ANALYSIS OF FLOW PHENOMENA IN STENTED CEREBRAL ANEURYSMS

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SUPERVISOR’S DECLARATION

We hereby declare that we have checked this project and in our opinion this project is satisfactory in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering.

…………………................

Name of Supervisor:
Position:
Date:

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 concurrently submitted for award of other degree.

Signature:
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Date: 25/11/2009

Dedicated to my beloved family

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ABSTRACT

Investigation on the changes of flow phenomena in saccular aneurysms at the Cerebral had been studied. Due to the aneurysms, the stent placement was done to prevent the rupture of aneurysms. The velocity profile and pressure distribution after and before installing the stent had been identified at the different locations of aneurysms. For each location, there is three cases with the different size of aneurysms that are 3.5 mm, 4.5 mm and 5.5 mm in radius. To identify the changes in local hemodynamic due to stent implantation, stented and non stented aneurysm models using selected stent were taken into considerations. The simulation of the model was studied under incompressible, non-Newtonian, viscous, non pulsatile condition in which we investigated computationally in a three-dimensional configuration using a Computational Fluid Dynamics (CFD) program. The minimum velocity had obtained after stents placement. In the first model, the minimum velocity obtained for non stented is 0.374 m/s for case 1, 0.421 m/s for case 2 and 0.36 m/s for case 3. After stenting implementation, the higher minimum velocity were increased for all cases. For case 1 is 0.416 m/s, case 2 is 0.443 m/s and case 3 is 0.404 m/s. In the second model, the minimum velocity for non-stented aneurysms is 0.487 m/s for case 1, 0.424 m/s and 0.343 m/s for case 3. After stenting, the velocity also increased. For case 1 is 0.495 m/s, case is 0.454 m/s and case 3 is 0.382 m/s. The different locations of aneurism, will give the different result of velocity profile and pressure distribution. In the first model, the peak pressure for non-stented aneurysms is 453 Pa and for stented is 422 Pa. While, in second model, for non-stented aneurysms, the peak pressure is 455 Pa and 432 Pa for stented aneurysms. Finally, the correlations obtained from this numerical result could be used to investigate the pressure distribution around the diseased segment.

ABSTRAK

Kajian mengenai fenomena aliran darah di dalam aneurism sakular pada bahagian Cerebral telah dijalankan. Disebabkan adanya aneurism, stent telah diletakkan untuk menghalang aneurism daripada pecah. Profil halaju dan taburan tekanan dikenalpasti sebelum dan selepas meletakkan stent pada aneurism di lokasi yang berbeza. Untuk setiap lokasi, terdapat tiga kes dengan saiz aneurism yang berbeza iaitu 3.5 mm, 4.5 mm dan 5.5 mm dalam radius. Untuk mengenalpasti perubahan hemodinamik darah disebabkan oleh implant stent, model aneurism tanpa dan bersama stent yang telah dipilih di ambil kira. Simulasi model dikaji dengan parameter aliran mampat, non-Newtonian, bendalir likat dan keadaan tiada denyut menggunakan program dinamik bendalir tiga dimensi (CFD). Aneurism pada berlainan lokasi, akan memberikan profil halaju dan taburan tekanan yang berbeza. Halaju minimum telah diperolehi, selepas implant stent. Dalam model pertama, halaju minimum telah diperolehi untuk tanpa stent ialah 0.374 m/s untuk kes 1, 0.421 m/s untuk kes 2 dan 0.36 untuk kes ketiga. Selepas stent diletakkan, halaju minimum telah meningkat bagi semua kes. Untuk kes 1, halajunya ialah 0.416 m/s, kes 2 ialah 0.443 m/s dan kes 3 ialah 0.404 m/s. Dalam model kedua, untuk model tanpa stent, halajunya ialah0.487 m/s untuk kes 1, 0.424 m/s untuk kes 2 dan 0.343 m/s untuk kes ke 3. Selepas stent diletakkan, halaju minimumnya turut bertambah. Untuk kes 1, halajunya ialah 0.495 m/s, kes 2 ialah 0.454 m/s dan kes 3 ialah 0.382 m/s. Aneurism pada lokasi yang berbeza akan memberikan nilai halaju dan taburan tekanan yang berbeza. Dalam model pertama, tekanan yang diperolehi ialah 453 Pa untuk tanpa stent dan 422 Pa untuk dengan stent. Manakala untuk model kedua, tekanan yang diperolehi ialah 455 Pa untuk tanpa stent dan 432 untuk dengan stent. Perkaitan yang telah diperolehi dari kajian ini boleh dimanfaatkan untuk lanjutan taburan tekanan disekitar aneurism.

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LIST OF ABBREVIATIONS

WSS	Wall Shear Stresss
FVM	Navier-Stokes Finite-Volume
CFD	Computational Fluid Dynamics
ICA	Intracranial aneurysm
DSA	Medical substraction angiography
GTA	Computer tomographic angiography
MRA	Magnetic resonance angiography
CT	Computer-assisted tomographic
PTV	Particle-tracking velocimetry

LIST OF SYMBOLS

u_i	velocity in the i-th direction
P	pressure
f_i	body force
ρ	density
μ_i	viscosity
δ_{ij}	Kronocker delta
A	area
a	acceleration vector
B	body force vector per unit volume
E	total energy
K	thermal conductivity of working fliud
L	length
m	mass
Re	Reynolds number
P	pressure
Q	volume flow rate
T	temperature
t	time
U	internal energy for system

CHAPTER 1

INTRODUCTION

1.1 ANEURYSMS

Aneurysms is a localized, blood-filled dilation (balloon-like bulge) of a blood vessel caused by disease or weakening of the vessel wall. Aneurysms most occur in arteries at the base of the brain (the circle of Willis) and in the aorta (the main artery coming out of the heart, a so-called aortic aneurysm). A sign of an arterial aneurysm is a pulsating swelling that produces a blowing murmur on auscultation (the act of listening for sounds in the body) with a stethoscope.

There are four main locations where aneurysms always happen that are Cerebral Aneurysms or Brain, Aorta Aneurysms, Abdominal Aneurysms and Thoraic Aortic Aneurysms. As the size of an aneurysm increases, there is an increased risk of rupture, which can result in severe hemorrhage or other complications including sudden death. Severe bleeding can occur if the aneurysms break or rupture. Not all aneurysms are life-threatening. But if the bulging stretches the artery too far, this vessel may burst, causing a person to bleed to death. An aneurysm that bleeds into the brain can lead to stroke or death. Aneurysms usually appear in either fusiform or saccular.

A fusiform aneurysms is spindle shaped without a neck. While, the second type of aneurysms is saccular. The saccular aneurysms are the most frequent cerebral aneurysms showing a berrylike outpouchings of the vessel wall: they often develop at the curved side of the vessels or at the apex of bifurcations.

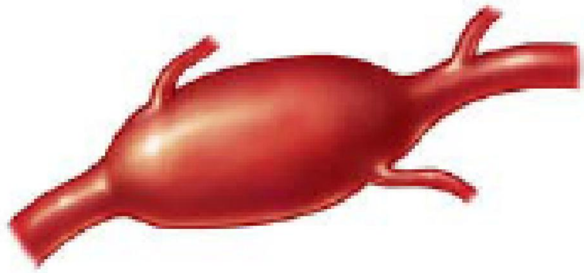
No.	Type	Figure
1	Saccular	
2.	Fusiform	

Figure 1.1: Types of Aneurysms

(Source: http://emedicine.medscape.com/article/252142-overview)

1.1.1 Causes

There is not very clear why there is some people get aneurysms. Some ideas said that, a person can be born with a defect or weak area in one of the artery layers. Besides that, trauma can weaken or damage the artery wall. There are many factors that cause the aneurysms. Generally, the causes of aneurysms are due to atherosclerosis, atheroma, congential defects, heart attacks, smoking, obesity, hypertension, trauma and others. However, atherosclerosis is the most common cause of aneurysms which about 80%. The following increase the risk of aneurysms;

- Atherosclerosis (a build-up of fatty plaque in the arteries).
- High blood pressure.
- Smoking.

- Deep wounds, injuries, or infections of the blood vessels.
- A congenital abnormality (a condition that you are born with).
- Inherited diseases. An inherited disease such as Marfan syndrome, which affects the body's connective tissue, causes people to have long bones and very flexible joints. People with this syndrome often have aneurysms.

1.1.2 Symptoms

Symptoms will depend upon the location of the aneurysm. Common sites that aneurysms occurred include the abdominal aortic artery, the intracranial muscles (supplying blood to the brain), and the aorta (supplying blood to the chest area). Many aneurysms are present without symptoms and are discovered by feeling or on x-ray films during a routine examination.

When symptoms occur, they include a pulsing sensation, and there may be pain if the aneurysm is pressing on internal organs. If the aneurysm is in the chest area, for example, there may be pain in the upper back, difficulty in swallowing, coughing or hoarseness. A ruptured aneurysm usually produces sudden and severe pain, and depending on the location and amount of bleeding, shock, loss of consciousness and death. Emergency surgery is necessary to stop the bleeding.

In some cases, the aneurysm may leak blood, causing pain without the rapid deterioration characteristic of a rupture. Also, clots often form in the aneurysm, creating danger of embolisms in distant organs. In some cases, the aneurysm may dissect into the wall of an artery, blocking some of the branches. Dissecting aneurysms usually occur in the aortic arch (near its origin, as it leaves the heart) or start in the descending thoracic portion of the aorta after it gives off the branches to the head and arms. Symptoms vary according to the part of the body that is being deprived of blood; they are usually sudden, severe and require emergency treatment.

1.1.3 Diagnosis of Aneurysms

There were many tests use, in order to diagnose Aneurysms. The first one is Angiogram. Angiogram is an x-ray examination of the arteries, veins or heart chambers, obtained by injecting a radiopaque (contrasting dye) into the bloodstream to make these structures more visible. Next is, Magnetic resonance imaging (MRI). A diagnostic technique that uses the response of atoms to a strong magnetic field to produce cross-sectional images of soft tissues, such as veins and arteries. The third one is called Spinal tap**.** Spinal tap is a puncture of the spinal cavity with a needle to extract the spinal fluid for diagnostic purposes.

The fourth is Ultrasound. In ultrasound, there is use of high-frequency sound waves to produce an image or photograph of an organ or tissues. Next is called Echocardiography. Echocardiography is a diagnostic procedure that uses ultrasound waves to visualize structures within the heart. And the last one is called X-ray**.** X-ray is a photograph obtained by bombarding a target in a vacuum tube with high-velocity electrons, enabling them to penetrate solid matter and act on photographic film.

1.1.4 Treatments

Treatment depends on the size and location of the aneurysm and your overall health. Aneurysms in the upper chest (the ascending aorta) are usually operated on right away. Drugs may be prescribed to lower blood pressure and reduce the risk of rupture. Abdominal aneurysms that are large or increasing in size should be treated surgically. Enlarging thoracic aneurysms should be considered for surgery. A dissecting or ruptured aneurysm requires emergency surgery.

Cardiologists at the Texas Heart Institute were among the first to use a nonsurgical technique to treat high-risk patients with abdominal aortic aneurysms. This technique is useful for patients who cannot have surgery because their overall health would make it too dangerous. The procedure uses a catheter to insert a device called a stent graft. The stent graft is placed within the artery at the site of the aneurysm. The blood flows through the stent graft, decreasing the pressure on the wall of the weakened artery. This decrease in pressure can prevent the aneurysm from bursting.

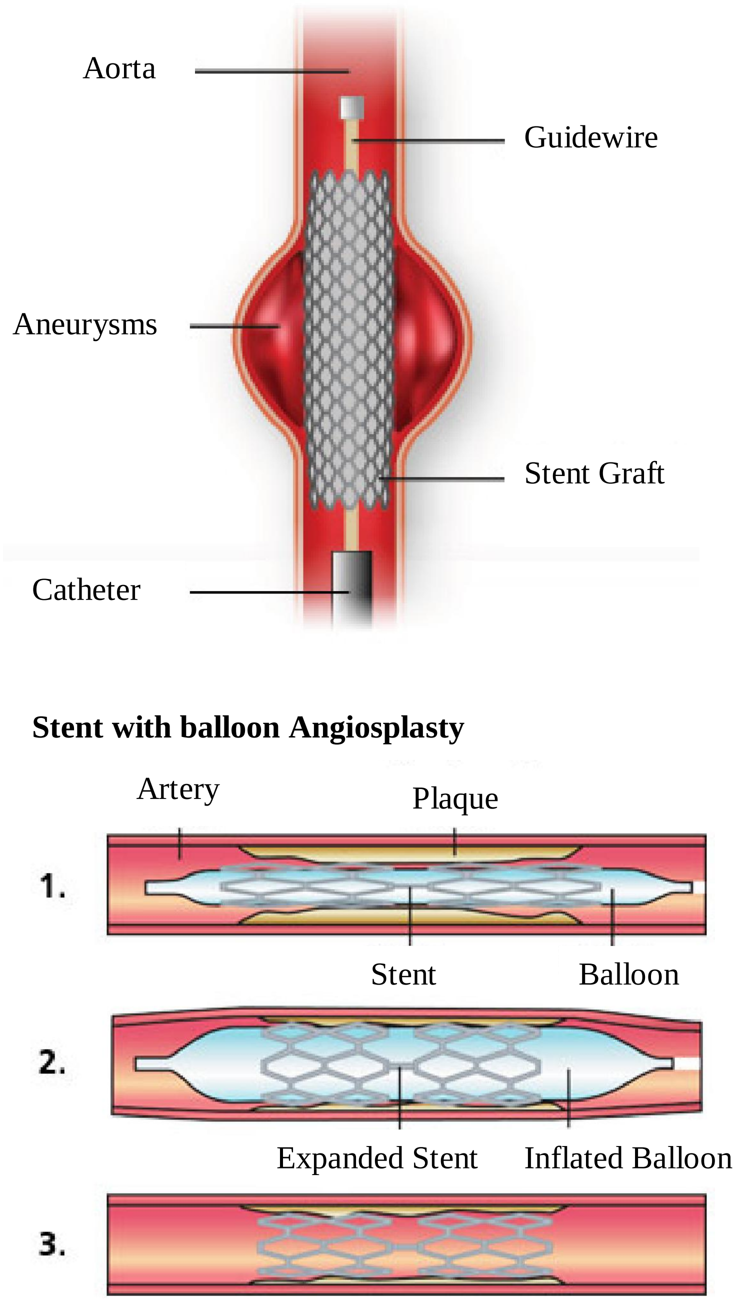


Figure 1.2: Stenting Procedure

(Source; http://www.radiology.ucsf.edu/ir/angioplasty, 2008)

Benefits of the procedure include no general anesthesia (you are awake for the procedure), a shorter hospital stay (about 24 hours), a faster recovery, and no large scars. Figure 1.3 shows the rupture of aneurysms.

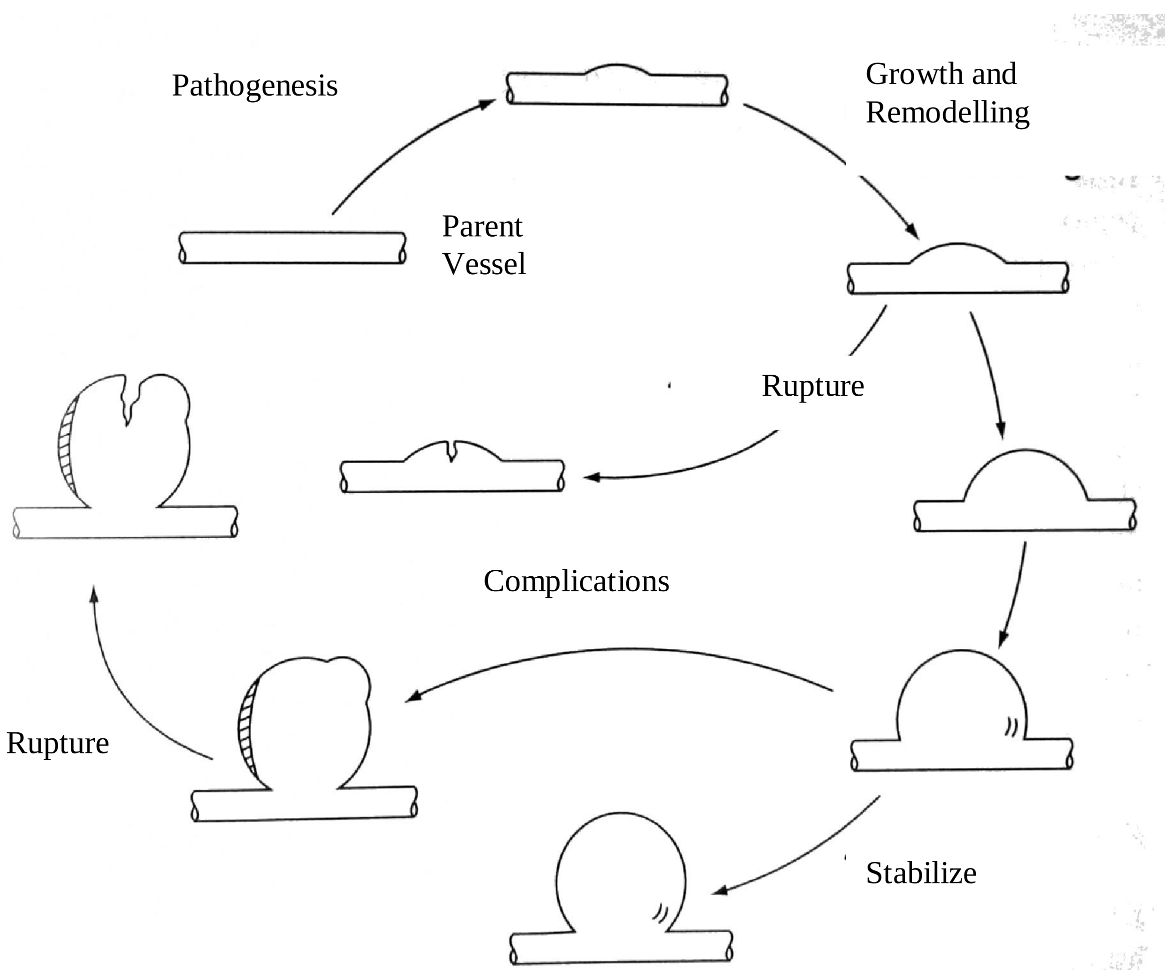


Figure 1.3: Rupture of aneurysms

1.2 STENT

A stent can be defined as any medical device that supports tissue, but most commonly, a stent refers to a specific medical device that is placed into an artery. Besides that, a stent can be defined as a small mesh tube that's used to treat narrowed or weakened arteries in the body. It is a man-made 'tube' inserted into a natural passage/conduit in the body to prevent, or counteract, a disease-induced, localized flow constriction. Stents are usually made of metal mesh, but sometimes they're made of fabric. Fabric stents, also called stent grafts, are used in larger arteries. Stent should modify the blood circulation in aneurysms but not stop it. An arterial stent is a mesh-like tube, often made of metal that can expand once it is inserted into an artery. The most frequent placement of stents is in coronary arteries, which are typically blocked by plaque built up inside. A stent is inserted into an artery during angioplasty and typically inflated with a balloon catheter. The procedure begins at either the femoral artery in the groin, or the axillaries artery in the armpit and the stent is guided to the proper artery. The stent acts as a kind of scaffolding for the artery during any surgical repair or procedure. Usually, the stent is left in the artery permanently. The stent supports the narrowed or blocked artery, keeping it open for blood to flow more freely.

Figure 1.4 Graft Stent

Stent(Source: http://www.health-news-blog.com, 2009)

Drug –eluting stents sometimes referred to as a “coated” or “medicated” stent, a drug-eluting stent is a normal metal stent that has been coated with a pharmacologic agent (drug) that is known to interfere with the process of restenosis (reblocking). Restenosis has a number of causes; it is a very complex process and the solution to its prevention is equally complex. However, in the data gathered so far, the drug-eluting stent has been extremely successful in reducing restenosis from the 20-30% range to single digits. There are three major components to a drug-eluting stent. The first one is type of stent that will carry the drug coating. Secondly is the method by which the drug is delivered (eluted) by the coating to the arterial wall (polymeric or other). Lastly, is depending on the drug itself.

A stent graft is a tubular device, which is composed of special fabric supported by a rigid structure, usually metal. The rigid structure is called a stent. An average **stent** on its own has no covering, and therefore is usually just a metal mesh. Although there are many types of stent, these stents are used mainly for vascular intervention.

1.3 CEREBRAL ANEURYSMS

1.3.1 Cerebral Aneurysms

A cerebral aneurysm is a bulge in the wall of an artery in the brain. It occurs when there is a weakness in the artery's wall. The bulge may slowly enlarge over time. It can rupture or burst and bleed. Cerebral aneurysms are occurring near arterial bifurcations in the circle of Willis as shown in figure 1.6 below;

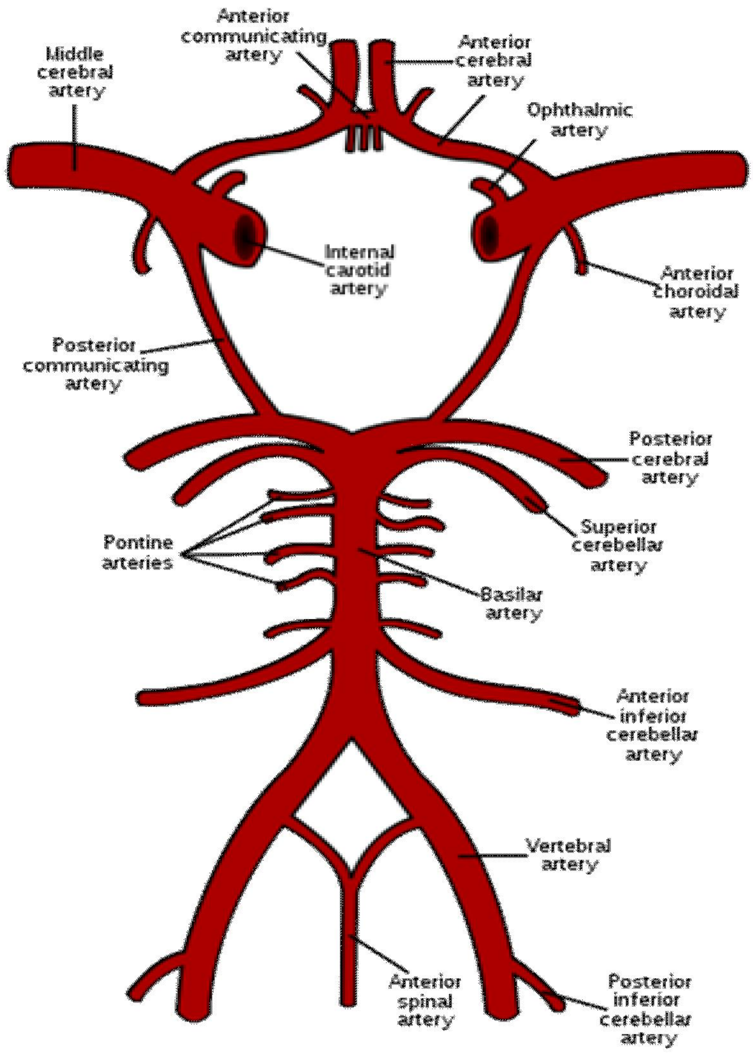


Figure 1.5: Circle of Willis

(Source; http://www.stroke-recovery-advocate.com/brain-blood-supply.html)

Cerebral aneurysms are frequently observed in the outer wall of curved vessels. They are found in the internal carotid artery, near the apex of bifurcated vessels including the anterior communicating artery (ACA), anterior cerebral artery and the middle cerebral artery (MCA). Cerebral aneurysms disease has been reported to affect around 1-5% of the population. Although many cases of this disease are unruptured, the catastrophic consequences of subarachnoid hemorrhage (SAH) following rupture of cerebral aneurysms make optimal treatment of patients. Rupture of a cerebral aneurysm can be dangerous for a patient and occurs most commonly between 40 and 60 years of age. When an aneurysm ruptures, blood leaks from the ruptured wall into the subarachnoid space, or the brain itself, potentially causing serious damage. Aneurysm growth and rupture depends on multiple factors: geometrical factors such as aneurysm size and shape or the ratio of the aneurysm dome height to the neck width; biological factors such as decreased concentration of structural proteins of the extracellular matrix in the intracranial arterial wall; and hemodynamic factors, especially wall shear stresses.

