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Numerical Modelling of Blood Cells Distribution in Flow through Cerebral Artery Aneurysm

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ABSTRACT

Recent aneurysm studies have focused on the correlation between different parameters and rupture risk; however, there have been conflicting findings. Computational fluid dynamics (CFD) allows for better visualization but idealized aneurysm models may neglect important variables such as aneurysm shape and blood flow conditions. In this paper, one case of an aneurysm was studied with CFD using a non-Newtonian Power Law Model to investigate the correlation between wall shear stress and blood cells distribution. Results show that velocity of blood flow decreased as it entered the aneurysm and the neck of the aneurysm experienced a greater magnitude of wall shear stress than the remainder of the cerebral artery. Besides, the blood cells generally begin at low velocities and increase after the first curve of the artery. Findings and further studies with larger cases of patients will improve treatment and prevention of aneurysm ruptures.

INTRODUCTION

An aneurysm is a ballooning of an artery, cerebral artery that carry blood from the heart to other parts of the body. They can occur throughout the body, including the aorta and the brain. Often times, small aneurysms go undetected and are discovered unexpectedly when other medical tests are performed. When a cerebral aneurysm bursts, symptoms include sudden headache, stiff neck, and nausea, and the subsequent intracranial hemorrhage is associated with high mortality rates [1].

Aneurysms develop due to the weakening of the cerebral artery wall. Research has been done to determine the correlation of different parameters to risk of aneurysm rupture. Prior studies show that factors such as larger aneurysm size, aspect ratio, and size ratio are associated with an increased risk of rupture [2, 5]. Recently, hemodynamic factors have been of interest to predict aneurysm rupture more accurately. Larger areas of low wall shear stress (WSS), the force tangential to wall, along the dome has been associated with increased risk of rupture [3, 4]. On the contrary, high wall shear stress is correlated with formation of bifurcation aneurysms and is negatively correlated with the formation of sidewall aneurysms.

Looking at various hemodynamic parameters will provide a better understanding of aneurysm formation, growth, and rupture, leading to improved treatment for patients with unruptured aneurysms. This study aims to examine blood cells distribution through simulations on ANSYS Fluent for computational fluid dynamics (CFD) analysis. Previous studies with CFD analysis used idealized models and structures of aneurysms. By using real patient aneurysm geometries, more specific results can be provided for the respective patient [6]. Simulations are run using non-Newtonian models to investigate the correlation of WSS to aneurysm rupture. Using the CFD approach allows for better visualization and understanding of the hemodynamics and correlation of parameters to rupture risk.

METHODOLOGY

Aneurysm Geometry and Meshing

In order to have an appropriate model of an aneurysm, a neurologist specializing in aneurysms in the cerebral artery from the Hospital Universiti Kebangsaan Malaysia (HUKM) provided angiograms of four real-life cases of patients who had an aneurysm. For each case, the angiograms were in Digital Imaging and Communications in Medicine (DICOM) format which has 256 stacks of images. The images were analyzed in order to determine what the most optimal geometry of each aneurysm would be for future simulations.

To prepare the images for simulation use in ANSYS Fluent, the images must first be passed through Mimics Research 19.0. Mimics allows for segmentation of the aneurysm and surrounding cerebral arterys so that a better and more focused image of the aneurysm could be produced. For the purposes of the simulation, the inlet cerebral artery to the aneurysm was made to be significantly longer than the outlet cerebral artery. The segmented image need to be passed through 3-matic Research 11.0. This software will take the image and produce a mesh file that is compatible with ANSYS Fluent. Figure 1-4 shows the procedure from when the image is received the neurologist to the final mesh.

