ANALYSIS OF BLOOD FLOW IN ABDOMINAL AORTIC ANEURYSM USING COMPUTATIONAL FLUID DYNAMIC

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SUPERVISOR'S DECLARATION

I hereby declare that I have checked this project and in my opinion, this project is adequate in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering.

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STUDENT'S DECLARATION

I hereby declare that the work in this project is my own except for quotations and summaries which have been duly acknowledged. The project has not been accepted for any degree and is not concurently submitted for award of other degree.

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Dedicated to my parents

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Lastly, special thanks goes to my beloved parents who always supported me from the very beginning to achieve my goals and sacrifice much in their life for my well-being. I am indebted to their painstaking attitude, which always kept me on the right track.

ABSTRACT

Aneurysm is an abnormalities occurs in blood vessel that involve the size increment and dilations where the cause of the disease not yet been founded. Abdominal aortic aneurysm was occurring at abdomen aorta. The abnormal diameter size of abdominal aorta was cause by ballooning or bulge that lead to changes in blood flow behavior. Investigation on the behavior of blood flow in abdominal aortic aneurysm was taken place to determine the pressure distribution and velocity profile in the aneurysm region. The diameter of normal aorta was 20 mm and the diameter of aneurysm aorta was considered as 60 mm from the literature. The flow of blood in aorta will be disturbed when the diameter of aorta was changed. Aneurysm is acting like diffuser that increases the pressure and decreases the velocity when blood entering the aneurysm region. Oppositely when it leaving the aneurysm the pressure wills decreases back and the velocity will be increase like nozzle. It was proved that the flow behavior inside aneurysm region would be different compared to the normal aorta from the previous study. The size of aorta influences the pressure and velocity of blood. The flow inside aneurysm region was disturbed due to pressure and velocity changes and resulting the formation of vortex. Reynolds number was establishing by using different initial velocity of blood flow and different diameter of aorta. The simulation of the model was studied under incompressible and non-Newtonian condition which investigated computationally by fluid dynamic software. The studies was done without experiment set-up but based on numerical approach only.

ABSTRAK

Aneurysm adalah suatu penyakit yang berlaku kepada salur darah dimana terjadi ketidaknormalan pada saiz diameter salur darah dan puncanya masih belum diketahui. Abdomen aneurysm berlaku kepada salur darah yang terletak di bahagian perut. Saiz diameter bagi saluran darah abdomen yang tidak normal telah menyebabkan pembesaran atau pengembangan yang membawa kepada perubahan reaksi pengaliran darah. Penyelidikan terhadap keadaan pengaliran darah di dalam aneurysm abdomen dijalankan untuk menentukan taburan tekanan dan profil halaju di dalam kawasan aneurysm. Saiz diameter bagi saluran darah abdomen yang normal adalah 20 mm dan saluran darah aneurysm abdomen ialah 60 mm berdasarkan kepada rujukan dari penyelidikan sebelum ini. Pengaliran di dalam salur darah akan terganggu apabila saiz diameter salur darah tersebut berubah. Halaju dan tekanan darah berubah apabila ia sampai kepada kawasan aneurysm di dalam salur darah tersebut. Telah terbukti bahawa pengaliran salur darah di dalam salur darah abdomen aneurysm akan berbeza berbanding dengan pengaliran di dalam salur darah yang normal. Pengaliran di dalam salur darah abdomen telah terganggu kerana terdapat perubahan tekanan dan halaju dan ini telah menyebabkan pembentukan pusaran darah. Nombor Reynold ditentukan dengan menggunakan menggunakan halaju awal darah yang berbeza dan saiz diameter salur darah yang berbeza. Simulasi bagi model ini dikaji berdasarkan parameter aliran mampat dan bukan bendalir Newtonian dimana ianya dikaji secara perkomputeran dengan menggunakan program bendalir dinamik. Kajian ini hanya dijalankan dengan pendekatan berdasarkan pengiraan matematik tanpa melibatkan sebarang eksperimen.

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LIST OF SYMBOLS

u_i	velocity in the i^{th} direction
P	Pressure
f_i	Body force
ρ	Density
μ_i	Viscosity
∂_{ij}	Kronecker delta

LIST OF ABBREVIATIONS

AAA	Abdominal Aortic Aneurysm
CFD	Computational Fluid Dynamics
CAD	Computer Aided Design

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Aneurysm is ballooning or bulge that occurs in a blood vessel cause by disease or vessel wall that is weaken. The diameter of the blood vessel will increase greater than its original size and can lead to rupture, bleeding inside the body and often fatal. Aneurysm consists of four types which is abdominal aortic aneurysm, dissection aneurysm, thoracic aortic aneurysm and cerebral aneurysm. Type of aneurysm is shown in figure 1.2 until figure 1.5.

The word aneurysm comes from the Greek aneurysma meaning widening. Aneurysm consist of different shape that is maybe saccular (balloon like expansions of only a portion of the wall) or fusiform (gradual dilation of the complete circumference of the artery) as presented in figure 1.1. The different shapes have not been related to any specific cardiovascular disease or clinical manifestation (Contran et, 1999). Abdominal aortic aneurysm can be found in abdominal aorta which is located below renal arteries above iliac bifurcation). This is a common vascular problem and the rate of incidence has increased greatly with the increase in life expectancy of the population. AAA is often not detected at early stages and, in most cases, remains latent until symptoms occur as their size greatly increases or until they are diagnosed during an incidental exam (Szilagyi, 1982).

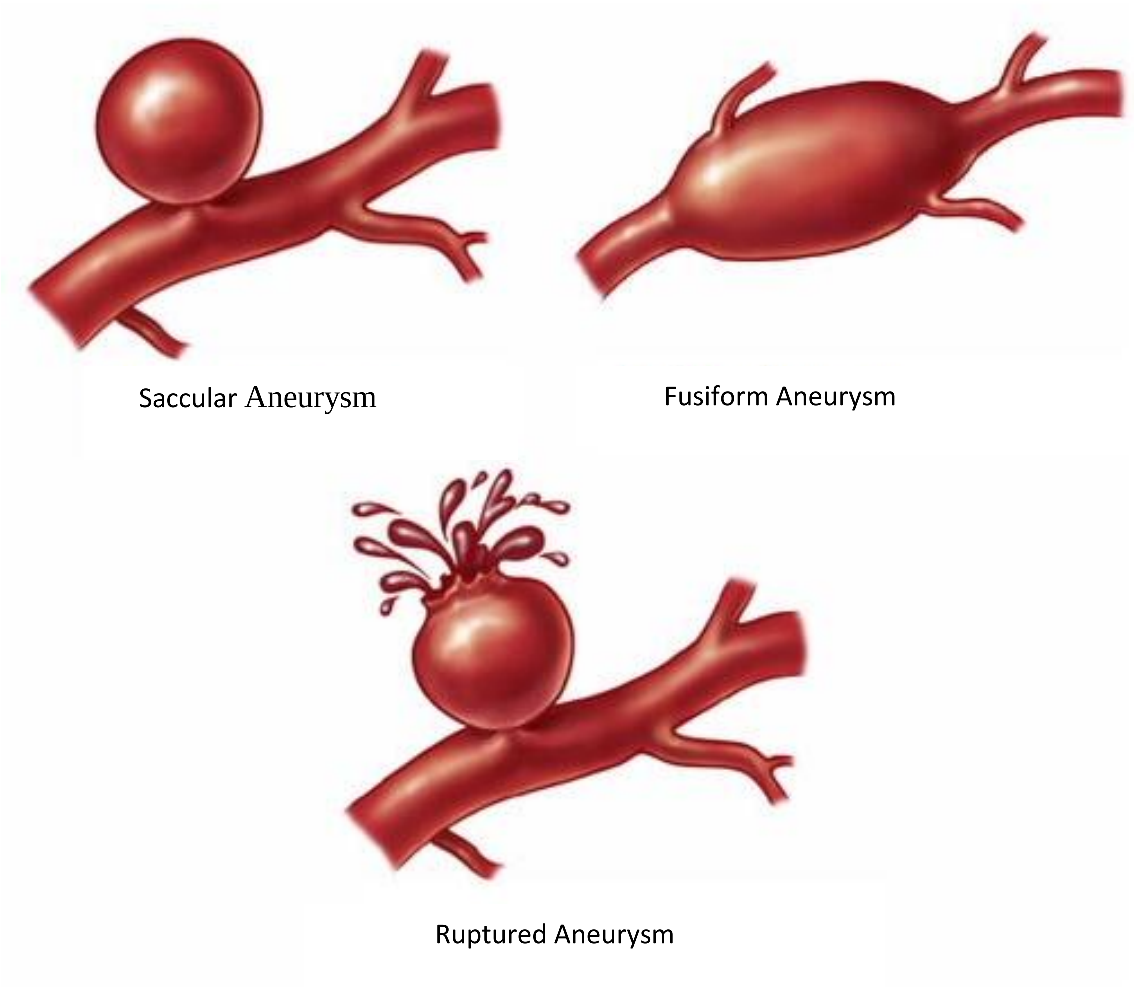

Figure1.1: Shapes of aneurysm

Source: http://www.daviddarling.info

Figure 1.1 shows that aneurysm shape consists of saccular, fusiform and ruptured aneurysm. Every shape consists of different geometry and size. Ruptured aneurysm is very dangerous to the human. Ruptured aneurysm is cause by weakening of the arterial wall. Beside the blood pressure inside the artery is very high and can exert tremendous dynamic force toward arterial wall. Between times, the wall structure cannot stand any further force and finally this lead to the rupture.

1.2 TYPES OF ANEURYSM

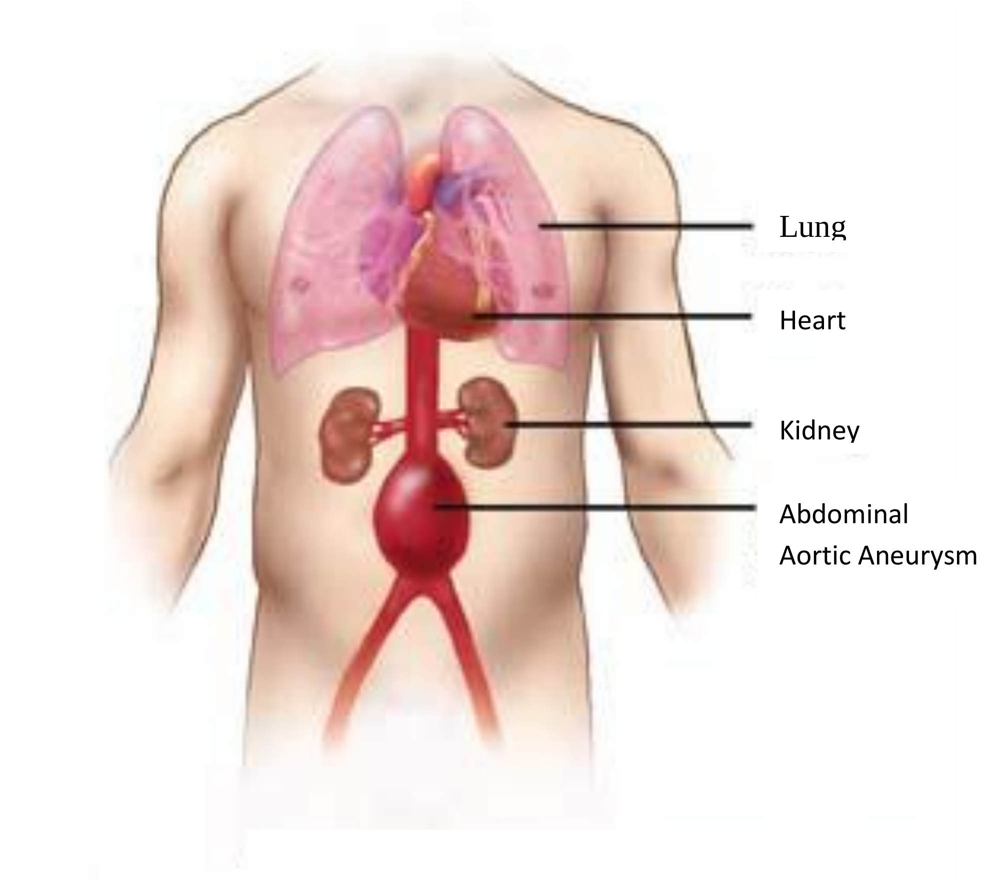

Figure 1.2: Abdominal Aortic Aneurysm

Source: http://aaadoctor.org/

Figure 1.2 shows that abdominal aortic aneurysm is located along the portion of the aorta that passes through the abdomen . It is a large blood vessel that supplies blood from the heart to the abdomen, pelvis and leg. The tendency of the aneurysm to break is base on the size. The larger the aneurysm, the more possiblities for it to break. This type of aneurysm can occur and develop in anybody, but record often said that males that over 60 is more likely to be involved.