Aneurysms come in a variety of shapes and sizes. The most common type is a berry aneurysm (Refer to figure 1.6 below). It is round like a berry and connected to the artery by a stem or neck. There are two general types of aneurysms: fusiform and saccular. A fusiform aneurysm is spindle-shaped without a neck. The saccular aneurysms are the most frequent cerebral aneurysms showing a berrylike outpouchings of the vessel wall: they often develop at the curved side of the vessels or at the apex of bifurcations. A giant aneurysm is like a berry aneurysm, but it is large, 1¼ inches or 3 centimeters or more in diameter.

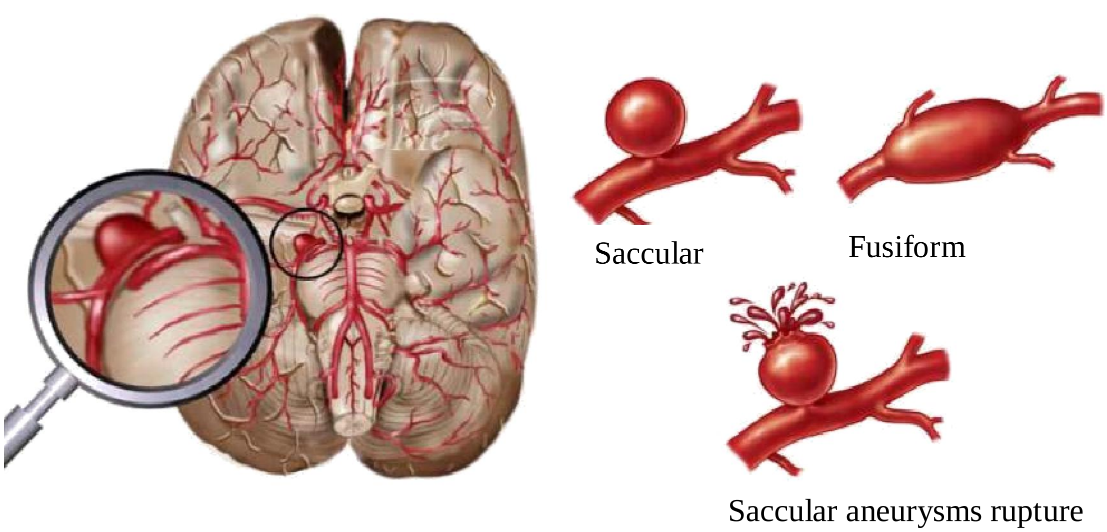


Figure 1.6: Type of Cerebral Aneurysms

(Source: 2001 eCureMe.com)

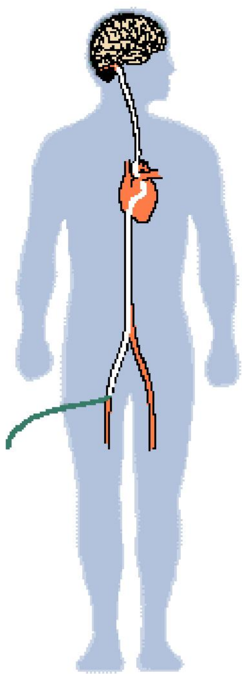
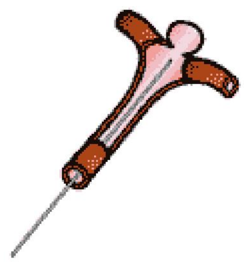
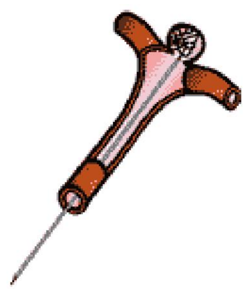
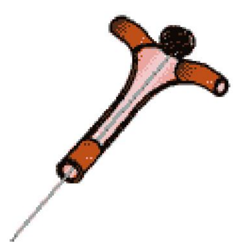
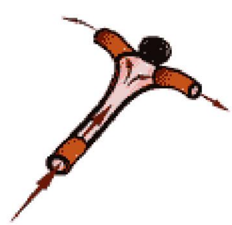
1.3.2 Cerebral Aneurysms Treatments.

One of the first objectives will be to treat the cerebral aneurysm to prevent it from bleeding. There are two ways to prevent or treat the aneurysms. Either surgery or endovascular treatment may be offered to repair the aneurysm. The timing and type of treatment will depend on the location and size of the aneurysm and the patient's medical condition. A stent is a flexible cylindrical tube made of a mesh of stainless steel or alloys. Due to its limited permeability, the stent modifies the blood flow in the aneurysms. Emergency treatment for individuals with a ruptured cerebral aneurysm generally includes restoring deteriorating respiration and reducing intracranial pressure. Surgical clipping was introduced by Walter Dandy of the Johns Hopkins Hospital in 1937. It consists of performing a craniotomy, exposing the aneurysm, and closing the base of the aneurysm with a clip. The surgical technique has been modified and improved over the years. Surgical clipping has a lower rate of aneurysm recurrence after treatment.

For endovascular treatment, was introduced by Guido Guglielmi at UCLA in 1991. It consists of passing a catheter into the femoral artery in the groin, through the aorta, into the brain arteries, and finally into the aneurysm itself. Once the catheter is in the aneurysm, platinum coils are pushed into the aneurysm and released. These coils initiate a clotting or thrombotic reaction within the aneurysm that, if successful, will eliminate the aneurysm. These procedures require a small incision, through which an catheter is inserted. In the case of broad-based aneurysms, a stent may be passed first into the parent artery to serve as a scaffold for the coils ("stent-assisted coiling"), although the long-term studies of patients with intracranial stents have not yet been done.

1.3.3 Process of Treatments

Table 1.1: Process of Treatments

	 The catheter is carefully guided into the aneurysm.
	 Soft platinum coils are deposited through the microcatheter into the aneurysm.
	 The coils conform to the often irregular shape of an aneurysm. An avg. of 5-6 coils is required for each aneurysm.
	 Coils will prevent blood flow into the aneurysm.

1.4 Objectives

The first objective of this project is to determine the flow phenomena in the stented cerebral aneurysms. In this project, the selected stent will be used to determine the effect of stenting to the aneurysms. The stent used in the aneurysms to check whether the stent will help to increase the velocity and decrease the pressure of the blood. Blood flow is the greatest influences that lead to the rupture.

The second objective is to analyze the effect of aneurysms location to flow and blood parameters. The cerebral aneurysms is locate at the brain and focus on the saccular shape of aneurysms. In this objective, the project will focused on two different locations of aneurysms to determine whether the location will influence the flow phenomena of the blood.

1.5 Project Scope

In order to achieve those objectives, some limitations were decided to range the whole study. Therefore, the main concerned is to analyze selected stents based upon different aneurysms location in COW (Circle of Willis). Furthermore, the Non Pulsatile blood flow will be used.

All the solutions of the problem presented in this study will be based on numerical approach only. The results of these analyses through numerical solutions are expected to explain the pressure distribution and velocity profile of the blood vessel.

CHAPTER 2

FLUID FLOW BEHAVIOUR IN ANEURYSMS

2.1 FLOW BEHAVIOUR IN ANEURYSMS

The flow dynamics of cerebral aneurysms have been studied in numerous experimental models and clinical studies to investigate the role of hemodynamic forces in the initiation, growth, and rupture of cerebral aneurysms. Most investigators or researchers in this world are focusing on blood flow and wall stress analysis which develop from clinical data of aneurysms models. There are many causes that make the aneurysms rupture or burst. The ruptures of aneurysms occur mainly due to the diameter, wall thickness and blood pressure inside aneurysms (Yamada et Al., 1994) but actual cause of the rupture not yet fully understood. There have been several research efforts to investigate the flow phenomena inside aneurysms using numerical solution (Gyorgy Paa´l et al, 2007).

The flow dynamics can be visualized by tracking the paths of blood particles as they are released from the inlet boundary of the computational domain. Some blood particles never enter the aneurysm, and some enter the aneurysm at the distal neck. The particles, which enter the aneurysm, leave it at the distal neck or join the inflow and flow chaotically inside the aneurysm sack. Blood vessels and stent-grafts are flexible, interactions between blood flow and wall deformation can involve a wide range of fluid-mechanical phenomena. The flow will affect movement of the walls and wall movements in turn influence the flow field. Hence, simultaneous fluid-structure interactions (FSIs) should be considered when studying the hemodynamics and biomechanics of stented aneurysms. Numerical simulations have been used during the last decade to analyze blood flow phenomena in aneurysms. Unlike experiments, numerical simulations can be relatively inexpensive to conduct. Computational fluid dynamics (CFD) simulations provide a means of comparing and validating experimental work without the often difficult process of observing a real physiological system.

Previous efforts in numerical simulations of aneurysm flow have shown the presence of many flow phenomena. Bluestein et al. (1996) performed laminar and turbulent simulations of flow in an aneurysm with a steady inlet velocity. Results showed that a recirculation region formed within the aneurysm and promoted thrombosis (the obstruction of blood vessels by local clotting) and rupture conditions.

The recirculation region generated oscillating wall shear stress gradients and high levels of wall shear at the distal end of the aneurysm, which is the most common location of aneurysm rupture. The recirculation region was observed to be considerably larger and stronger in laminar flow conditions than in turbulent flow conditions. It is more physiologically realistic to use an inlet velocity that mimics the pulse cycle by varying in time instead of the steady velocity used in Bluestein's study. Steinman et al. (2002) presented a CFD model of pulsatile flow within an anatomically realistic carotid aneurysm constructed from in vivo imaging of a human subject. Their model successfully reproduced velocity streamlines from an earlier in vivo model of similar geometry and demonstrated regions of elevated wall shear stress.

From the analysis, there was vortex formed in the blood vessel. The vortex occurred due to the pressure imbalance of the blood that leads to the swirl in aneurysms. Vortex formation and complex flow structure existence in blood vessel around the aneurysm becomes a common finding from previous numerical study. The fluid flow pattern inside the aneurysms is complex and depends on the shape and size of the aneurysms geometry. Fluid flow have the greatest influence on aneurysms growth and rupture (Liepsch, 2001; Hoi et.al., 2004)

The high vorticity observed in the aneurysm dome at high arterial vessel, and a low wall shear stress can lead to degeneration of endothelial cells via the apoptotic cell cycle. Hence, as the wall shear stress observed in our model is less than those of the main vessel, the differences between wall shear stresses might be related to the weakening of the aneurysm dome. Interestingly, cerebral aneurysms are often found to rupture at its dome. Thus, low shear stress might offer an explanation as to why aneurysm dome is a common rupture site. The pulsatile flow becomes more unstable as its mean velocity is increased. In a 1995 paper, Mast and Pierce hypothesize that a nonlinear coupling between aneurysm vibration and unstable arterial flow is the cause of narrow-band sounds associated with some intracranial aneurysms. As we can observe from the pulsatile flow videos, arch-shaped streamlines oscillate from the upstream side of the dome opening to the downstream side of the opening during each momentary back flow when the flow changes direction. The frequency of the oscillation seems to be dictated by both the speed of the flow and the size of the dome opening. Another effect of a pulsatile flow is the accompanied oscillatory wall shear stress due to the change of flow direction. This can be observed in the maximum speed pulsatile flow video as particles around the dome area vibrates back and forth. According to Liou et al., oscillatory wall shear stress acting around the already weakened dome region may cause it to grow continuously. The formation of vortex in can be seen in Figure 2.1 below.

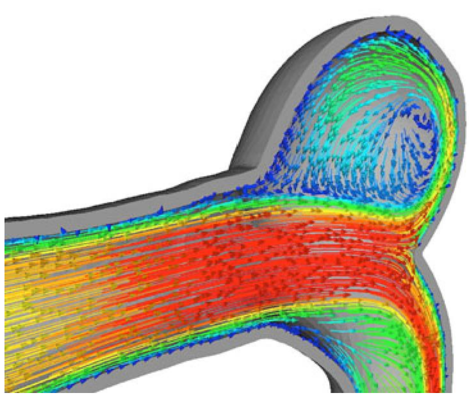


Figure 2.1 Flows in Aneurysms

(Source: http://www.tafsm.org/PROJ/CVFSI/CAIBLR/)

2.2 Flow behavior in Cerebral Aneurysm

In recent years, computational methods are able to accurately predict the velocity field in three-dimensions for pulsatile flow, in tortuous and complex vascular geometries. This capability, together with the advent of medical imaging methods that are able to determine the lumenal geometry and inflow conditions in vessels of interest, provide the impetus to question whether it might be possible to predict the hemodynamic influences on the vessel wall on a patient-specific basis. Figure 2.1 below shows the location of aneurysms always happened.

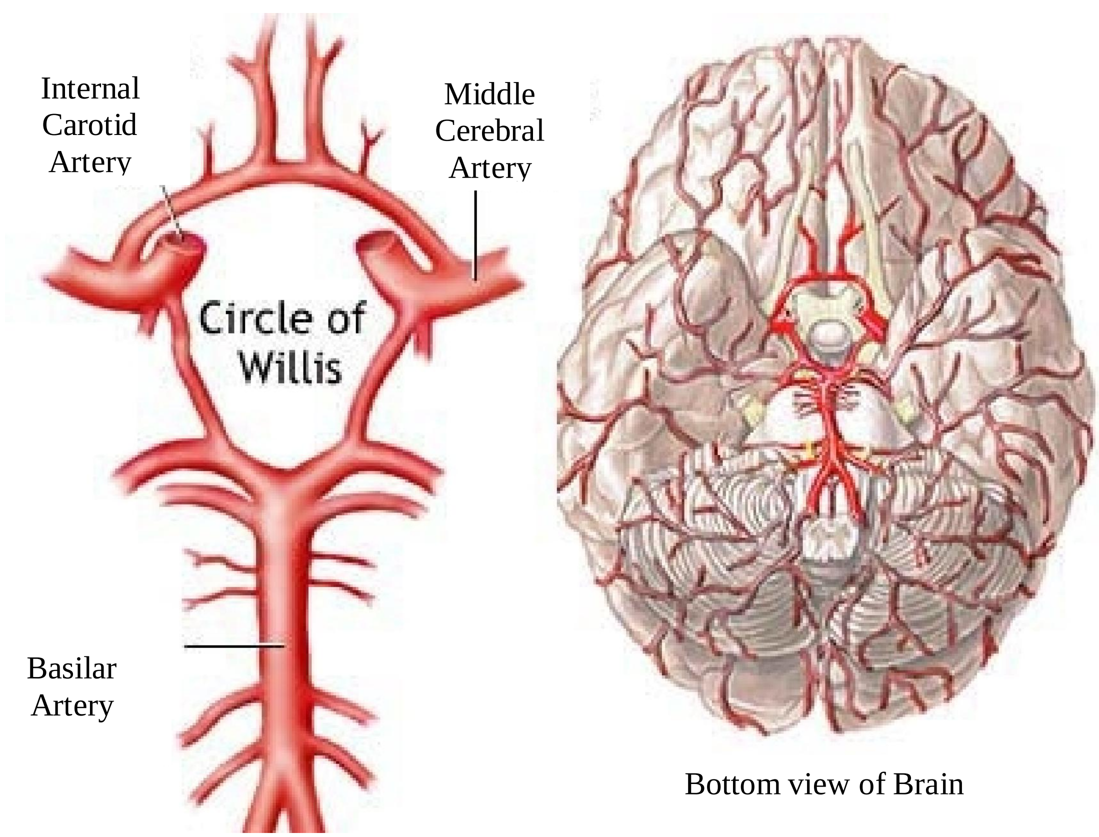


Figure 2.2: Location of Aneurysms in Circle of Willis (http://www.nlm.nih.gov/medlineplus/ency/imagepages/18009.htm)

The flow related aspects dominate the life cycle of cerebral aneurysms. Understanding the role of blood and its flow mechanics will provide access to the deeper understanding of the cerebral aneurysm life. Besides that, the understanding can the role of blood flow will provide possibilities to assess rupture risk and to improve endovascular treatment methods. In order to improve the treatment method, the analysis must be done because there is no other method to measure blood flow patterns. With the advent of flow diversion using stents as treatment, the cause rather than the symptom may be addressed.

Cerebral aneurysms, a vessel disease marked by undue dilation of an arterial lumen indicating wall weakness and therefore exposing the patient to vessel rupture risk, are comparable to other complex systems that are governed by multiple parameters, and that in the case of cerebral aneurysms exhibit yet partially understood relationships (J.R Cebral et al, 2006).

Among others, the parameter of special interest is flow because it plays a significant role in all the different segments of the aneurysm life cycle, i.e. initiation, growth and rupture. When it comes to minimally invasive endovascular treatment, preliminary clinical results indicate that control of local flow parameters may alleviate from aneurysm disease. Such flow control is today conceivable by use of flow diverting devices such as stents. Different from today's treatment of symptoms with insertion of intraaneurismal flow diverters (coils) to induce thrombosis, application of flow correction in the parent vessel with stents would treat the cause and bears the potential to have better long-term efficacy (P. Lylyk et. Al, 2006).

Understanding flow and developing methods to assess and plan for correction is important to the surgical planning. A significant contribution to treatment and treatment planning using modern medical imaging can be expected. Patients with this highly prevalent disease (2-4%) but overall low rupture incidence (10/100'000/year) will benefit of better rupture risk assessment and better treatment.

2.3 Hemodynamic of cerebral aneurysm

Hemodynamics plays an important role in the progression and rupture of cerebral aneurysms. Hemodynamics of cerebral aneurysm which is a force involved in the circulation of blood i.e. hemodynamics concerns the physical factors governing blood flow within the circulatory system. Parameters are believed to be responsible for aneurysm initiation, growth and rupture (Steiger et al, 1990). The important hemodynamic parameters include pulsatile nature of blood flow, blood pressure and wall shear stress. These fluid mechanical forces also intricately regulate structure and function of endothelial cell layer, the innermost layer of a vessel wall (Barakat et al, 2000). Aneurysm and parent vessel geometry, neck size, blood viscosity, wall elasticity etc. affect the hemodynamics of cerebral aneurysms. However, in large vessels, wall elasticity, non-Newtonian viscosity, slurry particles in the fluid, body forces and temperature are often neglected because of their secondary importance (Wootton et al, 1999).

2.3.1 Wall Shear Stress (WSS)

The temporal and spatial variations in wall shear stress (WSS) within the aneurysmal saccular are hypothesized to be correlated with the growth and rupture of the aneurysm. The current work describes the blood flow dynamics in 34 patient-specific models of saccular aneurysms located in the region of the anterior and posterior circulation of the circle of Willis (Alvaro Valencia et al, 2007). The models were obtained from three-dimensional rotational angiography image data and blood flow dynamics was studied under a physiologically representative waveform of inflow. The three-dimensional continuity and momentum equations for unsteady laminar flow were solved with commercial software using non-structured fine grid sizes. The vortex structure, the wall pressure, and the WSS showed large variations, depending on the morphology of the artery, size of the aneurysm, and form. A correlation existed between the mean WSS on the aneurysmal saccular for lateral unruptured and ruptured aneurysms with an aneurysm surface index, which is defined as the ratio between the aneurysm area and the artery area at model inlet, respectively.

2.3.2 Pulsatile Flow

The pulsatile flow reveal characteristic features of the cardiovascular system. Fukushima et al. (2008) carried out aneurysms flow experiments as well as two-dimensional simulations. They determined as the flow velocity increased, center of an intra-aneurysmal vortex moved from proximal end to distal end of an aneurysm. During a period of the cardiac cycle, transient reversal flow occurred, which caused the vortex to appear and disappear. They assume that pulsatile flow produced a flow pattern that was quite different than the steady flow. They determined that the presence of an oscillatory component in the flow velocity altered the steady flow pattern. A pair of vortices behind, and a horseshoe vortex in the front of the stenosis characterized the pulsatile flow pattern. Taylor et al. (1994) also showed periodic changes in the location and width of the above-mentioned vortex. They can induce vibrations of the aneurysm wall that contribute to progression and eventual rupture (Ortega et al, 1999). For the present CFD study to capture the pulsatile flow dynamics, which was done using physiological velocity waveform in a basilar artery. Figure 2.2 below shows velocity vector field and maximum systole of pulsatile flow simulation.