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Fig. 1 Angiogram image in DICOM format

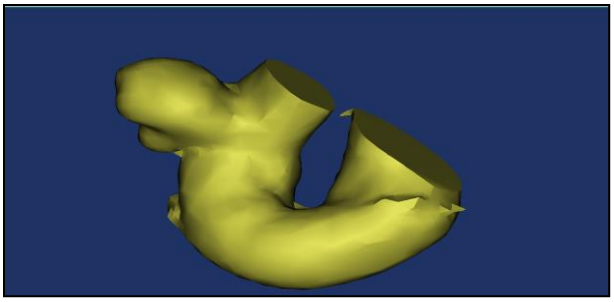


Fig. 2 Segmentation using Mimics Research 19.0

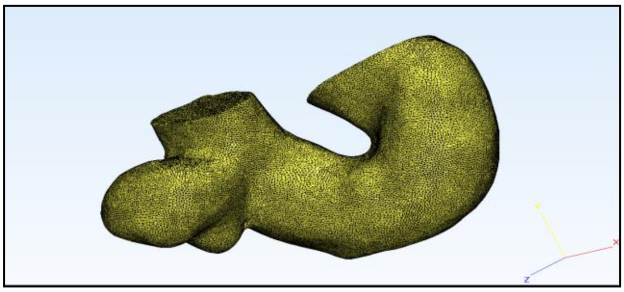


Fig. 3 Mesh Creation using 3-matic Research 11.0

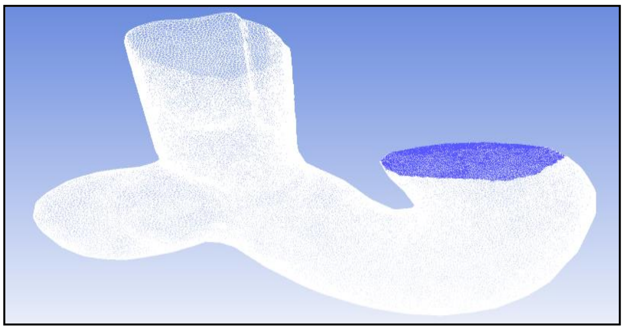


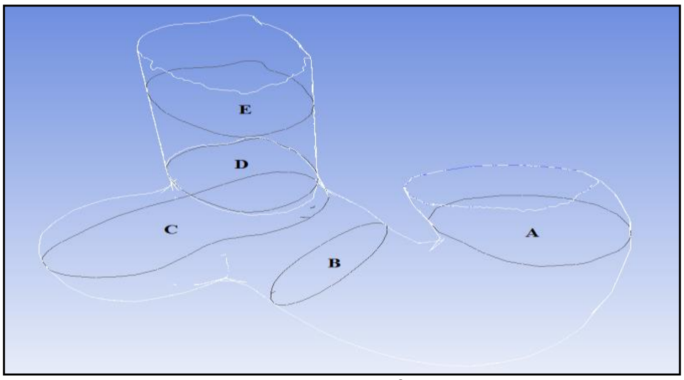
Fig. 4 Final Mesh in ANSYS Fluent 16.0

Simulation Modeling

ANSYS Fluent 16.0 was used to model the blood flow in the cerebral artery and aneurysm. The mesh file was imported to ANSYS Fluent and checked to ensure the mesh quality. The scaling of the mesh was adjusted to millimeters to correspond to the actual size of the artery. In addition, multiple viewing planes must be created in order to analyze the velocity of blood flow at specific points of the cerebral artery. For this simulation, there were five viewing planes: after the inlet, before the aneurysm, after the aneurysm, before the outlet, and a plane parallel to the outlet at the aneurysm. Figure 5 depicts the location of the view planes as well as the final mesh that was used for the simulation.

The simulation was set to Transient and pressure based with absolute velocity formulation. The Discrete Phase Model (DPM) was used to simulate the blood cells moving through the cerebral artery. The inert particles with diameter of 0.02mm and a non-spherical physical model of 1.5 represent the blood cells. The injection of the blood cells was set to the surface type and injected from the inlet of the cerebral artery.

As for the materials needed in the simulation, the fluid was specified as blood. Table 1 shows the parameter conditions for blood.



In addition, the inert particle was modified to be blood cells with a density of 1019 kg/m^3.