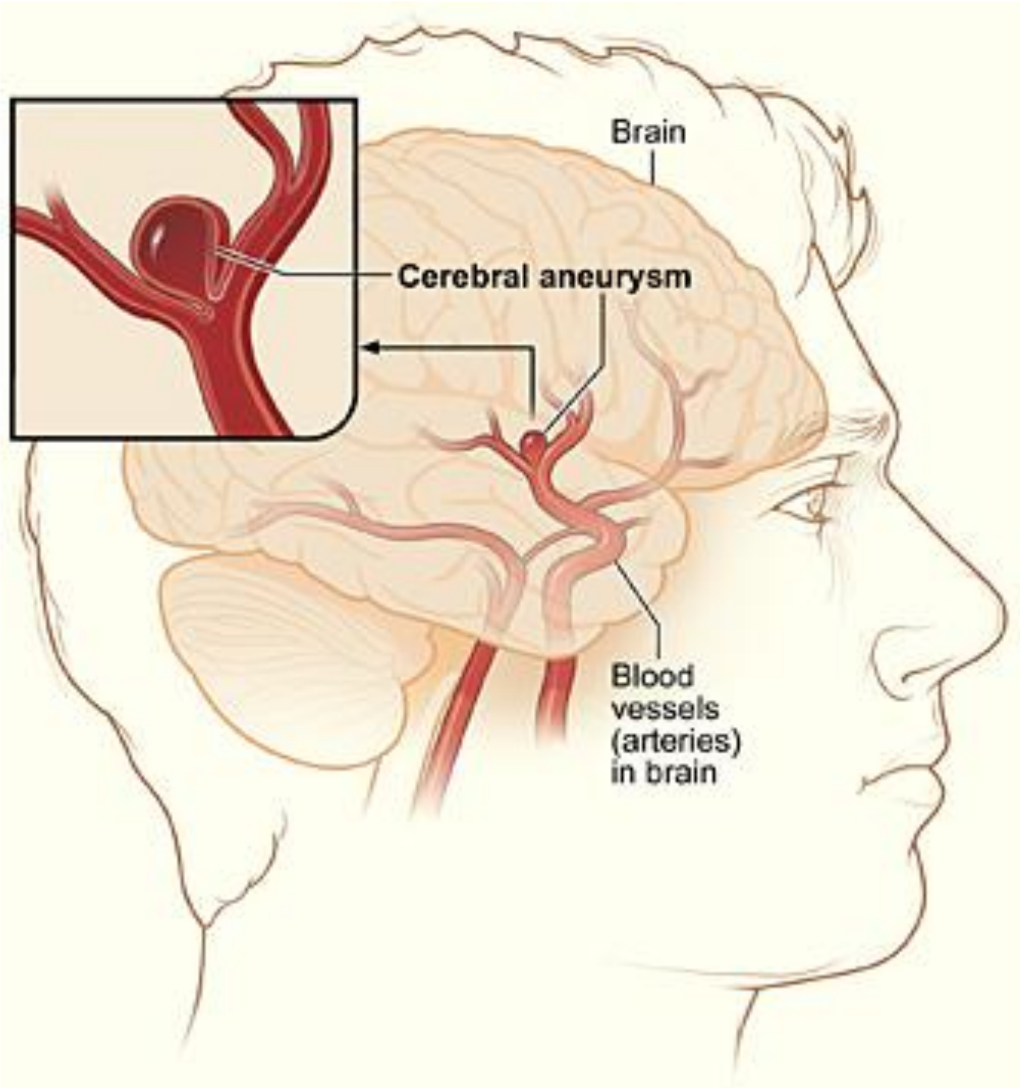

Figure 1.3: Cerebral Aneurysm

Source: http://www.nhlbi.nih.gov

Figure 1.3 shows the location of the cerebral aneurysm. It occurs at the blood vessel (arteries) in the brain. The size of cerebral aneurysm much smaller compare to abdominal aortic aneurysm, but the threat is same. Typically aneurysms occur at branching points of arteries. Cerebral aneurysm often under ¼ inches in diameter especially that is located in front of the brain.

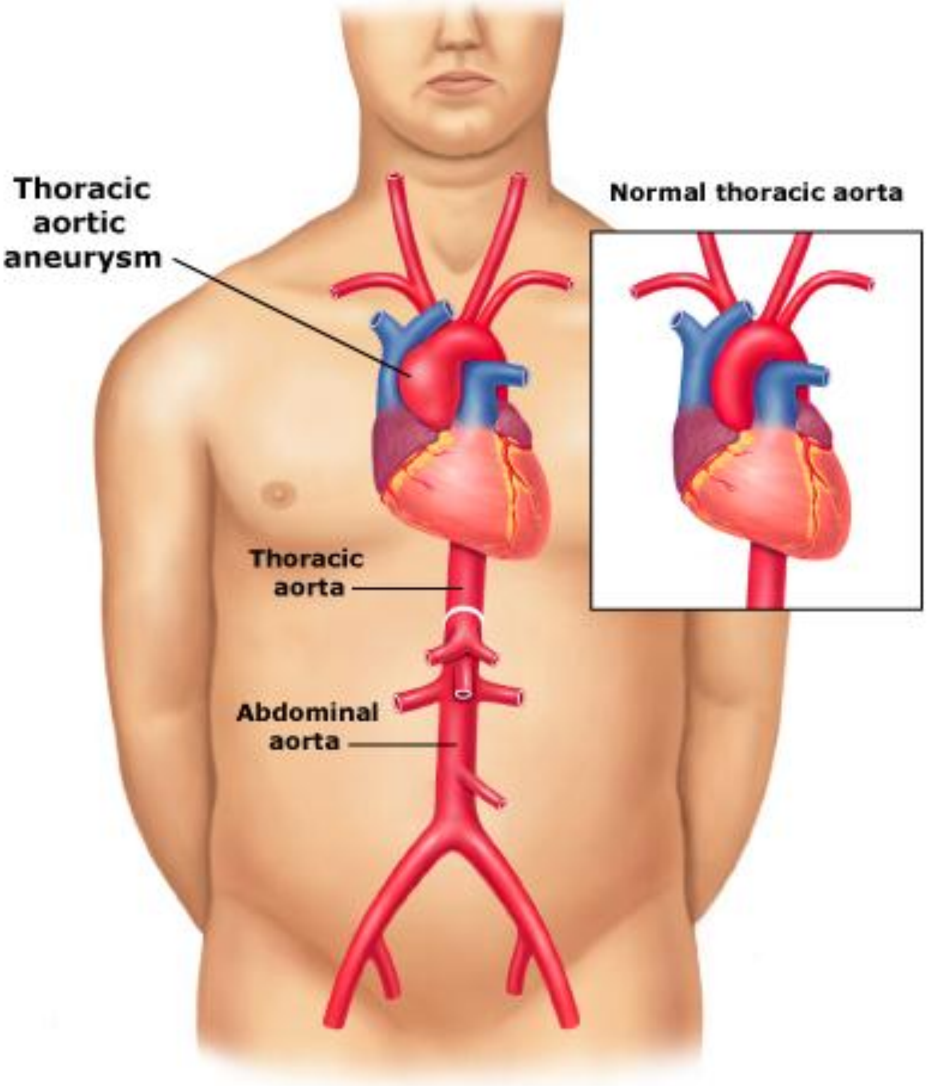

Figure 1.4: Thoracic Aortic Aneurysm

Source: http://www.uptodate.com

Figure 1.4 shows the location of the thoracic aortic aneurysm that involved on the chest region. It is the main blood vessel that carries blood from the heart. The normal diameter of aorta is about an inch or even smaller. If the aneurysm occurs, the diameter cans growth to be 3 inches or even higher.

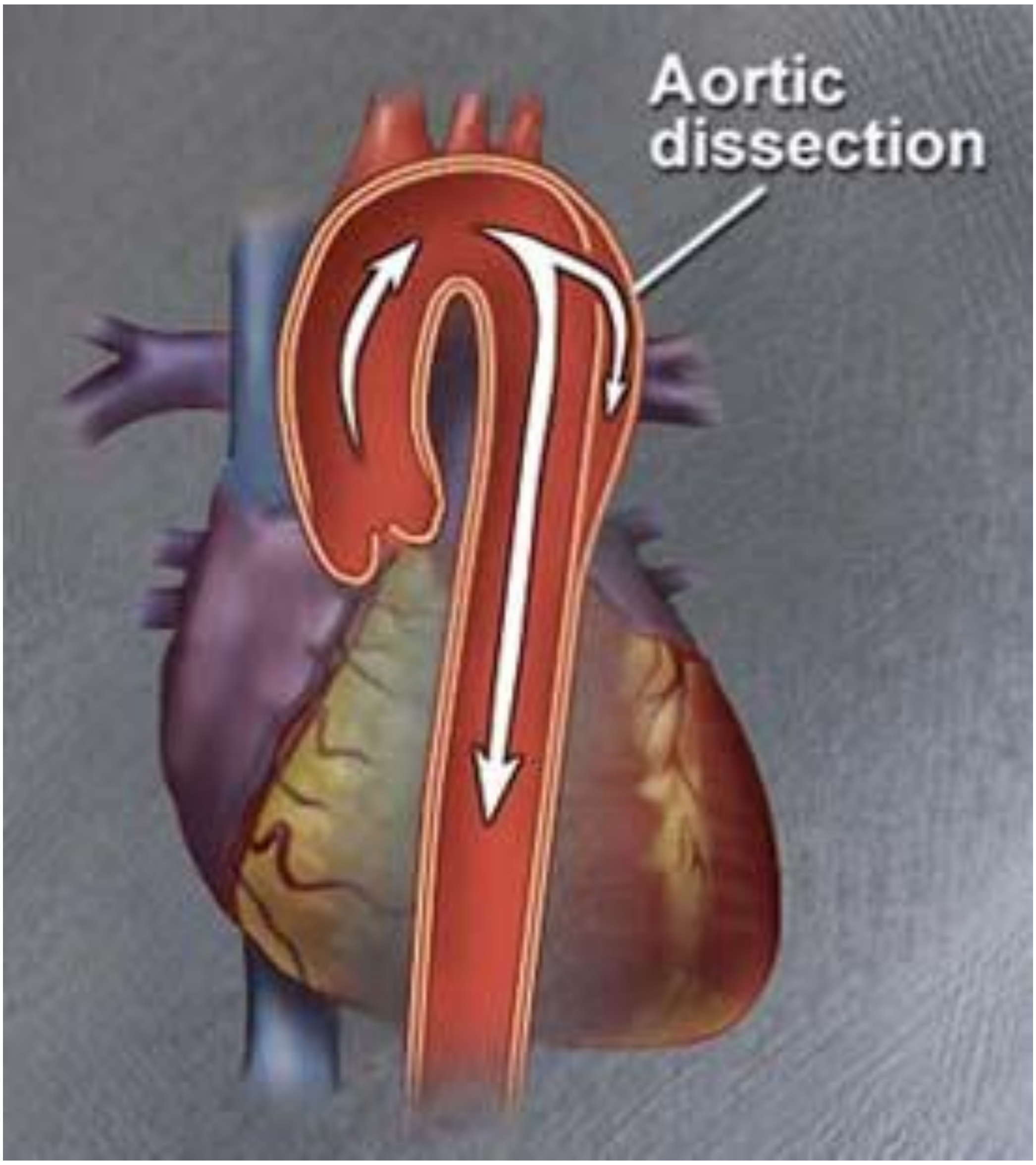

Figure 1.5: Dissecting Aneurysm

Source: http://www.vascularweb.org

Figure 1.5 shows that the location of dissecting aneurysm. The wall of the aorta rips (dissects) longitudinally. The bleeding that occur on the weaken wall can splits the wall in this resulting the dissecting aneurysm. It is also because when tear begins in the wall of the aorta and its three layers is separated. This type of aneurysm can occur anywhere along the aorta.

1.3 AAA FORMATION

The real and exact cause of abdominal aortic aneurysm formation are not been found yet. From previous studies, the atherosclerosis (buildup of fatty deposits in the arteries) is being said as the reason, but according to Ernst, 1993, it is clear that the cause of AAAs is not simply a compilation due to atherosclerosis, but the latter maybe a secondary response to an injured aortic wall.

Many theories have been suggested to explain the formation of AAAs wall. Several theories state that structural defect of the aortic wall can lead to the loss of biomechanical function and it cannot perform under good level of functionality and finally it leads to the uncontrolled expansion. The theory proposed by Dobrin (1989) was the aneurysm formation is due to local weakening of the intima and media layers of the abdominal aorta. Excessive hemodynamic load applied to the aortic walls that have inadequate strength to withstand it can cause the expansion of AAA.

The strength of the aortic wall is being decreased due to initial depletion of elastin (the tissue that gives elasticity to blood vessel). Beside that the depletion of collagen (the tissue that provides stiffness) also was the reason of weakening of the wall. Where is this action is take place was not specify by Dobrin. Maybe this can be the future research to find specific place or which wall layers this process would occur.

1.4 SYMPTOM AND DIAGNOSIS

Symptoms of aneurysm will depend upon the location of the aneurysm (Li Zhonghua, 2005). Aneurysm usually cannot be detected during early stages in most cases, but the symptom only majorly occurs as the size greatly increased. It can be detect during daily or routine examination. During the occurrence of the symptom, it can cause severely pain. People who suffer it will face pulsing sensation, difficulty swallowing, pain, coughing or hoarseness.

The detection of the aneurysm can be done by simple physical examination such as X-Ray or ultrasonography. Besides that, there are also Angiography, Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) that being the common ways to detect Abdominal Aortic Aneurysm.

1.5 TREATMENTS

The treatments for aneurysm have two methods. First is open surgical repair and second is minimally invasive endovascular repair. For open surgical repair, the patient chest or abdomen must be operated to allow the installation of graft at the weaken region or bulge region. The installation of graft will provide new path and allow blood to move freely compare from previous condition without graft. Blood can flow through the graph and the collision with the bulge wall can be minimized.

In cerebral aneurysm case, some part of the head skull must remove temporarily if open surgery method is taken place. We can use tiny metal clips to place at the neck of the aneurysm. The purpose of this action is to block the blood flow from entering the aneurysm bulge region. This open surgery method have disadvantages such as the patient that being treat will face large incision, higher cost of hospitalization, rate of recovery is low and can lead to longer pain.

The second method is Minimally Invasive Endovascular Repair. This treatment performed inside patient's body using long catheters. This method is guided by X-rays. To perform this method in aortic aneurysm, the small incision must take place at femoral artery. Then the stent graphs being released when it passes through leg artery until it reach the aneurysm region.

After the graft completely been place at the aneurysm site as plan, blood likely flow through the new synthetic vessel and it protect the weaken aneurysm wall from the blood speed and movement that can cause the collision. From these phenomena, the ruptured aneurysm probability can be decrease and somehow it will be prevented.