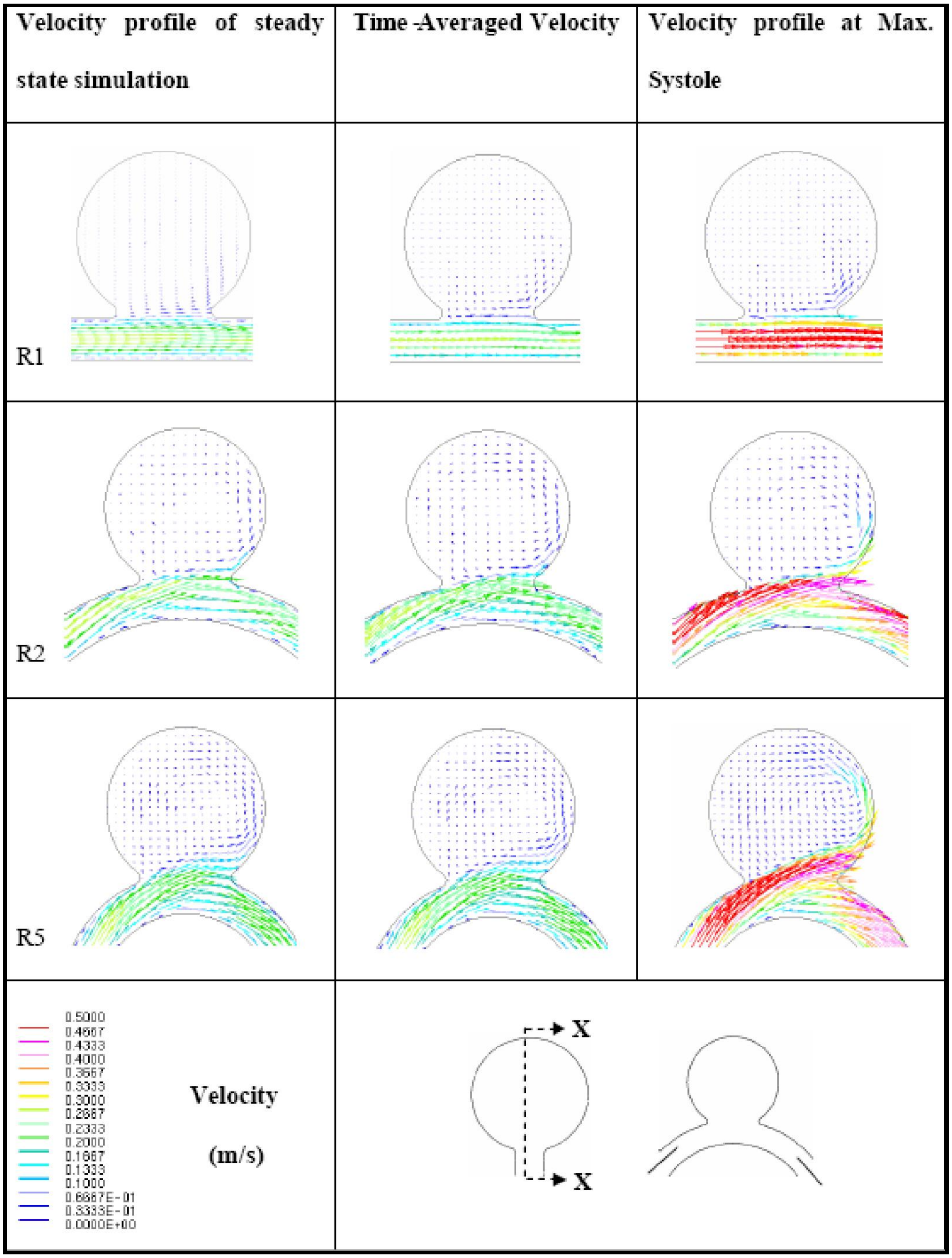


Figure 2.3: Velocity vector field and maximum systole of pulsatile flow simulation (Yie Meng Hoi, 2003)

2.4 Flow in stented Cerebral Aneurysm

Stent installation is the best solution for the aneurysm problem in order to prevent further rupture or burst of aneurysms. Investigation on arterial wall structure and behaviour are relevant to fluid interaction with the aneurismal vessels. According to M.P.Marks (1994), stents are flexible cylindrical mesh tubes made of stainless steel or alloys. However, according to Liepsch (2001) and Hoi (2004), the fluid flow is understood to have the greatest influence on aneurysms growth and rupture. Stent and coil implantation is a promising minimally invasive endovascular technique, which can sometimes be utilized successfully for inoperable regions, in order to prevent further rupture of a cerebral aneurysm leading to hemorrhage. In his previous works, he focused on the flow reduction ability of the stent itself and revealed that the positioning effect plays important roles in the treatment.

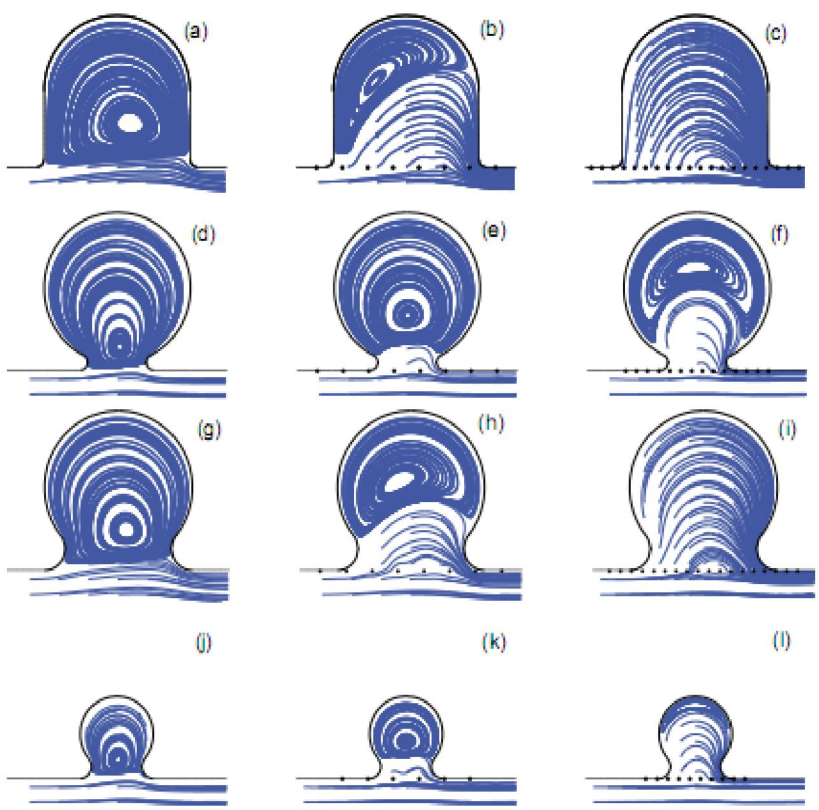


Figure 2.4: Flow in Stented and non-stented

(M. Hirabayashi et al, 2004)

Generally the positioning effect makes it difficult to predict the flow reduction performance in advance, because he does not have enough parameters, which can describe the flow reduction effect with accuracy. Then he proposes new basic parameters to understand the flow pattern in the stented aneurysm and its effect on the velocity reduction and to verify the flow reduction mechanism based on these parameters. In order to design the functional stent, it is important to identify the effective parameters. Numerical simulations will provide a useful tool to characterize the stented flow and define new parameters to improve the treatment effect resulting from a stent implantation.

Several experimental and numerical studies on stented flows have been reported. They emphasize the existence of large coherent vortex structures within lateral aneurysms model; however they do not discuss well the flow reduction mechanism. In stented aneurysms numerical works, flow behaviour around the stent revealed that the positioning effect plays important roles in the treatment (Hirabayashi et. al., 2006). The positioning effect makes it difficult to predict the flow phenomena because there are no stent parameters, can describe the flow effect with accuracy.

Hirabayashi et. al., (2006) proposed new basic parameters to understand the flow pattern in the stented aneurysms and its effect on the velocity change to verify the flow reduction mechanism based on these parameters. Identifying the effective parameters during development of new design to obtain high efficiency stent is very important. To characterize the stented flow and define new parameters, the numerical solution is used. This because the numerical solution will provide a useful tool in order to improve the treatment effect resulting from a stent implantation. The ideal stent would optimize and reduce the pressure on the aneurysms wall.

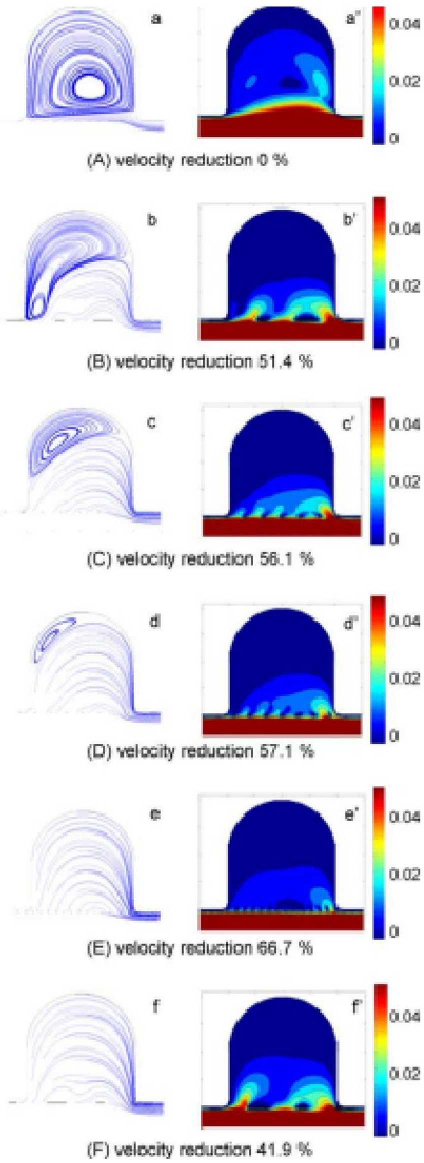


Fig. 1. Flow pattern variation due to the stent.

Flow pattern variation
due to the stent.

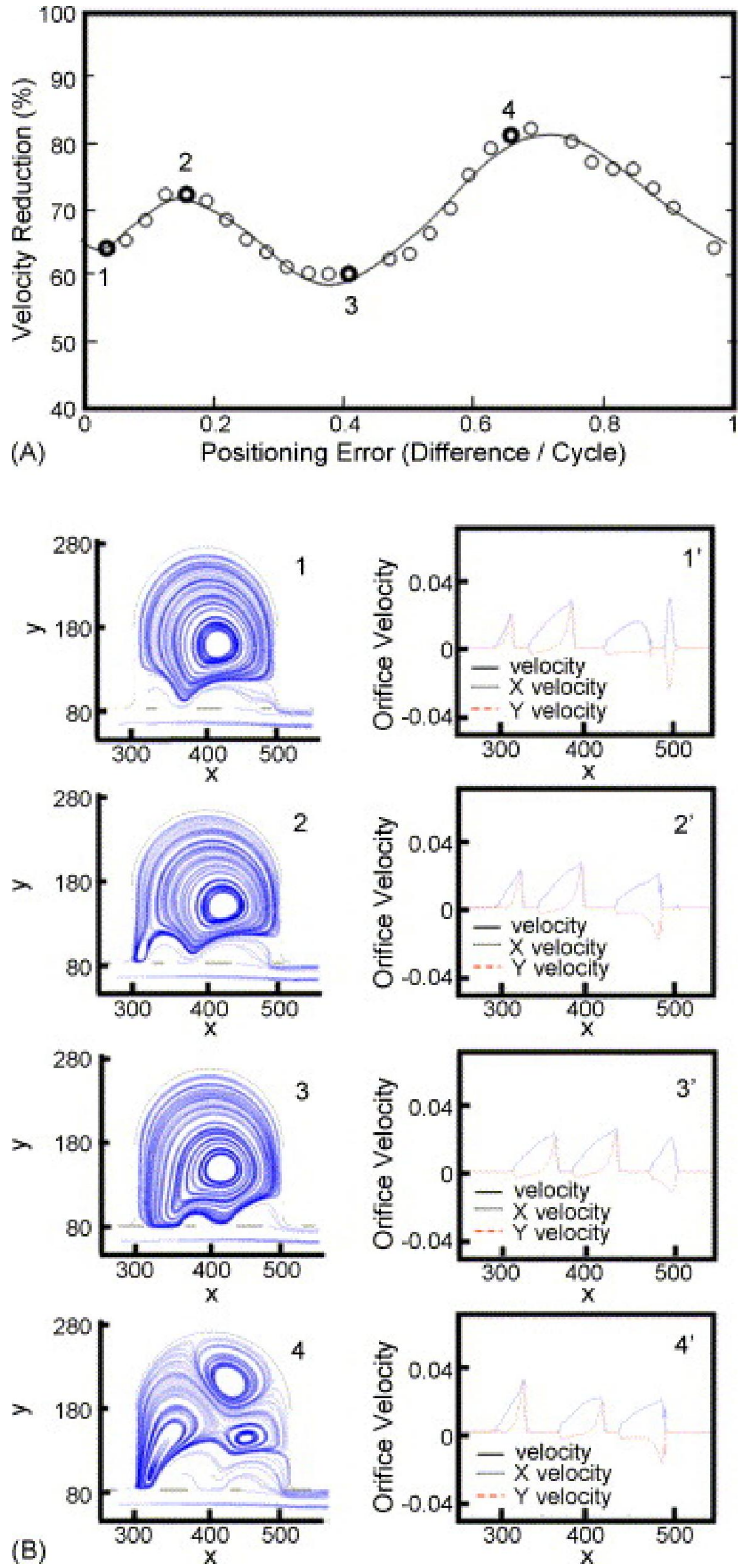


Figure 2.5: Velocity Reduction

(M. Hirabayashi et al, 2006)

2.5 Closure

This project will focus on the flow at the branches at the Circle of Willis. In many cases from medical report, the branches are the main part for bloods have a trouble flow and many diseases detect in this area. Artheoclorosis, aneurysm and high blood pressure are come from the branches. The pressure and the velocity of the blood will be the changes in the analysis using finite volume method in the Computational Fluid Dynamics (CFD).This method is the 1st degree of accuracy method and we cannot use experiment to analysis the data. It is because we cannot do the analysis on the human or dead body. From the analysis with the real condition and parameter, we will conclude that the analysis can get the almost similar result compare to the real one.

CHAPTER 3

METHODOLOGY

3.1 GEOMETRY OF MODEL

This study focus particularly on the model of aneurysm at artery with diameter of 6 mm with the aneurysm size is 14 mm diameter and 21 mm length. The modeling was completely done in CAD software package namely COSMOS with data of the aneurysm parameter taken according to the stent produce nowadays. The wall thickness of the aneurysm is set to 0.5 mm and model of aneurysm as shown in figure 3.1.

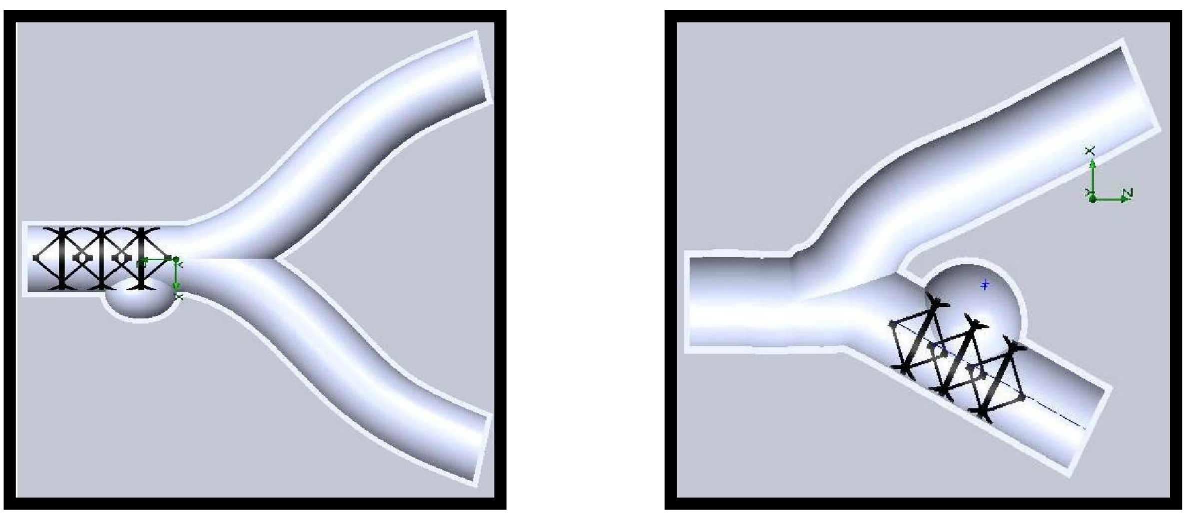


Figure 3.1: The geometry model of aneurysm

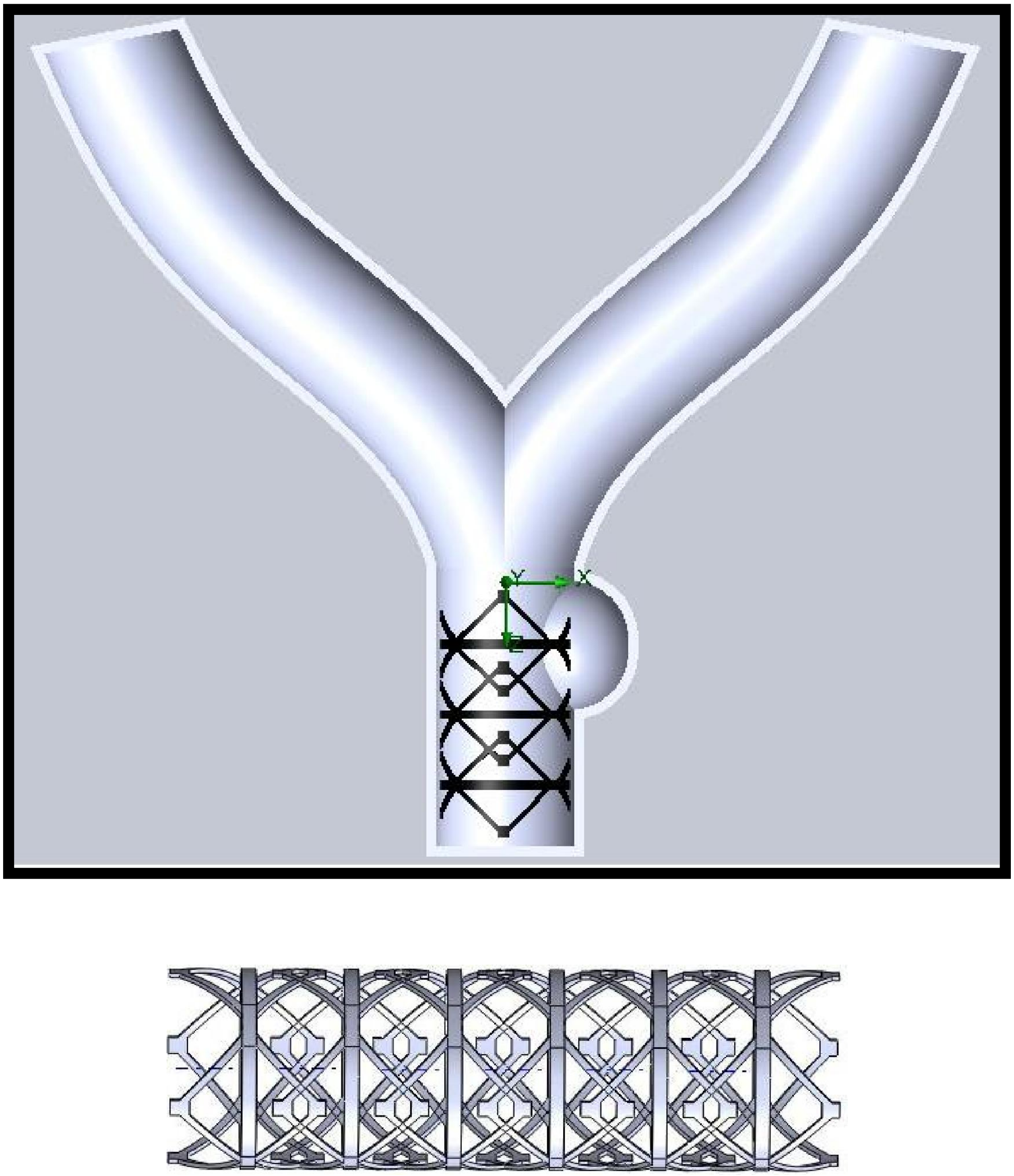


Figure 3.2: The geometry model of stent

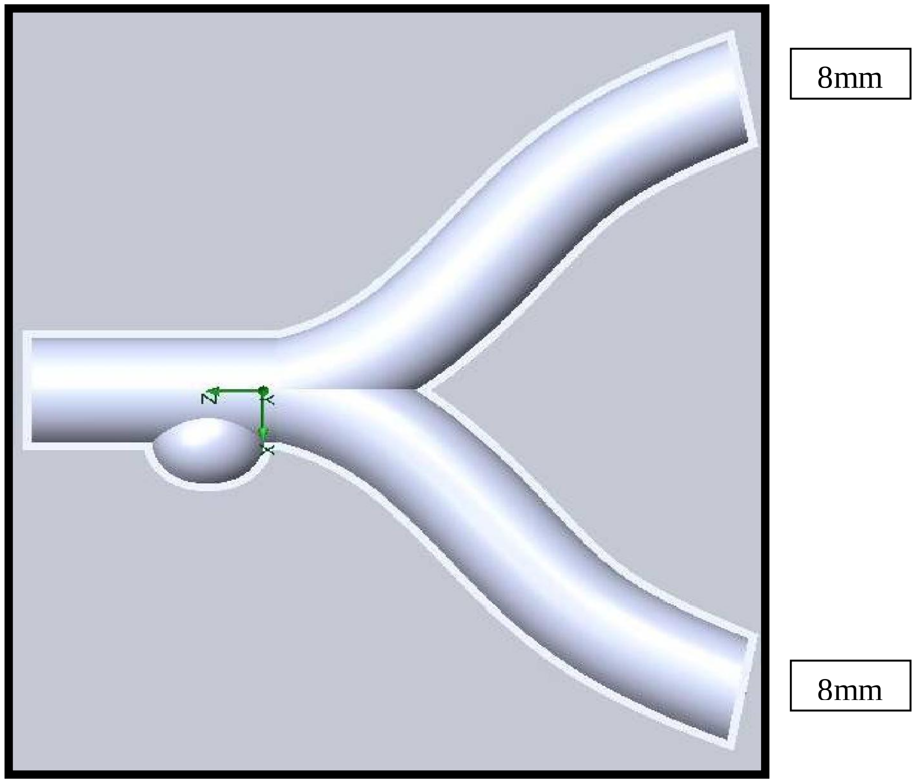


Figure 3.3: First Model

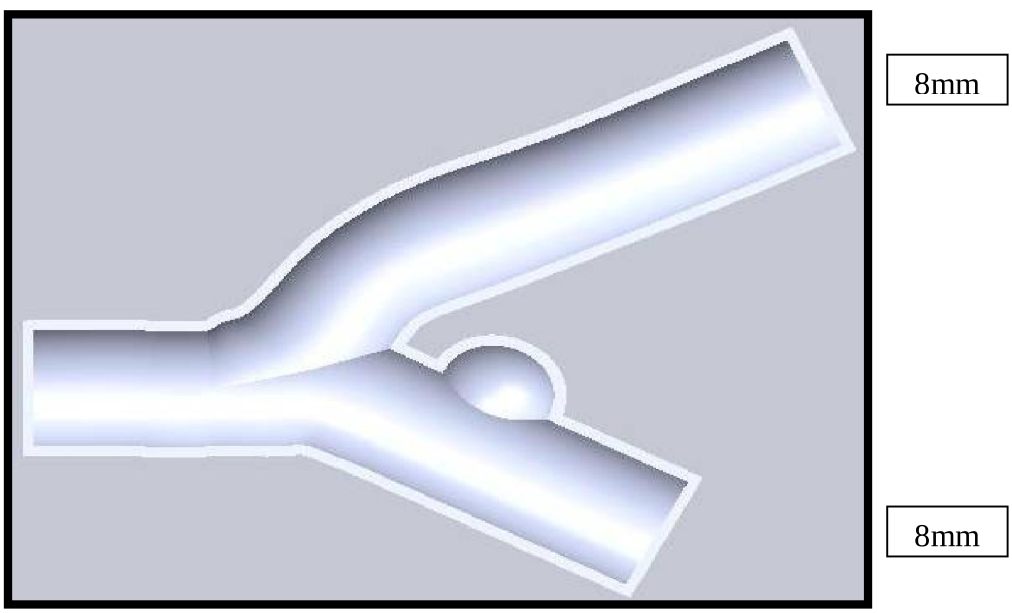


Figure 3.4: Second Model

3.2 GOVERNING EQUATION OF BLOOD FLOW

Blood flow in artery is considered to be incompressible, consisting of the continuity and Navier-Stokes equations. The governing equations are written as follows for a computational domain Ω:

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

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

u_i= velocity in the i^{th} direction

P = Pressure

f_i =Body force

ρ =Density

μ_i =Viscosity

∂_{ij} =Kronecker delta

The shear stress, τ at the wall of aneurysm calculated base on a function of velocity gradient only:

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

Where ∂u/∂y is the velocity gradient along the aneurismal wall taking considerations of fluid viscosity. Therefore, the simple viscous fluids considered with linear relationship. The equation of motion in terms of vorticity, ω as follows:

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

Where ω is the vorticity, ρ =Density and μ= viscosity with vector ^{2}V evaluated as well.

