EFFECT OF DOUBLE LAYER STENT TO FLOW PHENOMENA IN CEREBRAL ANEURYSM

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Thesis submitted in fulfilment of the requirements
for the award of the degree of
Bachelor of Mechanical Engineering

Faculty of Mechanical Engineering
UNIVERSITI MALAYSIA PAHANG

NOVEMBER 2009

SUPERVISOR'S DECLARATION

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

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STUDENT'S DECLARATION

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

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Dedicate to my beloved father, mother, siblings and to my late grandfather

ACKNOWLEDGEMENT

First and foremost, grateful to Allah SWT for making it possible for me to complete this project on time. I am grateful and would like to express my sincere gratitude to my supervisor Mr Mohamad Mazwan Bin Mahat for his ideas, guidance, continuous encouragement and constant support in making this research possible. I appreciate his consistent support from the first day I applied to graduate program to these concluding moments. I also sincerely thanks for the time spent proofreading and correcting my many mistakes.

My sincere thanks go to all my labmates and members of the staff of the Mechanical Engineering Department, UMP, who helped me in many ways and made my stay at UMP pleasant and unforgettable.

I acknowledge my sincere indebtedness and gratitude to my parents for their love, dream and sacrifice throughout my life. I cannot find the appropriate words that could properly describe my appreciation for their devotion, support and faith in my ability to attain my goals. To my siblings, thanks for the support and last but not least to my late grandfather, may god bless you.

ABSTRACT

The investigation is about the flow pattern in blood vessel that has been done at the aneurysm with the different type of stent. The velocity profile and the pressure distribution of blood had been identified from the stent implantation. There are three types of stent model in this case study which known as Type 1, Type 2 and Types 3. All types of stent that has been applied to the aneurysm are in double layer. A non-stented and stented aneurysm need be considered for identifying the changes in hemodynamics due to stent implantation. 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 fluid dynamics program. The different structure of stent has given the different flow pattern around the aneurysm region. The minimum velocity has been increased after the stent implantation and stent Type 3 has given the optimum result with the low pressure and the highest minimum velocity. Finally, the correlations obtained from this numerical result could be used to investigate the pressure distribution around the diseased segment.

ABSTRAK

Kajian mengenai perubahan bentuk aliran didalam salur darah telah dibuat ke atas aneurism dengan struktur stent yang berbeza. Profil halaju dan taburan tekanan darah diperolehi daripada hasil dari implant stent. Tiga rekabentuk stent yang di kaji iaitu jenis 1, jenis 2 dan jenis 3. Ketiga-tiga stent ini telah di implant dengan 2 lapis ke dalam aneurism. Aneurism tanpa implant stent dan aneurism dengan implant stent diambil kira dalam kajian untuk menentukan perubahan hemodinamik darah. Simulasi model dikaji dengan parameter aliran mampat, bukan Newtonian, bendalir likat dan keadaan tiada denyut menggunakan program dinamik bendalir tiga dimensi. Perbezaan struktur stent telah menghasilkan bentuk aliran yang berbeza disekitar aneurism. Halaju minimum telah di pertingkatkan selepas implant stent dibuat dan stent jenis 3 menghasilkan keputusan paling optimum dengan menghasilkan tekanan yang paling rendah dan nilai halaju minimum yang paling tinggi. Kajian dan analisis parameter atau faktor lain yang mempengaruhi aliran didalam aneurism perlu diambil kira untuk kajian masa akan datang.

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u_i : velocity in the *i*-th direction

P : pressure

f_i : body force

ρ : density

μ_i : viscosity

δ_{ij} : Kronocker delta

LIST OF ABBREVIATIONS

CAD : Computer Aided Design

CAE : Computer Aided Engineering

CFD : Computational Fluid Dynamics

CSS : Computational Solid Stress

LBM : Lattice-Boltzmann Method

POBA : Plain Old Balloon Angioplasty

SAT : Sub-Acute Thrombosis

WSS : Wall shear stress

YME : Young’s Modulus Elastic

CHAPTER 1

INTRODUCTION

1.1 OBJECTIVES

There are two objectives in this research. Firstly is to investigate the flow behavior inside aneurismal region after double layer stents is applied to the disease region. The other objective is to determine the effect of double layer stent blood flow parameter.

1.2 SCOPES

In this research, there are four scopes. Firstly, non pulsatile blood flow will be used. Then, all the solution will be base on the numerical approach only. Next, analyze selected stents will be based upon different structural pattern and lastly the application of stent will be on fixed aneurysms.

1.3 STENT

A stent can be defined as a medical device that supports tissue. Mostly a stent refers to a specific medical device that is placed into an artery. 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 will 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 will supports the narrowed or blocked artery, keeping it open for blood to flow more freely.

Stents can be divided into two basic categories which are balloon-expandable and self-expanding stents. Balloon-expandable stents have greater hoop strength, resulting in more resistance to elastic recoil after full expansion. They also deploy more precisely than self-expanding stents. Compared to balloon-expandable stent, self-expanding stents have greater longitudinal flexibility to maximize ease of delivery into tortuous vessels. They also recover from deformation secondary to extension and crushing forces, and are available in longer treatment lengths.

Stents can also be characterized by their metallic composition. The stents most commonly used today are constructed of stainless steel or thermomodulated nitinol. Bioabsorbable magnesium stents are currently in experimental trials. Bioabsorbable stents have the theoretical advantage of removing the long-term stimulus for neointimal hyperplasia from the vessel wall.

Mark D. Morasch has stated that stents can also be coated, drug-eluting, or covered with a graft material. Coated stents aim to decrease the likelihood of early thrombosis and to mitigate the longer-term risk of developing neointimal hyperplasia by coating the reactive metal surface with a nonreactive substance, such as carbon. Drug-eluting stents will release the pharmacologically active substances over a relatively short time period. This substance thought to modulate the neointimal response and to reduce hyperplasia and in-stent restenosis. Stents can be manufactured with either a Dacron (polyester) or an expanded polytetrafluoroethylene covering. This is called as stent-grafts were initially used to treat aneurysmal disease. To decreasing the frequency of in-stent restenosis, these covered stents is being used the increasing of frequency to treat long-segment occlusive disease.

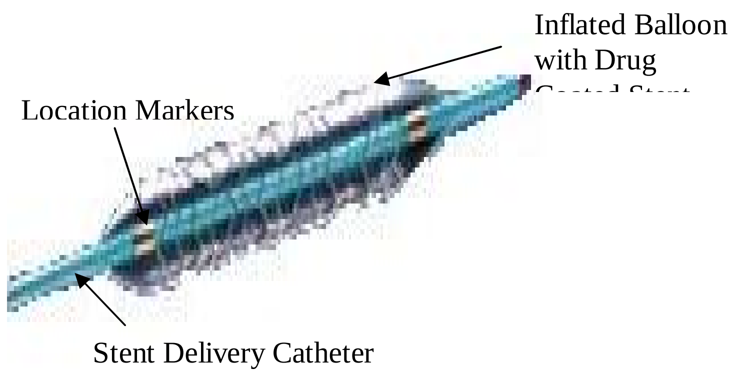


Figure 1.1: Drug-Eluting Stent

Source: http://www.medicineworld.org

Figure 1.2: Graft Stent

Source: http://www.angiocardio.com

Sometimes, drug-eluting stent can be referred 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 and it is a very complex process and the solution to prevent is equally complex. However, according to the data gathered, 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. Firstly is about the type of stent that carries the drug coating. Then, the method on how the drug is delivered (eluted) by the coating to the arterial wall (polymeric or other). Finally, the drug itself.

In addition, there are several decisions made by the interventional cardiologist that result in a successful stent placement, whether of the drug-eluting or bare metal variety. First, correcting size of the stent length to match the length of the lesion or the blocked area. Then, correcting the size of stent diameter to match the thickness of the healthy part of the artery and finally by sufficient deployment of the stent, once placed at the optimum site in the blocked artery, is expanded fully to the arterial wall. The result can be seen in small gaps between the stent and arterial wall which can lead to serious problems such as blood clots, or Sub-Acute Thrombosis (SAT)

Graft stents is a tubular structure composed of two parts. The stent is a mesh-like structure made of metal such as stainless steel. The function is to provide support to the graft. The latter is composed of a special fabric that is impervious to blood and lines the stent. The stent-graft is packed in small diameter tubes and expands to its original diameter when released from these tubes. The stent that most commonly use to treat aneurysms is stent-grafts.

Most stents are crafted from 316L stainless steel. The is a lots of examples of stent that used 316L stainless steel include the Cordis Palmaz-Schatz stent, the Cordis Crossflex stent, the Guidant MultiLink stent, and the Medtronic Bestent.

There are some disadvantages of steel stents include the high occurrence of subacute thrombosis and restenosis, bleeding complications, corrosion, and re-dilation of the stented vessel segment. According to the Medtronic website, the adverse effects of stents are death, myocardial infarction, and stent thrombosis, bleeding complications, stroke, vascular complications, stent failures and total occlusion of coronary artery.