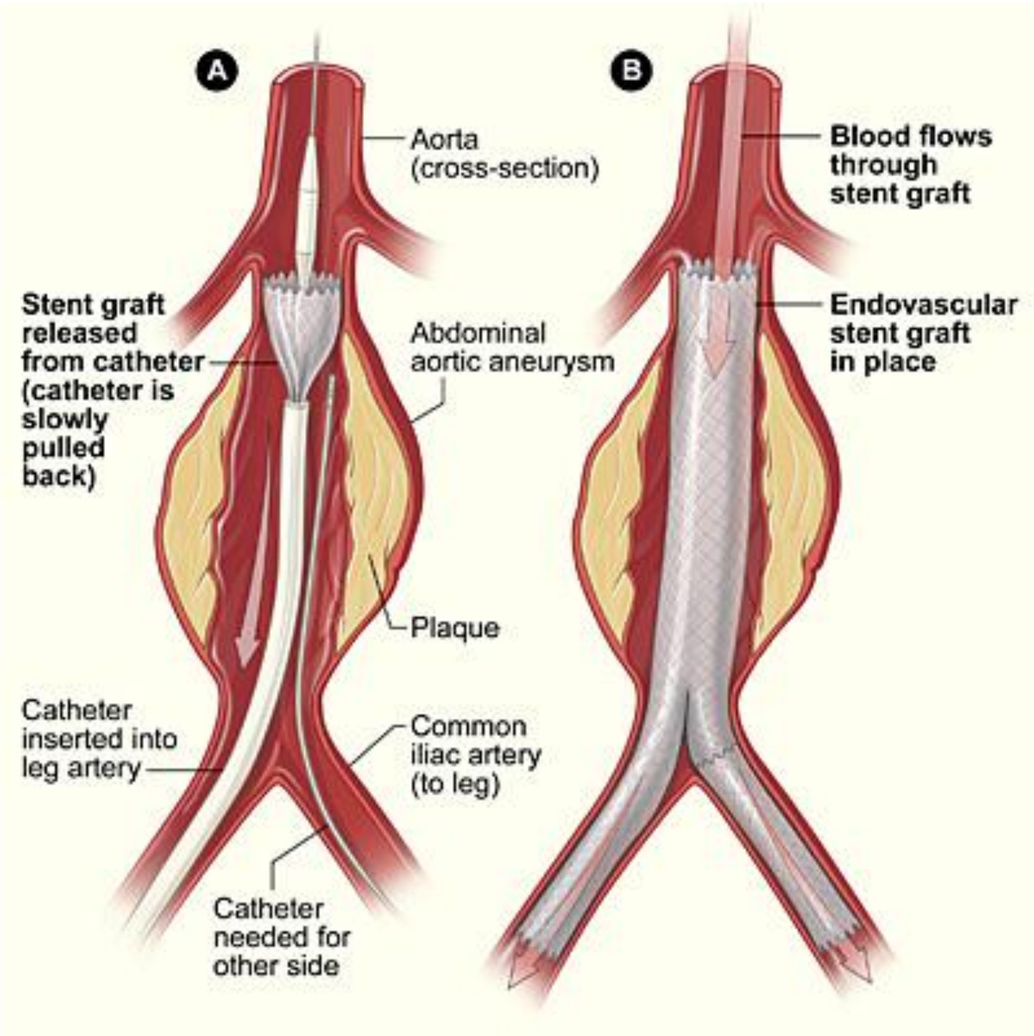

Figure 1.6: Stented AAA

Source: http://medicineworld.org

1.6 OBJECTIVES AND SCOPES

The first objective of this project is to determine the flow behavior inside abdominal aortic aneurysms and the second objective is to investigate the flow disturbances inside the abdominal aortic aneurysm using numerical approach. This project also includes the aim to obtain pressure distribution and velocity profile along the aneurysm. Beside that the objective also to find the correlation between inlet velocity and diameter of aorta to the peak pressure and velocity drop.

In order to achieve these objectives, some limitations were decided to range the whole study. There are four main types of aneurysms. In this project, only abdominal aortic aneurysm type will be considered by referring to model geometry from journal. The analysis of flow behavior takes place on non-stent abdominal aortic aneurysm and non pulsatile blood flow. All the solutions of the problem presented in this project will be based on numerical approach only. The result obtains from these analyses hopefully will explain the flow behavior inside the aneurismal region and flow behavior with varies inlet velocity and diameter of aorta as the parameter of study.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Many previous studies show that the assessment risk of AAA rupture is focused on the investigation of vascular hemodynamic and wall mechanic as two separate fields of studies (Ender A. Finol, 2001).

Both fluid mechanics and wall mechanics play important role in the research of the simulation of the blood flow in abdominal aneurysm and the rupture prediction. In early biomedical studies, they have proposed that this aneurysm disease that has abnormal aorta size is resulted from complex biochemical process in the vascular wall. Beside that the hemodynamic factor also is be considered because the interaction between the inner vascular wall and blood flow.

According to Zhonghua Li, 2005, once the induced mechanical stress exceeds the ultimate strength of the AAA wall, rupture is going to happen. There are some differences from engineering perspective compare to biological perspective that also can be put into consideration for the prediction of AAA rupture. The previous clinical investigation did not state that the characteristic of individual aneurysm such as aneurysms shape, material properties of the wall structure, wall thickness and physiological properties of blood flow in aorta. The prediction of rupture potential can be assist by concrete data if we can get many characteristic of aneurysms that can be consider to be the cause that can lead to the rupture. With knowledge of engineering, we can make the better assessment of rupture prediction.

2.2 FLOW BEHAVIOR IN UNDILATED ABDOMINAL AORTA

Much previous research had been performed in order to find the flow behavior in normal abdominal aorta. Researchers used both method or some of them use either experimentally or numerically. Each method have their own pro and cons. Technological advancements have made possible the use of Magnetic Resonance Imaging (MRI) and Doppler Ultrasonography (US) techniques to measure blood flow in arteries and veins in a minimally invasive manner. The usefulness of MRI and US method have been proved by comparing the the two in in-vivo velocity and flow rate measurements of healthy patients under resting condition. It shows a significant region of reverse flow at the end of systole (Vieli et al., 1989; Maier et al., 1989).

Under resting conditions, simultaneously flow rate and intraluminal pressure is being measure using catherer tip electromagnetic velocity probe (Mills et al., 1970). Determination of peak velocity is perform using hot film velocity probe at 28 ± 4 cm/s in the resting condition or absence of turbulence (Stein et al., 1979). According to Ender A. Finol (2001), the modeling of blood flow in the human abdominal aorta requires specifying how the flow behaves at the inlet cross section of the vessel segment. Whether it is done numerically or by utilizing in-vitro model, the inlet boundary condition in the majority of studies is assumed as a parabolic velocity profile (fully developed flow) or a flat velocity profile (uniform flow).

2.3 FLOW BEHAVIOR IN ABDOMINAL AORTIC ANEURYSM

Recent studies indicate that flow behavior in normal abdominal aorta is greatly different from the abdominal aortic aneurysms or the aorta that have increment of the diameter size from its original geometry. By referring to Zhonghua Li (2005), the simulation of the actual blood flow in AAA can be done by using CFX-ANSYS FSI software. He considered asymmetric abdominal aortic aneurysm as in figure 2.1. At t/T=0.2 as shown in figure 2.2, the blood flow accelerates to it maximum Reynolds number and it achieve the peak velocity. The maximum pressure occurs at inlet and minimum at the outlet.

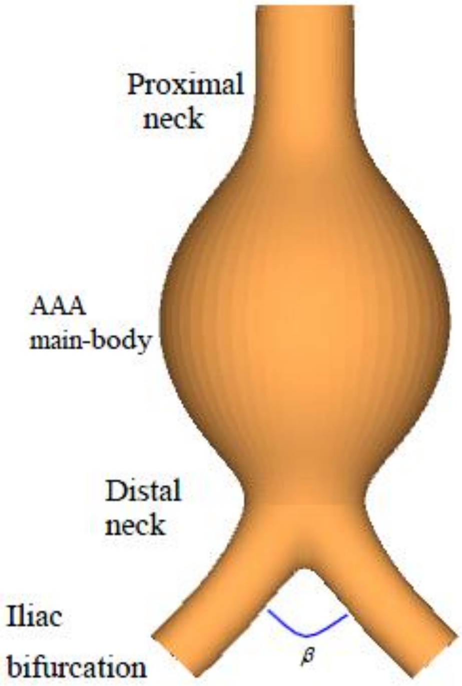

Figure 2.1: Axisymmetric AAA

Source: Zhonghua Li, 2005

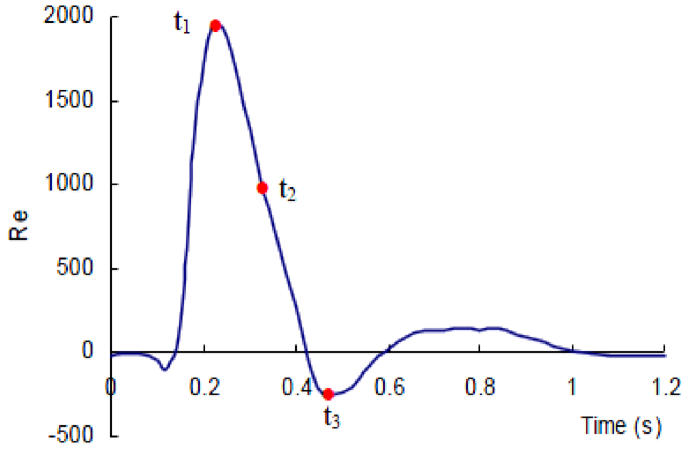

Figure 2.2: Inlet velocity waveform

Source: Zhonghua Li 2005

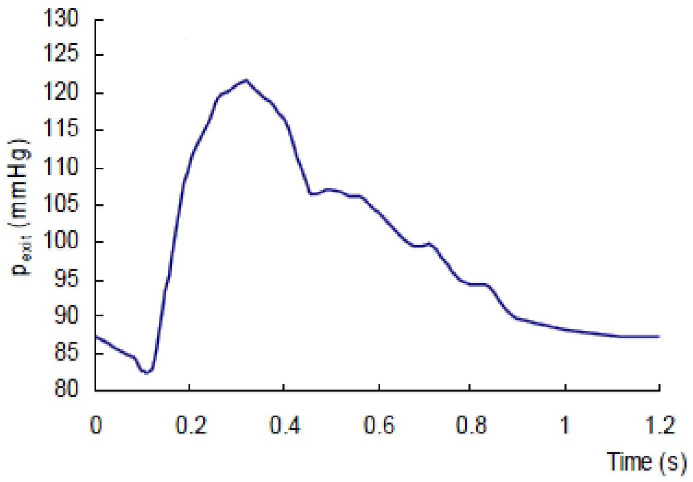

Figure 2.3: Exit pressure waveform

Source: Zhonghua Li, 2005

When the blood flow phenomena taken place in aneurysm, flow behavior in three different time can be observed at t/T=0.1, 0.2 and 0.27 as in figure 2.2. In this three different phase, there are differ in the observation. The pressure and velocity are not constant and will be changes due to the blood flow. The distribution of changes in wall deformation and wall stress also can be existed.

Phase number one is at t/T=0.1. In this moment, the blood pressure at the outlet is higher than the inlet. As the result, the pattern of the blood flow will change and be more complex compare to the normal flow in the normal aorta. This kind of flow will cause the formation of vortex and the blood flow from bifurcation to the proximal neck.

At t/T=0.2, the inlet is being increase in pressure likely that the pressure is moving towards the inlet. The blood pressure and velocity appear to be uniformly and during peak systole and blood flow accelerates to its peak velocity.

Lastly at t/T=0.27, maximum pressure move further to the iliac bifurcation and the acceleration of the blood flow is decrease or it being decelerate. During this moment, flow separation occurs near the proximal neck.

2.4 FLOW DISTURBANCE WITHIN AAA MODEL

In the previous medical literature often found the studies of blood flow in model of arteries, veins and capillaries that are clearly discuss the differences of flow patterns between disturbed and undisturbed states. Researcher often thinks that if the flow patterns of disturbed states are always and completely turbulent. According to Helps and McDonald (cited by Milnor, 1989), they proposed the states of the initial phase to be justify as the flow is not completely laminar but in transition to turbulence. If we consider the constant flow rate in cylindrical pipe, the transition from laminar to turbulence will be considered as a wavy motion of the parallel streamlines.

The flow pattern that had been disturbed will be either two which is stable or unstable. The stable flow shall be categorize as the flow that can damp all the disturbances downstream and have the ability to go back to its initial state or recover from the initial transients produced by geometry irregularities and local perturbations. The unstable flow is characterized by the occurrence of the vortices and it propagates downstream.

The disturbed flow conditions will give the response to the vessel wall. The effect of velocity gradients on the endothelial lining of the thoracic aorta have been studied by Fry (1968). As the result, the estimation of an acute yield strength value (379 dynes/cm^2) for endothelial cells. For short period of time, cells being exposed to the high stress level that exceeds maximum yields stress and cells substance will face deformation, disintegration and ultimate erosion. The physical force that being generated from turbulent flow will give vibration to the arterial wall and making the artery more distensible at certain frequencies and causing histological changes in its elastin (Roach, 1972). In order to quantify the response of arterial wall at the cellular level, endothelial cell culture studies have been considered to be done.

Disturbed flow patterns at different level of spatial shear stress gradient have been found to trigger responses of the innermost layer of the tunica intima by altering intercellular communication mechanisms (Satcher et al., 1992; DePaola et al., 1992; Davies et al., 1995). High shear conditions are correlated with a prothrombotic response of the endothelium (Grabowski, 1995). High gradients of shear stress under steady flow conditions result in a twofold increase in cell motility of in-vitro human endothelial cell monolayers (Tardy et al., 1997).

2.5 EXPERIMENTAL AND NUMERICAL STUDIES OF STEADY AAA FLOW

According to Ender A. Finol (2001), many laboratory experiments and numerical studies of blood flow at constant flow rates in models of various aneurysm shapes and sizes are reported in the literature since the 1970s. The principal objective to this kind of studies normally is the visualization of the flow streamlines and stress estimation induced by the flow.

Experimental and numerical studies conducted by Budwig et al. (1993) demonstrate the effect of flow patterns in the distribution of pressure and the shear stress at the wall. In this study, the pressure distribution and shear stress is established then they show how the pattern of the blood flow influences the parameters. As the results, they reported that peak pressure of wall and highest shear stress occurred at the downstream end of the AAA model.

Steady flow is numerically simulated in the laminar regime over a wide range of Reynold numbers using uniform flow with thin boundary layers at the inlet, the results of which are validated with Particle Image Velocimetry (Yu et al., 2000; Yu, 2000). The parameter that is involved in this study is different Reynold numbers.