3.3 SIMULATIONS ASSUMPTION, PARAMETER AND BOUNDARY CONDITIONS

For the simulation that carried out in this study, it is assumed that blood is an incompressible, Newtonian fluid and that the flow is laminar and assumption of Newtonian behavior is based on the findings of Perktold et al. (1989).Although the blood is actually non-Newtonian fluid. The simulation started from the beginning of systole with pressure defined at the artery while the wall was treated as no-slip wall. Then it is repeated with a different design. The parameter used in the simulation is listed in Table 3.1

Table 3.1: Parameters used in the simulation

Parameters	**Value**
Blood Velocity (Cerebral)	0.7 m/s
Pressure	463 Pa
Temperature	293 K (constant)

3.4 BOUNDARY CONDITIONS

3.4.1 Initial Velocity

Droppler ultrasound data measurement is used to set the initial condition of velocity to 0.7m/s (Marie Oshima et al, 2000).The velocity is differing according to the other place in our body. The velocity for cerebral is 0.7 m/s.

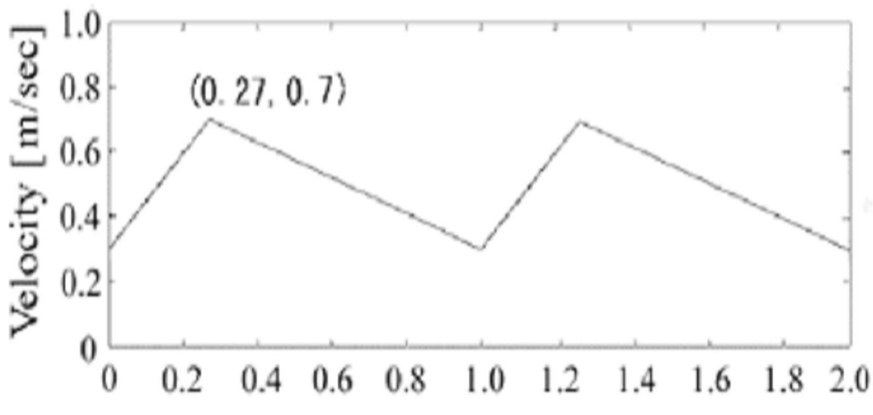


Figure 3.5: Initial condition.Graph Velocity versus Length.

(Marie Oshima et al (2(000).)

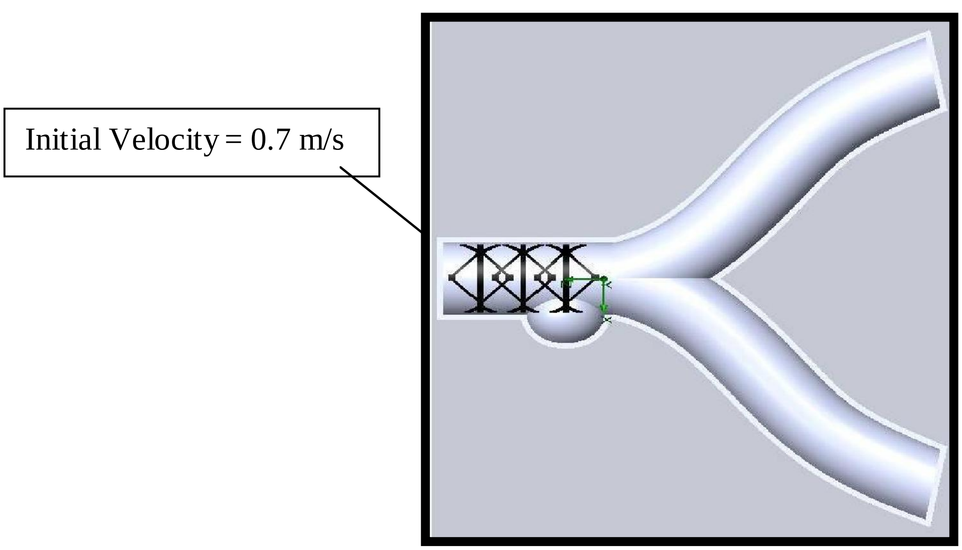


Figure 3.6: Inlet Velocity

3.4.2 Peak pressure systole and diastole

K.M. Khanafer et al, (2007) concluded that the vortex formation critical during the diastole which show significant change to the flow behavior. They analyzed numerically using a simulated physiological waveform in aneurysm. According to the discussions, peak deformation occur shortly after systolic peak flow velocity in the flexible wall model while in the CSS(Computational Solid Stress) model they take place at peak pressure. Due to the collision of the vortices with the wall that cause it to vibrate, local pressure increases which contributes to wall shear stress increase and weakening of the AA wall. Based on Figure 3.7 below, we can see the vortex formation.

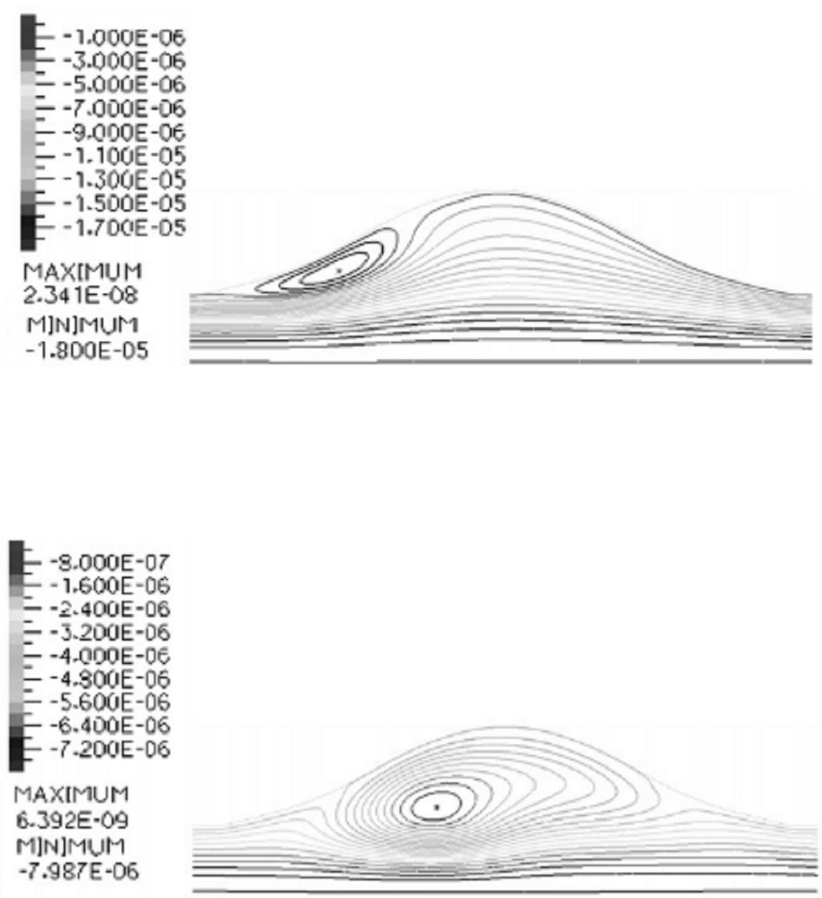


Figure 3.7: Vortex Formation
(K.M. Khanafer et al, (2007))

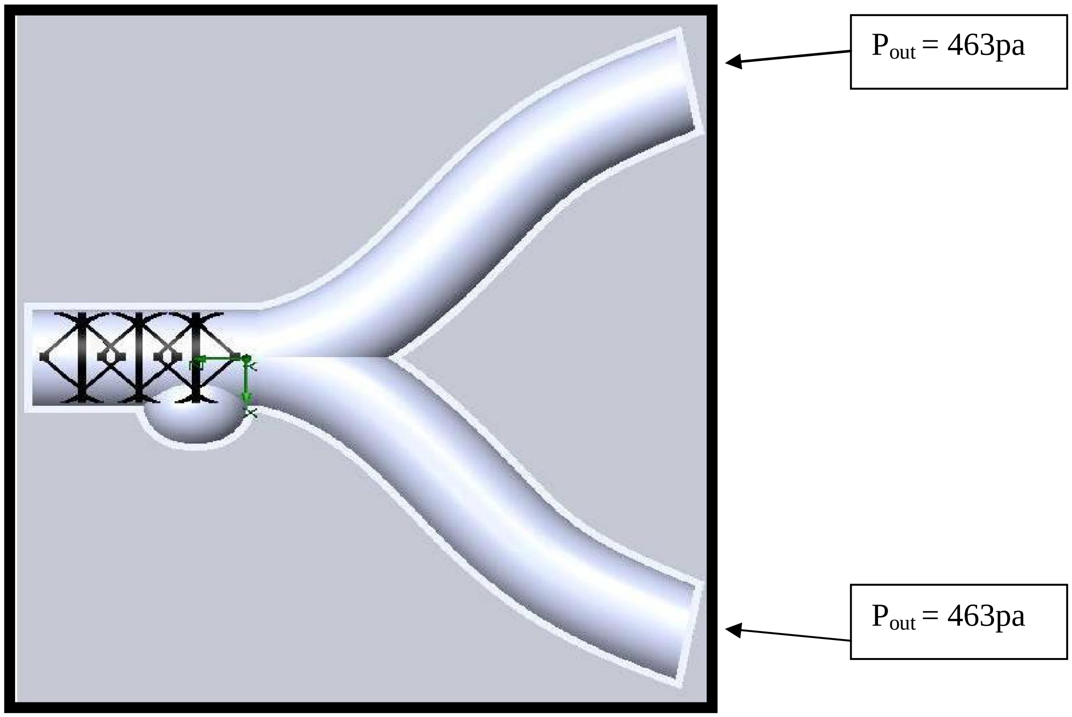


Figure 3.8: Pressure Output

CHAPTER 4

RESULT AND DISCUSSION

4.0 INTRODUCTION

In this chapter the data from the analysis using COSMOSflo will be assessed and the comparison for before and after treatment will be done. The discussion describes about the result and what were influencing the result of the experiment. Computational fluid dynamic simulations using the finite volume method have been applied to assess local changes of velocity, pressure, vorticity and shear stress in aneurysms, and these hemodynamic parameters are fairly well understood. The stent placement will affect the flow of blood inside the aneurysms.

4.1 RESULT

The result is based on the analysis that done in two condition. The first condition is the analysis of blood flow in cerebral aneurysms before the treatment or stenting process. The second condition is the analysis of flow phenomena in stented cerebral aneurysms. After an analysis performed, the flow phenomena in stented cerebral aneurysms is more stable compared to before the treatment. The analysis of aneurysms done in two different locations at the cerebral for three cases with the different size of dome for each case. The size of dome for each case is 3.5 mm, 4.5 mm and 5.5 mm in radius. The different locations will give the different result of velocity profile and pressure distribution.

4.2 VELOCITY PROFILE

From the simulation of blood vessel model, we can see the velocity profile. Velocity profile for stented and non-stented are different each other. The lowest minimum velocity refers to the simulations results and analysis for non-stented blood vessel. The magnitude of velocity for normal blood vessel is 0.7 m/s. Because of the aneurysms occurred, there will be velocity reduction once the flow passes through the aneurysms region. This because, there are energy losses during the blood flow. After stent implementation, the highest minimum velocity will be increased. The effect of stenting can be seen in Figure 4.1, Figure 4.2 and Table 4.1.

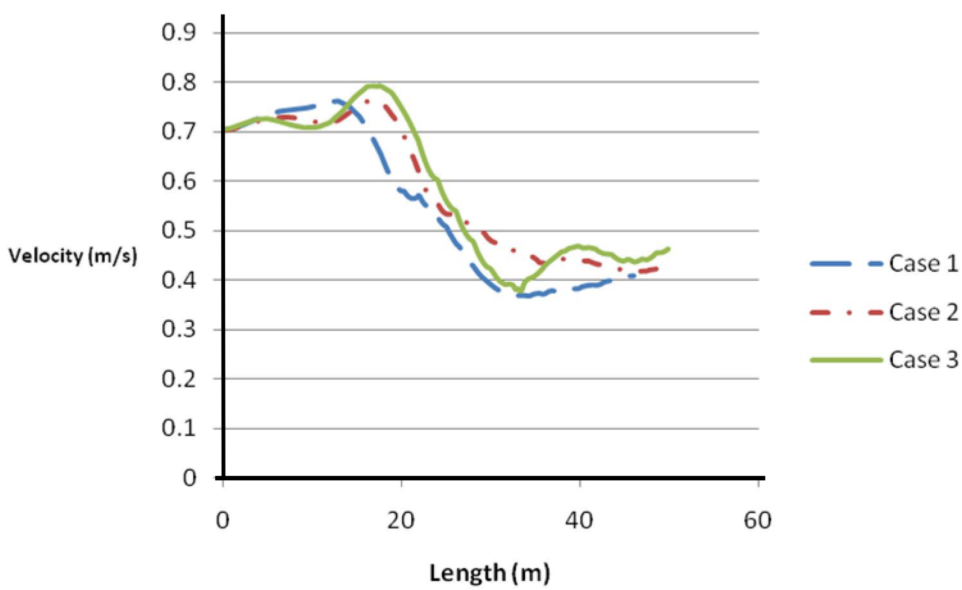


Figure 4.1: Velocity Profile for non-stented aneurysms for First Model

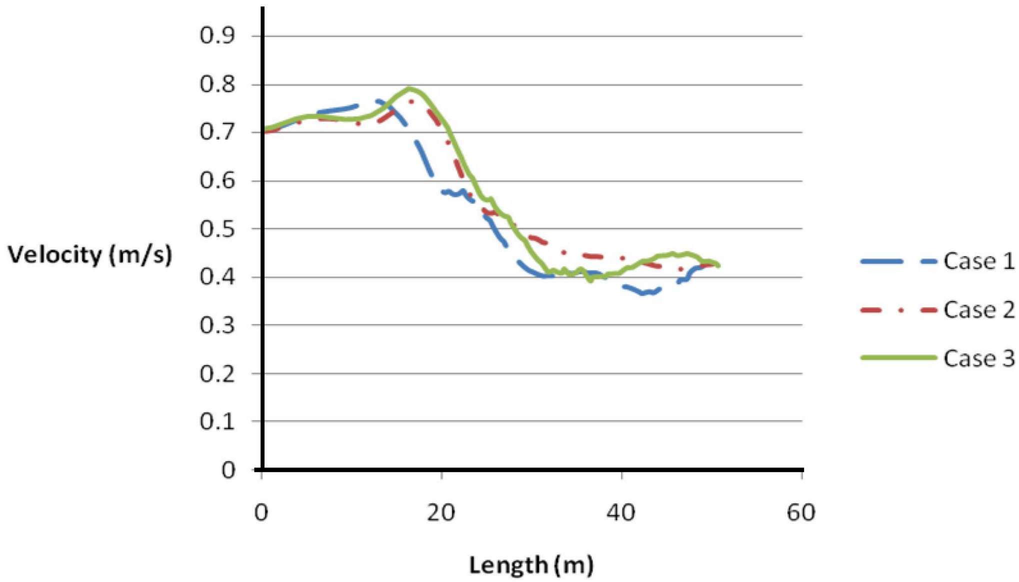


Figure 4.2: Velocity Profile for Stented aneurysms for First Model

Table 4.1: Minimum Velocity for non-stented and Stented Aneurysms for First Model

No	Aneurysms Case	Min Velocity(m/s) for non-stented	Min Velocity(m/s) for stented
1	**1**	**0.374**	**0.416**
2	**2**	**0.421**	**0.443**
3	**3**	**0.36**	**0.404**

Calculation percentage of velocity

Case I

$$\% = \frac{0.416 - 0.374}{0.374} \times 100$$

$$= 11.23\%$$

Case II

$$\% = \frac{0.443 - 0.421}{0.421} \times 100$$

$$= 5.23\%$$

Case III

% $= \frac{0.404 - 0.36}{0.36} \times 100$

$= 12.22\%$

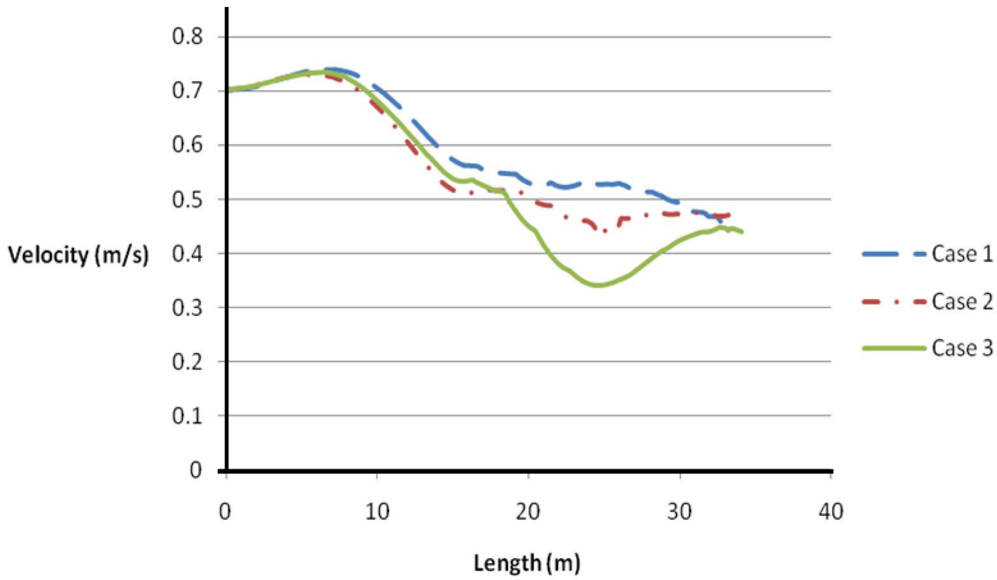


Figure 4.3: Velocity Profile for non-stented aneurysms for Second Model

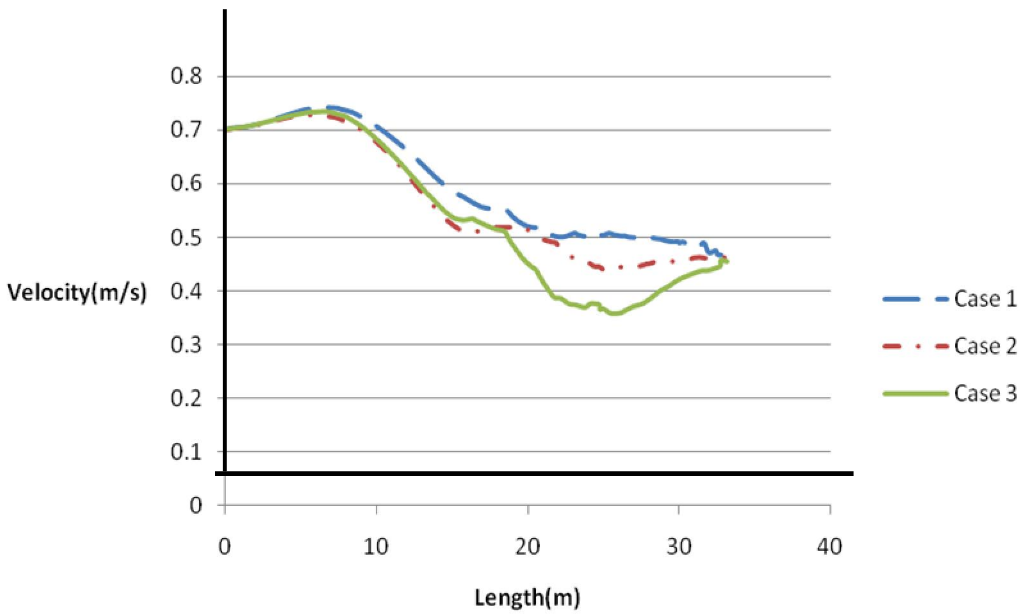


Figure 4.4: Velocity Profile for stented aneurysms for Second Model

Table 4.2: Minimum Velocity for non-stented and Stented Aneurysms for Second Model

No	Aneurysms Case	Min Velocity(m/s) for non-stented	Min Velocity(m/s) for stented
1	**1**	**0.487**	**0.495**
2	**2**	**0.424**	**0.454**
3	**3**	**0.343**	**0.382**

Calculation percentage of velocity

Case I

$$\% = \frac{0.495 - 0.487}{0.487} \times 100$$

$$= 1.64\%$$

Case II

$$\% = \frac{0.454 - 0.424}{0.424} \times 100$$

$$= 7.075\%$$

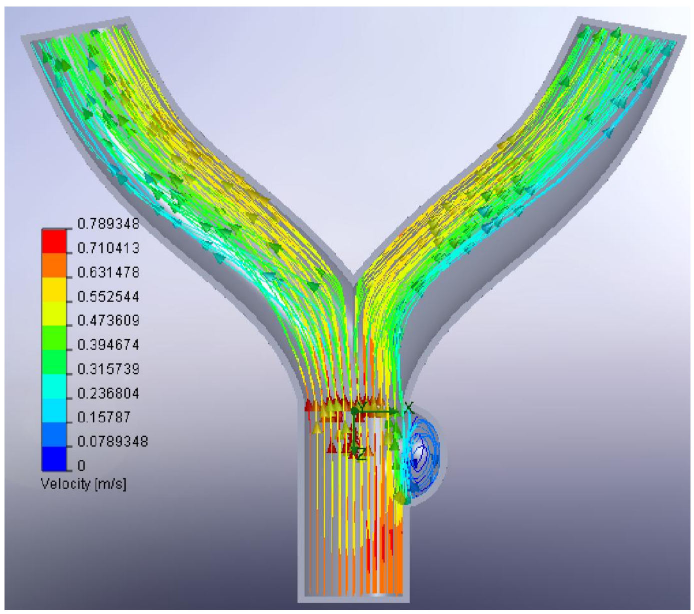
Case III

$$\% = \frac{0.382 - 0.343}{0.343} \times 100$$

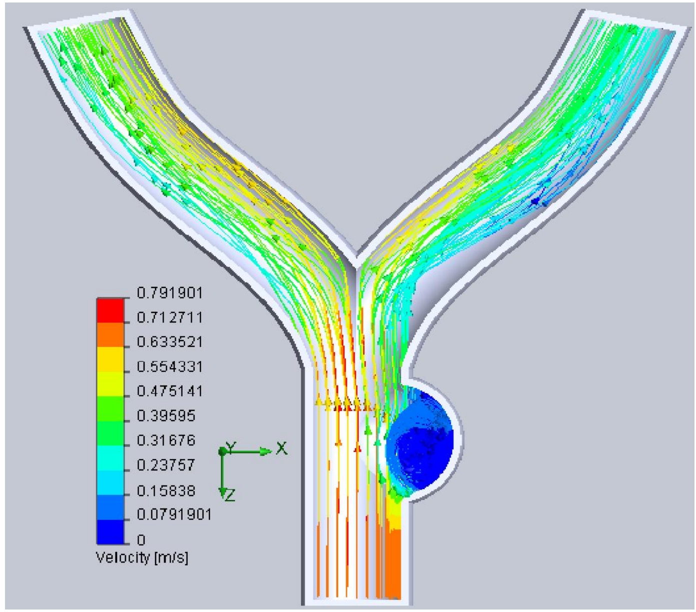
$$= 11.370\%$$

Stenting effect could be seen from the velocity profile inside the stented aneurysm at the same instances as previously selected for the non stented model. The large vortex formation that dominated the non stented aneurysm flow has reduced when selected stent applied. In Table 4.1 and 4.2 above, the higher minimum velocity obtained from the analysis. It shows that, the percentage of minimum velocity for each case is increased.