Table 1.1 shows the dimension and the material use for stent in nowadays. The sizes of stent depend on the aneurysm size.

Table 1.1: Dimension and material for stent nowadays

Material Used	**Stent Diameter (mm)**	**Stent Length (mm)**
316L Stainless Steel	5-7	12,18,28,38
316L Stainless Steel	5-12	16,22,38,59
316L Stainless Steel	4-8	10,15,20,29,39
Platinum	5-6	35,55
Platinum	5-6	15
Cobalt-Chromium With Tungsten	4-7	12,15,18,28

Source: http://www.evtoday.com

1.4 ANEURYSM

An aneurysm is an abnormal widening or ballooning of a portion of an artery, related to weakness in the wall of the blood vessel. Some common locations for aneurysms include Aorta (the major artery from the heart), Brain (cerebral aneurysm), Leg (popliteal artery aneurysm), Intestine (mesenteric artery aneurysm) and Splenic artery aneurysm.

The cause of aneurysms is not exactly clear. It can be defects in some of the parts of the artery wall. In certain cases (abdominal aortic aneurysms), high blood pressure is thought to be a contributing factor. Some aneurysms are congenital (present at birth). Atherosclerotic disease (cholesterol buildup in arteries) may contribute to the formation of certain types of aneurysms. Pregnancy is often associated with the formation and rupture of aneurysms of the splenic artery (an artery leading to the spleen).

The symptoms of aneurysms are depending on the location of the aneurysm. Some of aneurysms did not have any symptoms such as at the body and brain. Swelling with a throbbing mass at the site of an aneurysm is often seen if it occurs near the body surface. In the case, low blood pressure, high heart rate, and lightheadedness may occur. The risk of death after a rupture is high.

For a treatment, surgery is generally recommended but the timing and indications for surgery differ depending on the type of aneurysms. Some people are candidates for endovascular stent repair. A stent is a tiny tube used to prop open a vessel. This procedure can be done with a major cut, so you recover faster than you would with open surgery. Not all patients with aneurysms are candidates for stenting.

There is some ways to prevent the aneurysms such as to control of high blood pressure. Control of all risk factors associated with atherosclerotic disease (diet, exercise, cholesterol control) may help prevent aneurysms or their complications.

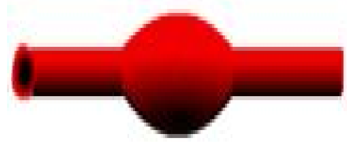
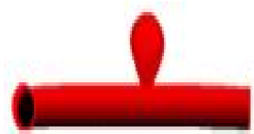
1.5 CEREBRAL ANEURYSM

A cerebral aneurysm (also known as an intracranial or intracerebral aneurysm) is a weak or thin spot on a blood vessel in the brain that balloons out and fills with blood. The bulging aneurysm can put pressure on a nerve or surrounding brain tissue. It may also leak or rupture, spilling blood into the surrounding tissue (called a hemorrhage). Some cerebral aneurysms, particularly those that are very small, do not bleed or cause other problems. Cerebral aneurysms can occur anywhere in the brain, but most are located along a loop of arteries that run between the underside of the brain and the base of the skull.

Table 1.2 shows the type of cerebral that can occurs on blood vessel in the brain. There are three types of cerebral aneurysm which is saccular, lateral and fusiform. A saccular aneurysm is a rounded or pouch-like sac of blood that is attached by a neck or stem to an artery or a branch of a blood vessel. It is also known as a berry aneurysm (because it resembles a berry hanging from a vine). This most common form of cerebral aneurysm is typically found on arteries at the base of the brain. Saccular aneurysms occur most often in adults. A lateral aneurysm appears as a bulge on one wall of the blood vessel, while a fusiform aneurysm is formed by the widening along all walls of the vessel.

Most cerebral aneurysms are congenital, resulting from an inborn abnormality in an artery wall. Cerebral aneurysms are also more common in people with certain genetic diseases, such as connective tissue disorders and polycystic kidney disease, and certain circulatory disorders, such as arteriovenous malformations.

Table 1.2: Types of aneurysm

TYPES OF CEREBRAL ANEURYSMS	Cerebral Aneurysm
Fusiform	
Berry	
Saccular	

Source: http://www.rnceus.com

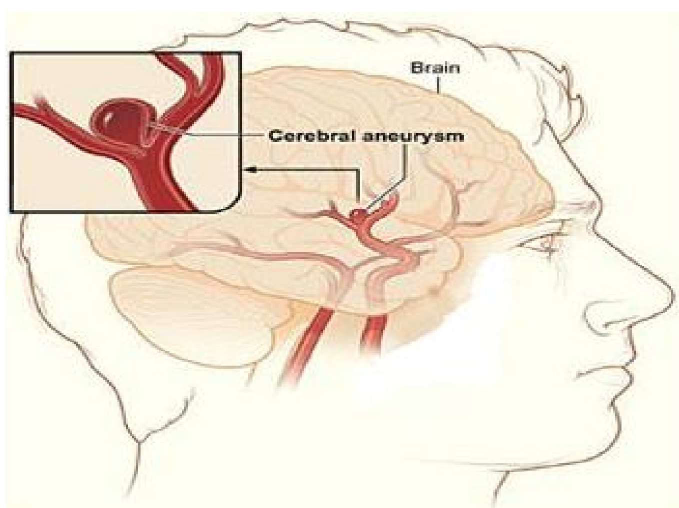


Figure 1.3: The area of cerebral aneurysm

Source: http://www.web-books.com

Other causes include trauma or injury to the head, high blood pressure, infection, tumors, atherosclerosis (a blood vessel disease in which fats build up on the inside of artery walls) and other diseases of the vascular system, cigarette smoking, and drug abuse. Some investigators have speculated that oral contraceptives may increase the risk of developing aneurysms.

Aneurysms that result from an infection in the arterial wall are called mycotic aneurysms. Cancer-related aneurysms are often associated with primary or metastatic tumors of the head and neck. Drug abuse, particularly the habitual use of cocaine, can inflame blood vessels and lead to the development of brain aneurysms.

Aneurysms are also classified by size. Small aneurysms are less than 11 millimeters in diameter (about the size of a standard pencil eraser), larger aneurysms are 11-25 millimeters (about the width of a dime), and giant aneurysms are greater than 25 millimeters in diameter (more than the width of a quarter).

Aneurysms may burst and bleed into the brain, causing serious complications including hemorrhagic stroke, permanent nerve damage, or death. Once it has burst, the aneurysm may burst again and rebleed into the brain and additional aneurysms may also occur. The rupture may cause a subarachnoid hemorrhage bleeding into the space between the skull bone and the brain.

A delayed but serious complication of subarachnoid hemorrhage is hydrocephalus, in which the excessive buildup of cerebrospinal fluid in the skull dilates fluid pathways called ventricles that can swell and press on the brain tissue. Another delayed postrupture complication is vasospasm, in which other blood vessels in the brain contract and limit blood flow to vital areas of the brain. This reduced blood flow can cause stroke or tissue damage.

Not all cerebral aneurysms burst. Some patients with very small aneurysms may be monitored to detect any growth or onset of symptoms and to ensure aggressive treatment of coexisting medical problems and risk factors. Each case is unique, and considerations for treating an unruptured aneurysm include the type, size, and location of the aneurysm; risk of rupture; patient's age, health, and personal and family medical history; and risk of treatment.

Two surgical options are available for treating cerebral aneurysms, both of which carry some risk to the patient (such as possible damage to other blood vessels, the potential for aneurysm recurrence and rebleeding, and the risk of post-operative stroke).

Microvascular clipping involves cutting off the flow of blood to the aneurysm. Under anesthesia, a section of the skull is removed and the aneurysm is located. The neurosurgeon uses a microscope to isolate the blood vessel that feeds the aneurysm and places a small, metal, clothespin-like clip on the aneurysm's neck, halting its blood supply. The clip remains in the patient and prevents the risk of future bleeding. The piece of the skull is then replaced and the scalp is closed. Clipping has been shown to be highly effective, depending on the location, shape, and size of the aneurysm. In general, aneurysms that are completely clipped surgically do not return.

A related procedure is an occlusion, in which the surgeon clamps off (occludes) the entire artery that leads to the aneurysm. This procedure is often performed when the aneurysm has damaged the artery. An occlusion is sometimes accompanied by a bypass, in which a small blood vessel is surgically grafted to the brain artery, rerouting the flow of blood away from the section of the damaged artery.

Endovascular embolization is an alternative to surgery. Once the patient has been anesthetized, the doctor inserts a hollow plastic tube (a catheter) into an artery (usually in the groin) and threads it, using angiography, through the body to the site of the aneurysm. Using a guide wire, detachable coils (spirals of platinum wire) or small latex balloons are passed through the catheter and released into the aneurysm.