Flow visualization studies for steady flow in in-vitro spherical models of aneurysm resulted in the determination of streamlines patterns inside the bulge models (Scherer, 1973). This kind of studies has similarities with this study. It focused on finding the streamlines patterns in the aneurysm region but the only difference is it done experimentally.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

In Computational fluid dynamics, it was consisted by three part which is pre-processor, solver, and lastly post processor. This process were relevant with any simulation that using CFD as the instrument to solve problem. Generally, CFD actually predicting fluid behavior and what would happen based on real problem quantitatively. Figure 3.1 below showed the process in CFD.

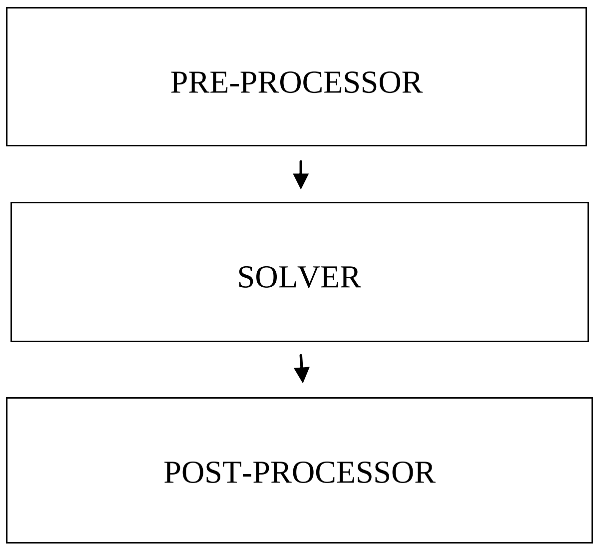

Figure 3.1: Flow in Computational Fluid Dynamic

3.2 SIMULATION ASSUMPTION AND PARAMETER

The simulation takes place in this study need assumption and parameter. It is assumed that blood is an incompressible, non-Newtonian fluid, the flow is laminar and isothermal at constant viscosity of 0.004 Kg/(ms). The wall was treated as no-slip condition. The parameter used in the simulation is listed in Table 3.1.

Table 3.1: Parameters in the simulation

Parameters	**Value**
Density	1.12 g/cm^3
Dynamic Viscosity	0.004 Pa s
Specific Heat	3631.38 J/KgK
Thermal Conductivity	0.3153 W/mK

3.3 GEOMETRY OF MODEL

The geometry of AAA model was referring to previous study from Anne Amblard, 2008 (Figure 3.3). The diameter of the normal aorta is 20 mm and the diameter of aneurysm is 60 mm. The average wall thickness is 1 mm and the dilation of the aneurysm is D/d=3. Length of the AAA model considers being 140 mm. The construction of modeling was completely done in CAD software package name SolidWork 2008. The geometry of the AAA was obtained from clinical data by CT scan imaging. The model is shown in figure 3.2.

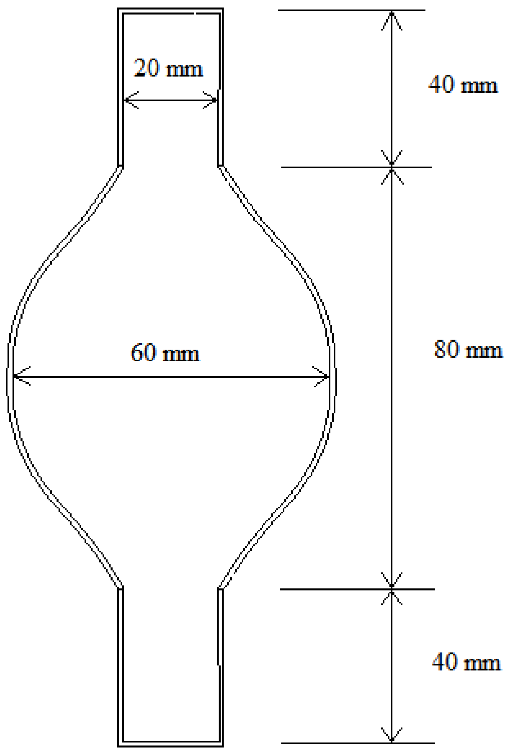

Figure 3.2: The geometry model of aneurysm

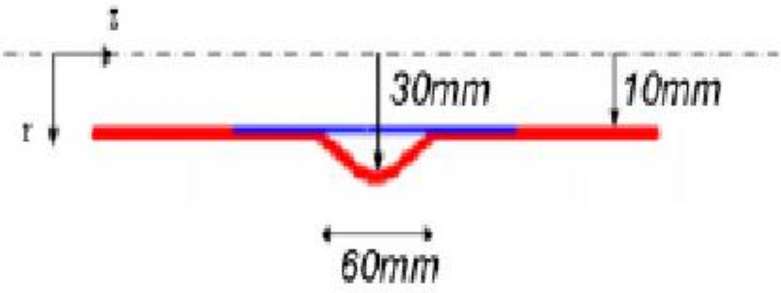

Figure 3.3: The model geometry taken from literature

Source: Anne Amblard, 2008

3.4 BOUNDARY CONDITION

After the construction of model geometry, the boundary condition of the analysis was stated. In this analysis, three main boundary conditions had been stated, which is first was the inlet velocity of the blood, static pressure and wall condition. The inlet velocity of blood flow when it enters the aneurismal region was considered as 1 m/s. The velocity of blood flow entering the aneurismal region actually was not constant and it varies with Reynolds number. The static pressure was considered as 16300 Pa. The pressure inside blood vessel was lesser than the pressure of the atmosphere. If not the blood vessel will failed or explode because it cannot withstand the differences in the pressure. Vascular wall in human body in was created by having elasticity characteristic. In real condition the structure of the vascular wall cannot be real wall that is fixed and not elastic because human body consists of flesh. Only bones have the hard and non elastic wall. That’s why the bulge of aorta occurs because the elasticity condition of vascular wall. Maybe the elasticity percentage and factor in the vascular wall of aneurysm region was decrease. In the simulation method, it was oppose with the real condition. We considered the boundary condition to be real wall or rigid because the consideration of elastic wall in this simulation was not possible. Real wall mean the wall not have the elastic properties or rigid. If the elasticity characteristic in vascular wall were to be considered, that studies can be proposed in PhD title. The elastic behavior of vascular wall can be simulating in that research. So for degree level, real wall is enough to be considered. The boundary condition was shown in figure 3.4.

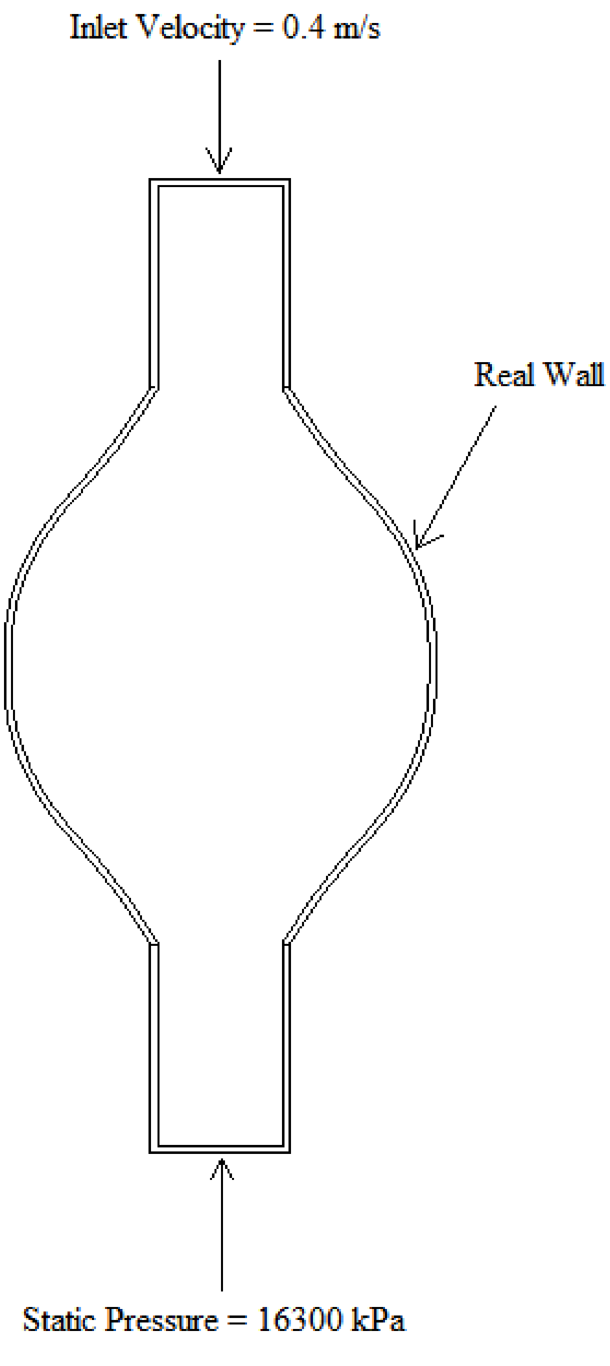

Figure 3.4: The boundary condition of AAA model

3.5 GOVERNING EQUATION OF BLOOD FLOW

In artery, blood flows are considered to be incompressible and it consist the continuity:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

Navier-Stokes equations:

$$\rho\left(\frac{\partial u_i}{\partial t} + u_j\frac{\partial u_i}{\partial x_j}\right) = -\frac{\partial P}{\partial x_j} + \mu\frac{\partial^2 u_i}{\partial x_j \partial x_j} + f_i \tag{2}$$

Where,

u_i= velocity in the i^{th} direction

P = Pressure

f_i =Body force

ρ =Density

μ_i =Viscosity

∂_{ij} =Kronecker delta

These governing equations are written for a computational domain Ώ.

At the wall of aneurysm, the shear stress will be calculated base on a function of velocity gradient only:

$$\tau = \mu\frac{\partial u}{\partial y} \tag{3}$$

The velocity gradient along aneurysm wall is ∂u/∂y taking consideration of fluid viscosity. With linear relationship, the simple viscous fluids will be considered. In terms of vorticity (ω), the equation of motion as follows:

$$\frac{\partial \omega}{\partial t} - \nabla\, X\, (V\, X\, \omega) = \frac{\mu}{\rho} \nabla^2 \omega \tag{4}$$

ω is vorticity, μ= viscosity with vector ∇^2V and ρ =Density. These equation solved by CFD software package namely COSMOSFloWorks 2008 in their finite volume form. The Navier-Stokes equations for 3D laminar flow were solved using finite volume based CFD solver.

3.6 FINITE VOLUME METHOD

In this project involved the studies only based on numerical approach. Computational fluid dynamic had been used as the tool in order to investigate the flow behavior inside aneurysm. The experimental approach was not to be considered because it not possible, even it was possible, the experimental setup was not uses the real blood vessel or real blood. In CFD, finite volume method was carried out to solve the equation and to simulate the blood flow.

Finite volume method is a method for representing and evaluating partial differential equations as algebraic equations [LeVeque, 2002; Toro, 1999]. There basic steps involved in the finite volume method that relevant to this project simulation. First, divide the computational domain into finite volumes or a number of control volumes also known as elements or cells. This can be called as grid generation. Next step was applying the conservation law to each finite volume or differential form of the governing equations would be integrated over each control volume. Computation of the flux across the boundary of each finite volume was required. Finally, the resulting system of equation would be solving by certain method. Figure 3.5 below show the solver in CFD software package namely COSMOSFloWorks. In this solver, the finite volume method was used.

3.7 VISUALIZATION OF SIMULATION

Last method in the simulation is to show the result of the simulation. It is called as post processor. In order to show the output of the simulation, the flow in the AAA model must be visualize. From this step, it's the only way to analyze the blood flow behavior in the AAA model. This step was more about how to convert the calculated data into the understanding visual or readable image. The important aspect to visualize the result of the simulation was to analyze, discuss and conclude the simulation that had been done. Besides that, the result shown was important to validate it with the previous literature whether it had some similarity or not. Post processor not only consists of flow streamlines, it was also consisting of graph, flow trajectories, animation and others. Figure 3.6 below show the result of the simulation in AAA model of this project.

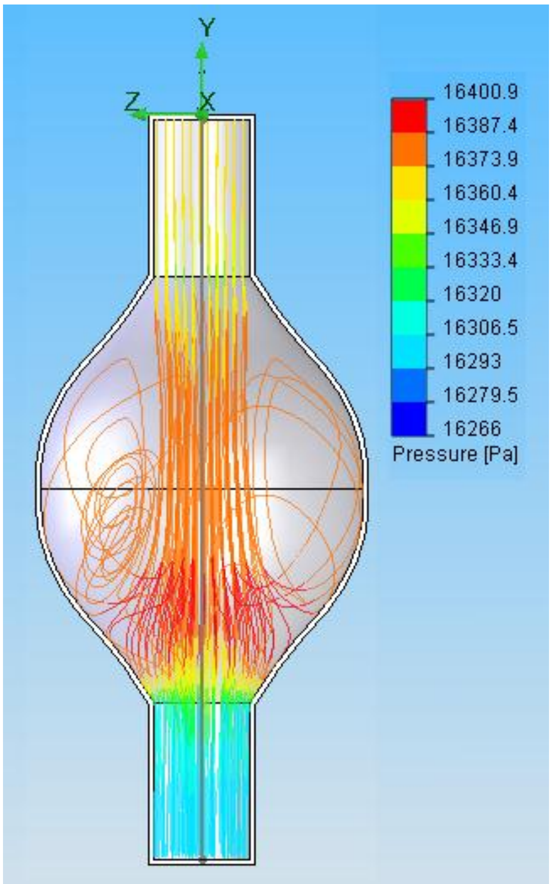

Figure 3.5: Visualization of blood flow streamlines in AAA model.

CHAPTER 4

RESULT AND DISCUSSION

4.1 INTRODUCTION

Computational fluid dynamics simulations using the finite volume method have been applied to access the flow behavior inside abdominal aortic aneurysm and the result was the pressure and velocity changes in aneurysm. The distribution of the pressure and velocity inside aneurysm was obtained as the main result of the simulation. In the aneurysm region, the pressure and velocity were not constant according to velocity changes in the aneurysm region.