Fig. 5 Final mesh geometry of aneurysm (bulge shown on the left) and the five viewing planes

Table 1 Parameters for blood as a fluid material

Density (kg/m^3)	Consistency Index (kg-s^n2/m)	Power Law Index (n)	Minimum Viscosity Limit(kg/m-s)	Maximum Viscosity Limit (kg/m-s)	Reference Temperature (K)
1080	0.2073	0.4851	0.00125	0.03	310

For the boundary conditions, the inlet of the cerebral artery was specified as a velocity inlet with a constant velocity of 0.31m/s and no initial gauge pressure. The inlet velocity was represented as "Magnitude, normal to Boundary" method with an absolute reference frame. For the outlet of the cerebral artery, it was specified to be a pressure outlet with a gauge pressure of 13332 pascal and the average pressure specification checked. The backflow direction specification method was set to "Normal to Boundary." The DPM setting for the outlet was set to escape.

Table 2 Reference Values for Simulation

Area (m^2)	Density (kg/m^3)	Length (mm)	Temperature (K)	Velocity (m/s)	Viscosity (kg/m-s)	Ratio of Specific Heats
1	1080	1000	288.16	0.3162831	1.7894e-0.5	1.4

Table 2 shows the values that were inputted for the "Reference Values" task page. Tables 3, 4, and 5 provide the values used for each task page of ANSYS Fluent. For "Monitors" and "Calculation Activities" task pages, none of the options were changed and were left at the default setting. The simulation was run for a total time period of two seconds.

Table 3 Solution Controls Values

Pressure	Density	Body Forces	Momentum	Discrete Phase Sources
0.3	1	0.1	0.5	1

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Table 4 Solution Initialization Values

Gauge Pressure (pascal)	X Velocity (m/s)	Y Velocity (m/s)	Z Velocity (m/s)
0	0.01434163	-0.003352355	0.31594

Table 5 Run Calculation Values.

Time Step Size (s)	Number of Time Steps	Max Iterations/Time Step	Reporting Interval	Profile Update Interval
0.0005	4000	300	1	1

In order to analyze the results, the velocity vectors and the pathlines were studied. The velocity vectors were specified to originate from the viewing planes that were initially created when the mesh was imported. The pathlines were used to validate the movement of the particles and to see the specific trajectory of the particles as they move through the cerebral artery.

RESULTS

The velocity pathlines of the blood cells are shown in Figure 6, where the fastest cells are indicated by red areas while the slowest cells are shown in blue. The spectrum of velocities are shown on the left in units of meters per second (m/s). The fastest blood cells are near the outlet (the long side) and towards the center of the cerebral artery.

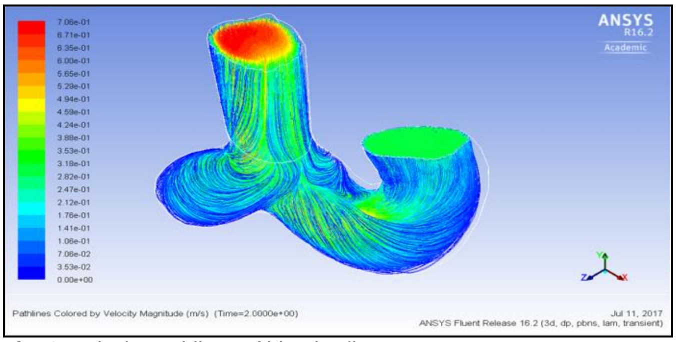
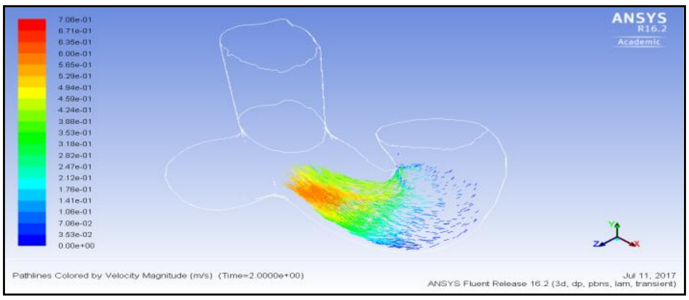


Fig. 6 Velocity pathlines of blood cells



The Pulse function was used to create an animation of the velocity pathlines as the blood cells traveled through the cerebral artery. The primary interest of this function is to understand how blood flows through the aneurysm. Figure 7a-7b illustrates how the blood flow divided into two streams as it passes through the aneurysm. The main blood flow stream proceeded to the outlet at a faster velocity than the other stream which circulated the aneurysm, as shown in Figure 7c. Eventually, all of the remaining blood cells in the aneurysm flowed towards the outlet shown in Figure 7d.