The coils or balloons fill the aneurysm; block it from circulation, and cause the blood to clot, which effectively destroys the aneurysm. The procedure may need to be performed more than once during the patient's lifetime.

Patients who receive treatment for aneurysm must remain in bed until the bleeding stops. Underlying conditions, such as high blood pressure, should be treated. Other treatment for cerebral aneurysm is symptomatic and may include anticonvulsants to prevent seizures and analgesics to treat headache. Vasospasm can be treated with calcium channel-blocking drugs and sedatives may be ordered if the patient is restless.

A shunt may be surgically inserted into a ventricle several months following rupture if the buildup of cerebrospinal fluid is causing harmful pressure on surrounding tissue. Patients who have suffered a subarachnoid hemorrhage often need rehabilitative, speech, and occupational therapy to regain lost function and learn to cope with any permanent disability.

1.6 INSTALLATION METHOD

The use of balloon remodeling technique coils with complex 3D shape, bioactive and hydrogel and stent-assisted coiling is the introduction of the new technical developments in terms of microcatheter improvements.

Balloons are used in the majority of interventional procedures. Balloons are inflated to compress the plaque against the artery wall in a procedure known as "angioplasty" and sometimes called "balloon dilatation", sometimes "PTCA" (percutaneous transluminal coronary angioplasty).

The stent is used as the initial therapy called "direct stenting". Even if the stent is used as the primary therapy but the process still involves a balloon for the stent itself is mounted on an angioplasty balloon in order for it to be delivered to the diseased area and deployed.

The balloon is inflated, and the stent along with it. When the balloon is deflated and withdrawn, the stent remains in place and serving as permanent scaffolding for the newly widened artery as shown base on figure 1.4. Within a few weeks, the natural lining of the artery, called the endothelium, grows over the metallic surface of the stent.

Stents have virtually eliminated many of the complications that used to accompany "plain old balloon angioplasty" (POBA) such as abrupt and unpredictable closure of the vessel which resulted in emergency bypass surgery. The additional structural strength of the stent can also help keep the artery open while the healing process progresses.

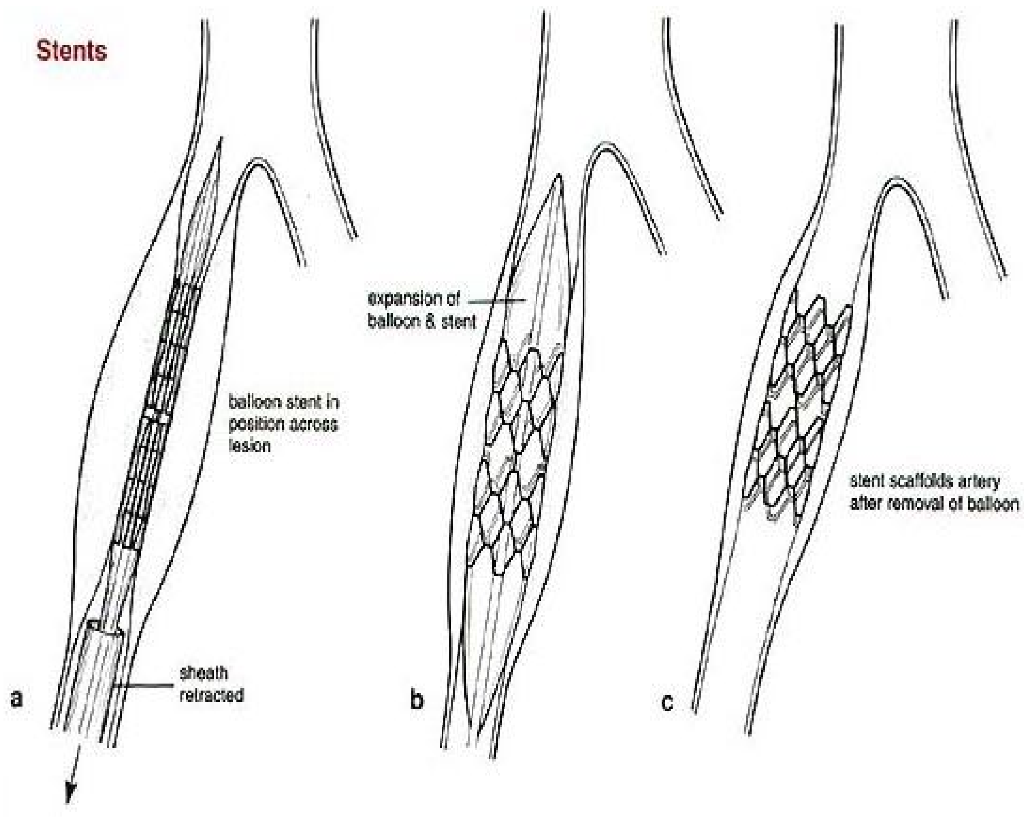


Figure 1.4: **S**tent Installation

Source: http://www.surgery.usc.edu

CHAPTER 2

FLOW BEHAVIOR IN ANEURYSM

2.1 FLOW BEHAVIOR IN ANEURYSM

Blood is a non-Newtonian fluid whereby its viscosity varies with shear stress. This flow behaviour of blood occurs because of the existence of red blood cells. At high shear stress red blood cells are disaggregated and blood acts as a Newtonian fluid but at low shear stress red blood cells aggregate, apparent viscosity increases, and blood behaves like a non-Newtonian fluid. The flow velocity inside the aneurysm, especially in the dome, was very low and the flow was almost stagnant in this region.

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. Although this work has characterized the complexity of intra-aneurysmal hemodynamics in experimental and computational models, the studies have largely focused on idealized aneurysm geometry.

Each of these approaches has had significant limitations in connecting the hemodynamic factors studied to a clinical event. In vitro studies have allowed very detailed measurement of hemodynamic variables but are of limited value in understanding the hemodynamic forces in an individual clinical case because the creation of the patient-specific geometric models is currently impractical for large population studies. A correlation between patient-specific clinical events and hemodynamic patterns must be undertaken to better understand the relative importance of these forces.

As the Blood flow in an aneurysm generally depends on its geometric configuration and relation to the parent vessel, the size of the orifice and the volume of the aneurysm. Hemodynamics factor such blood velocities, wall shear stress, and blood pressure will plays as important roles in the pathogenesis of aneurysms.

Some of researcher has investigated the problems using numerical simulation. They have made a research in to ways. The first way is by using artificial models which are supposed to reflect the important of geometrical and the flow of characteristics of aneurysm and the other way is making the simulation on the real models derived from medical imaging techniques.

For the technique of using the artificial models, the researcher needs to prepare the geometry and the numerical mesh. This is because of the relative simplicity, regularity and controllability of the geometry, the mesh has usually results the good quality. In the second approaches the arterial geometry is obtained on a digital format consisting of voxels. It is possible to perform simulations on this mesh consisting of small cubes but this have a rough appearance since the surfaces of all cubes are in one of the three coordinates direction. In this case, especially near the wall, the results will be unrealistic (Egelholff, 1999; Shipkowitz, 2000; Pa'al, 2004). Because of that, the leading factors that will cause aneurysm growth and rapture which is not clear but many of researcher think that the wall shear stress can be the main factor. So that hemodynamic stress is believed to be one of the important factors in the formation and growth of aneurysms. The wall pressure distribution was independent so the pressure at the aneurysm wall was almost same to that in the parent artery.

The WSS inside the aneurysm sac was low and was maximum at the distal neck (Gobin, 1994; Torii, 2006). At high shear stress the velocity as well as shear rate is high, the apparent viscosity is nearly constant and the blood acts as a Newtonian fluid. The high WSS in this region occurred due to the high velocity gradient which has been described earlier.

Numerical simulations have been used during the last decade to analyze blood flow phenomena in aneurysm. 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 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 (Bluestein, 1996). 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 presented a CFD model of pulsatile flow within an anatomically realistic carotid aneurysm constructed from in vivo imaging of a human subject (Steinman, 2002). Their model successfully reproduced velocity streamlines from an earlier in vivo model of similar geometry and demonstrated regions of elevated wall shear stress.

2.2 FLOW BEHAVIOR IN CEREBRAL ANEURYSM

Hemodynamics has long been known to be an important factor in the initiation and progression of vascular disease. 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.

Among other factors, flow related aspects dominate the life cycle of cerebral aneurysms. Understanding the role of blood and its flow mechanics may provide access to the deeper understanding of the cerebral aneurysm life, including possibilities to assess rupture risk and to improve endovascular treatment methods. 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.

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. Understanding flow and developing methods to assess and plan for correction is the topic of the session – numeric simulation and validation methods evolve and give the scientific background to such a vision. A significant contribution to treatment and treatment planning using modern medical imaging can be expected.