In this study, it was proven that the blood flow inside the aneurysm will face disturbances due to the pressure and velocity changes. This can be proved by the obtained graph from the simulation. From the graph of pressure versus length and velocity versus length of AAA, the analysis and discussion could be done. The formation of vortex also was shown in this simulation. The resulted simulation streamlines clearly shown that when the blood entering the aneurysm region; the velocity was begun to slow until the formation of the vortex.

From the simulation the result can be obtain as in visualization of the flow. Figure 4.1 shows pressure distribution of the blood flow in abdominal aortic aneurysm and Figure 4.2 shows the velocity profile before the blood is entering the aneurysm region and until it leaves the region. The different pressure distribute from the highest one to the lowest one. This result is very important because it shows the behavior of blood flow in aneurysm region.

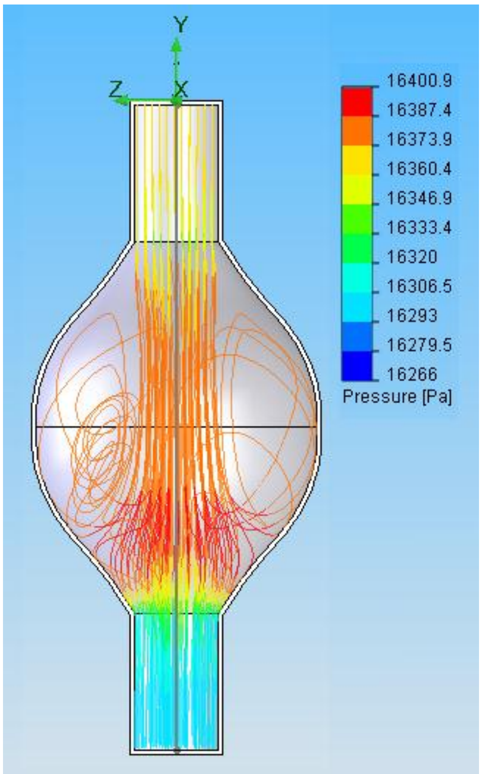

Figure 4.1: Pressure distribution in the aneurysm

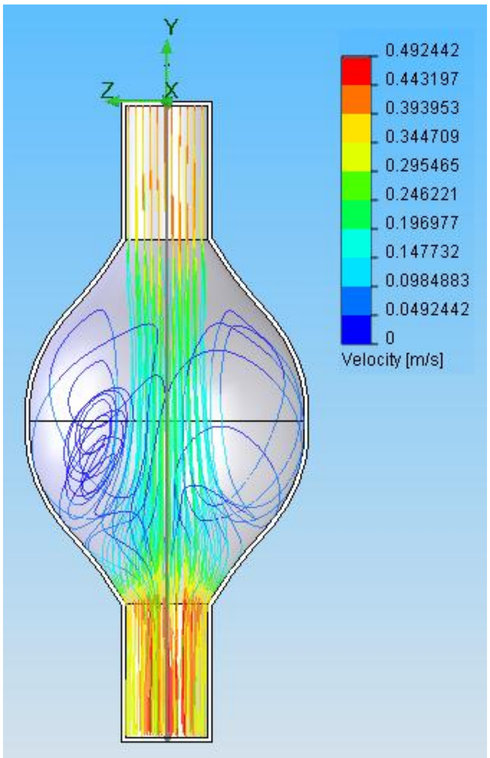

Figure 4.2: Velocity profile in the aneurysm

4.2 BEHAVIOUR OF FLOW WITH DIFFERENT INITIAL VELOCITY AND AORTA DIAMETER

The simulation is taken place by different initial velocity of blood into the aneurysm. The initial velocity is varies between 0.4 m/s until 0.8 m/s as shown in table 4.1. Beside that the aorta diameter also to be considered differently that varies between 0.018 m until 0.020 m as shown in table 4.1. This result obtains from the calculation using formula of Reynold Number. The consideration of different value of initial velocity and diameter of aorta is purposely be done because to find the Reynold Number. This value of Reynold Number that been obtain can shows us the strength of the vortex formation in the aneurysm region. As we know the higher value of Reynold Number tells us that it can lead to the formation of the high amount of vortices in the aneurysm region that is not very good to the blood vessel wall condition.

Table 4.1: Varies initial velocity of blood and aorta diameter that produce certain Reynold Number

Initial velocity (m/s)	Aorta diameter (m)	Reynold number
0.4		2385
0.5		2981
0.6	0.018	3578
0.7		4174
0.8		4770
0.4		2518
0.5		3147
0.6	0.019	3776
0.7		4406
0.8		5035
0.4		2650
0.5		3313
0.6	0.020	3975
0.7		4638
0.8		5300

4.3 PRESSURE DISTRIBUTION

The result that been obtain from the first simulation can be analyze with further specific analysis using different initial velocity. As in table 4.1, different initial velocities are being chosen to investigate the differences between it. So, the results from the simulation using different initial velocities can be shown in figure 4.3, 4.4 and 4.5.

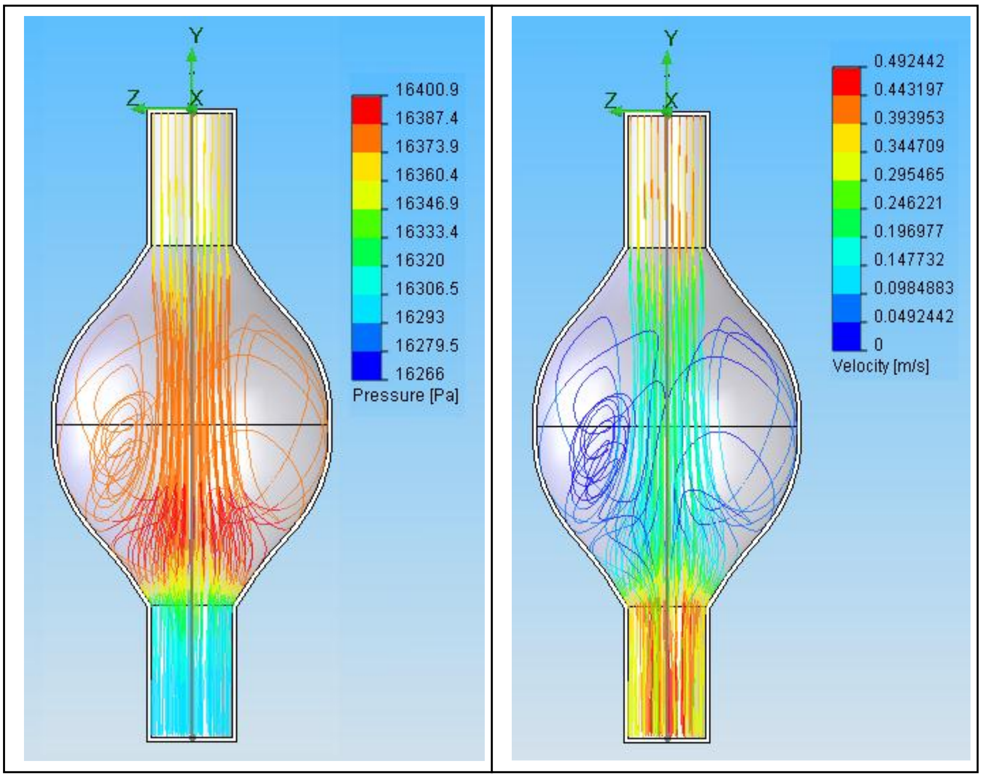

Figure 4.3: Pressure distribution and velocity profile in the AAA using inlet velocity 0.4 m/s

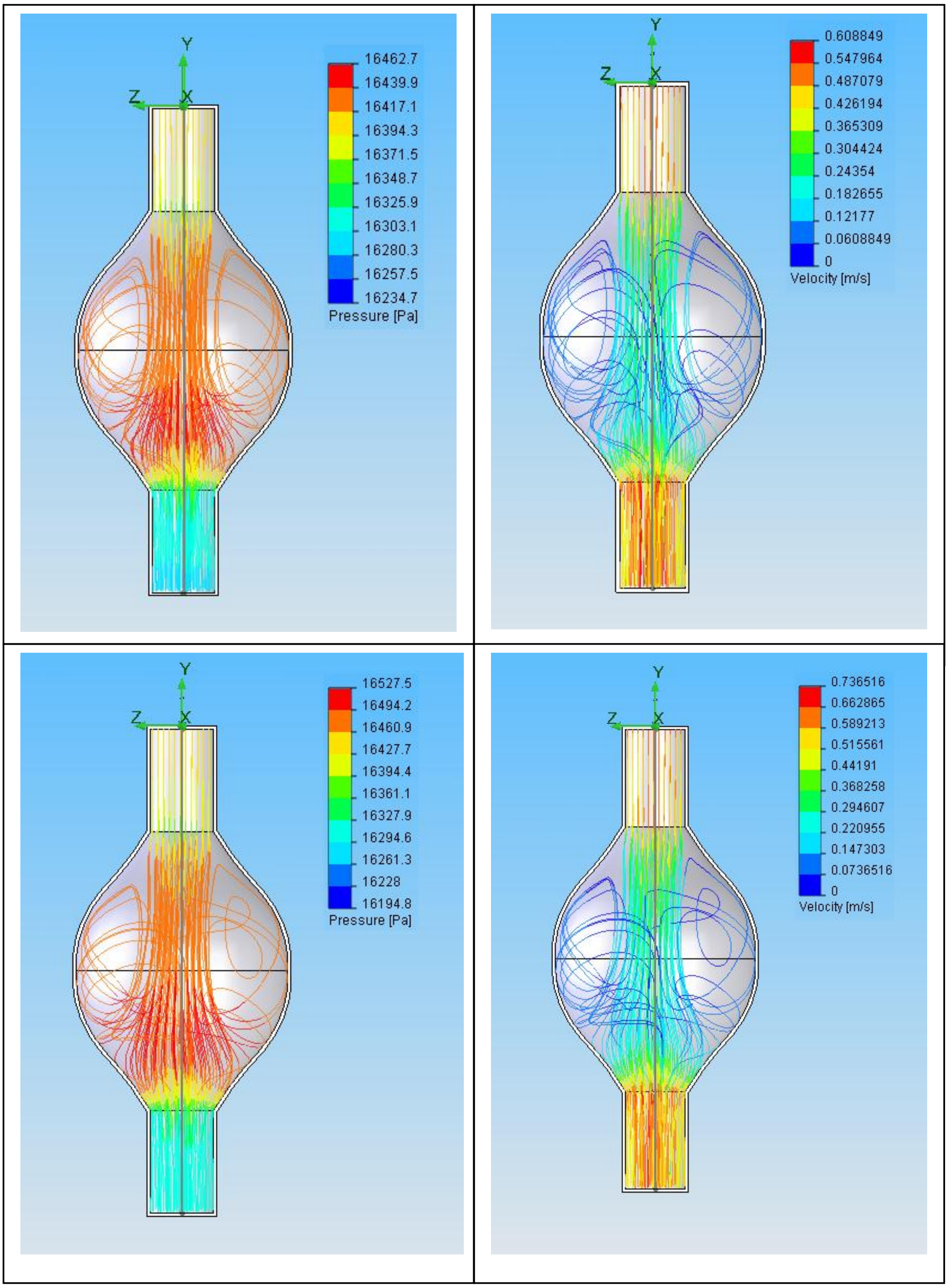

Figure 4.4: Pressure distribution and velocity profile in the AAA using inlet velocity 0.5 and 0.6 m/s

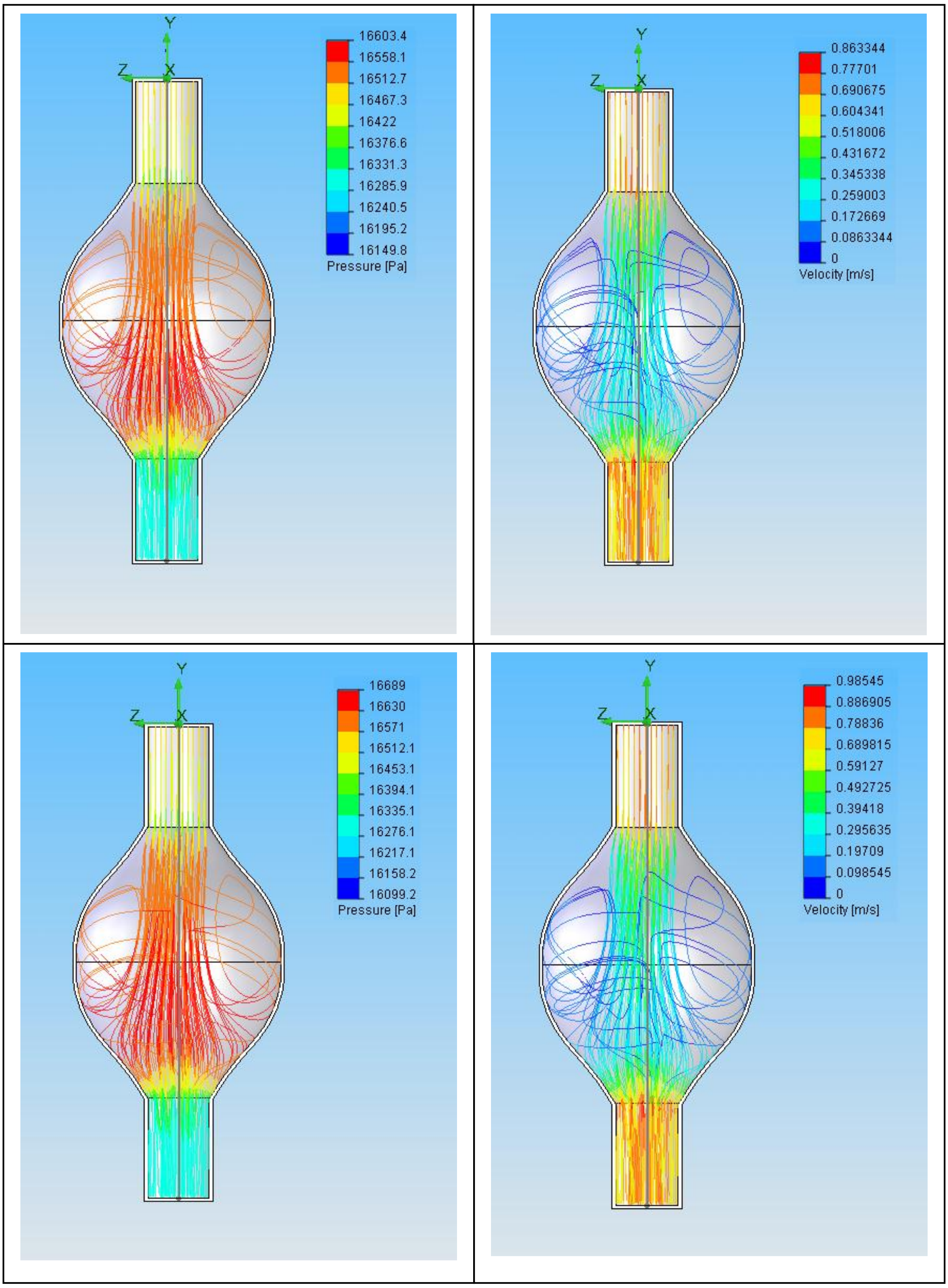

Figure 4.5: Pressure distribution and velocity profile in the AAA using inlet velocity 0.7 and 0.8 m/s

The result above is obtained from the simulation. For further analysis, the graph of pressure and velocity versus length has been constructed as in figure 4.5. In this simulation, different inlet velocity has been taken into consideration because we want to analyze pressure distribution among it. As we can see in the figure 4.5, the pattern of the series is same but the value of the pressure is different among each others.