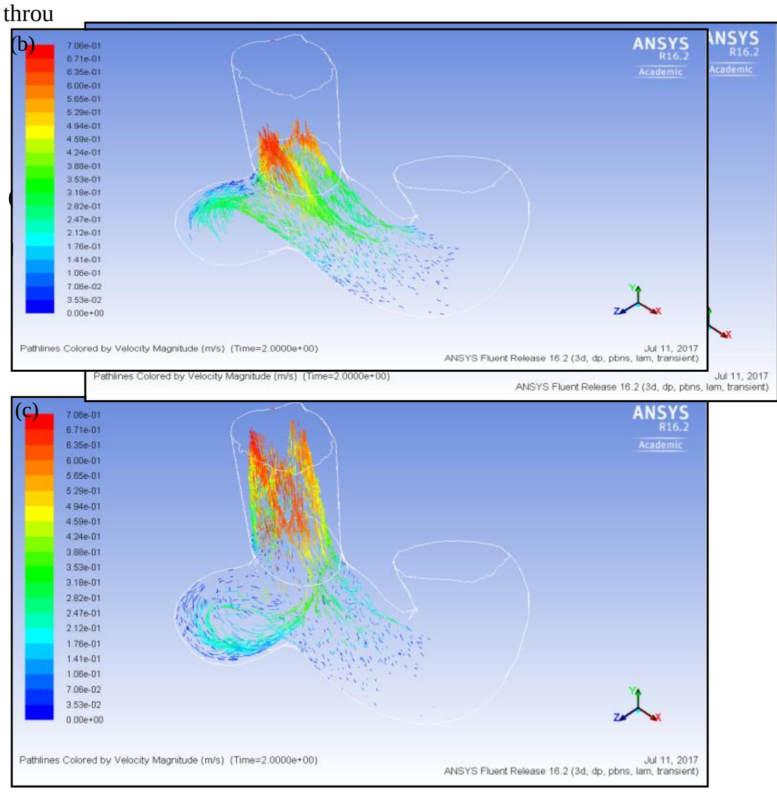
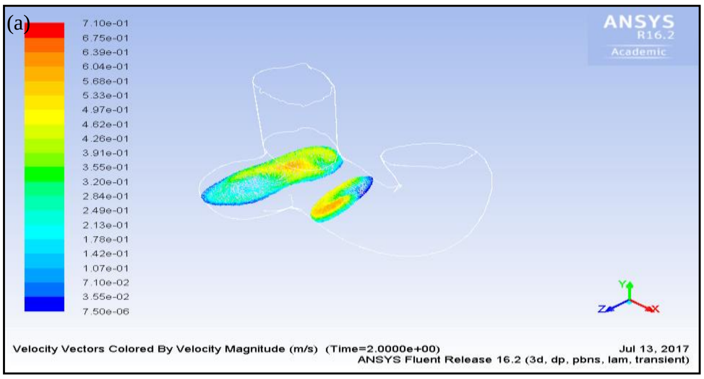


Fig. 7 *Velocity pathlines at the aneurysm using the Pulse function. 7a shows a uniform blood flow before reaching the aneurysm. 7b illustrates the division of the blood flow upon reaching the aneurysm 7c displays the circulation of the blood cells remaining in the aneurysm.The remaining blood cells eventually leave the aneurysm, shown in 7d.*

Velocity vectors were also analyzed at desirable locations, or planes, as mentioned in the Methodology section. Areas with the fastest particles were indicated by red and long arrows. Figure 8a demonstrates that the blood cells generally begin at low velocities. They begin to increase velocities after the first curve of the artery.