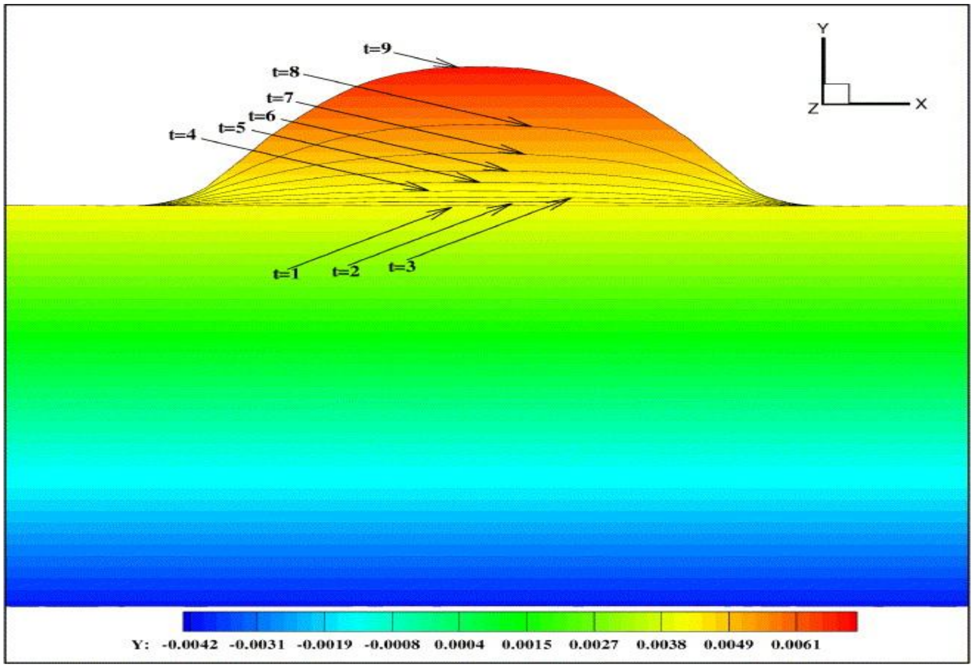


Figure 2.1: Geometrical evolution contours due to the Young's Modulus of Elasticity I

Some of the researcher has made a research about the Young’s Modulus Elasticy (YME). Figure 2.1 shows the evolution of the aneurysmal shape only due to the dynamic alteration of the Young's modulus of elasticity. If we consider that the final YME values for time *t*=9 of the ring- and the ellipsoid-shaped regions are highly abnormal (20 000 and 40 000 Pa, respectively) when at the same time the displacement is not so significant, (compared to cases of giant aneurysms, (Vinuela, 1997)) it can conclude that this mechanism alone is not enough to describe the aneurysmal evolution.

In all likelihood, this mechanical process is reflecting a primary malfunction of the endothelial cell layer and the corresponding loss of vascular tone. Moreover, although there exists evidence of apoptosis of the smooth muscle cells during the growth of the aneurysm, we do not know why and how exactly this takes place, (Kondo, 1998; Schmid, 2003; Thompson, 1997; Sakaki, 1997).

Definitive evidence that the endothelial cell activity is directly connected with the apoptotic processes is missing. In effect, this loss of tone is assumed to account for the initialization of the lesion. This comment is in agreement with the observed high concentration of endothelial cells at high shear stress regions (Hoshina, 2003) while histological data indicate that the endothelial cell layer within the aneurysmal lumen is quite normal (Sugiu, 1995). This conclusion would indicate that, while we have an unusually high concentration of endothelial cells at the early stages of the decease, at the later stages we have a normal alignment of the cells with respect to the inner layer of the aneurysmal lumen.

The YME dynamical evolution up to time *t*=5, along with the arterial adaptation mechanism (i.e. canceling of the internal stresses values and establishment of a stress-free state for the resulted geometry from the *t*=5 simulation) that took place at time 6a resulted in the sequence of the geometries that are depicted in Figure 2.2. It is obvious that the resulting geometry for *t*=6*a* is significantly more deformed than the one achieved by the simple loss of tone/apoptosis mechanism.

The exact magnitude of this particular deformation is of course also dependent on the fact that a total loss of stresses was assumed in the fibers of the wall during this step, an assumption that, as we discussed, is useful for demonstration purposes but possibly not entirely realistic. The influence and the importance of the adaptation procedure will be examined in the future, in correlation with availability of micro-histology data.

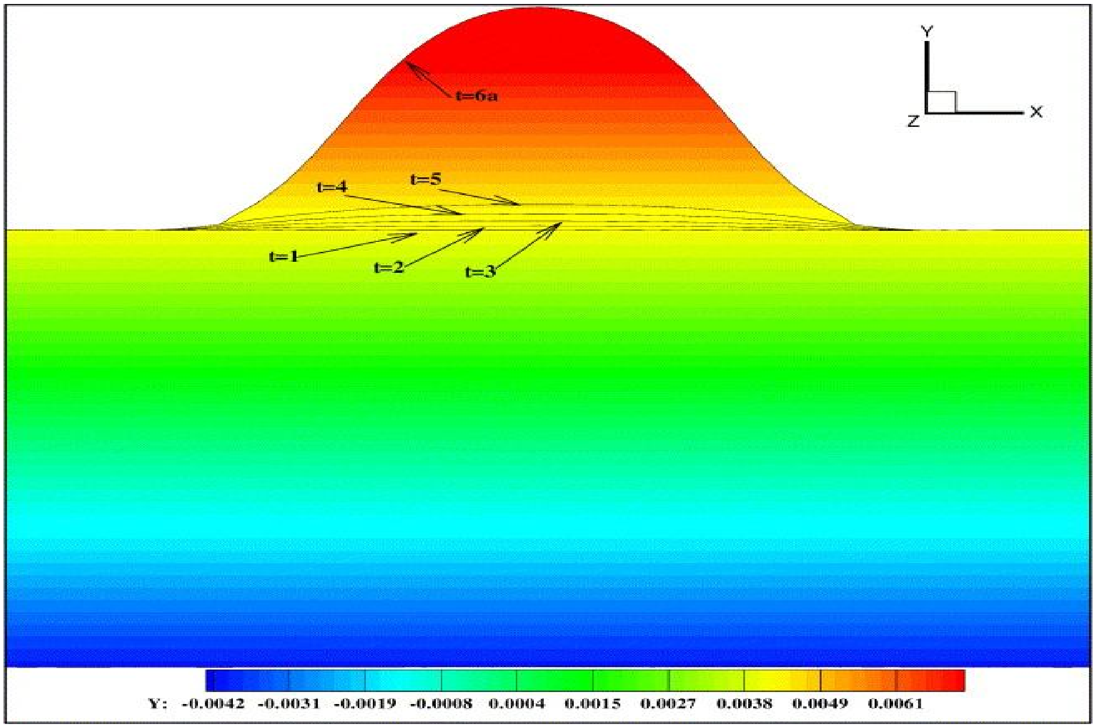


Figure 2.2: Geometrical evolution contours due to the Young's Modulus of Elasticity II

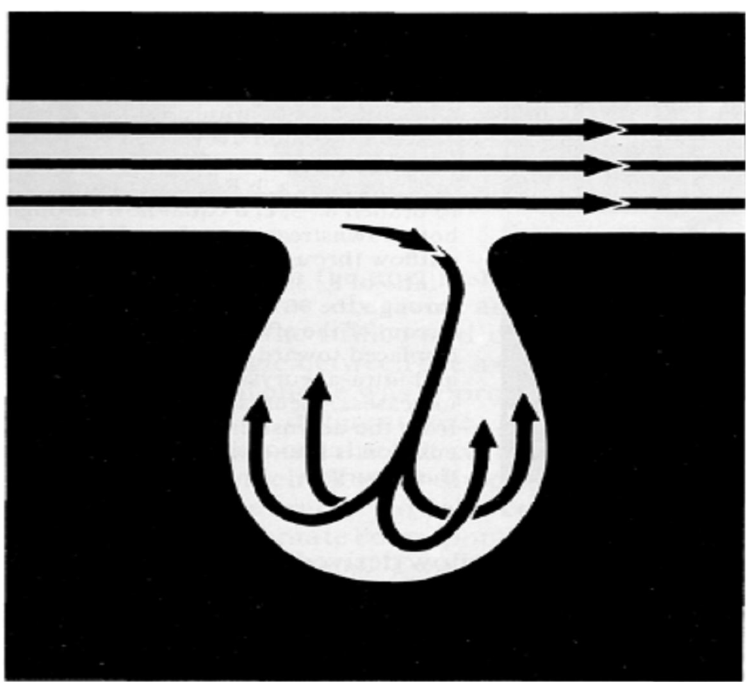


Figure 2.3: Circulation in the lateral aneurysm

According to Figure 2.3 that two further dark isochromates of a curvilinear shape were observed near the up- and downstream walls of the aneurysm. Observation of particle motion indicated that these zones corresponded to sectors of outflow from the fundus. The intra-aneurysmal turnover is summarized in Figure 2.3. A discrete fluctuation of the inflow isochromate near its origin at the aneurysmal lip was seen with peak flow during pulsatile perfusions, otherwise there was no indication of a disruption of the laminar flow structure or of turbulence in these lateral aneurysms (Hans J. Steiger, 1987).