The data of pressure and velocity can be obtained from the simulation. From this data we can find the correlation that possible for pressure distribution and velocity profile. As in table 4.2, the correlation between various inlet velocity and peak pressure can be establish. When the inlet velocity is increases, peak pressure in the aneurysm region also increase. The correlation can be said that the inlet velocity of blood is directly proportional to the peak pressure in the aneurysm region.

Table 4.2: Peak Pressure for different inlet velocity

No	Inlet Velocity (m/s)	Peak Pressure (Pa)
1	0.4	16381
2	0.5	16430
3	0.6	16486
4	0.7	16552
5	0.8	16627

Pressure distribution in AAA can be shown in figure 4.6. This graph shows the pressure distribution with different inlet velocity. The velocities that had been choose is 0.4, 0.5, 0.6, 0.7 and 0.8 m/s. The lowest and highest inlet velocity is 0.4 and 0.8 respectively. Peak pressure also can be seen in the graph. Each inlet velocity has different peak pressure. For velocity that is equal to 0.8 m/s, the peak pressure happens to be 16628 Pa, but at 0.4 m/s the peak pressure is lower that is 16382 Pa. The length of the bulge region is start at 0.04 until 0.12 m. The pressure steadily increases when the blood starting to enter the bulge region at length between 0.02 until 0.04 m, but when it finally enter the bulge region the pressure become constant at its peak value. The pressure decreases steadily when the blood flowing out from the bulge region to the normal aorta.

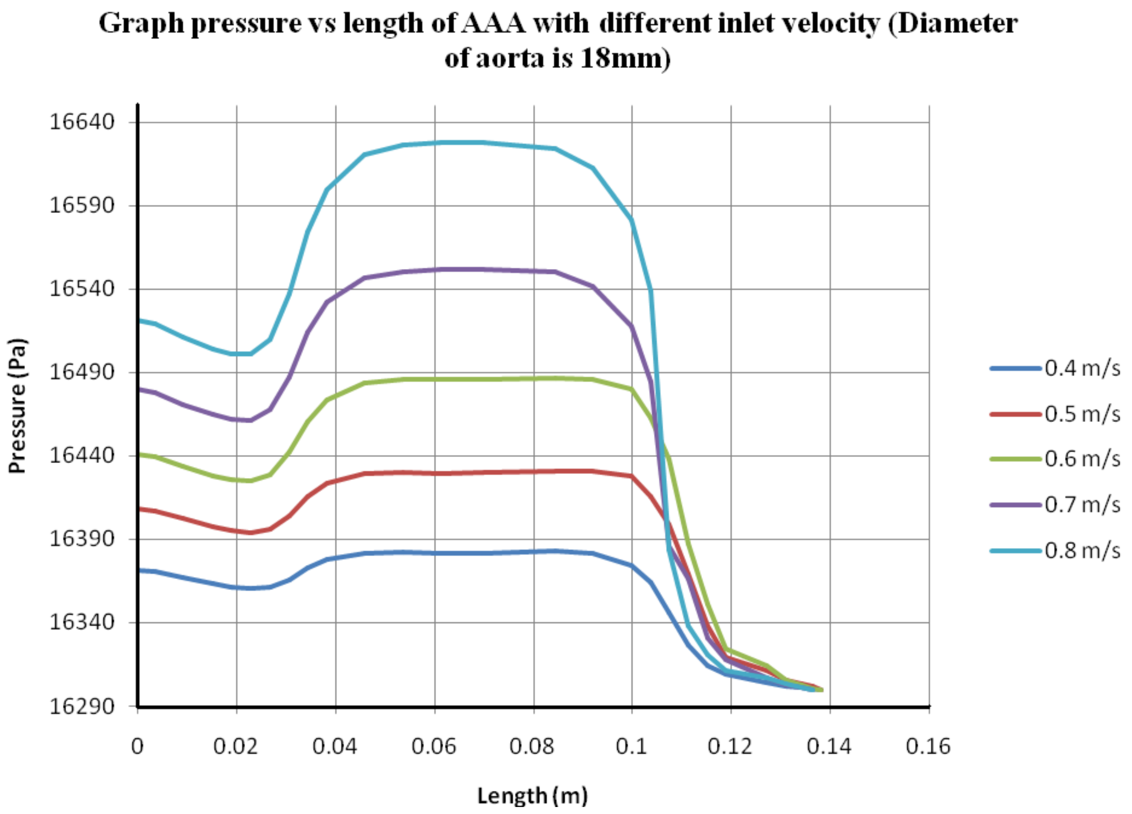

Figure 4.6: Pressure distribution in AAA with different inlet velocity

The other parameter that involved in this study is diameter of aorta. Beside considering different value of inlet velocity, different diameter of aorta also be considered to find the pressure distribution. Different diameter of aorta contribute to different value of peak pressure as show in table 4.3. There are three different diameter of aorta are being considered that is 0.018, 0.019 and 0.020 m. The correlation that can be establish is, bigger diameter of aorta cause lower value of peak pressure in the aneurysm region. Lowest value and highest value of peak pressure is 16373 Pa and 16382 Pa respectively. Graph pressure versus length of AAA with different diameter of aorta can be plotted as in figure 4.7. Blue, red and green lines represent the diameter of aorta that is 0.018, 0.019 and 0.020 m respectively. Like the previous graph, the pressure starts to increase when the flow entering the the aneurysm region at length 0.02 until 0.04 m. Inside the aneurysm region or the bulge region, the peak pressure is constant for each cases until the pressure decrease back when the blood flowing out from the aneurysm to the normal aorta at length 0.10 until 0.12 m.

Table 4.3: Peak Pressure for different diameter of aorta

No	Diameter of Aorta (m)	Peak Pressure (Pa)
1	0.018	16382
2	0.019	16378
3	0.020	16373

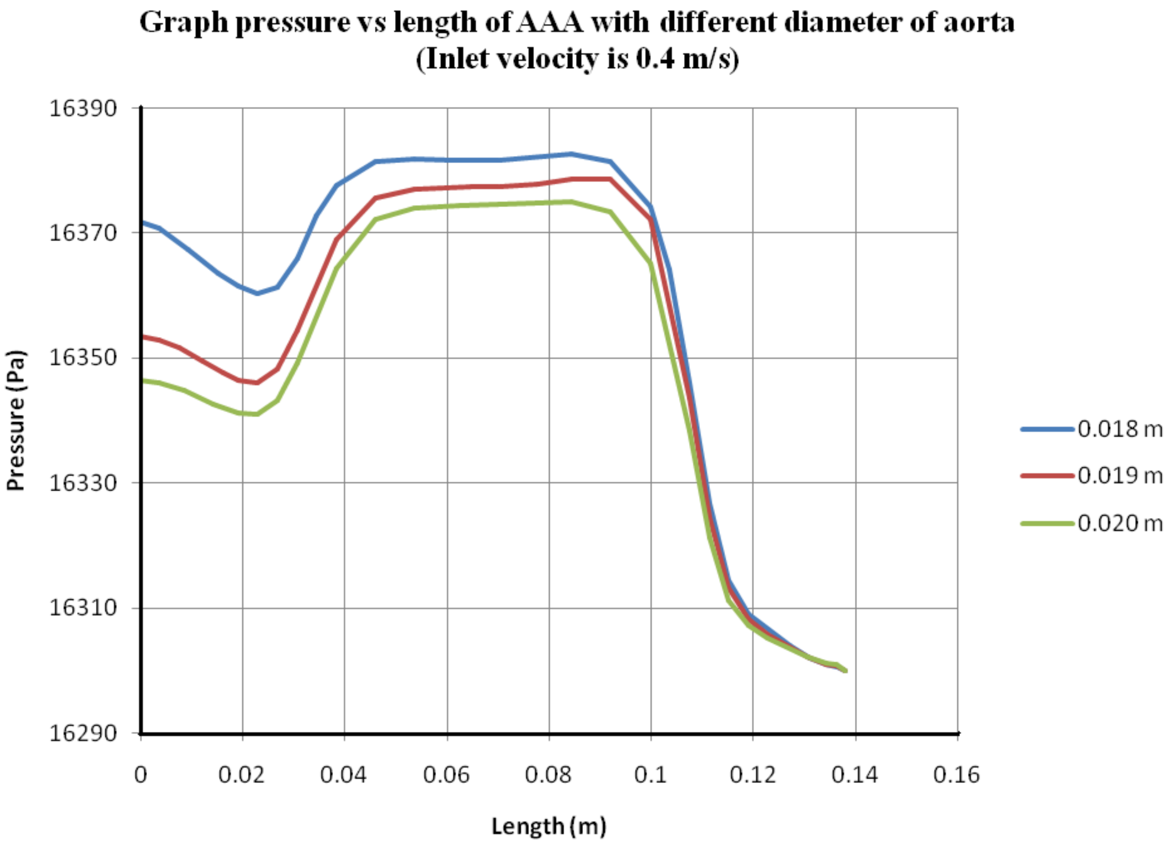

Figure 4.7: Pressure distribution in AAA with different diameter of aorta

4.4 VELOCITY PROFILE

Velocity profile in AAA with five different inlet velocities can be shown in figure 4.8. Each case gives different value of velocities but has the same pattern among the each different inlet velocities. The values of velocity not same except the minimum one that lies in the aneurysm region is exactly same that is about 0.2 m/s. This means that the velocity of the blood will decrease dramatically when it enter the aneurysm region where the formation of vortex will be existed. Aneurysm region or bulge region is start at length 0.04 m. As in the graph, at the point before entering the bulge, velocity increase a little bit and then it decrease dramatically until the lowest velocity that lies in the most largest diameter of aneurysm. Largest diameter of aneurysm that is 0.060 m located at the middle of AAA geometry that is 0.08 m.

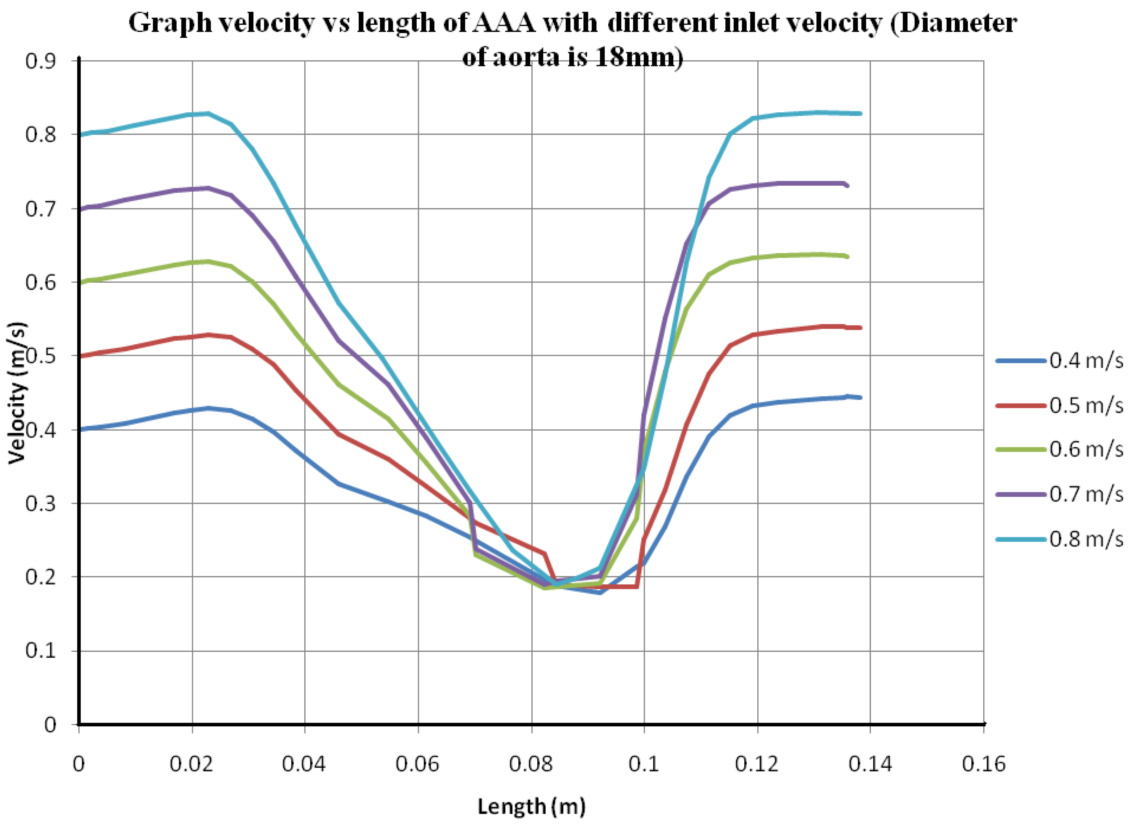

Figure 4.8: Velocity profile in AAA with different inlet velocity

Table 4.4: Percentage of velocity drop with different value of inlet velocity

No	Inlet Velocity (m/s)	Min Velocity (m/s)	Velocity Band Width (m/s)	Percentage of velocity drop (%)
1	0.4	0.2	0.2	50.0
2	0.5	0.2	0.3	60.0
3	0.6	0.2	0.4	66.7
4	0.7	0.2	0.5	71.4
5	0.8	0.2	0.6	75.0

From the analysis of graph velocity versus length of AAA with different inlet velocity as in figure 4.8, the importance correlation can be establish as shown in table 4.4. This table summarized the correlation between inlet velocity and the percentage of velocity drop. Low inlet velocity cause lower percentage of velocity drop in the aneurysm region that is only 50 percent but high value of inlet velocity cause higher percentage of velocity drop that is 75 percent.