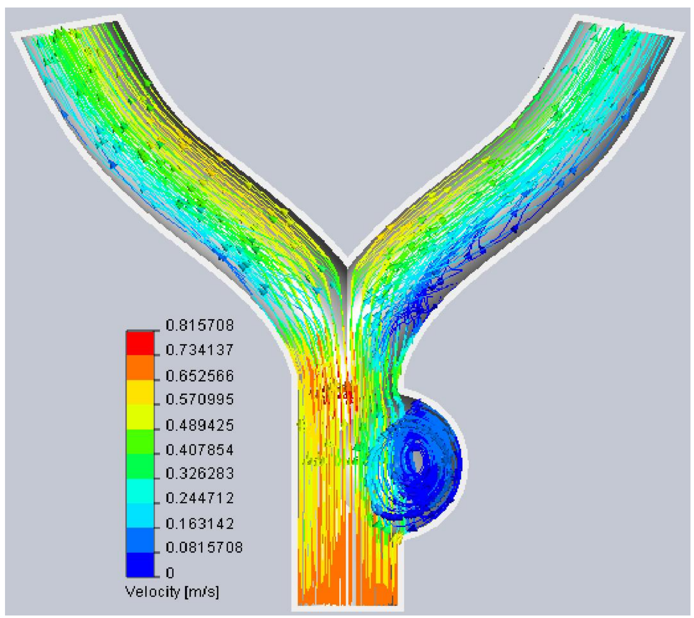
Figure 4.5 below, shows the velocity streamlines for three cases of aneurysms for first model with different size of aneurysms. The vortex formation can be seen in all cases. In cases 3, the large vortex was formed and reduced the minimum velocity. From the analysis, the lowest minimum velocity obtained in cases 3 due to the larger size of aneurysms compared to the case 1 and case 2. The larger size of aneurysms will caused the greater losses of energy. The minimum velocity for case 1 is 0.374 m/s, case 2 is 0.421 m/s and case 3 is 0.36 m/s.



(a)



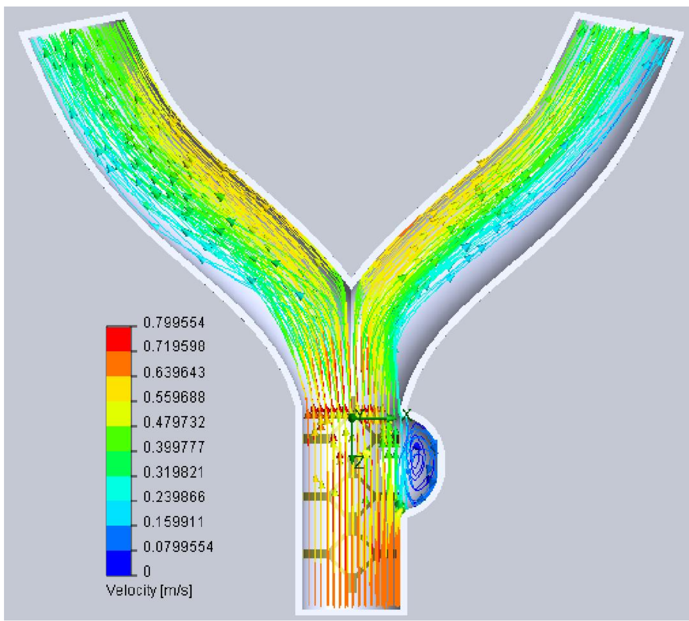
(b)



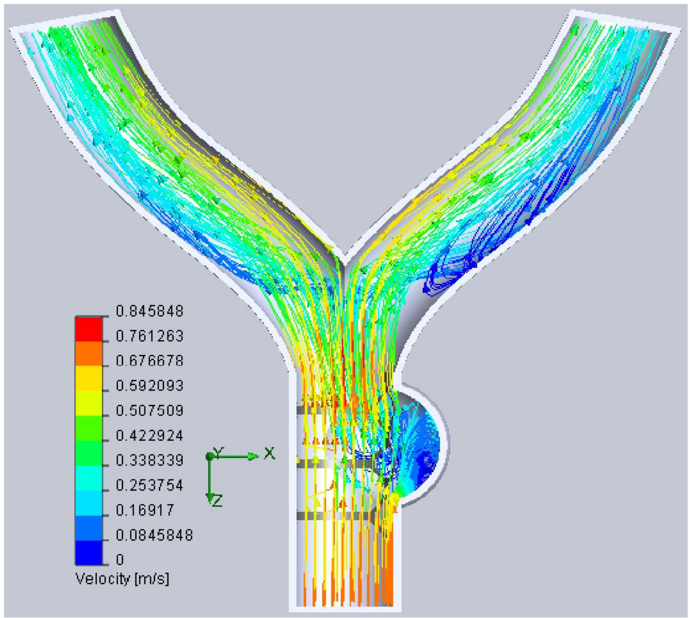
(c)

Figure 4.5: (a) Case 1 (b) Case 2 (c) Case 3
Velocity Streamlines for non-stented Aneurysms of First Model

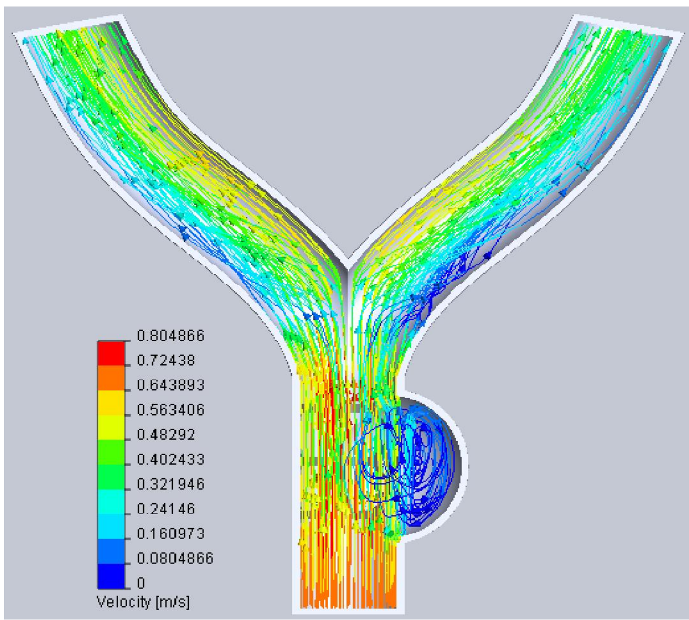
For Figure 4.6 below, shows the velocity streamlines for stented aneurysms of first model. To increase the higher minimum velocity, a selected stent is been used in blood vessel. The vortex formation for all cases were reduced after the stenting implementation compared to the before stenting implementation. Although there are still vortex formed in the aneurysms, but the higher minimum velocity for all cases are increased. The minimum velocity for case 1 is 0.416 m/s, case 2 is 0.443 m/s and case 3 is 0.404 m/s. The higher minimum velocity for all cases were increased compared to before stenting implementation.



(a)



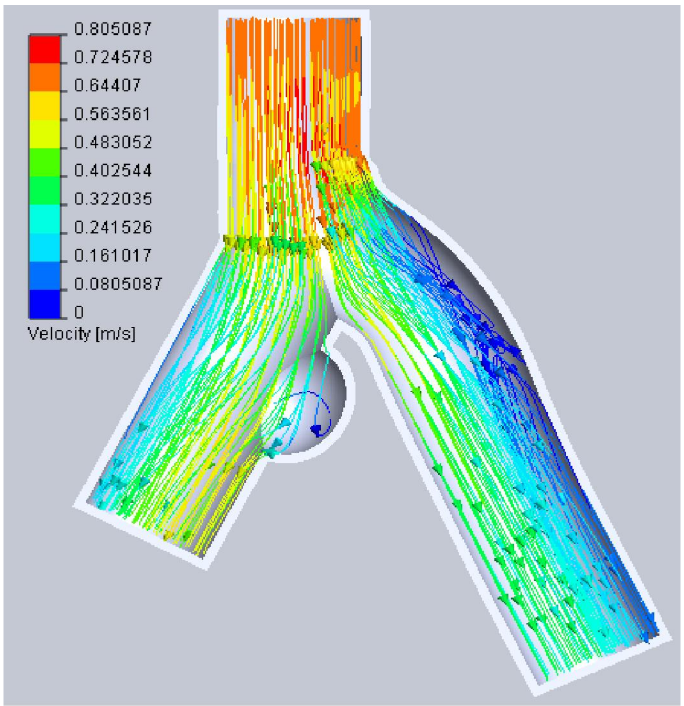
(b)



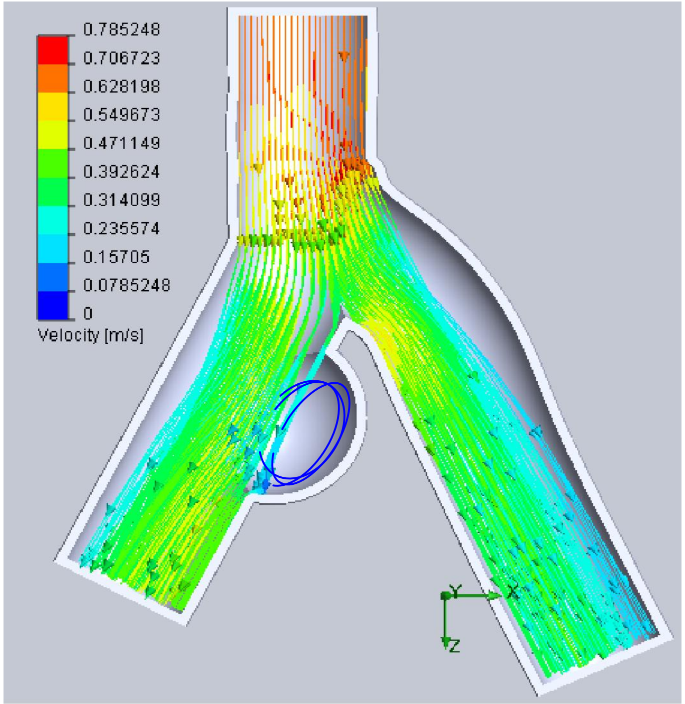
(c)

Figure 4.6: (a) Case 1 (b) Case 2 (c) Case 3
Velocity Streamlines for Stented Aneurysms of First Model

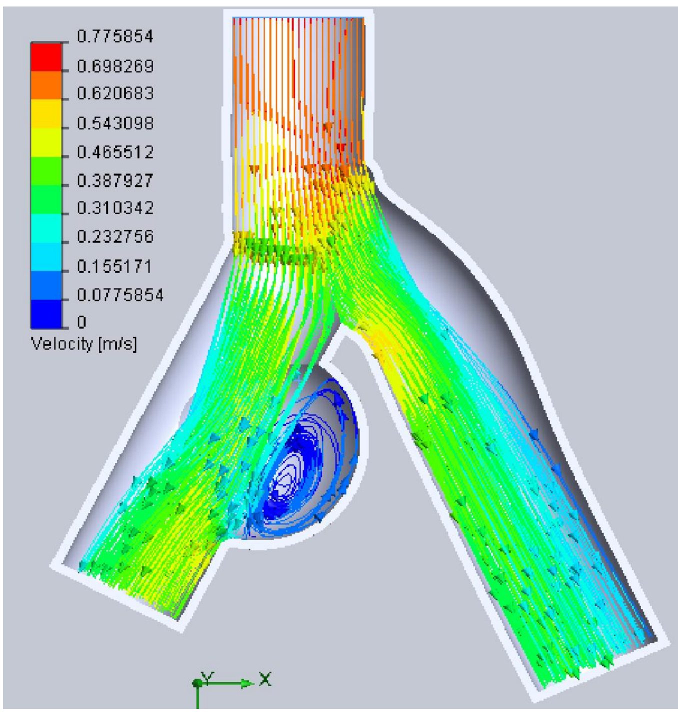
Figure 4.7 below, shows the velocity streamlines for three cases of aneurysms for second model with different size of aneurysms. The vortex formation can be seen in all cases. In cases 3, the large vortex was formed and reduced the minimum velocity. From the analysis, the lowest minimum velocity obtained in cases 3 due to the larger size of aneurysms compared to the case 1 and case 2. The larger size of aneurysms will caused the greater losses of energy. From the analysis of the second model, the minimum velocity obtained for Case 1 is 0.487 m/s, Case 2 is 0.424 m/s and Case 3 is 0.343 m/s. The reduction of velocity was large compared to the inlet velocity that is 0.7 m/s.



(a)



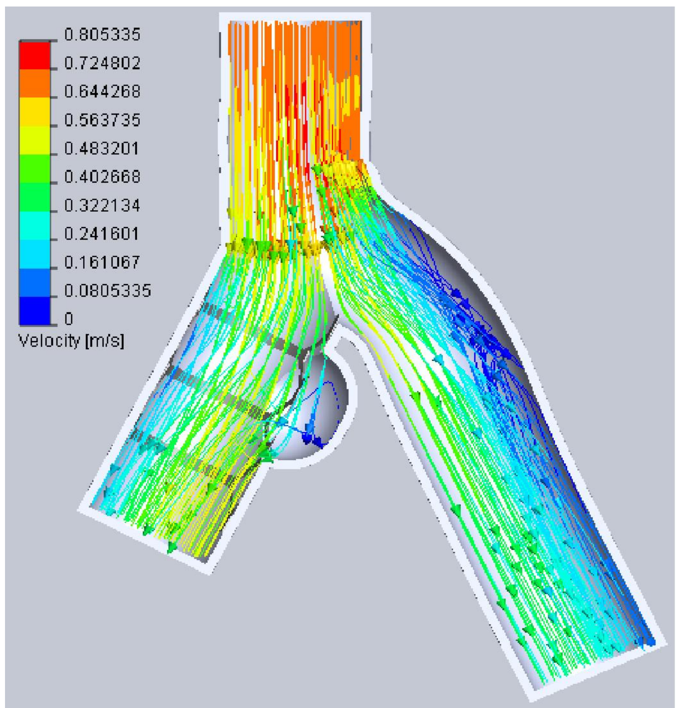
(b)



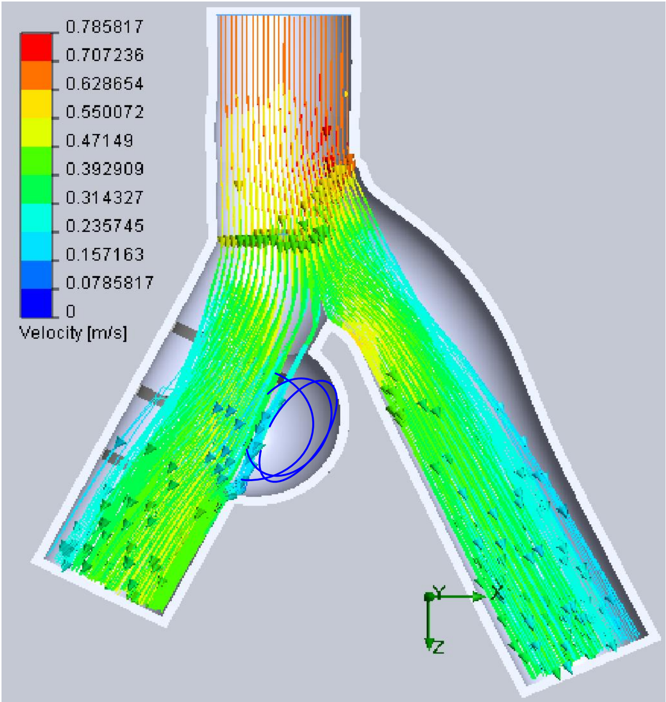
(c)

Figure 4.7: (a) Case 1 (b) Case 2 (c) Case 3
Velocity Streamlines for non-stented Aneurysms of Second Model

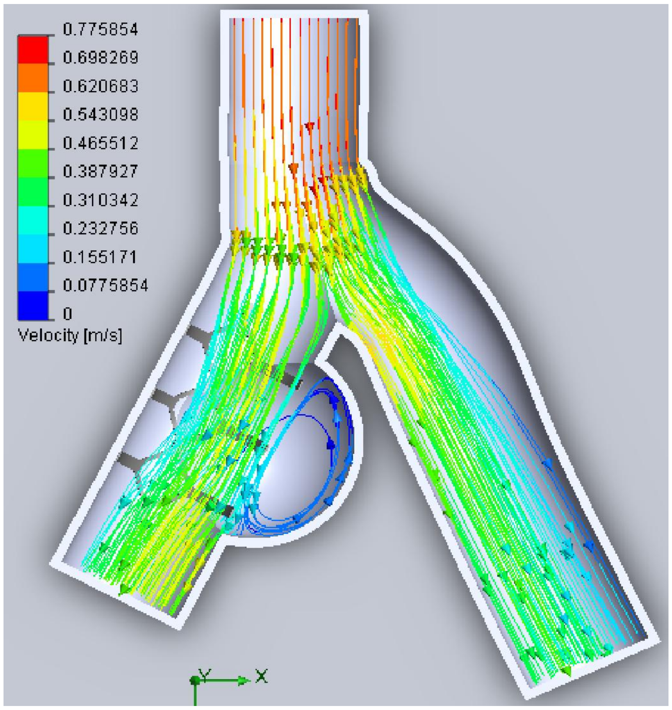
After stenting implementation, the vortex formed in the aneurysms was decreased. The stent implant will help to reduce the energy losses and increase the minimum velocity due to the vortex formation. In Figure 4.8 below, the effect of stent can be seen. Stent should modify the blood circulation in the aneurysms but not stop it from enter the aneurysms or dome. From the analysis done, the minimum velocity for all cases of second model was increased. For Case 1, the minimum velocity is 0.495 m/s, case 2 is 0.454 m/s and case 3 is 0.382 m/s. The increase of minimum velocity can prevent the aneurysms from rupture.



(a)



(b)



(c)

Figure 4.8: (a) Case 1 (b) Case 2 (c) Case 3
Velocity Streamlines for stented Aneurysms of Second Model

4.3 PRESSURE

Figure 4.9 and 4.10 represented the pressure profile inside the aneurysms for the first and second model. In the first model of non-stented aneursyms for all case, the high pressure was noted in the aneurysms region and peak pressure occurs before the flow enters the distal neck of aneurysms. The increased of pressure inside the aneurysms area was because of the growth of the aneurysms. The higher the size of aneurysms, the peak pressure will be higher.

After stenting process, the effect of stenting can be seen. The stent disturbed the flow of blood. This make the level of flow activity become higher and reduced the pressure. For the both models, the peak pressures were decreased as in Figure 4.9 and 4.10.

In Figure 4.9 below, the peak pressure before the stenting process was 453 Pa. After stenting process, the peak pressure reduced to 422 Pa. The effect of stenting can be seen from the reduction of pressure.

In Figure 4.10, the reduction of peak pressure can also be seen. Before the stent placement, the peak pressure was obtained that was 455 Pa. After the stent placement, the peak pressure was reducing to 432 Pa. The reduction of peak pressure was depending on the stent that used. In this analysis, the type of stent was not considered.

Bernoulli principle gives the relationship between velocity and pressure. According to Bernoulli principle, the exit pressure will be higher than the inlet pressure. The detail has been proved by the numerical calculation enclosed with the sample calculation. The data for calculation has been taken from the result of simulation. The initial value and the end result can be considered reliable.