2.3 FLOWS IN STENTED ANEURYSM

Stent installation is the best solution for the aneurysm problem in order to prevent further rupture.Stents are flexible cylindrical mesh tubes made of stainless steel or alloys. 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 (M.P.Marks, 1994).

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. 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.

New basic parameters has performed to understand the flow pattern in the stented aneurysm.It will effect on the velocity reduction and to verify the flow reduction mechanism based on the new basic parameters (M.Hirabayashi, 2006).

To get a better qualitative analysis on the flow reduction efficiency by the stent implementation, he then investigates the variation of the flow pattern in the stented aneurysm. The variation of the pore size and the struts position of stent will change the flow pattern. In Figure 2.4 we find out that the vortex and the laminar flow in the aneurysm dome drive another vortex but they only consider the single vortex flow. We can see that the flow pattern does not predict the velocity reduction effect directly and the Figure 2.4F.If we compared the Figure 2.4F and 2.4E, it shows the same laminar flows but the different is at the velocity reduction effect.

To know the velocity reduction effect from the flow pattern, he has analyzed the formation mechanism of the flow patterns. To characterize the relationship between the flow pattern and the velocity reduction, he introduced new analyses on the driving flow and the driving pore. The driving flow is the inlet flow, which drives the dominant flow in the aneurysm dome and the driving pore is the inlet pore of the driving flow at the aneurysm orifice. The driving flow and the driving pore are determined by the flow pattern.

Figure 2.4 suggests that the driving flow drives the dominant flow in the aneurysm dome, which determines the velocity reduction effect. The position and size of the driving pore seem to play important roles in the velocity reduction because they determine the velocity of the driving flow.

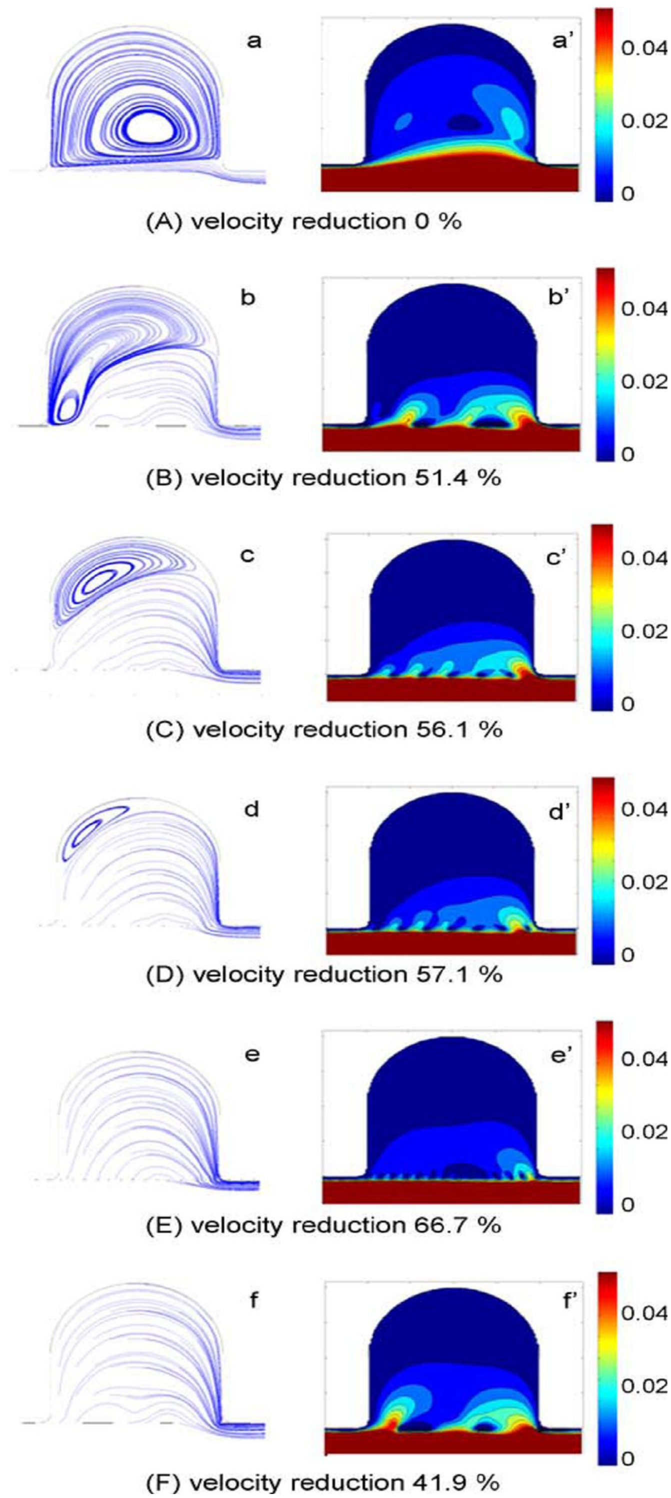


Figure 2.4: Flow pattern according different velocity reduction and the laminar flow.

To understand flow pattern effect on the velocity reduction, they measured the velocity reduction of non stented aneurysm. The driving flow is strong enough to drive the vortex inside the aneurysm (Hirabayashi, 2006). At every point from 1 to 4, the formation of vortex clearly been seen from the complex flow structure at point 4. He also investigates the variation of the flow pattern in the stented aneurysm. According to the variation of the pore size and the strut position of stents, the low patterns change.

Figure 2.5 show that there are three types of flows in the stented aneurysm. (I) vortex driven by orifice flows, (II) vortex driven by aneurysm flows and (III) laminar flows driven by orifice flows. Based on these observations, the flow pattern in the stented aneurysm can be classified into three groups: (I) + (III), (II) + (III), and (III). In more complex cases, we find that the vortex and the laminar flow in the aneurysm dome drive another vortex; however, we consider the single vortex flow in order to discuss the fundamental problem here.

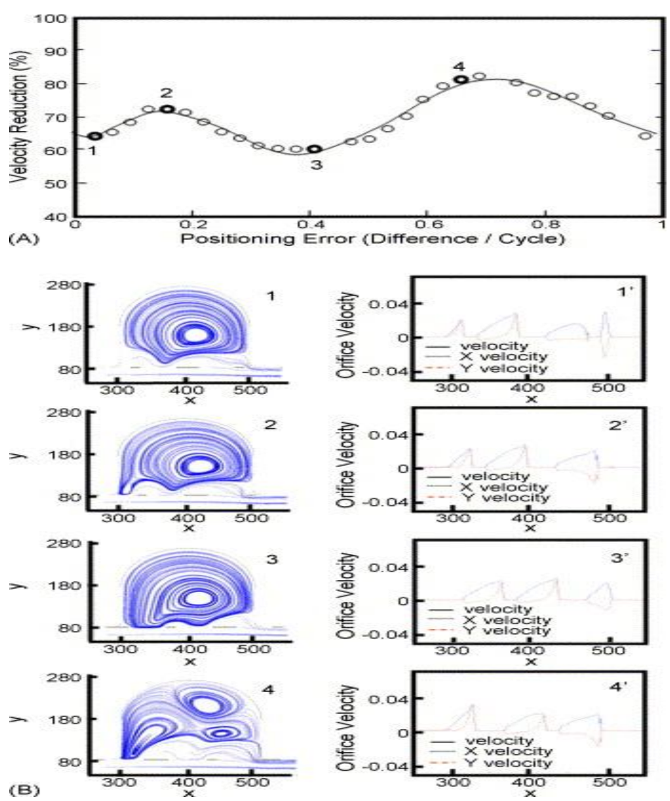


Figure 2.5: Complex flow structures driven by orifice flow

CHAPTER 3

METHODOLOGY

3.1 GEOMETRY OF MODEL

This study focus particularly on the model of aneurysm at artery with diameter of 8 mm with the aneurysm size is 16 mm diameter and 35 mm length. The modeling was completely done in CAD software, SOLIDWORK 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.