Velocity profile for different diameter of aorta can be shown in figure 4.9 that the inlet velocity is set to be 0.4 m/s. Three colored line blue, red and green is represented as diameter of aorta that is 0.018, 0.019 and 0.020 m respectively. The observation can be made is minimum velocity for each cases are differ. Smallest diameter of aorta gives lowest value of velocity in the aneurysm region that is 0.17 m/s. Oppositely largest diameter of aorta gives highest velocity that is happen to be 0.25 m/s. To summarize the correlation between the velocity and the diameter of aorta, table 4.5 and 4.6 is being established. In table 4.5, there is velocity band width of each cases of different diameter of aorta. Diameter of aorta also influence the velocity drops in the aneurysm region. Refer to the table 4.6; small diameter of aorta gives much more velocity drop that is 57.5 percent than larger diameter of aorta that gives lower velocity drop that is 37.5 percent. The correlation can be simply said as when the diameter if aorta increase, the pressure drop will be decrease. The correlation also showed in figure 4.10 and 4.11 that is graph velocity band width versus diameter of aorta and graph percentages of changes versus diameter of aorta respectively.

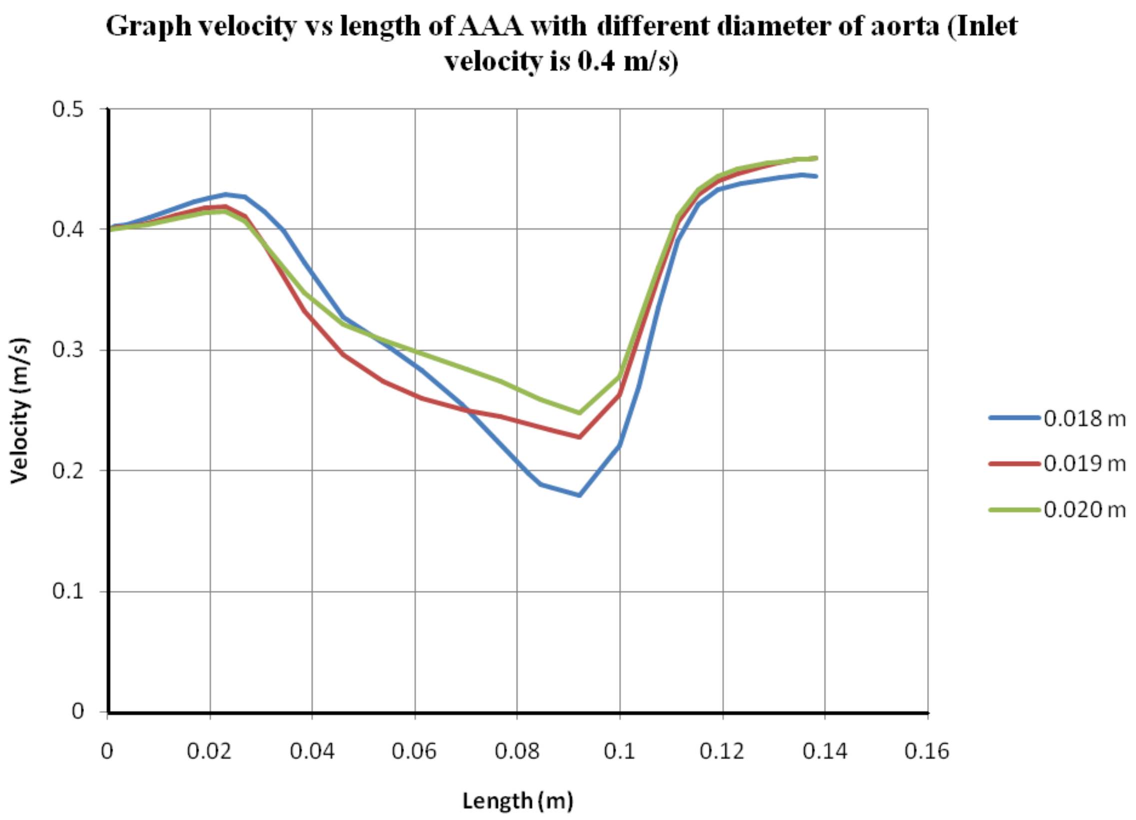

Figure 4.9: Velocity profile in AAA with different diameter of aorta

Table 4.5: Minimum Velocity for different diameter of aorta

No	Diameter of Aorta (m)	Inlet Velocity (m/s)	Min Velocity (m/s)	Velocity Band Width (m/s)
1	0.018	0.4	0.17	0.23
2	0.019	0.4	0.21	0.19
3	0.020	0.4	0.25	0.15

Table 4.6: Percentage of velocity drop for different diameter of aorta

No	Diameter of Aorta (m)	Percentage of velocity drop (%)
1	0.018	57.5
2	0.019	47.5
3	0.020	37.5

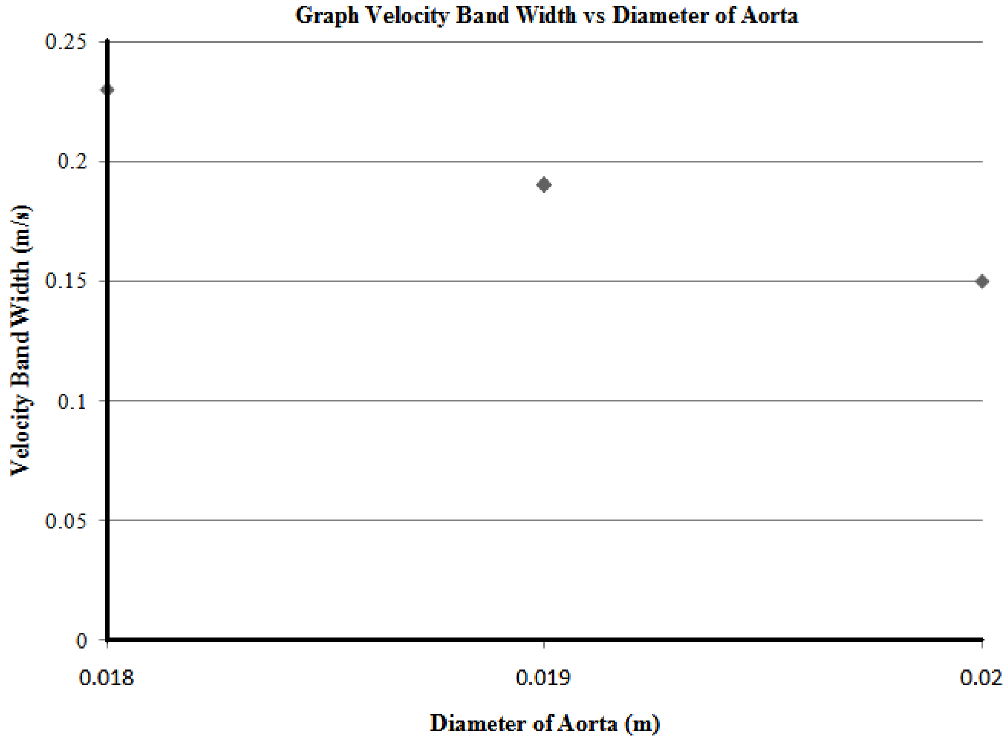

Figure 4.10: Velocity Band Width for different diameter of aorta

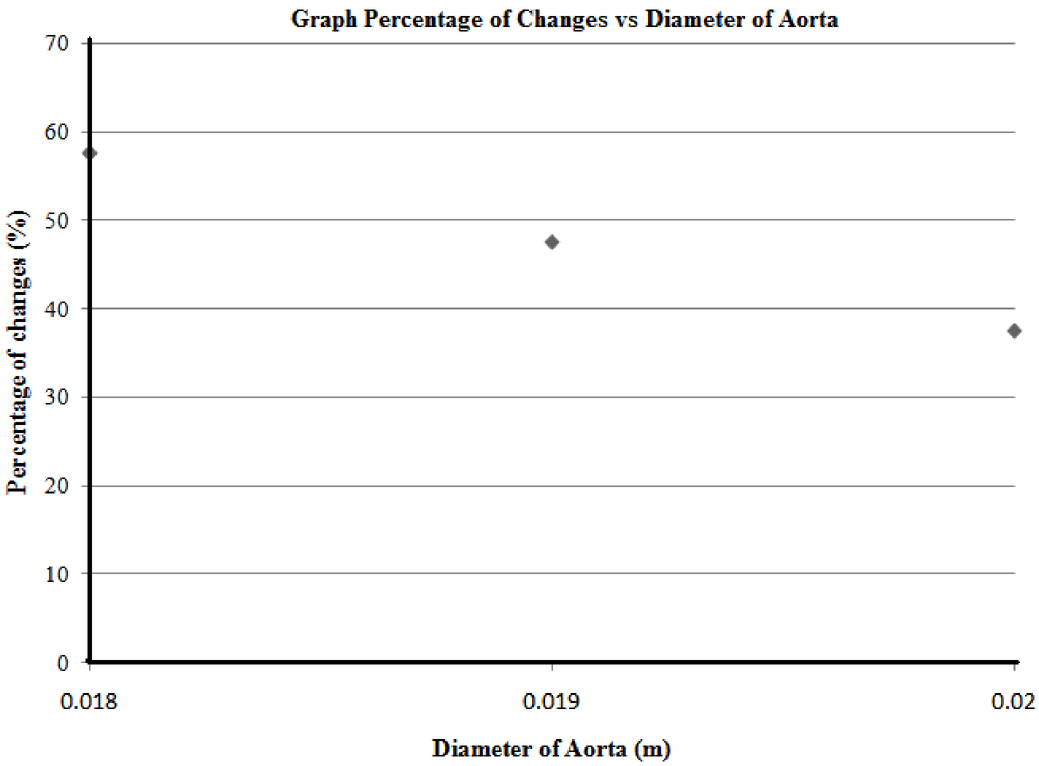

Figure 4.11: Percentage of velocity drop for different diameter of aorta

Finally, to summarize the result obtain in the simulation, the correlation that relevance in the pressure distribution and velocity profile can be shown in table 4.7 and 4.8 respectively. In table 4.7, the correlation obtain is when the inlet velocity is increase, the peak pressure also will be increase and when the diameter of aorta is increase, oppositely the peak pressure will be decrease. In table 4.8, when the inlet velocity is increase, the percentage of pressure drop also will be increase and when the diameter of aorta is increase, oppositely the percentage of velocity drop will be decrease.

Table 4.7: Correlation obtained in the pressure distribution

Parameters	Peak Pressure
Increase in inlet velocity	Increase
Increase in diameter of aorta	Decrease

Table 4.8: Correlation obtained in the velocity profile

Parameters	Percentage of velocity drop
Increase in inlet velocity	Increase
Increase in diameter of aorta	Decrease

4.5 VORTEX FORMATION

Vortex is spiral motion, rapidly rotating or spinning flow of fluid within a limited area. The rate and speed of the rotation were great at the center and it is decrease with the distance from the center. From the result obtained from the simulation, it was clear that when the changes in pressure and velocity existed in aneurysm region, the vortex formation occurred. Vortex often turbulent, but in this project, the flow of vortex suppose to be transition from laminar to turbulent.

The existent of vortex needed to be studied because it can lead to the vibration and high shear force towards aneurysm wall. The blood will collide with the aneurysm wall and give the force to it. If this continuously happen, it can lead to rupture of the aneurysm wall because it cannot withstand such a pressure and force. The effect of Reynolds number to the vortex strength must be investigate in future work in order to find whether high Reynolds number can cause more vortex strength or not. If the amount of vortex is high, further studies must carry out to find whether it can cause the probability of rupture to be low or high.

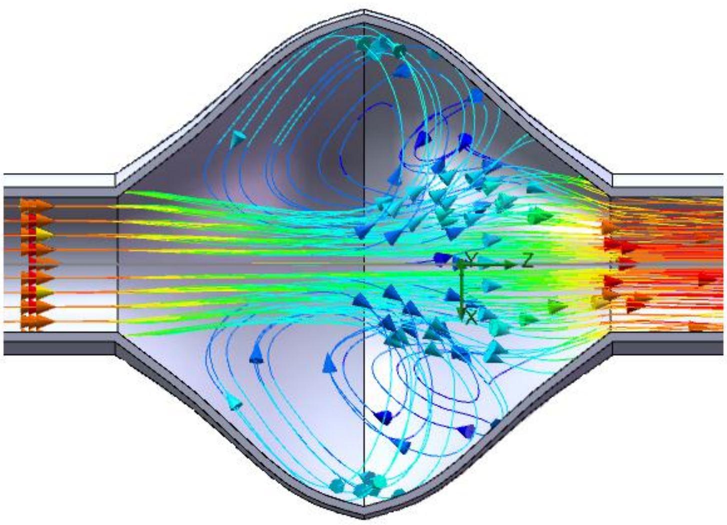

Figure 4.12: The vortex formation within aneurysm region

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

This study provides pressure distribution and velocity profile of blood flow in abdominal aortic aneurysm by numerical approach using computational fluid dynamic simulation. The data obtain from the simulation will be analyze to find the relevance correlation. For pressure distribution, if inlet velocity before entering aneurysm increase, peak pressure also will be increase. Highest inlet velocity stated is 0.8 m/s and this will cause the peak pressure value to be 16627 Pa. This mean increasing in peak velocity showing the flow will be more disturb. It will be opposite compare to the diameter of aorta. If the diameter of aorta is increase, oppositely peak pressure will decrease. The largest diameter of aorta stated is 0.02 m and this will cause peak pressure became 16373 Pa. It means larger diameter of the aorta contribute to more stable flow.