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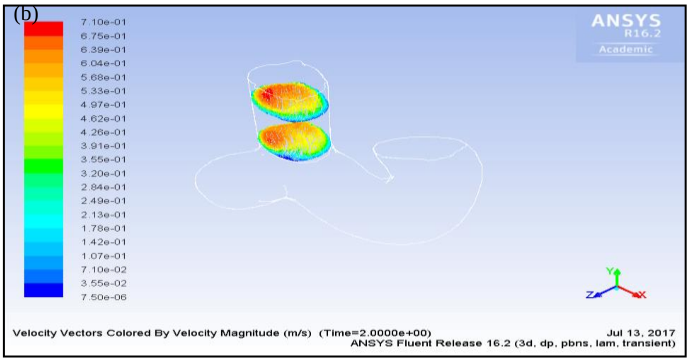

Fig. 8 *(a) Velocity Vectors at plane B and plane C (b) Velocity Vectors at plane D and plane E*

However, the fastest blood cells were concentrated along the wall of the artery that was opposite of the aneurysm. Figure 8a demonstrates this observation, where the slower blood cells circulated in the aneurysm, or the top half of the artery. The blood cells that did not enter the aneurysm dramatically increased in velocity due to the sharp division between the aneurysm and artery (Figure b). Figures 8 and 9 confirms that the change in velocities is consistent from the sharp division to the outlet.

ANALYSIS AND DISCUSSION

In this simulation, Non-Newtonian Power Law model was used to describe the behaviour of blood. In order to calculate the WSS, the following relationship is used [8]:

$$\tau_w = -\ \mu\gamma = -\ \mu\ \frac{\partial v}{\partial r}$$

where:
τ_w is wall shear stress
μ is viscosity of blood
γ is shear rate

The shear rate, $\dot{\gamma}$ is defined as the radial derivative of blood flow velocity ($\partial v/\partial r$). The WSS is evaluated using the velocity gradient at the wall and almost synonymous with shear rate. High shear rate present when the diameter is small and flow is fast and the low shear rate present when the diameter is large and flow is slow.

WSS is a frictional force between blood and endothelium of the artery. At any point where a high velocity was observed, the WSS intensified. However, the greatest stress occurs at the neck of aneurysm. This observation agrees the WSS equation $\tau w = -\ \mu\gamma = -\ \mu\ (\partial v/\partial r)$. The blood cell concentration at this location is low because the cells quickly leave the region due to high flow velocity. At the region where the velocity is slow, the WSS is conversely reduced.

Consequently, some of the cells will not have enough momentum to leave the aneurysm area quickly. It was noted that the thinning of artery wall depended on the interaction between platelets, blood cells and smooth muscle cells. Hence, the risk of rupture could increase as indicated in the velocity field, where the highest velocity is at the neck of the aneurysm where the blood cells are entering and leaving the aneurysm dome. There is a significant change in the flow cross-sectional area. A sudden change in velocity may cause the abrupt pressure loss in aneurysm area. The velocity reduced and the flow recirculation formed at low pulse rate.

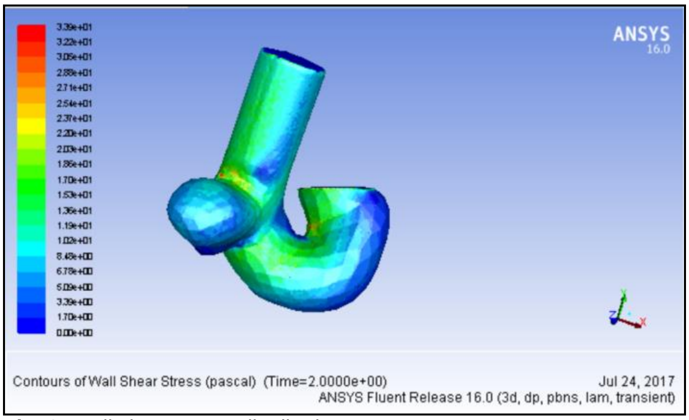

Fig. 9 Wall shear stress distribution

FUTURE WORK

Despite the noticeable correlation between WSS and blood cell velocities, this is merely one aneurysm case. Every patient's aneurysm has a unique shape and position along the artery. Both of these characteristics ultimately contribute to varying blood cell velocities and different risks of rupture. More patient studies may yield different correlations between WSS and blood cell velocities. Another critical factor in determining rupture is WSS. While WSS values are obtainable through current results, the exact value of rupture is still undetermined since it varies with each patient. Once a range of WSS values are established through additional patient studies, it can be compared with literature values for maximum WSS of a cerebral artery**.**

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