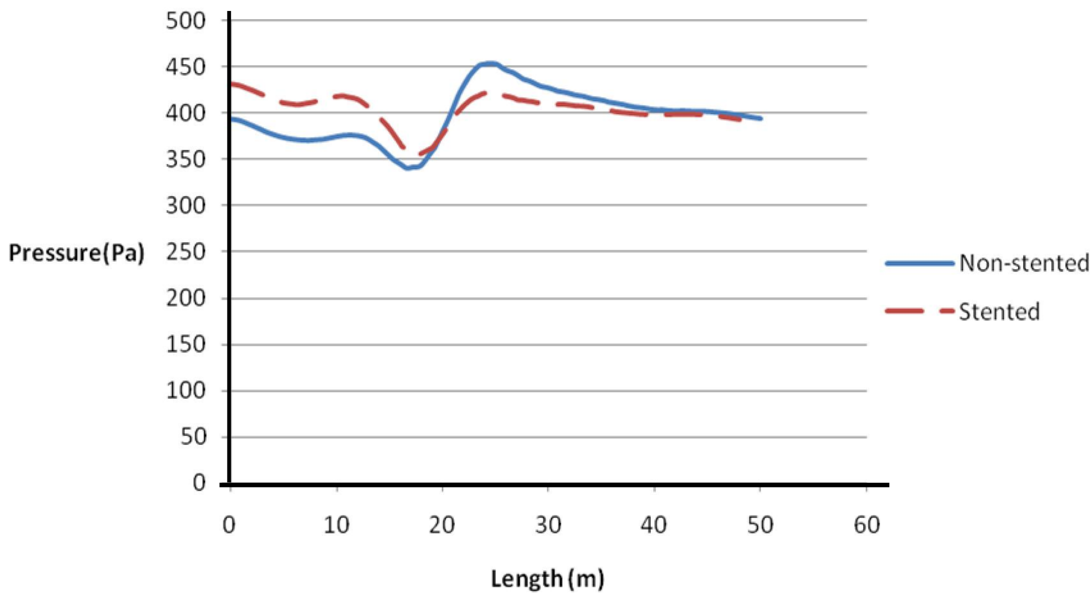


Figure 4.9: Pressure for Stented and non-stented aneurysms for First Model

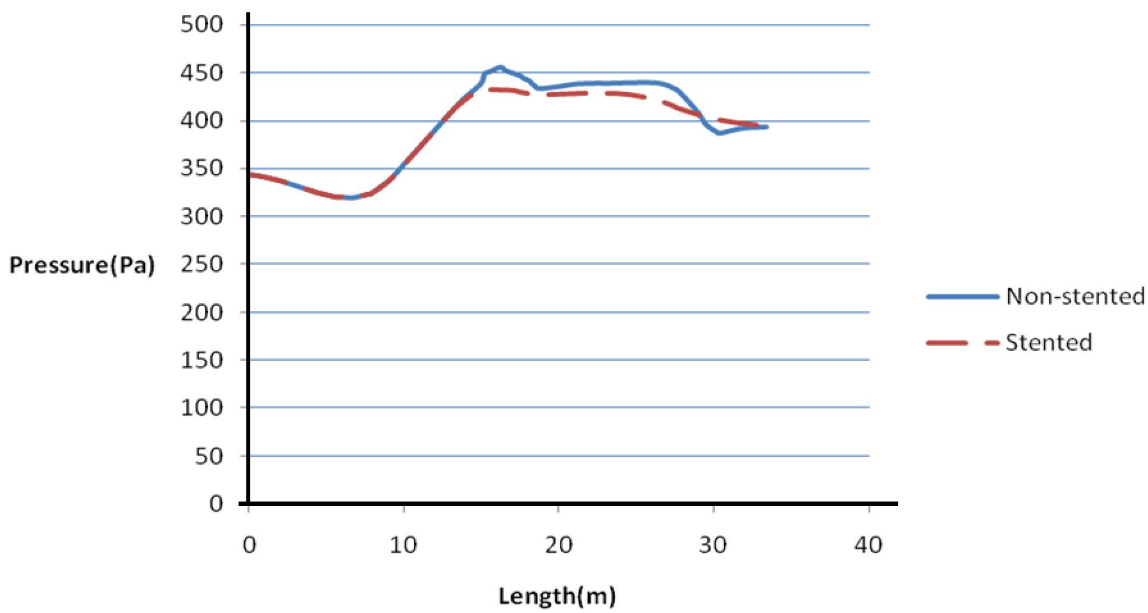


Figure 4.10: Pressure for Stented and non-stented aneurysms for second Model

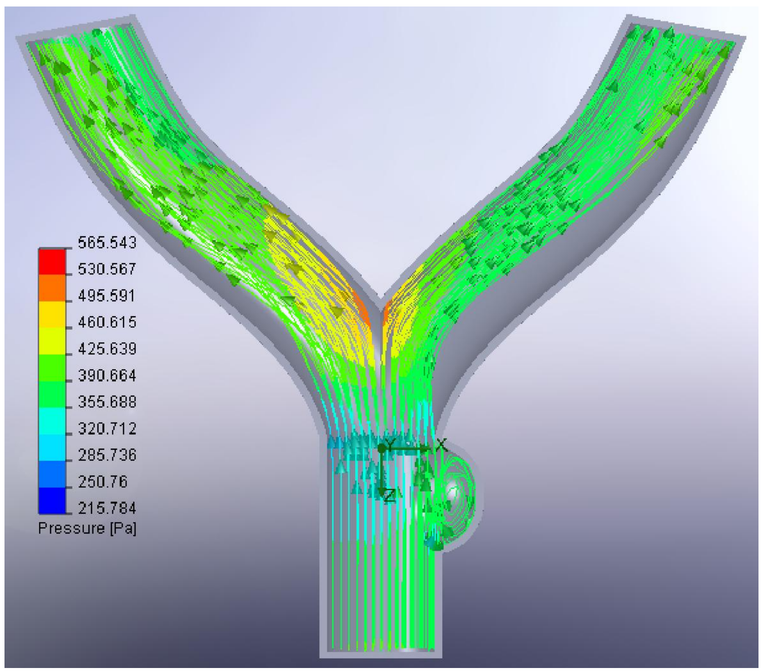
Table 4.3: Peak Pressure of non-stented and Stented Aneurysms for First Model

No	Aneurysms Case	Peak Pressure (Pa)
1	**Non-stented**	**453**
2	**With Stent**	**422**

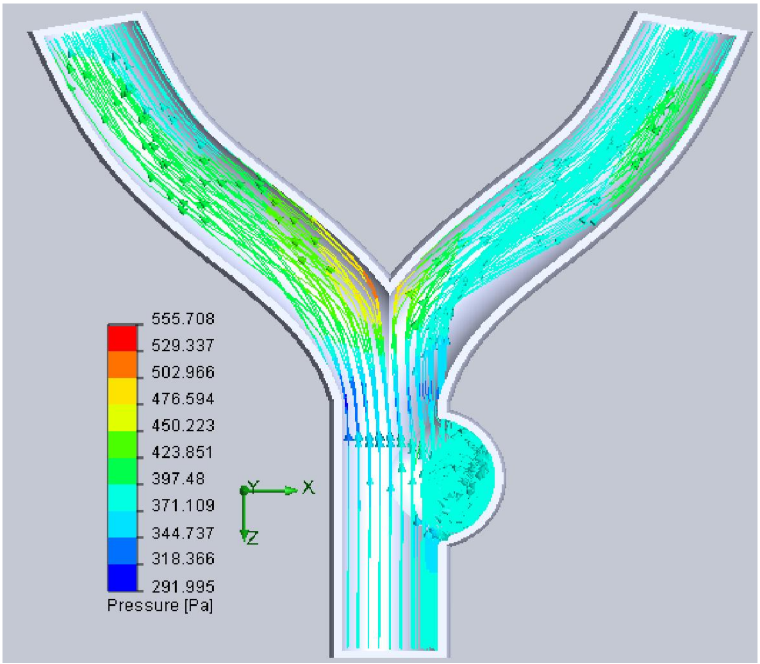
Table 4.4: Peak Pressure of non-stented and Stented Aneurysms for Second Model

No	Aneurysms Case	Peak Pressure (Pa)
1	**Non-stented**	**455**
2	**With Stent**	**432**

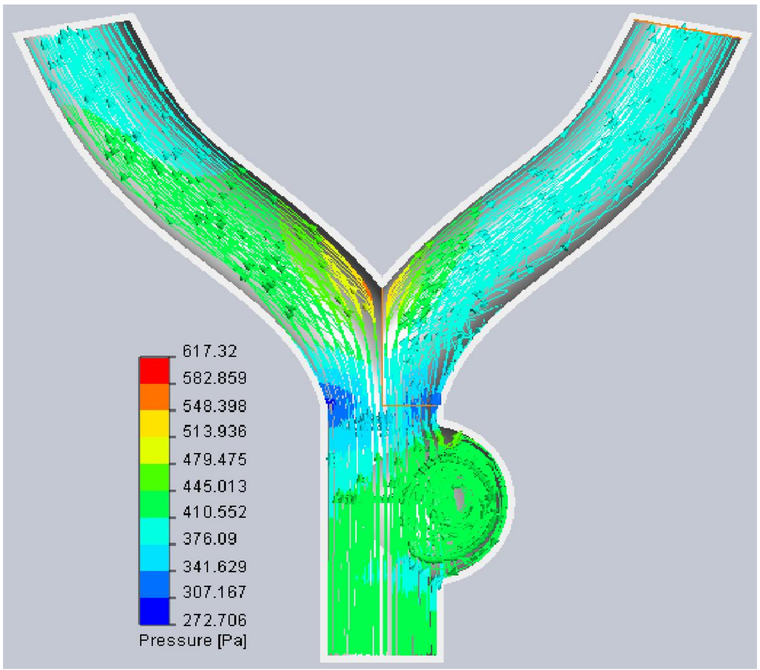
In Figure 4.11 below, the effect of aneurysms to the pressure distribution can be seen. Due to the aneurysms occurred, the pressure of blood were increased. The increased of pressure inside the aneurysms area was because of the growth of the aneurysms. The higher the size of aneurysms, the peak pressure will be higher. For case 1, the pressure obtained is 456 Pa, Case 2 is 453 Pa and case 3 is 454 Pa.



(a)



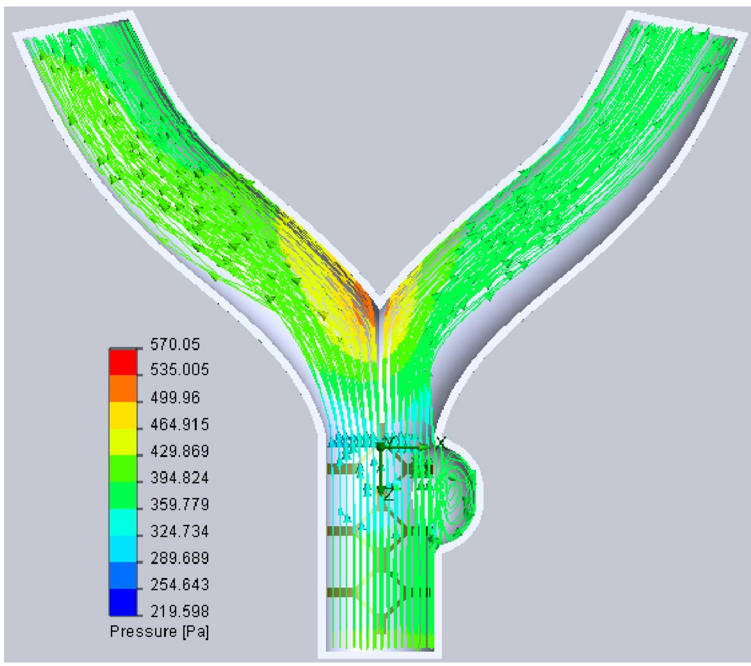
(b)



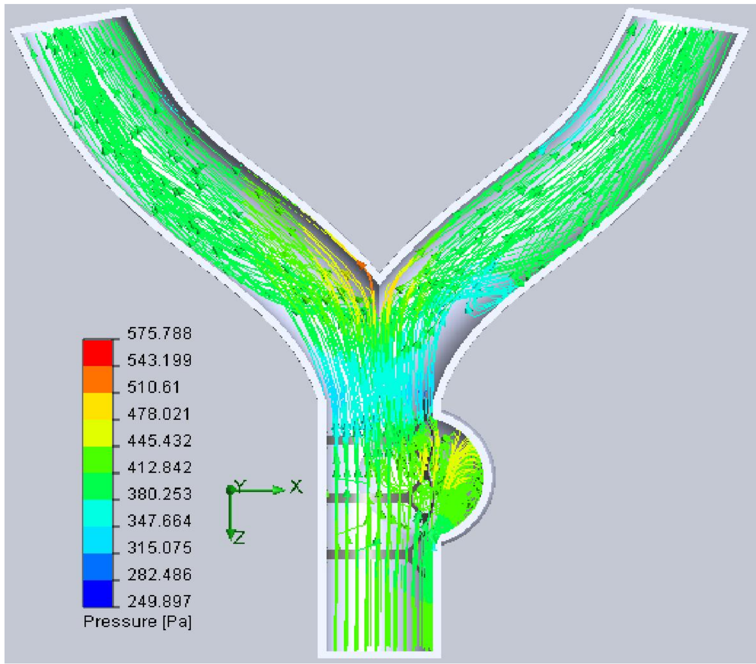
(c)

Figure 4.11: (a) Case 1 (b) Case 2 (c) Case 3
Pressure for non-stented Aneurysms of First Model

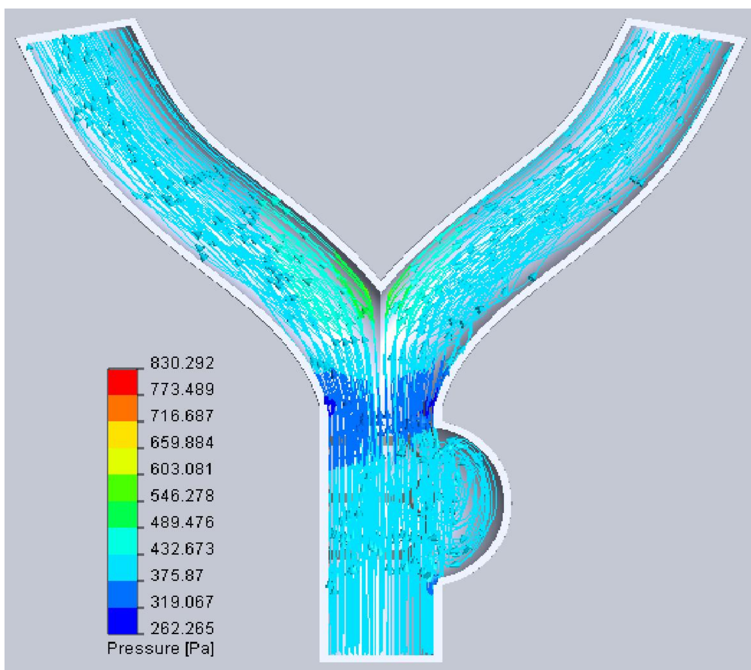
After stenting implementation, the vortex formed in the aneurysms was decreased. The stent implant will help to reduce the energy losses and decrease the pressure due to the vortex formation. Stent should modify the blood circulation in the aneurysms but not stop it from enter the aneurysms or dome. In Figure 4.12 below, the vortex formed in the aneurysms was decreased. This will help to reduce the peak pressure. For case 1, the pressure obtained is 450 Pa, Case 2 is 422 Pa and case 3 is 445 Pa. The decrease of peak pressure depends on the type of selected stent. In this analysis, the analysis was not focused on type of stent but only focused on the stenting effect.



(a)



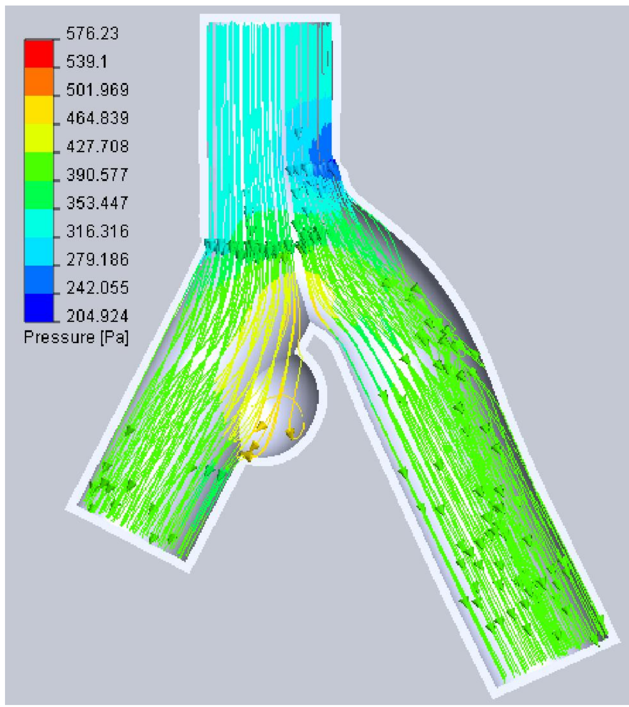
(b)



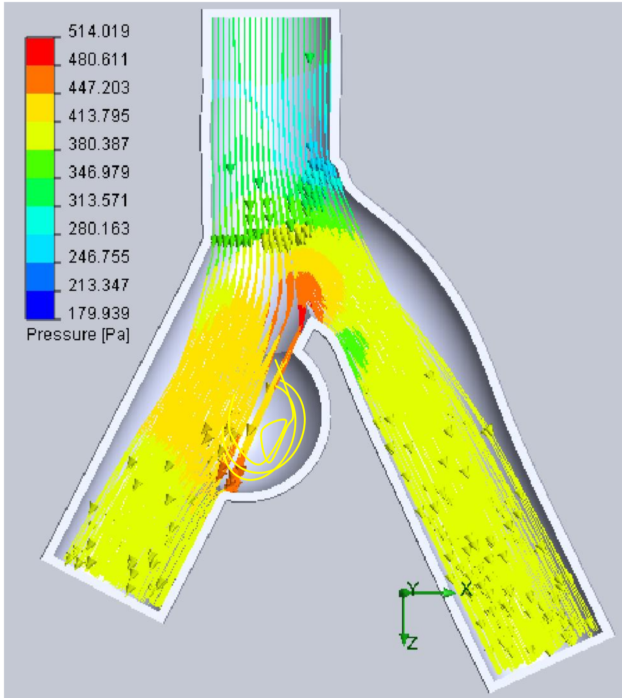
(c)

Figure 4.12: (a) Case 1   (b) Case 2   (c) Case 3
Pressure for Stented Aneurysms of First Model

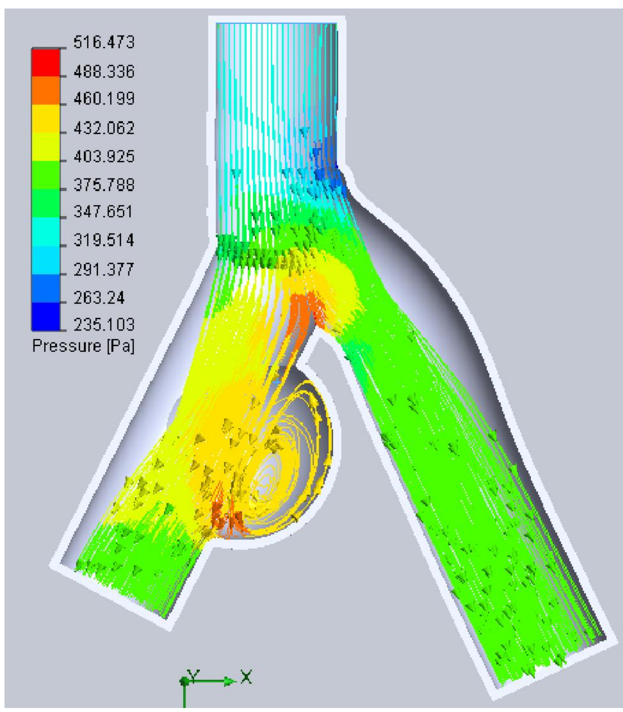
While, in Figure 4.13 below, the effect of aneurysms to the pressure distribution of second model can be seen. Due to the aneurysms occurred, the pressure of blood were increased. The increased of pressure inside the aneurysms area was because of the growth of the aneurysms. The higher the size of aneurysms, the peak pressure will be higher. For case 1, the pressure obtained is 427 Pa, Case 2 is 438 Pa and case 3 is 454 Pa. Each case gives different value of peak pressure. The higher value of peak pressure is obtained in case 3.



(a)



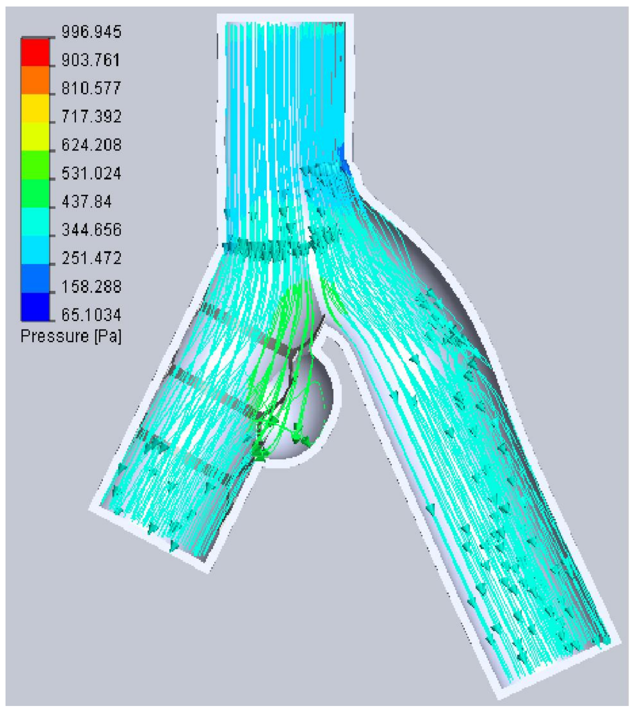
(b)



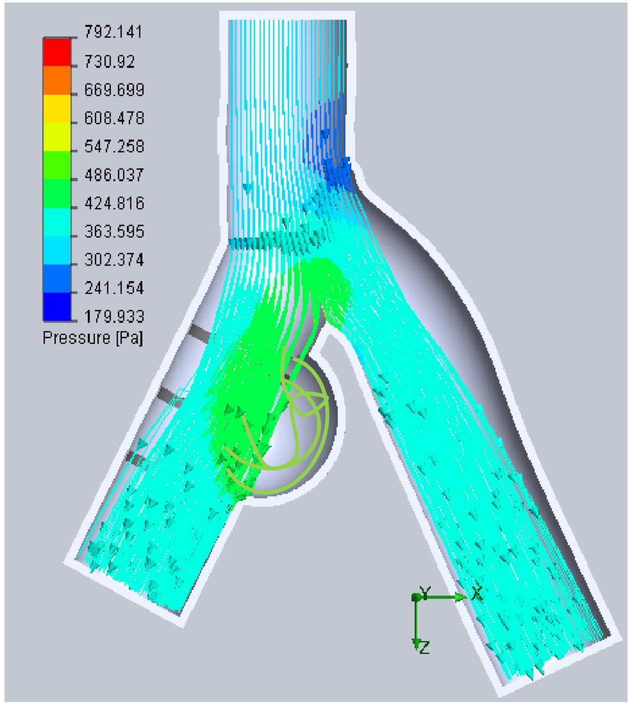
(c)

Figure 4.13: (a) Case 1 (b) Case 2 (c) Case 3
Pressure for non-stented Aneurysms of Second Model

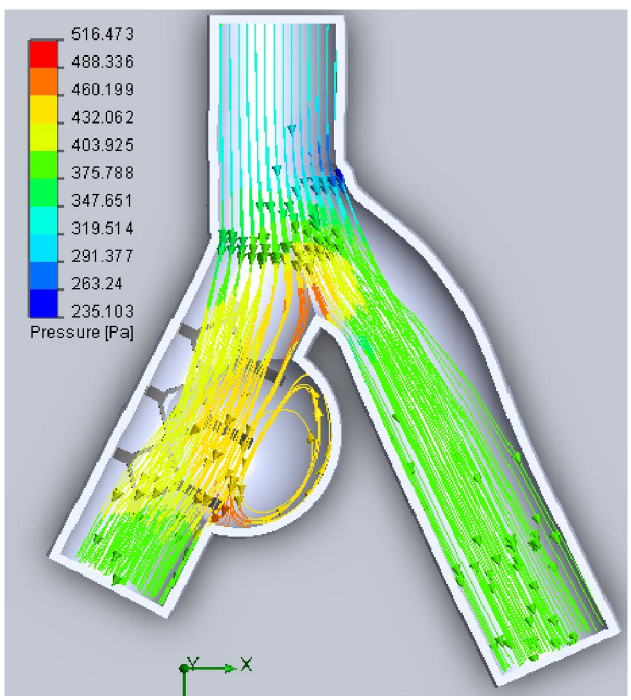
After stenting procedure, the vortex formed in the aneurysms was also decreased. The stent implant help to reduce the energy losses and decrease the pressure due to the vortex formation. In Figure 4.14 below, the vortex formed in the aneurysms was decreased after stenting process. This will help to reduce the peak pressure of aneurysms. For case 1, the pressure obtained is 419 Pa, Case 2 is 428 Pa and case 3 is 435 Pa. The value of peak pressure obtained is different compared to the first model. This shows that, different locations will give different value of peak pressure.



