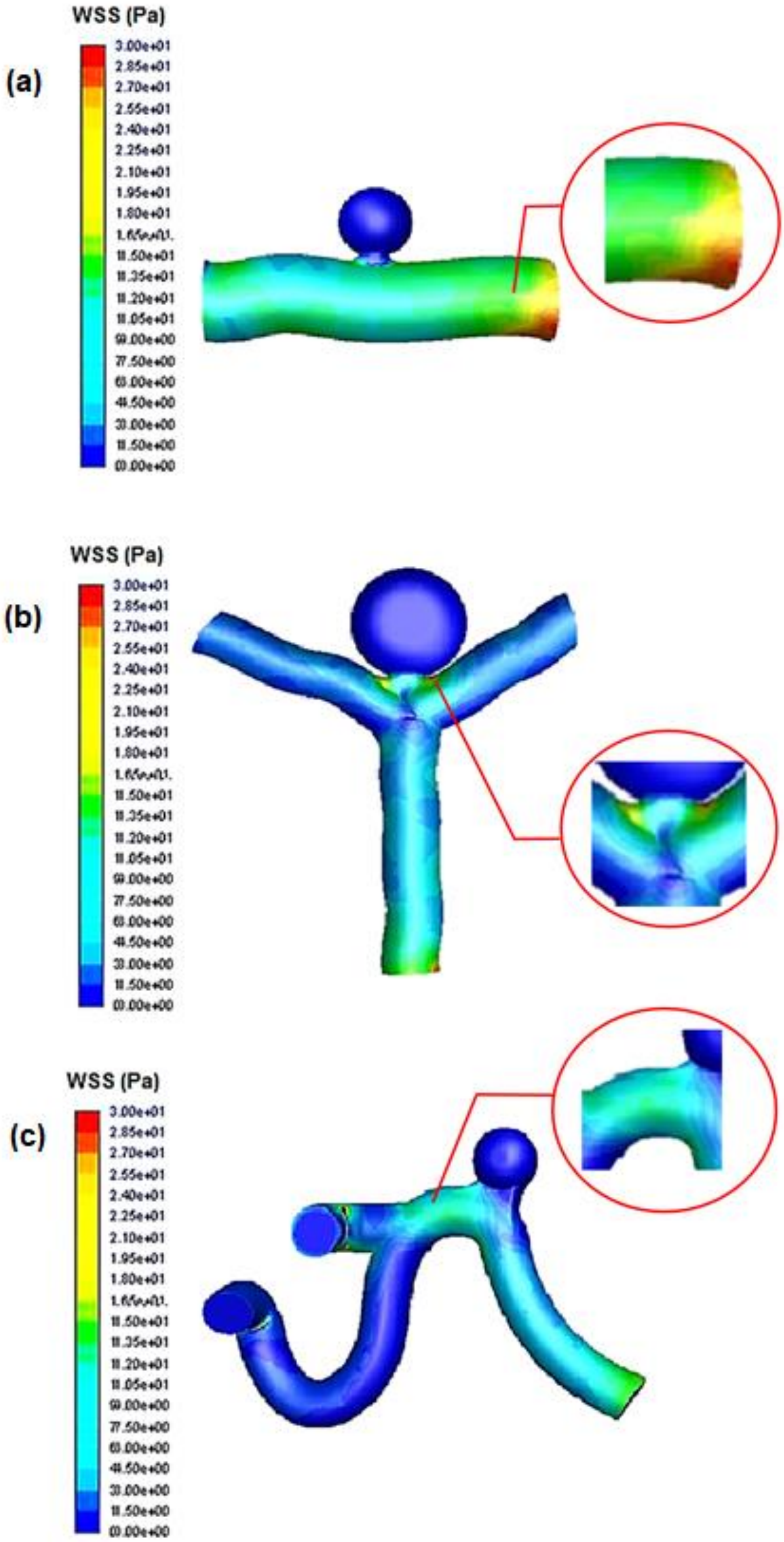

Figure 3. Distribution of WSS for a) Model A, b) Model B; and c) Model C. Red circle represented the location of maximum WSS of the simplified aneurysm models.