The correlation for velocity profile also can be established. For velocity profile, amount of velocity drop are measured. By putting the highest inlet velocity equal to 0.8 m/s, the percentage of velocity drop became 75 percent. Minimum velocity that occurred inside aneurysm region is 0.2 m/s. If inlet velocity before entering aneurysm is increase, velocity bandwidth also will be increase. It means higher inlet velocity causing to more velocity drop. But if diameter of aorta is increase, oppositely velocity bandwidth will be decrease. Suppose largest diameter of aorta is 0.02 m, it result lowest percentage of velocity drop that is 37.5 percent. It is same as pressure distribution, larger diameter of aorta contribute to more stable flow.

5.2 RECOMMENDATIONS

In order improve the investigation of the flow behavior inside abdominal aortic aneurysm, some recommendation will be introduce as below:

1. Repeat the simulation by using different geometry of aneurysm. Diameter of aneurysm will be one of the parameter that been changes to find the correlation between it and the peak pressure or velocity drop.
2. Analyze the formation of the vortex. What causing it and investigate the correlation between the amount of vortex and the peak pressure or velocity drop.
3. Simulate the flow by using other software that has more percentage of accuracy.

Different geometry of aneurysm is important to investigate the flow pattern in AAA because every patient has different shapes and geometry of the aneurysm according to the seriousness of the disease. That's why the further investigation by using different geometry of aneurysm is important. Diameter of aneurysm can be decided as the parameter involved in the study.

The formations of vortex not only being observed but it also must be analyze numerically and come out with measurable data. The vortex strength must be established to find the correlation that is relevance. Researchers must investigate the cause of these phenomena and find the correlation between the aneurysm sizes and the amount of vortex.

The simulation also can be done in other software that is more accurate and give better results. This is also important because higher percent of accuracy will give better and clearer understanding beside it also will gives more realistic condition.

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APPENDICES

PRESSURE VS LENGTH DATA FOR VARIOUS INLET VELOCITIES

Length (m)	Pressure (Pa)	
	Inlet Velocity =0.4 m/s	Inlet Velocity =0.5 m/s
0	16371.75424	16408.03528
0.003701956	16370.74024	16406.77789
0.009188055	16367.31395	16402.49819
0.015223912	16363.42772	16397.2636
0.019064912	16361.4254	16395.19051
0.022905912	16360.32552	16394.12819
0.026746912	16361.24867	16396.19356
0.030587912	16365.88949	16404.22529
0.034428912	16372.79627	16415.60949
0.038269912	16377.66951	16423.42146
0.045951912	16381.40053	16429.47398
0.053633912	16381.91572	16430.27241
0.061315912	16381.57908	16429.67685
0.07009713	16381.70255	16430.01195
0.084361912	16382.63981	16430.85537
0.092043912	16381.5051	16431.09876
0.099725912	16374.16812	16428.1544
0.103566912	16364.19249	16415.64158
0.107407912	16346.11024	16398.87368
0.111248912	16326.70953	16369.13916
0.115089912	16314.35464	16338.31362
0.118930912	16309.05072	16319.22988
0.127161626	16303.94432	16311.37944
0.131094252	16302.03447	16305.61981
0.134295956	16300.87865	16303.66684
0.136518382	16300.5062	16302.01084
0.138	16300	16300

Length (m)	Pressure (Pa)		
	Inlet Velocity =0.6 m/s	Inlet Velocity =0.7 m/s	Inlet Velocity =0.8 m/s
0	16441.02165	16479.82115	16521.29962
0.003701956	16439.51091	16478.05145	16519.26825
0.009188055	16433.80011	16470.73679	16510.88653
0.015223912	16428.01295	16464.5886	16503.77833
0.019064912	16425.6247	16461.89196	16500.71914
0.022905912	16424.88838	16461.558	16500.93416
0.026746912	16428.92405	16467.82004	16510.09503
0.030587912	16442.28987	16487.32405	16537.13929
0.034428912	16460.74441	16513.86863	16573.90005
0.038269912	16473.38292	16532.05292	16599.45626
0.045951912	16483.42396	16547.05521	16620.79926
0.053633912	16485.51954	16550.62442	16626.20475
0.061315912	16485.85681	16551.63098	16627.56353
0.07009713	16486.07251	16552.03421	16627.65092
0.084361912	16486.6075	16550.10805	16624.22347
0.092043912	16485.73819	16541.46115	16612.31246
0.099725912	16480.07881	16517.45863	16581.78539
0.103566912	16462.3776	16484.52808	16538.64379
0.107407912	16438.17225	16385.97995	16383.62364
0.111248912	16387.67273	16366.15324	16337.83556
0.115089912	16351.0465	16330.78075	16320.59629
0.118930912	16324.38123	16317.58831	16311.32836
0.127161626	16313.91083	16306.58078	16306.86731
0.131094252	16305.78234	16302.84449	16303.49712
0.134295956	16302.25146	16300.79551	16301.13514
0.136518382	16300.56827	16300	16300
0.138	16300		

VELOCITY VS LENGTH DATA FOR VARIOUS INLET VELOCITIES

Length (m)	Velocity (m/s)	
	Inlet Velocity =0.4 m/s	Inlet Velocity =0.5 m/s
0	0.4	0.5
0.001480783	0.402528535	0.502501243
0.003701956	0.403818905	0.504575838
0.008090627	0.409383314	0.510311005
0.016870055	0.422795136	0.523768274
0.019613627	0.426321695	0.526512903
0.022905912	0.429217631	0.529270374
0.026746912	0.426698527	0.525536964
0.030587912	0.415190425	0.510636507
0.034428912	0.398266869	0.488442745
0.038269912	0.372214397	0.454189481
0.045951912	0.327270674	0.394007814
0.054731341	0.302635163	0.36115974
0.061315912	0.282797919	0.323791854
0.069	0.255235115	0.280640213
0.07009713	0.250398142	0.273693094
0.082167055	0.197652718	0.232025929
0.084361912	0.188173993	0.190885358
0.092043912	0.179375206	0.187949406
0.098628484	0.214185225	0.18747454
0.099725912	0.220134671	0.25129282
0.103566912	0.269514704	0.319123011
0.107407912	0.335777801	0.406449134
0.111248912	0.390459472	0.476495422
0.115089912	0.420692043	0.514131153
0.118930912	0.433074439	0.529133906
0.123320627	0.438090466	0.534254109
0.131094252	0.443136024	0.54041843
0.135036764	0.444738908	0.540619064
0.135777573	0.444857619	0.539214305
0.138	0.443962093	0.538177074

Length (m)	Velocity (m/s)		
	Inlet Velocity =0.6 m/s	Inlet Velocity =0.7 m/s	Inlet Velocity =0.8 m/s
0	0.6	0.7	0.8
0.001480783	0.603183966	0.703173917	0.803180076
0.003701956	0.604580213	0.704562675	0.805362517
0.008090627	0.610413496	0.711390896	0.812428389
0.016870055	0.624231387	0.725477635	0.82775055
0.019613627	0.626825062	0.727234786	0.828591144
0.022905912	0.628727064	0.728556126	0.815259744
0.026746912	0.621792886	0.718716068	0.780793713
0.030587912	0.600642737	0.692012854	0.734753348
0.034428912	0.570968372	0.656077829	0.67670373
0.038269912	0.530768652	0.607246124	0.57321975
0.045951912	0.460945986	0.520650696	0.496481372
0.054731341	0.41442316	0.461665217	0.382028582
0.061315912	0.356526271	0.390177924	0.317260813
0.069	0.283424703	0.301995106	0.305804976
0.07009713	0.229996215	0.238864728	0.237365711
0.082167055	0.18622678	0.190209145	0.189725743
0.084361912	0.187959318	0.194653642	0.199300875
0.092043912	0.191962697	0.202077109	0.212783979
0.098628484	0.28106761	0.312531135	0.348147341
0.099725912	0.370080989	0.419762862	0.474426928
0.103566912	0.480037086	0.551349327	0.626966252
0.107407912	0.56512074	0.653205505	0.742445157
0.111248912	0.610182691	0.706568146	0.801469998
0.115089912	0.627521977	0.726343871	0.823160713
0.118930912	0.632862949	0.731852643	0.828268997
0.123320627	0.637354143	0.73480417	0.831055207
0.131094252	0.63787354	0.734969219	0.829920498
0.135036764	0.636209893	0.734169835	
0.135777573	0.635003589	0.730576447	
0.138			

PRESSURE VS LENGTH FOR VARIOUS AORTA DIAMETERS

Length (m)	Pressure (Pa)
	Aorta Diameter =0.018 m
0	16371.75424
0.003701956	16370.74024
0.009188055	16367.31395
0.015223912	16363.42772
0.019064912	16361.4254
0.022905912	16360.32552
0.026746912	16361.24867
0.030587912	16365.88949
0.034428912	16372.79627
0.038269912	16377.66951
0.045951912	16381.40053
0.053633912	16381.91572
0.061315912	16381.57908
0.07009713	16381.70255
0.084361912	16382.63981
0.092043912	16381.5051
0.099725912	16374.16812
0.103566912	16364.19249
0.107407912	16346.11024
0.111248912	16326.70953
0.115089912	16314.35464
0.118930912	16309.05072
0.127161626	16303.94432
0.131094252	16302.03447
0.134295956	16300.87865
0.136518382	16300.5062
0.138	16300

Length (m)	Pressure (Pa)
	Aorta Diameter =0.019 m
0	16353.42923
0.003701956	16352.89363
0.007541912	16351.6255
0.012343162	16349.47216
0.016184162	16347.61546
0.019064912	16346.3714
0.022905912	16345.99583
0.026746912	16348.1713
0.030587912	16354.46318
0.038269912	16368.96172
0.045951912	16375.66646
0.053633912	16377.03003
0.064608198	16377.34355
0.07009713	16377.41415
0.077777341	16377.8184
0.084361912	16378.55546
0.092043912	16378.67701
0.099725912	16372.22539
0.107407912	16343.62322
0.111248912	16324.51665
0.115089912	16313.24265
0.118930912	16308.21458
0.122771912	16305.7854
0.130453912	16302.16842
0.134295956	16300.97387
0.136147977	16300.7481
0.138	16300

Length (m)	Pressure (Pa)
	Aorta Diameter =0.019 m
0	16346.46487
0.003701956	16346.04369
0.008502162	16344.74077
0.014263662	16342.66964
0.019064912	16341.09952
0.022905912	16340.99327
0.026746912	16343.14745
0.030587912	16349.24715
0.038269912	16364.24995
0.045951912	16372.09984
0.053633912	16373.96991
0.062413341	16374.45566
0.07009713	16374.54596
0.084361912	16374.92758
0.092043912	16373.30256
0.099725912	16365.0706
0.107407912	16338.37999
0.111248912	16321.17665
0.115089912	16311.15096
0.118930912	16307.0895
0.122771912	16305.16775
0.130453912	16302.24636
0.134295956	16301.10683
0.136147977	16300.88189
0.138	16300

VELOCITY VS LENGTH FOR VARIOUS AORTA DIAMETERS

Length (m)	Velocity (m/s)
	Aorta Diameter =0.018 m
0	0.4
0.001480783	0.402528535
0.003701956	0.403818905
0.008090627	0.409383314
0.016870055	0.422795136
0.019613627	0.426321695
0.022905912	0.429217631
0.026746912	0.426698527
0.030587912	0.415190425
0.034428912	0.398266869
0.038269912	0.372214397
0.045951912	0.327270674
0.054731341	0.302635163
0.061315912	0.282797919
0.069	0.255235115
0.07009713	0.250398142
0.082167055	0.197652718
0.084361912	0.188173993
0.092043912	0.179375206
0.098628484	0.214185225
0.099725912	0.220134671
0.103566912	0.269514704
0.107407912	0.335777801
0.111248912	0.390459472
0.115089912	0.420692043
0.118930912	0.433074439
0.123320627	0.438090466
0.131094252	0.443136024
0.135036764	0.444738908
0.135777573	0.444857619
0.138	0.443962093

Length (m)	Velocity (m/s)
	Aorta Diameter =0.019 m
0	0.4
0.001850978	0.401490477
0.003701956	0.40185031
0.007541912	0.404481823
0.013303412	0.411351491
0.019064912	0.418288155
0.022905912	0.419277714
0.026746912	0.411114396
0.030587912	0.387717244
0.038269912	0.332738853
0.045951912	0.296105355
0.053633912	0.273742472
0.061315912	0.259722345
0.069	0.251010907
0.07009713	0.250034386
0.076679912	0.244250461
0.086282412	0.23348503
0.092043912	0.227856425
0.099725912	0.262417577
0.107407912	0.36027208
0.111248912	0.406160612
0.115089912	0.429019362
0.118930912	0.440236395
0.122771912	0.446403912
0.127573162	0.452430828
0.130453912	0.455504246
0.134295956	0.457767323
0.136147977	0.458050876
0.138	0.459565045

Length (m)	Velocity (m/s)
	Aorta Diameter =0.020 m
0	0.4
0.001850978	0.401183282
0.003701956	0.401460911
0.007541912	0.403502186
0.014263662	0.409724534
0.019064912	0.414006508
0.022905912	0.41443431
0.026746912	0.406534556
0.030587912	0.387720461
0.038269912	0.347075042
0.045951912	0.321615505
0.053633912	0.307683431
0.07009713	0.284332441
0.076679912	0.274068449
0.084361912	0.259160744
0.092043912	0.24740742
0.099725912	0.27772492
0.107407912	0.368231519
0.111248912	0.41082328
0.115089912	0.432597356
0.118930912	0.444159381
0.122771912	0.45017653
0.128533412	0.454675139
0.131414423	0.456401056
0.134295956	0.457656248
0.136147977	0.457831192
0.138	0.459164488