(a)



(b)



(c)

Figure 4.14: (a) Case 1 (b) Case 2 (c) Case 3
Pressure for Stented Aneurysms of Second Model

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

This study established the correlation between the location of aneurysms to the flow of phenomena and blood parameter. The analysis was done for stent and non-stented aneurysms to determine the velocity profile and pressure distribution.

Based on the plotted graph, the minimum velocity for both locations of aneurysms were different. From the plotted result, the second model gives the higher minimum velocity compare to the first model. For the both locations and cases, the higher minimum velocity was obtained after stenting process.

Stenting effect could be seen from the velocity profile inside the stented aneurysm at the same instances for the non stented model. The large vortex formation that dominated the non stented aneurysm flow has reduced when the selected stent applied.

As the conclusion, the stent will decrease the pressure and increase the minimum velocity. This help to prevent the rupture or burst of the aneurysms. Each location will give the different value of velocity and pressure. The aneurysms will affect the normal blood parameter.

5.2 RECOMMENDATIONS

In order to obtain strong correlation between the location of aneurysms to the flow of phenomena and blood parameter, the recommendations are as below:

1. For the selected stent used, the stent must be the best stent among the stent. So that, the effect of stenting to the flow phenomena can be seen clearly.
2. Pulse may have effect on the rupture of aneurysms in their growth rate. Therefore, future studies should consider the pulsatile condition of blood flow simulation by introducing the different Reynolds number.
3. The aneurysms size may differ from case to case. So, by varying the aneurysms size this study will be able to predict the effect of dome size to the flow behavior.
4. The analysis of aneurysms should be done in more different location in Circle of Willis.

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APPENDIX : Data for Plotted Results

First Model Without Stent For Case 1	
Length (mm)	Velocity
0	0.70334851
0.454720422	0.70399372
1.596853821	0.70944573
2.979315753	0.71971533
4.318489098	0.72992352
5.330431955	0.73662184
5.620191288	0.73817345
6.312053123	0.74154303
6.888953372	0.74330846
8.13357678	0.74604694
9.305983273	0.74861179
9.881140145	0.75068462
10.45362807	0.75346893
11.57737796	0.75984737
11.87849341	0.76160682
12.63544907	0.76228883
13.02112356	0.76262012
13.70637944	0.75633003
14.16427737	0.75238817
14.71624558	0.74249954
15.31638305	0.73195239
15.71111596	0.72148974
16.51179462	0.69953885
16.66572499	0.69406257
17.58988421	0.66047891
17.74439159	0.65490762
18.39748461	0.62577633
18.80601888	0.61092542
19.07837505	0.60243506
19.17982534	0.59857226
19.4578235	0.59035889
19.73582165	0.58426467
20.01381981	0.58031728
20.18724605	0.57955735
20.36067229	0.57966772
20.54415254	0.57462324
20.8272998	0.56883789
21.09198493	0.56577981
21.35667005	0.56467191
21.62135518	0.56543974
21.82930914	0.56746462
22.03726311	0.57056359
22.39586924	0.55962478
22.69410515	0.5525189
22.99234106	0.54786272
23.29057697	0.54560259
23.58881289	0.54568828
24.20266054	0.5245155
24.49890216	0.51647437
24.79514377	0.51081127
25.09138538	0.50749446
25.32338306	0.49897598
25.52869024	0.49223018
26.01415769	0.47769533
26.29431796	0.47102677
26.57447824	0.46637651
26.95682909	0.4540814
27.27324474	0.44547738
27.86403112	0.43176921
28.05809932	0.42841101
28.68847078	0.4132928
29.00365651	0.40684783
29.2125731	0.40330279
30.23330786	0.38761138
31.07860597	0.37702132
32.15935991	0.37064367
32.65141109	0.36757829
32.89926391	0.36681424
33.37681851	0.36801935
33.69518824	0.36773456
33.84456378	0.36776428
34.29269043	0.36674944
34.51258181	0.36733169
34.98341195	0.3710473
35.45424209	0.37210919
36.03011898	0.37052279
36.54259892	0.37578825
36.87130519	0.37715843
37.03565832	0.3772407
37.20001145	0.37692612
37.3600897	0.37705459
37.71066043	0.3767293
37.9011529	0.37700375
38.31510101	0.38040282
38.62494105	0.38240836
38.93478109	0.38286604
39.28960544	0.38128884
39.5117519	0.38134618
39.95604482	0.38186311
40.29813854	0.38533969
41.12492963	0.38849657
41.62100428	0.38890348
41.85443979	0.38867352
42.30607574	0.389924
42.91278408	0.39603253
43.73306878	0.3985288
44.18642956	0.40058563
44.40406832	0.40041668
44.93324649	0.40207304
45.46842954	0.40696614
45.76336869	0.40725738
46.09763444	0.40778838

First Model Without Stent for Case 2	
Length (mm)	Velocity
0	0.70213353
0.27940681	0.70344501
0.838220429	0.70442667
1.854617281	0.70969052
3.266381839	0.71813528
4.785231566	0.72544095
6.102034971	0.72892774
7.419954724	0.72957885
8.739380738	0.72678233
9.633483232	0.7232895
10.05880016	0.7212828
11.37568769	0.71788035
12.69163287	0.72162527
13.56807918	0.73096604
13.89958832	0.73516285
14.35638548	0.74093064
15.0197741	0.75003903
15.33949661	0.75449925
16.0919225	0.76072121
16.66521293	0.76554724
17.23536979	0.76173368
17.98815787	0.75656562
19.13158002	0.73046632
19.31568838	0.72615971
20.16437621	0.69656127
20.66053898	0.67896518
21.18320738	0.65574866
21.52521506	0.64077239
21.72692056	0.63064741
22.06306879	0.61479465
22.32296891	0.60131548
22.58286902	0.58928589
22.86099246	0.57860067
23.13911591	0.569868
23.41723935	0.56311533
23.57526453	0.56058789
23.81552011	0.55794818
24.0557757	0.55676222
24.23446896	0.5502177
24.50173993	0.5423304
24.76901091	0.53695612
25.03628188	0.5340158
25.24958587	0.53325967
25.59460639	0.53347671
25.93962692	0.53608294
26.27855707	0.52707377
26.61748723	0.5215556
26.8545206	0.51892287
27.09155397	0.51790799
27.37391194	0.51591248
27.65626991	0.51571008
27.88993682	0.50956666
28.12360372	0.50481208
28.4394092	0.49969016
28.75521467	0.49698348
29.07102015	0.49664628
29.28857851	0.49513827
29.54039158	0.48880196
29.86947745	0.48216356
30.19856333	0.47777548
30.52764921	0.47559877
30.88910508	0.47571312
31.12223147	0.47291699
31.43992851	0.466804
31.75762555	0.46259258
32.07532259	0.46025582
32.28002296	0.45977847
32.48472334	0.46006742
33.20635852	0.45784574
33.49994531	0.45170267
33.79353209	0.45016236
34.08711887	0.45021723
34.57779862	0.44815363
35.24010686	0.44009782
35.47448438	0.43500558
35.93294776	0.4343388
36.44310552	0.42944402
37.01524931	0.43302718
37.19248423	0.43122904
37.81975462	0.44220869
38.13164364	0.44239943
39.06731069	0.44325882
39.3320562	0.44177066
39.66497859	0.44084448
40.66374579	0.43838185
40.84025995	0.43857899
40.91528082	0.43865681
41.83453143	0.43239562
42.10947053	0.43143781
42.7117796	0.42921021
43.1612919	0.42654242
43.76093224	0.4236275
44.04335115	0.42321693
44.32577006	0.42284977
44.73291294	0.41999779
45.33482895	0.41871935
45.63452389	0.41917873
45.93421883	0.41971347
46.51369146	0.41718409
46.73102084	0.41742313
47.48315064	0.41821648
47.79186871	0.42020401

First Model Without Stent For Case 3	
Length (mm)	Velocity
0	0.705040143
0.274535233	0.706561808
0.8236057	0.707733756
1.775632647	0.713582847
3.244666	0.722898129
3.620136099	0.725310086
4.682735976	0.72681678
5.018103236	0.727232997
6.091035682	0.723099861
7.299014419	0.716828648
7.470321626	0.715882098
8.218968342	0.712534031
8.820220626	0.710422976
9.210660593	0.709113878
10.08265132	0.709617123
10.61044007	0.710105122
11.31984163	0.714919302
12.01109592	0.719896415
12.52714714	0.728284158
13.40942879	0.742520293
13.71479649	0.748945109
14.80866054	0.771333023
15.99960727	0.789419537
16.20931496	0.792851727
17.14985606	0.792977646
17.38499133	0.792958899
17.61089456	0.794113435
18.60700771	0.78367906
19.04083876	0.77688049
20.58726681	0.731640406
21.68645568	0.690734861
21.84984695	0.685316831
22.07724098	0.672130279
22.49129395	0.649434985
22.67795288	0.63989407
22.8646118	0.631413101
23.05127073	0.623997985
23.2510932	0.617358062
23.45091566	0.611979763
23.65073812	0.607865817
23.85056059	0.605016903
24.05038305	0.603431562
24.39040732	0.586441327
24.58608312	0.577677158
24.96786049	0.563146673
25.15396206	0.557268718
25.34006364	0.552248024
25.52616521	0.548096905
25.71226678	0.544795296
25.89836835	0.542330836
26.08446993	0.540691073
26.55911382	0.51800946
26.92759484	0.503379624
27.29607587	0.491874781
27.6645569	0.483449413
28.04158564	0.477876322
28.49406233	0.458323111
28.85587495	0.444901576
29.21768757	0.434471296
29.41088249	0.43026359
29.60407741	0.426925382
29.99046725	0.422694829
30.69137533	0.404689633
31.08850328	0.397281822
31.48563123	0.392769316
31.6841952	0.391578902
31.84111776	0.391874038
31.99804031	0.392609878
32.42463333	0.390983584
32.80130222	0.380947578
32.99483172	0.383447496
33.38189073	0.378097348
33.76894973	0.395512897
34.15600873	0.402047245
34.30734493	0.403753066
34.58673115	0.405425195
34.99888886	0.409949514
35.41104657	0.416313652
35.82320427	0.424507967
35.96951784	0.427937795
36.11583141	0.431597643
37.75113046	0.455365999
37.92453973	0.457770112
38.3249898	0.459654538
38.72543987	0.464571623
39.28604503	0.467071499
39.78463802	0.469495605
40.12838005	0.466502851
40.47212208	0.465402234
40.68719196	0.465581928
40.90226185	0.466506973
41.65401353	0.463753713
41.6800052	0.463755026
42.08202808	0.458347765
42.48405096	0.454889494
42.88607385	0.453373925
43.08708529	0.453341927
43.36482947	0.452333727
43.53202603	0.452167891
43.91016487	0.445995553
44.28830372	0.441751398
44.66644257	0.439427279
44.85551199	0.438982458
45.00123177	0.439889627
45.29267134	0.442508954
45.48716274	0.44205609
45.88968581	0.43832814
46.09094734	0.437143617
46.25876992	0.437794357
46.76223765	0.44144975
46.93006022	0.443234968
47.29832228	0.441823503

First Model With Stent For Case 1	
Length (mm)	Velocity
0	0.70334
0.43848172	0.703934
1.580604497	0.709212
2.89983081	0.718762
4.205873369	0.728595
5.312350394	0.735851
5.479912812	0.736746
6.410465752	0.741199
6.691005694	0.742137
7.870500268	0.745373
9.017497876	0.748254
9.713580363	0.75068
10.13255703	0.752993
11.22136667	0.759451
11.86271302	0.763395
12.26135206	0.763757
13.00730152	0.764189
13.31504311	0.761235
14.15689173	0.752857
14.31741294	0.749783
15.20887842	0.732829
15.29773788	0.73128
16.16984562	0.709604
16.4553361	0.703158
16.72357871	0.694656
17.04774123	0.683297
17.68451551	0.660693
17.89827704	0.65106
18.56835255	0.621572
18.73596754	0.61481
19.0859068	0.601186
19.40110389	0.589475
19.6744286	0.582588
19.94775331	0.577757
20.22107803	0.575017
20.44251993	0.575
20.76359883	0.577535
21.01731426	0.573301
21.27920132	0.57103
21.54108839	0.570524
21.80297545	0.571717
22.06486251	0.574544
22.32674958	0.578946
22.53427868	0.572659
22.79589187	0.565944
23.05750506	0.560994
23.31911825	0.557778
23.58073144	0.556262
23.84234463	0.556417
24.18112047	0.5442
24.44049715	0.535008
24.69987383	0.527604
24.95925051	0.52197
25.33365989	0.516919
25.56253244	0.507748
25.791405	0.499796
26.21995179	0.486591
26.41962603	0.48118
26.62371167	0.476957
26.8277973	0.473821
27.06610452	0.465553
27.30441173	0.458165
27.54271895	0.451644
27.8284338	0.445714
28.08880584	0.439978
28.34917789	0.435927
28.59750648	0.42982
28.91707822	0.423817
29.23664996	0.418675
29.5909794	0.413868
29.75774845	0.412268
30.07500052	0.409797
30.66196212	0.404707
31.20401229	0.401556
31.40661702	0.401123
31.5545896	0.40163
32.09817157	0.402147
32.23406707	0.402062
32.3767052	0.402089
32.80461957	0.410161
33.01132927	0.402123
33.23254702	0.403964
33.72230618	0.406915
34.04881228	0.407565
34.47086858	0.406978
34.70616685	0.407504
35.26402335	0.410673
35.42530246	0.410919
35.83889593	0.410013
36.17689379	0.408134
36.42385641	0.407634
36.86360475	0.408302
37.01426054	0.408265
37.46622793	0.405746
37.83820157	0.400935
38.13967671	0.398645
38.96926698	0.395442
40.17654898	0.380086
40.29334568	0.379245
40.43201646	0.379434
41.00420625	0.376295
41.42901815	0.372899
41.84516917	0.369317
42.12575857	0.366102
42.29735533	0.365188
42.6019302	0.36725
42.90650508	0.36833
43.21107995	0.368436
43.53792676	0.367022
44.1701328	0.3747
44.49194606	0.376532
45.1701328	0.3787
45.49194606	0.383532
46.1701328	0.3847
46.49194606	0.393532
47.21312382	0.3947
47.56456064	0.408353

First Model With Stent For Case 2	
Length (mm)	Velocity
0	0.702134
0.27940681	0.703445
0.838220429	0.704427
1.854617281	0.709691
3.266381839	0.718135
4.785231566	0.725441
6.102034971	0.728928
7.419954724	0.729579
8.739380738	0.726782
9.633483232	0.72329
10.05880016	0.721283
11.37568769	0.71788
12.69163287	0.721625
13.56807918	0.730966
13.89958832	0.735163
14.35638548	0.740931
15.0197741	0.750039
15.33949661	0.754499
16.0919225	0.760721
16.66521293	0.765547
17.23536979	0.761734
17.98815787	0.756566
19.13158002	0.730466
19.31568838	0.72616
20.16437621	0.696561
20.66053898	0.678965
21.18320738	0.655749
21.52521506	0.640772
21.72692056	0.630647
22.06306879	0.614795
22.32296891	0.601315
22.58286902	0.589286
22.86099246	0.578601
23.13911591	0.569868
23.41723935	0.563115
23.57526453	0.560588
23.81552011	0.557948
24.0557757	0.556762
24.23446896	0.550218
24.50173993	0.54233
24.76901091	0.536956
25.03628188	0.534016
25.24958587	0.53326
25.59460639	0.533477
25.93962692	0.536083
26.27855707	0.527074
26.61748723	0.521556
26.8545206	0.518923
27.09155397	0.517908
27.37391194	0.515912
27.65626991	0.51571
27.88993682	0.509567
28.12360372	0.504812
28.4394092	0.49969
28.75521467	0.496983
29.07102015	0.496646
29.28857851	0.495138
29.54039158	0.488802
29.86947745	0.482164
30.19856333	0.481778
30.52764921	0.47956
30.88910508	0.475713
31.12223147	0.472917
31.43992851	0.471804
31.75762555	0.470593
32.07532259	0.468026
32.28002296	0.461598
32.48472334	0.460067
33.20635852	0.454846
33.49994531	0.451703
33.79353209	0.450162
34.08711887	0.450217
34.57779862	0.451815
35.24010686	0.450098
35.47448438	0.447006
35.93294776	0.445339
36.44310552	0.443444
37.01524931	0.443027
37.19248423	0.443229
37.81975462	0.442209
38.13164364	0.442399
39.06731069	0.443259
39.3320562	0.441771
39.66497859	0.440844
40.66374579	0.438382
40.84025995	0.438579
40.91528082	0.438657
41.83453143	0.432396
42.10947053	0.431438
42.7117796	0.42921
43.1612919	0.426542
43.76093224	0.423627
44.04335115	0.423217
44.32577006	0.42285
44.73291294	0.419998
45.33482895	0.418719
45.63452389	0.419179
45.93421883	0.419713
46.51369146	0.417184
46.73102084	0.417423
47.48315064	0.418216
47.79186871	0.420204
48.40930487	0.421759
48.71802295	0.423326
48.97600095	0.425557
50.03769214	0.427328

First Model With Stent For Case 3	
Length (mm)	Velocity
0	0.705036
0.299599185	0.707612
0.898797554	0.708921
1.821128909	0.714663
3.309158372	0.724613
3.875367085	0.727954
4.764508201	0.731323
5.09114186	0.732574
6.188740418	0.732684
6.488867362	0.732699
7.584164545	0.730016
8.98341192	0.72695
9.2917623	0.72625
10.29562117	0.727086
10.69620744	0.727355
11.54705871	0.731657
12.09822663	0.734367
12.76877451	0.741611
13.49663243	0.749824
13.95554676	0.757553
14.91444244	0.773968
15.10119295	0.776183
16.16331703	0.788596
16.29168855	0.790062
17.6896939	0.779769
19.08801454	0.748933
19.23794408	0.744439
19.55873674	0.736451
20.5211147	0.712055
20.86925856	0.697843
21.85825155	0.657729
22.09128303	0.648842
22.45832682	0.632842
22.8253706	0.618897
23.00889249	0.612897
23.19241438	0.608524
23.37593627	0.605315
23.58672161	0.596214
24.09788116	0.575925
24.28069492	0.569674
24.46350867	0.564959
24.64632242	0.562108
24.82913617	0.560342
25.01194993	0.559549
25.19476368	0.559835
25.31409215	0.56079
25.43342061	0.562206
25.77235172	0.549427
25.94181728	0.5441
26.29579018	0.535472
26.64976309	0.529512
27.00315086	0.52585
27.3559535	0.52432
27.54659385	0.51648
27.73723419	0.509488
27.92787453	0.503335
28.50275213	0.487791
28.86282572	0.480609
29.22289931	0.475933
29.54777106	0.464027
29.87948311	0.453829
30.21803547	0.445423
30.69829656	0.434975
31.07052103	0.429002
31.45840732	0.41878
31.8462936	0.410256
32.23417989	0.413392
32.44062828	0.414077
32.93501214	0.409521
33.38928748	0.408776
33.59441753	0.41686
34.20980768	0.404997
35.01947775	0.41097
35.20427997	0.414873
35.57388441	0.415958
36.4978955	0.392324
36.66335244	0.399367
37.48266034	0.401213
38.2807036	0.402222
38.46100695	0.406455
39.65696177	0.407658
39.83555475	0.40953
40.03652788	0.412581
40.63944729	0.420018
40.82404486	0.419549
41.19323999	0.420465
41.2614921	0.421252
42.36441856	0.433486
42.57086271	0.433162
43.13831632	0.434784
43.70576993	0.439779
44.02345952	0.443674
45.03484082	0.445163
45.65058214	0.448749
46.02343057	0.445507
46.396279	0.444848
47.0891515	0.447805
47.26264463	0.448759
48.16694516	0.443636
48.52373487	0.439878
48.87559407	0.433451
49.25459878	0.432786
49.6111195	0.43325
49.68338668	0.433456
50.2823819	0.429565
50.4967062	0.428267
50.65404726	0.424791

Second Model Without Stent For Case 1	
Length (mm)	Velocity
0	0.7
0.477461903	0.7032272
1.010398333	0.704104
2.05840461	0.7096726
2.886056192	0.7166863
3.771441431	0.7245331
4.484775127	0.7304858
4.628085219	0.7315822
5.201325586	0.7359739
5.45697931	0.7370645
6.16851943	0.7402012
6.248921501	0.7405717
7.000480237	0.7401857
7.296684494	0.7401423
8.344592688	0.7333003
9.392509	0.7185062
9.865493346	0.7087195
10.44040693	0.696757
11.17948833	0.6783569
11.49005353	0.6708383
12.37087722	0.6459813
12.54451713	0.6414279
13.39495479	0.6151525
13.50178592	0.6121836
14.32461899	0.5884894
14.57809698	0.5820164
14.68837459	0.579471
15.15806422	0.5711494
15.47119064	0.5663757
15.63027217	0.5645756
15.78935369	0.5629409
16.56943122	0.5619524
16.9132699	0.5567134
17.44860038	0.5529498
18.12666352	0.5493953
18.28273315	0.5488706
19.03380057	0.5472882
19.16058946	0.5471892
19.37019112	0.5419428
19.65660785	0.5361054
19.94302458	0.5317123
20.22944132	0.5287604
20.40671722	0.5276362
20.71344078	0.5268653
21.02016435	0.5275439
21.32688791	0.5296652
21.48024969	0.5312645
21.79431118	0.5266262
22.07412845	0.5240456
22.35394572	0.5229987
22.63376299	0.5234713
22.78877737	0.5243786
23.10418303	0.5265065
23.4195887	0.5298816
23.73499437	0.5344926
23.86811875	0.5333306
24.29538503	0.5298252
24.60599982	0.5283815
24.75037859	0.5281028
24.89475737	0.528102
25.18351491	0.5289356
25.49310669	0.5282653
25.80269847	0.5292122
25.95749436	0.5302926
26.24170125	0.5273827
26.38390982	0.5262511
26.66204909	0.5218564
26.94018835	0.518717
27.21832762	0.5168334
27.34095409	0.5163837
27.46358056	0.5161788
27.58620703	0.5162188
27.74310978	0.5149103
27.90001253	0.5141365
28.05691528	0.5138973
28.16040847	0.5140228
28.58001942	0.5088996
28.78982489	0.5070003
29.05201382	0.5024966
29.31420275	0.4989916
29.52369575	0.496898
29.73318876	0.495445
29.99405259	0.4945325
30.17337163	0.4901651
30.35269068	0.487916
30.53183727	0.4795432
30.57111376	0.4788702
31.57111379	0.4758782
31.87315829	0.4693375
32.18231748	0.4688366
32.43360583	0.4685747
32.68489418	0.4598575