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

$$\boldsymbol{\tau} = \boldsymbol{\mu}\frac{\boldsymbol{du}}{\boldsymbol{dz}} \tag{3}$$

where $\boldsymbol{\mu}$ is the dynamic viscosity, $\boldsymbol{u}$ is the velocity of the fluid along the boundary, and $\boldsymbol{z}$ 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].

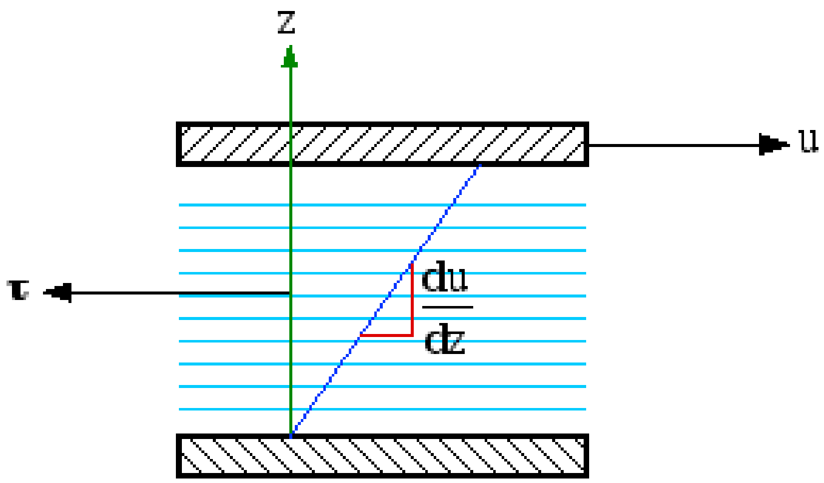

Figure 4. Illustration of WSS acting along the boundary

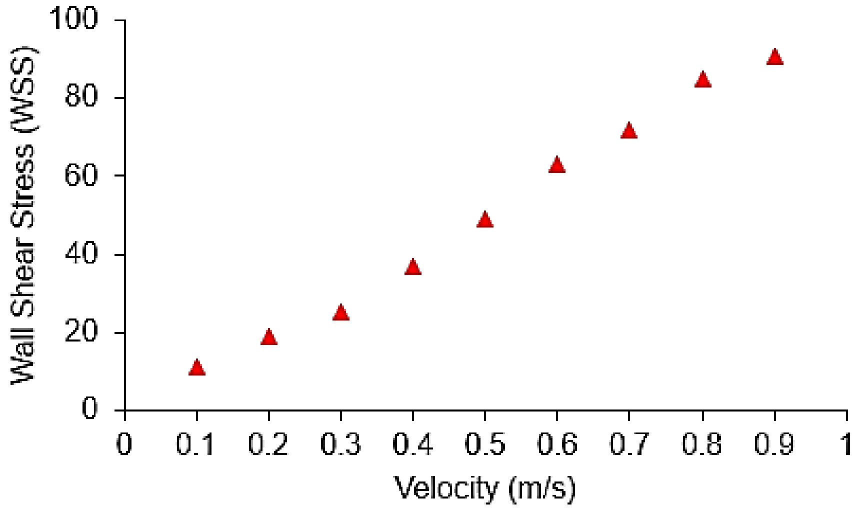

Figure 5. Maximum WSS versus inlet velocity

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 flew 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].