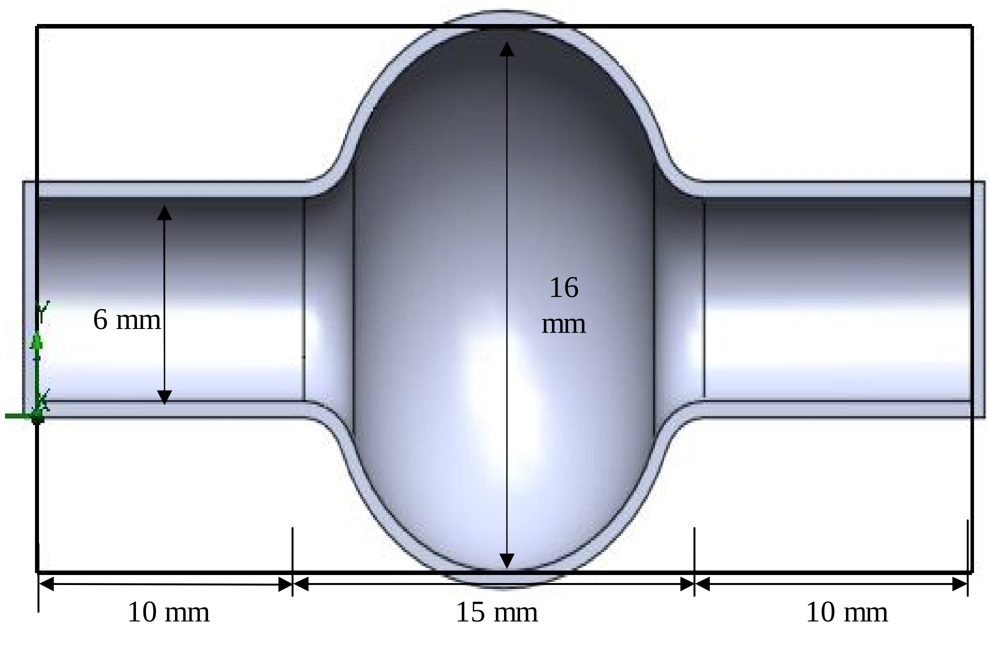


Figure 3.1: The geometry model of aneurysm

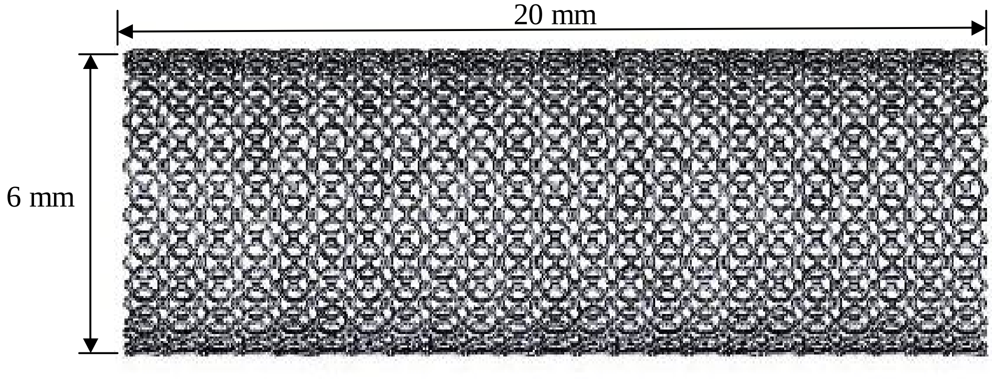
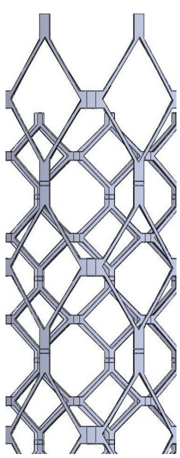
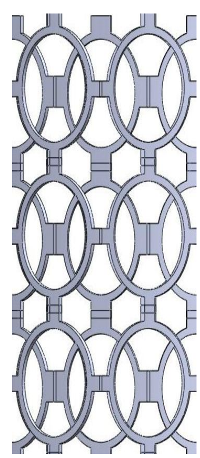


Figure 3.2: The geometry model of stent

Figure 3.2 shown the geometry model of stent with a diameter of 6 mm and the length of stent is 20 mm. The geometry of all stent is same and the different is only about the design. There are 3 types of stent model that been used to do the analysis as shown in Table 3.1. The design of stent is based on the designs that have been in release in market. All the three types of stent used has een modified to double layer stent.

Table 3.1: Stent type 1, 2 and 3 model

Type 1	Type 2	Type 3
		

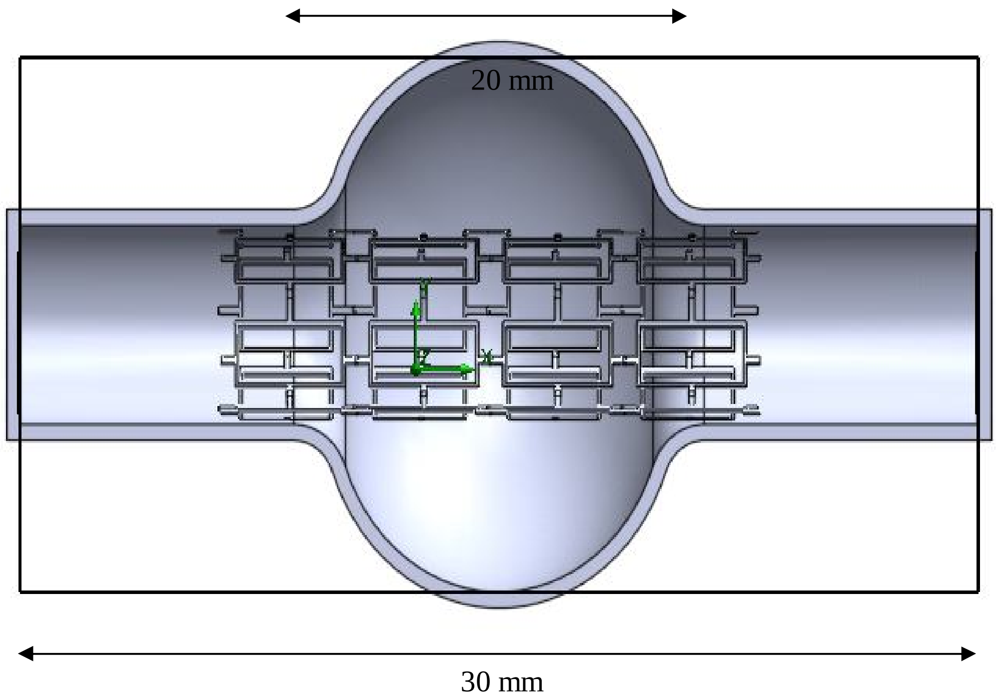


Figure 3.3: Stented aneurysm

Figure 3.3 is stented aneurysm. The stent that been installed to the aneurysm is a double layer stent. The first and the second stent have the same design but only the size and the rotating angle of stent is different.

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 $\nabla^2 V$ evaluated as well. Solution of these equations in their finite volume form is accomplished through a commercial software package, CAE-CFD namely EFD Lab. The Navier-Stokes equations for 3D laminar flow with were solved using a finite-volume based CFD solver integrated in the EFD Lab software.

3.3 ASSUMPTIONS , PARAMETER AND BOUNDARY CONDITIONS

To run the simulation, it is assumed that blood is a Newtonian fluid and that the flow is laminar and assumption of Newtonian behavior is based on the findings (Perktold, 1989). 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 3.2.

Table 3.2: Parameters used in the simulation

Parameters	**Value**
Blood Velocity (Cerebral)	0.7 m/s
Pressure	463 Pa
Temperature	273 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 different according to the other place in our body. The velocity for cerebral is 0.7 m/s. In figure 3.4 shows the initial condition that’s been used by Marie Oshima. While in figure 3.5 show the initial velocity that will be applying in this case study. In this case study, the velocity will be set to 0.7 m/s.

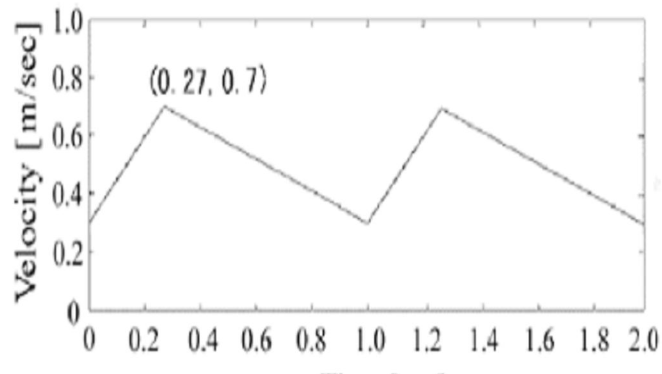


Figure 3.4: Graph Velocity versus Length.

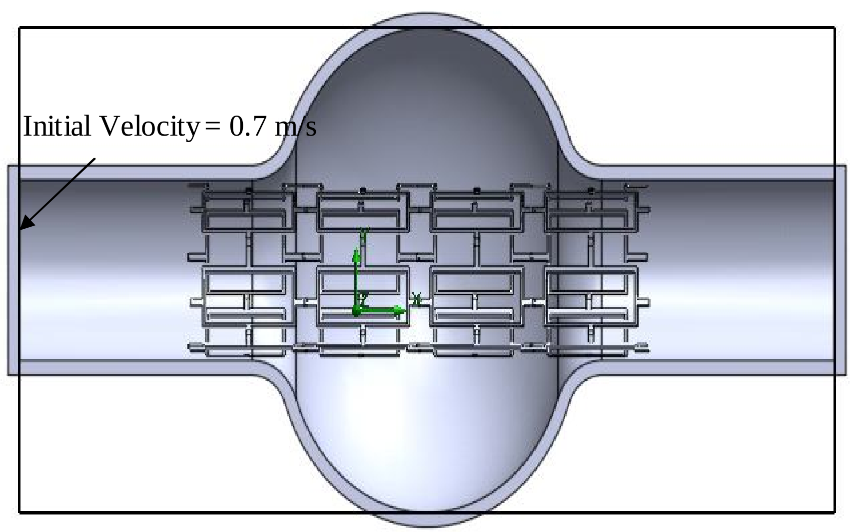


Figure 3.5: Velocity condition

3.4.2 Peak Pressure Systole and Diastole

The vortex formation critical during the diastoles, it show significant change to the flow behavior (K.M. Khanafer, 2007). He 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. Figure 3.6 show the outlet pressure that will be applied to the model. The value of the outlet pressure is 463 Pa.