Second Model Without Stent for case 2	
Length (mm)	Velocity
0	0.701918418
0.237071893	0.703312151
0.711215679	0.703975554
1.291335592	0.706803037
1.759035741	0.709083884
2.226997985	0.712614814
3.230836798	0.720026261
3.94575305	0.724907136
4.18138668	0.725960675
4.970082675	0.729277896
5.12079095	0.729383917
5.949383744	0.730103755
6.874003428	0.726507178
6.99699087	0.726059717
7.748904723	0.717834327
8.044612764	0.714655064
8.558701214	0.704493772
9.092254065	0.693985444
9.379681338	0.686357986
10.13992519	0.666123484
11.18763182	0.633537465
11.64957078	0.617434391
12.37004988	0.592428431
12.90169517	0.573467623
13.05224088	0.568545286
13.90495155	0.542099103
14.21004513	0.533176624
14.3699855	0.5290822
14.83128088	0.519777313
15.29257626	0.512392648
15.47526996	0.510066976
15.76007164	0.510227845
16.04487332	0.511179392
16.32967499	0.512877651
16.6146551	0.515282318
16.81572976	0.519002111
17.78405381	0.516584471
18.25951584	0.516417715
18.8551331	0.516852673
19.26554652	0.517243702
19.54827589	0.510575215
19.85387563	0.504492966
20.44861206	0.495274374
20.74527718	0.491822936
21.07234108	0.489308418
21.52348819	0.487620149
21.79332767	0.479855832
22.06316715	0.473545214
22.33849604	0.468647292
22.91761521	0.461688153
23.21591608	0.45986516
23.36506651	0.459601926
23.66336738	0.460369195
23.75611635	0.46102283
24.15325382	0.455401044
24.4706384	0.442774549
24.78802298	0.429074528
25.04424283	0.442980037
25.33462231	0.445432321
25.6250018	0.457152332
25.91538129	0.451452624
26.07075187	0.464161982
26.24522304	0.464624647
26.40719824	0.464489286
26.89312383	0.4653861
27.18351107	0.466922201
27.44033515	0.471893626
27.59921891	0.47188968
27.91698644	0.470032749
28.04836003	0.471040231
28.44248081	0.475709469
28.63019628	0.476106388
28.94869986	0.473558294
29.26720344	0.472266658
29.42645523	0.472092074
29.55668674	0.472244041
29.81714975	0.473173485
30.11403919	0.471718688
30.26248391	0.471626763
30.55937334	0.472713358
30.71794158	0.474018473
30.87650982	0.475804434
31.00086459	0.475708009
31.40941952	0.471964091
31.56399911	0.471128465
31.87315829	0.470366004
32.18231748	0.470815178
32.43360583	0.469337547
32.68489418	0.468836555
33.00381993	0.469631548
33.34549249	0.472231926
33.64176601	0.468574713
33.92076194	0.474269717
33.96063	0.477691868
33.96063005	0.477691868

Second Model Without Stent For Case 3	
Length (mm)	Velocity
0	0.70116067
1.034604443	0.70480891
1.274454887	0.70606187
2.036636462	0.71007385
2.360060321	0.71242184
3.172586736	0.71833187
4.148692995	0.7254518
5.192571179	0.73124881
5.529684765	0.73300737
6.019210701	0.73337767
6.708207545	0.73400936
7.648727892	0.72723184
7.88672837	0.72557999
9.06525757	0.70480077
10.24388582	0.67560256
10.70066385	0.66260331
11.42264463	0.64201313
12.10754259	0.62016997
12.60621024	0.60500275
13.24465674	0.5834153
13.53253459	0.57596302
14.13477372	0.5578812
14.45398873	0.54901907
14.76944173	0.54211834
15.08489473	0.53607573
15.34502447	0.53391248
15.60515421	0.53259243
15.84915682	0.53273334
16.33716204	0.5352056
16.43017468	0.53295291
17.05576454	0.52445433
17.83708805	0.51552323
18.40951933	0.51137894
18.74069408	0.49544561
19.00307674	0.48423937
19.46346349	0.46659843
19.6614676	0.45978742
19.93102904	0.45217275
20.20059048	0.4457933
20.47015193	0.44064601
20.66825675	0.4308837
21.01083855	0.41469736
21.35342034	0.40068175
21.69600213	0.38882892
22.10007727	0.37746905
22.41883666	0.37130576
22.73759605	0.36717322
23.06124782	0.35926141
23.47381973	0.35049727
23.77331355	0.34562455
24.07280737	0.34226847
24.37230119	0.34042288
24.67179501	0.34007969
24.71737619	0.34020515
24.94257414	0.34049979
25.4438979	0.34412132
26.04291619	0.35078348
26.3409286	0.35398569
26.638941	0.35821879
26.88169183	0.36242751
27.66520833	0.37941186
28.69094004	0.40110943
29.21075516	0.40902863
30.01434441	0.42336195
31.33747087	0.43781693
31.77809861	0.43871324
32.04395438	0.44038672
32.30981015	0.4429108
32.66046502	0.44754248
32.67905615	0.44761547
33.10754273	0.44545808
33.21312373	0.44154581
33.45675427	0.44545808
34.10754273	0.43954581

Second Model With Stent For case 1	
Length (mm)	Velocity
0	0.70000001
0.468338068	0.7031578
1.010186956	0.70408043
2.058005706	0.70960638
2.850497968	0.71633775
3.719020733	0.72417179
4.532056758	0.73123125
5.200783819	0.73659299
6.109992959	0.74067132
6.248528069	0.7412743
7.296386796	0.74020419
7.617050339	0.73779248
8.344631842	0.73238114
9.029326242	0.72247643
9.394081481	0.71727913
10.32140267	0.69915531
10.44616909	0.69679408
11.43004128	0.67478005
11.50345419	0.67323878
12.26304881	0.65425809
12.58851037	0.64644916
12.73783848	0.64218403
13.48447904	0.62189373
13.82436975	0.61282646
14.40930007	0.5978511
14.70265285	0.59093954
15.24892633	0.58176279
15.65863143	0.57586428
15.74276468	0.57498
16.08923304	0.56862106
16.6622174	0.55984209
16.88462025	0.55693839
17.51394056	0.55315169
18.16938733	0.55048833
18.31481558	0.55017028
18.60567208	0.54969511
18.75912613	0.54461296
18.91258018	0.54003793
19.06603423	0.53596883
19.36251414	0.52946994
19.64856584	0.52470281
19.80383454	0.52258069
20.11437193	0.51966484
20.42490933	0.51851547
20.61381059	0.51851707
20.80271185	0.51907521
20.94695692	0.5150324
21.08366721	0.51183802
21.35708777	0.50680726
21.63050834	0.50357701
21.93066145	0.50141226
22.08073801	0.50100509
22.22992504	0.50118422
22.52829911	0.50284057
23.0288373	0.50836953
23.21529074	0.50590954
23.50377455	0.50330122
23.79225836	0.50205522
23.93650026	0.50194197
24.01406813	0.50521058
24.30902399	0.50967531
24.60397985	0.50637287
24.8989357	0.50420034
25.19389156	0.50716232
25.35950948	0.50794682
25.60252911	0.5056635
25.9091832	0.50380732
26.2158373	0.50295632
26.36916435	0.5029081
26.58260412	0.50122664
26.72420626	0.50057144
27.00741055	0.50017707
27.29061483	0.50100461
27.54034875	0.50278684
27.65425098	0.50275711
27.76815321	0.50299285
28.00265883	0.50087351
28.23716445	0.49926613
28.47167007	0.49817037
28.70883565	0.497583
28.92023414	0.49532965
29.13163263	0.49369147
29.34303113	0.49266973
29.60945395	0.4922763
29.87587678	0.4928661
29.94005088	0.49059759
29.97985182	0.4900252
30.03407984	0.49116232
30.1738887	0.49194339
30.31742679	0.49043819
30.60450298	0.4820362
30.76804559	0.48439611
30.9315882	0.48423937
31.33888026	0.48659843
31.60068617	0.48978742
31.89979918	0.47217275
32.34846868	0.4757933
32.49802518	0.46817037
32.72047339	0.467583

Second Model With Stent For case 2	
Length (mm)	Velocity
0	0.7
0.505108315	0.70322396
1.060164305	0.70415978
1.309641058	0.70534497
2.087242559	0.7091137
2.229394552	0.7101559
3.105686523	0.71657212
4.153303562	0.72378306
5.090703066	0.72759563
5.337848339	0.72804479
6.034591487	0.72808952
6.248544996	0.72811318
6.895918013	0.72508165
7.296161958	0.72327938
7.758350657	0.71817249
8.343752991	0.71183412
8.593633189	0.70709377
9.391339834	0.69207714
10.14709476	0.67285184
10.43895006	0.66541472
11.49968831	0.6334378
11.64772878	0.62842985
12.78746669	0.59015381
13.04854843	0.58133127
14.07286288	0.54831482
14.37353516	0.53935341
14.65289464	0.53155999
15.13755063	0.52095592
15.46065463	0.51481845
15.597193	0.51289761
15.73373138	0.51113437
16.02319076	0.51059944
16.31265014	0.51076522
16.60210953	0.51159434
16.8455353	0.51359554
17.22983441	0.51995331
17.83472914	0.51919501
17.99659952	0.51899242
18.80858491	0.51946487
19.18702496	0.51981315
19.41135407	0.51976557
19.69046607	0.52042373
20.12282921	0.51064792
20.67638069	0.50091905
21.10006195	0.4952603
21.52187678	0.49194339
21.80158649	0.49043819
22.05336912	0.4820362
22.32753282	0.47439611
22.62407759	0.46790217
23.07137383	0.46081046
23.37287678	0.4573197
23.67437974	0.45567978
23.76749726	0.45565594
23.86061478	0.45580519
24.33471944	0.44676721
24.65639204	0.44616555
24.97806464	0.43967502
25.12191646	0.43959284
25.56345663	0.44115806
25.87112965	0.44352209
26.02496615	0.44536647
26.36822965	0.44491017
26.62351752	0.44545381
26.78316618	0.44531859
27.10246348	0.44571506
27.24601329	0.44642828
27.67666272	0.44962241
27.82021252	0.45103992
27.9662951	0.45148787
28.17883247	0.45308678
28.39136983	0.45538263
29.0009994	0.4573917
29.31689607	0.45603134
29.4748444	0.45578896
29.61465326	0.45603243
30.03407984	0.45809974
30.1738887	0.45923459
30.31742679	0.45905376
30.60450298	0.45980224
30.76804559	0.46100069
30.9315882	0.46267182
31.33888026	0.46351114
31.60068617	0.46212002
31.89979918	0.46155641
32.34846868	0.46260881
32.49802518	0.46346566
32.72047339	0.4628658
33.03773346	0.46329055
33.35499353	0.46512398
33.59924648	0.47151229
33.65478211	0.47175807

Second Model With Stent For Case 3	
Length (mm)	Velocity
0	0.7011607
1.034604443	0.7048089
1.274454887	0.7060619
2.036636462	0.7100738
2.360060321	0.7124218
3.172586736	0.7183319
4.148692995	0.7254518
5.192571179	0.7312488
5.529684765	0.7330074
6.019210701	0.7333777
6.708207545	0.7340094
7.648727892	0.7272318
7.88672837	0.72558
9.06525757	0.7048008
10.24388582	0.6756026
10.70066385	0.6626033
11.42264463	0.6420131
12.10754259	0.62017
12.60621024	0.6050028
13.24465674	0.5834153
13.53253459	0.575963
14.13477372	0.5578812
14.45398873	0.5490191
14.76944173	0.5421183
15.08489473	0.5360757
15.34502447	0.5339125
15.60515421	0.5325924
15.84915682	0.5327333
16.33716204	0.5352056
16.43017468	0.5329529
17.05576454	0.5244543
17.83708805	0.5155232
18.40951933	0.5113789
18.74069408	0.4954456
19.00307674	0.4842394
19.46346349	0.4665984
19.6614676	0.4597874
19.93102904	0.4521727
20.20059048	0.4457933
20.47015193	0.440646
20.66825675	0.4308837
21.01083855	0.4146974
21.35342034	0.4006817
21.69600213	0.3888289
22.10007727	0.387469
22.41883666	0.3813058
22.73759605	0.3761732
23.06124782	0.3752614
23.47381973	0.3714973
23.77331355	0.3706245
24.07280737	0.3772685
24.37230119	0.3773423
24.67179501	0.3750797
24.71737619	0.3662052
24.94257414	0.3674998
25.4438979	0.3591213
26.04291619	0.3597835
26.3409286	0.3639857
26.638941	0.3682188
26.88169183	0.3716243
27.66520833	0.3794119
28.69094004	0.4011094
29.21075516	0.4090286
30.01434441	0.4233619
31.33747087	0.4378169
31.77809861	0.4387132
32.04395438	0.4403867
32.30981015	0.4429108
32.66046502	0.4475425
32.67905615	0.4576155
33.10754273	0.4554581

First Model Without Stent	
Length (mm)	Pressure(Pa)
0	393.5562041
0.838220429	392.1202887
1.854617281	387.5314708
2.456823884	384.5918121
3.266381839	380.3557988
3.469121856	379.2930345
4.785231566	374.2335074
6.102034971	371.4195587
7.419954724	370.4131726
8.739380738	371.5910896
10.05880016	374.6192256
11.37568769	376.2532925
12.69163287	373.7082074
13.56807918	367.8016374
13.89958832	365.3249498
14.01271938	364.4831954
15.0197741	353.6817372
15.33949661	350.1973441
16.0919225	344.6639902
16.66521293	340.4864543
17.23536979	341.6036816
17.98815787	343.293032
18.94747167	357.3491046
19.13158002	360.0980422
19.31568838	362.8880336
20.16437621	383.1220025
20.66053898	395.2813382
21.18320738	409.5213575
21.52521506	418.9089605
21.72692056	423.5790641
22.06306879	430.4056314
22.32296891	435.3666709
22.58286902	440.0015992
22.86099246	443.9260988
23.13911591	447.4265098
23.41723935	450.5028322
23.57526453	451.7013914
23.81552011	452.4421691
24.0557757	452.7242128
24.23446896	453.2742308
24.50173993	453.4468465
24.76901091	453.3405083
25.03628188	452.955216
25.24958587	452.0508798
25.93962692	446.7446035
26.61748723	443.9037135
26.8545206	442.4361755
27.09155397	440.8682425
27.65626991	436.586041
28.12360372	434.9138826
28.4394092	433.460128
29.28857851	428.8709822
29.86947745	427.5207891
30.52764921	425.2468317
30.88910508	423.6764077
31.43992851	422.6285693
32.07532259	420.9056975
32.28002296	420.2322023
32.48472334	419.4997678
33.20635852	418.2348631
33.49994531	417.4121686
34.08711887	415.5297952
34.57779862	414.786051
35.24010686	413.4127889
35.47448438	412.6018874
35.7088619	411.7632014
36.44310552	410.3456916
37.19248423	408.8443134
37.36226866	408.2011365
38.13164364	406.4872081
39.06731069	405.2397251
39.66497859	404.0255367
40.33082339	403.3299562
40.66374579	403.2920861
40.84025995	403.3117073
41.52811456	402.4949313
42.10947053	402.2437897
42.7117796	402.4481809
43.1612919	402.106173
44.04335115	401.7153496
44.32577006	401.6540778
44.73291294	401.7384182
45.63452389	400.9004407
46.73102084	399.7719063
47.48315064	398.5989052
48.71802295	396.3487416
48.97600095	395.7657319
50.03769214	394.0276731

First Model With Stent	
Length (mm)	Pressure (Pa)
0	431.8303736
0.833522491	430.3406375
1.865457051	425.9449262
2.231744549	424.3819741
3.08615436	420.0545632
3.629716286	417.2969135
4.523585922	413.5120821
5.027101537	411.3945473
5.892907246	410.0709855
6.424402991	409.3411679
7.165506875	410.8421708
7.82258429	412.1079816
8.491693526	414.4955665
9.221814766	416.9986685
9.726087904	417.7669202
10.62079319	419.0253163
10.94112967	418.1379755
12.01840423	415.1965271
13.0347282	407.1441447
13.22691936	405.735093
13.41911051	404.3369105
14.26476347	393.3829112
14.82621094	386.4623789
15.18741334	381.1957722
15.35742183	378.5198946
16.03745578	367.4755298
16.22870068	364.2719059
17.00213683	358.2271353
17.19549587	356.7906204
17.34253206	355.8857204
17.63660444	354.2400632
17.75136345	355.1616471
18.3456275	358.4479833
18.90126263	361.7987207
19.08647434	363.0285703
19.28571623	365.949651
19.83519666	374.3445265
20.17105831	379.6649046
20.62916284	387.1595638
20.90249663	392.4180428
21.05252922	395.1765851
21.2025618	397.9244864
21.52676797	402.2058488
21.85097413	406.2037769
22.1751803	409.9182708
22.29527916	411.0067601
22.65845506	414.5907602
23.02163096	417.1671871
23.38480686	418.7360408
23.58608505	420.0311065
23.78736324	421.1228589
24.11762413	422.0394435
24.41403313	422.4333081
24.71044213	422.1880184
25.00685113	421.3035744
25.30727217	419.7523529
25.55985503	419.5801281
25.81243789	419.1752237
26.06502074	418.5376398
26.39613118	417.8431931
26.72724161	416.6704695
26.86135179	416.0540302
27.12957216	414.5857874
27.43886901	414.4378476
27.74816586	413.9805263
28.05943657	413.2130728
28.36027359	412.9781865
28.66111061	412.4078542
28.96194762	411.5020757
29.30267006	411.703658
29.65771579	411.5260143
30.01276152	410.9316326
30.23888755	410.8031458
30.46501358	410.5110607
30.82721488	409.7106692
31.19054918	409.9091642
31.55388347	409.7522322
31.7528393	409.5132068
31.95179514	409.1675803
32.26366474	408.8439324
32.69593571	407.9895561
32.97575844	408.0069111
33.25558117	407.8550373
33.5354039	407.5339347
33.91068251	406.8275083
34.53153883	405.2183292
35.12351486	404.5988552
35.7154909	403.5728148
35.93525469	403.0902446
36.30327433	401.8864082
37.52570397	400.4432026
38.05387269	399.9573115
38.64791026	399.1653089
39.01377966	398.9097218
39.37964906	398.8443897
40.17393948	398.9898066
40.53156927	398.7309205
40.88919906	398.6775717
41.21049591	398.7355332
41.79250027	399.0066615
42.15562977	398.984501
42.75406803	398.9163247
43.3525063	399.097995
43.51557715	399.0973537
44.51029747	398.6527097
44.8619815	398.2804747
46.00251109	396.9572947
47.07374396	395.2127136
48.0361935	393.4237018

Second Model Without Stent	
Length (mm)	Pressure (Pa)
0	343.440215
0.271702887	343.1894179
0.81510866	341.7501329
1.280074338	340.0406866
2.051600132	336.9703904
2.377534195	335.3042026
3.172498983	331.2325541
4.163759047	326.049445
4.35105414	325.0653301
5.211654134	321.7288439
5.529605439	320.4838397
6.068769757	320.0980426
6.708151896	319.6218439
7.681027453	323.2956559
7.886692262	324.0714332
8.543377676	331.8721783
9.0652364	338.0880608
10.04609702	355.4559527
11.42247373	379.9859798
12.69586229	403.3293043
12.96935521	408.143109
13.78983396	422.0707772
13.97696018	424.8226215
14.31575248	429.3631926
14.99333708	439.3582893
15.17844313	448.7704304
15.52447706	450.919024
16.21654492	455.6139067
16.57725985	451.8193361
17.46032283	446.7879121
17.7399615	443.6222611
18.01960017	441.9127427
18.38314376	436.476394
18.72080082	433.462471
19.6590493	434.9221649
19.98992909	435.4880805
20.4911379	436.8099253
21.10882571	438.1501964
21.44076569	438.4898947
22.52589512	438.9676077
22.76418181	438.8752966
23.10671543	438.8142804
24.08050917	439.1714783
25.28729515	439.6178719
25.62954924	439.6739698
26.24887793	439.2573353
26.35482549	439.0994038
26.69751803	438.0518207
27.04152188	436.3144476
27.35658905	433.8601889
27.67165623	431.0417146
28.30167998	420.4988853
28.81201963	411.1524804
29.00734739	407.3504186
29.23202762	401.5273204
29.45670785	396.0878658
29.80098019	391.7119914
30.08292795	388.9304345
30.36487571	386.8272658
31.02781576	389.2825242
31.73847935	391.8676995
32.36220036	392.6471171
33.11984437	393.1937062
33.36591675	393.3945944

Second Model With Stent	
Length (mm)	Pressure (Pa)
0	343.440215
0.271712549	343.1895236
0.815137647	341.7537041
1.274454887	340.0642535
2.036636462	337.0499072
2.360060321	335.3944983
3.172586736	331.2257097
4.148692995	326.0959384
4.351146092	325.0274254
5.192571179	321.7395758
5.529684765	320.4153561
6.019210701	320.0731116
6.708207545	319.5961634
7.648727892	323.2366659
7.88672837	324.1524346
9.06525757	338.1884289
10.70066385	367.111487
11.59553644	383.2729335
12.10754259	392.7245845
13.24465674	412.8104295
13.53253459	416.9601455
13.81555871	420.8601874
14.45398873	428.4968231
14.76944173	431.4225566
15.08489473	432.3017992
15.60515421	432.6805334
15.84915682	432.7157908
16.43017468	432.2683679
17.05576454	431.8742517
17.40491807	430.3999273
17.83708805	429.069134
18.12330369	428.0374903
18.40951933	427.3452726
19.00307674	427.4613859
19.93102904	427.9162483
20.66825675	428.3355371
21.69600213	428.9480623
22.41883666	428.8502138
22.73759605	428.7208827
23.06124782	428.8066202
23.77331355	428.5360448
24.37230119	427.7297494
24.71737619	427.0190181
25.72002371	424.1655982
26.04291619	423.0923714
26.638941	420.0614193
26.88169183	418.6777324
27.36719349	415.6504325
27.66520833	413.2406564
29.21075516	405.3098414
29.91826497	402.2501355
30.01434441	401.8966395
31.33747087	398.3063119
31.77809861	397.4880442
32.66046502	395.7160148
33.10754273	395.2843705