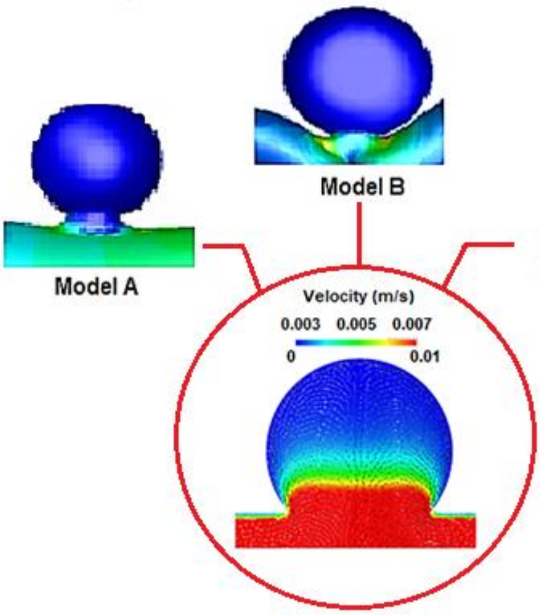

Figure 6. Comparison of WSS between three models of aneurysms region. The red circle illustrated the details of the velocity vector in aneurysm occurred in real condition.

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.

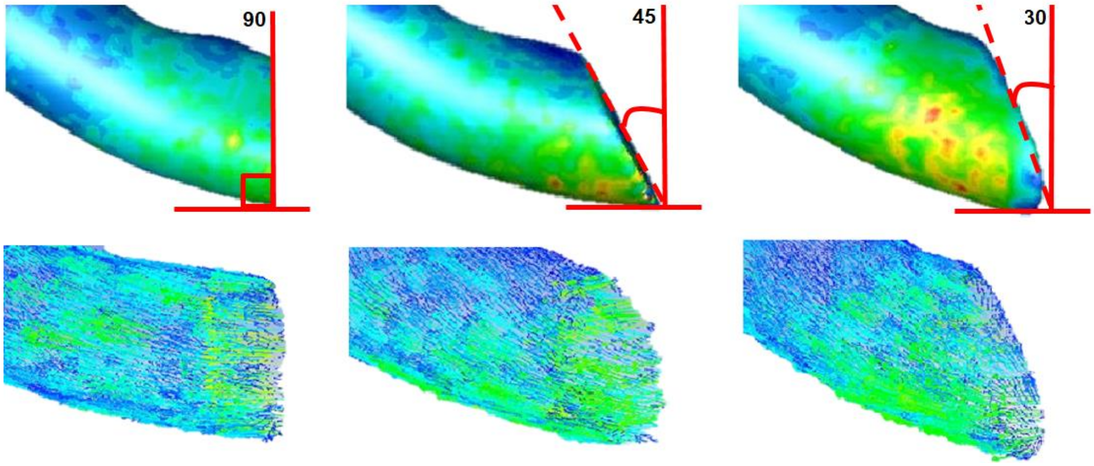

Figure 7. Illustration of velocity field distribution based on different cutting shapes.

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.

5. Acknowledgments

A big thank you dedicated to the support from Universiti Malaysia Pahang under grant RDU190153, KPT grant (FRGS/1/2019/ICT02/UMP/02/1), and MedEHiT for providing us with a good environment and facilities to complete this research. By this opportunity, we would like to thank Dr. Nur Hazreen Mohd Hasni from JKNP and Mr. Idris Mat Sahat from Human Engineering Group, Universiti Malaysia Pahang, for sharing valuable information following our research interest. We would face many difficulties without their assistance.

References

[1] M. J. Wermer, I. C. Van Der Schaad, and A. Algra, and G.J. Rinkel, “Risk of rupture of unruptured intracranial aneurysms with patient and aneurysm characteristic: an updated meta-analysis,” *Stroke*, vol. 38, pp. 1404–1410, 2007.
[2] Y. Miura *et al.*, “Low wall shear stress is independently associated with the rupture status of middle cerebral artery aneurysms,” *Stroke*, vol. 44, pp. 519–521, 2013.
[3] K. D. Dennis, D. F. Kallmes, and D. Dragomir-daescu, “Cerebral aneurysm blood flow simulations are sensitive to basic solver settings,” *J. Biomech.*, vol. 57, pp. 46–53, 2017.
[4] P. M. Munarriz *et al.*, “Basic principles of hemodynamics and cerebral aneurysms,” *World Neurosurg.*, vol. 88, pp. 311–319, 2016.
[5] J. R. Cebral, F. Mut, J. Weir, and C. M. Putman, "Association of hemodynamic characteristics and cerebral aneurysm rupture,” *AJNR Am. J. Neuroradiol.*, vol. 32, pp. 264-270. 2011.
[6] H. G. Morales, I. Larrabide, A. J. Geers, M. L. Aguilar, and A. F. Frangi, “Newtonian and non-

newtonian blood flow in coiled cerebral aneurysms," *J. Biomech.*, vol. 46, no. 13, pp. 2158–2164, 2013.