Therefore, the simulation will emphasize on the diastole condition with the pressure setting as follows:-

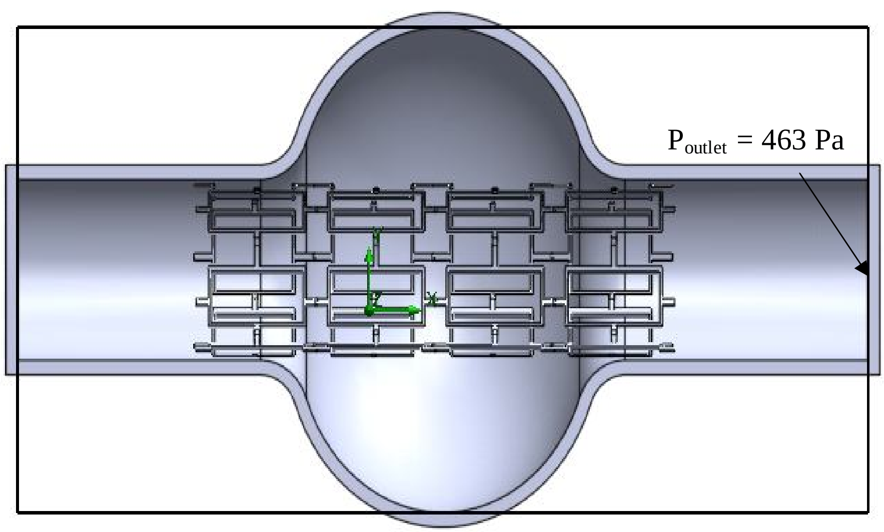


Figure 3.6: Pressure condition

CHAPTER 4

RESULT AND DISCUSSION

4.1 INTRODUCTION

Computational fluid dynamic simulations have been applied to assess local changes of velocity and pressure in aneurysms and these hemodynamic parameters are fairly well understood. Stent placement on side wall aneurysms has changed the flow patterns within the aneurysms.

In this study, stent implantation to the aneurysms has proven that the pressure can be reduced and the minimum velocity in the stented aneurysms can be increased. The data analysis was compared with three different types of stent to establish the effect of stent implantation in blood flow behavior.

The effect of stent plantation before and after the stent was applied will discuss. The flow behavior inside the aneurysm region will be different this is because of the used of stent is to reduce the amount of blood that will flow inside the aneurysm region and not to stop the blood flow into the region. So, the vortex inside the aneurysm region will be decreased. If the vortex inside the region is decreased, the pressure inside the region will decrease so that it will be able to avoid rupture inside the region.

4.2 VELOCITY PROFILE

Velocity profile inside the aneurysms region is presented in Figure 4.2, Figure 4.3 and Figure 4.4 according to the different type of stent. In Figure 4.1, it is the velocity profile inside the aneurysms region without stent implantation. The velocity pattern shows that the lowest velocity occurs to the simulations results of non stented blood flow behavior before stent placement. Once the flow passes through the aneurysms region, the velocity is reduced and that's mean there is velocity reduction occurred at the distal neck. It also means that there are energy losses of the fluid and unable to recover even the flow entering the normal artery. Stent designs need to be effectively chosen in order to reduce the flow. After stent implantation, the minimum velocity has been increased that is because the energy losses of fluid have been decreased.

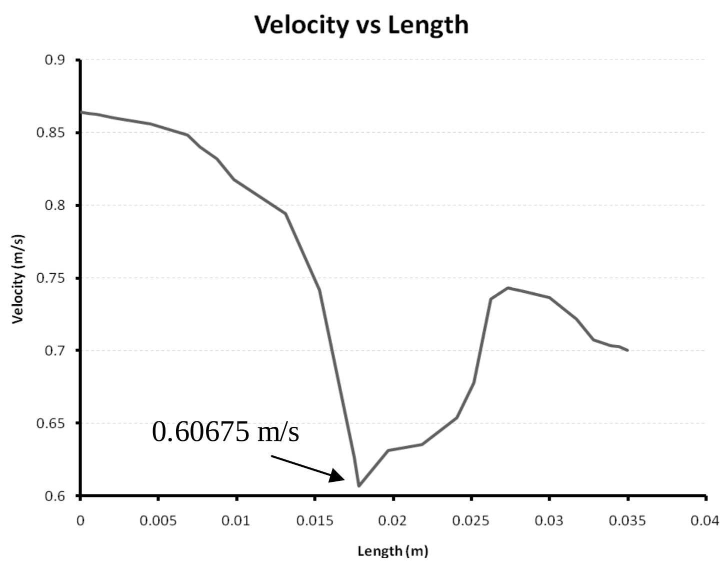


Figure 4.1: Velocity profile in non stented aneurysms region

Figure 4.1 show the graph of velocity versus length. The graph obtains from non stented aneurysm which is before the stent is applied. The value of minimum velocity is 0.60675 m/s. From figure 4.1, the velocity will decreased before the blood flow inside the region and suddenly the velocity will drop when blood flow inside the region.

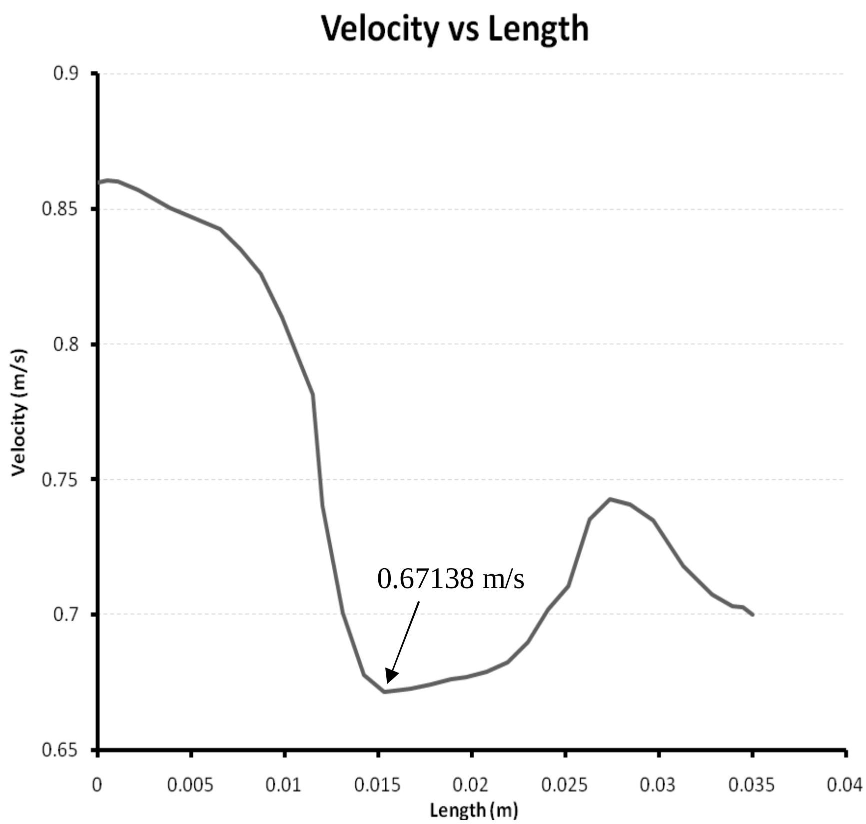


Figure 4.2: Velocity profile in stented aneurysm for stent Type 1

Figure 4.2 show the graph of velocity versus length for stented aneurysm for stent type 1. The value of minimum velocity has been increased compared before the stent was applied which is 0.67138 m/s. The minimum value has been increased and the velocity bandwidth is 0.16366 m/s.