[7] M. A. H. M. Adib, S. Ii, and Y. Watanabe, and S. Wada, "Minimizing the blood velocity differences between phase-contrast magnetic resonance imaging and computational fluid dynamics simulation in cerebral arteries and aneurysms," *Med. Biol. Eng. Comput.*, vol. 55, no. 9, pp. 1605–1619, 2017.

[8] M. A. H. Mohd Adib, "Measurement of threshold image intensities on the difference of vascular model: effect on computational fluid dynamics for patient-specific cerebral aneurysm," *J. Biomimetics, Biomater. Biomed. Eng.*, vol. 27, pp. 55–59, 2016.

[9] J. L. Chen, G. H. Ding, X. J. Yang, and H. Y. Li, "Effects of parent artery segmentation and aneurismal-wall elasticity on patient-specific hemodynamic simulations," *J. Hydrodyn.*, vol. 23, no. 5, pp. 660–668, 2011.

[10] M. Kroon, "Simulation of cerebral aneurysm growth and prediction of evolving rupture risk," *Model. Simul. Eng.*, vol. 2011, pp. 1-10, 2011.

[11] O. Schubiger, A. Valavanis, and W. Wichmann, "Growth-mechanism of giant intracranial aneurysms; demonstration by CT and MR imaging," *Neuroradiology*, vol. 29, pp. 266–271, 1987.

[12] S. H. Lim, M. A. H. Mohd Adib, M. Abdullah, and R. Hassan, "Qualitative and Quantitative Comparison of Hemodynamics Between MRI Measurement and CFD Simulation on Patient-specific Cerebral Aneurysm – A Review," *J. Adv. Res. Fluid Mech. Therm. Sci.*, vol. 68, pp. 112–123, 2020.

[13] C. A. Taylor, and D. A. Steinman, "Image-based modeling of blood flow and vessel wall dynamics: applications, methods and future directions" *Ann. Biomed. Eng.*, vol. 38, pp. 1188–1203, 2010.

[14] L. Stainier, "A variational approach to modeling coupled thermo-mechanical nonlinear dissipative behaviors," *Advances in Applied Mechanics*, vol. 46, pp. 69–126, 2013.

[15] L. Boussel *et al.*, "Phase-contrast magnetic resonance imaging measurements in intracranial aneurysms in vivo of flow patterns, velocity fields, and wall shear stress : comparison with CFD," *Magn. Reson. Med.*, vol. 61, pp. 409–417, 2009.

[16] H. Isoda *et al.*, "Comparison of the hemodynamics of intracranial aneurysms between MR fluid dynamics using 3D cine phase-contrast MRI and MR-based computational fluid dynamics," *Neuroradiology*, vol. 52, pp. 913–920, 2010.

[17] M. Spiegel *et al.*, "Tetrahedral vs. polyhedral mesh size evaluation on flow velocity and wall shear stress for cerebral hemodynamic simulation," *Comput. Methods Biomech. Biomed. Engin.*, vol. 14, pp. 9–22, 2011.

[18] S. Ii, M. A. H. M. Adib, Y. Watanabe, and S. Wada, "Physically consistent data assimilation method based on feedback control for patient-specific blood flow analysis," *Int. J. Num. Meth. Biomed. Eng.*, vol 34, pp. e2910, 2018.

[19] M. A. H. M. Adib, and N. H. M. Hasni, "Effect on the reconstruction of blood vessel geometry to the thresholds image intensity level for patient aneurysm," *J. Biomimetics, Biomater. Biomed. Eng.*, vol. 22, pp. 89–95, 2015.