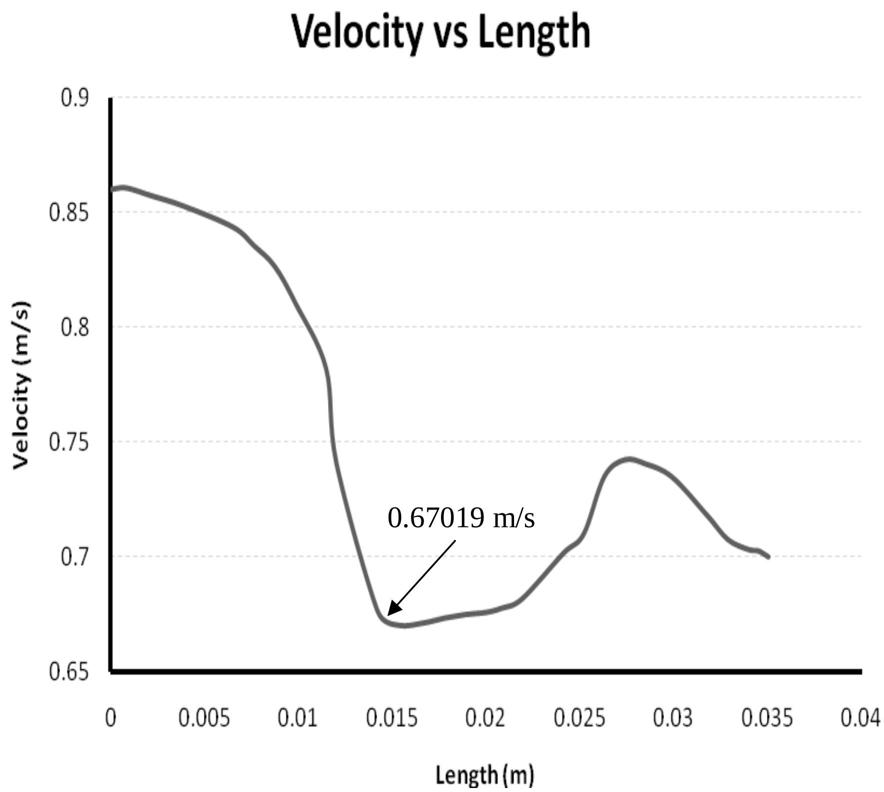


Figure 4.3: Velocity profile in stented aneurysm for stent Type 2

In figure 4.3, the value of minimum velocity is 0.67019 m/s. It is lower than the case before that using stent type 1. Stent type 2 has decreased the amount of blood flow compared to stent type 1. The velocity bandwidth is 0.15651 m/s.

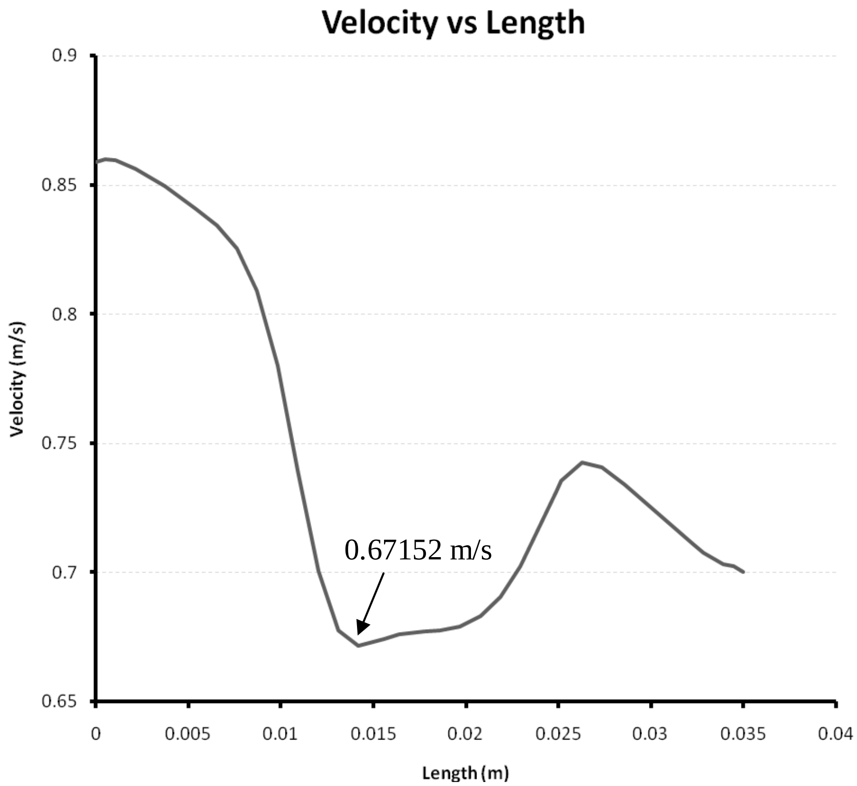


Figure 4.4: Velocity profile in stented aneurysm for stent Type 3

Figure show the increased of minimum velocity in stented aneurysm when stent type 3 is applied. The value of minimum velocity is 0.67152 m/s which the highest minimum value compared to stent type 1 and type 2. The velocity bandwidth for this case is 0.15399 m/s.

The effect of stenting can be seen from velocity profile inside the stented aneurysm as shown in Figure 4.1 to Figure 4.4.The minimum velocity has been increased after the stent was applied. It does not exist strongly as for non stented aneurysms which throughout the entire flow nearly changed the velocity inside the aneurysms closely to the arterial flow velocity. Stent type 3 has the highest value for the minimum velocity compared to stent type 1 and 2 as shown in table 4.1.

When the stent type 1 applied to the aneurysms, the minimum velocity increased 10.652% compared to type 2 with 10.455%. The effective minimum velocity increased was stent type 3 with 10.675% with its velocity bandwidth is 0.15399 m/s. The different stents will results a different velocity bandwidth. In general, the results conclude that different type of stents will produced different value of minimum velocity percentage and the velocity bandwidth will decreased if the percentage of minimum velocity increased.

Table 4.1: Minimum Velocity and Velocity Bandwidth for all stent types

No	Stent Type	Min Velocity(m/s)	Max Velocity (m/s)	Velocity Bandwidth(m/s)
1		0.60675	0.8177	0.21098
2	1	0.67138	0.8350	0.16366
3	2	0.67019	0.8267	0.15651
4	3	0.67152	0.8255	0.15399

Calculation percentage of velocity

Type 1

$$\% = \frac{0.67138 - 0.60675}{0.60675} \times 100$$

$$= 10.652\%$$

Type 2

$$\% = \frac{0.67019 - 0.60675}{0.60675} \times 100$$

= 10.455%

Type 3

$$\% = \frac{0.67152 - 0.60675}{0.60675} \times 100$$

= 10.675%

Stent type 3 provides the percentage of minimum velocity compared to other type as shown in table 4.2. The calculation to get the percentage value has shown as above.

Table 4.2: Percentage of Minimum Velocity for all stent types

No	**Type**	**Percentage (%)**
1		0
2	1	10.652
3	2	10.455
4	3	10.675

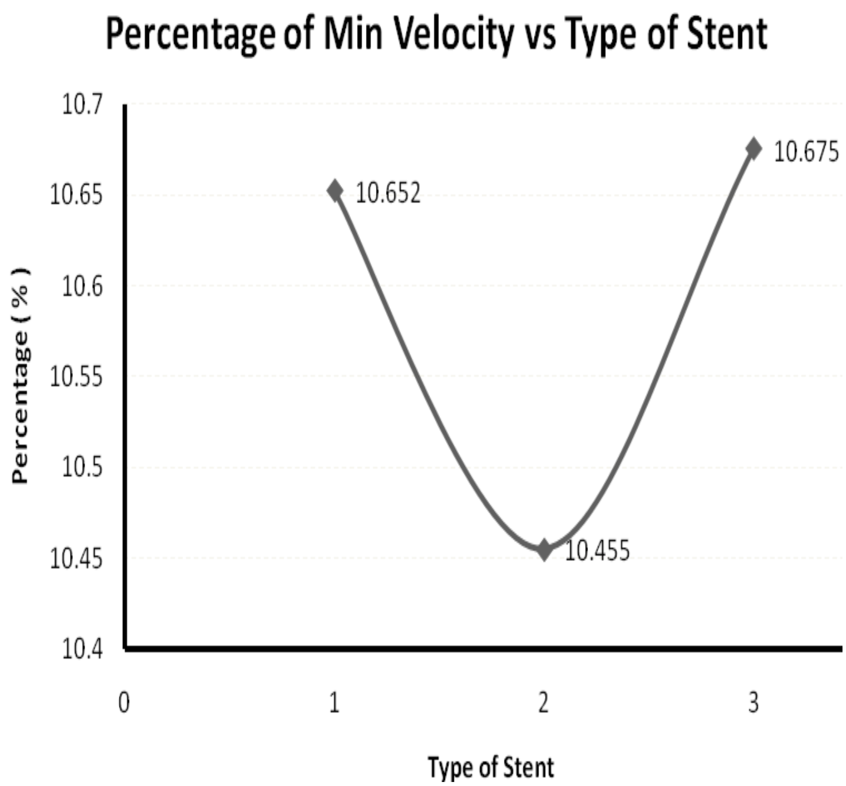


Figure 4.5: Percentage of Minimum Velocity for 3 types of Stents

Figure 4.5 show the graph of minimum velocity for 3 different type of stent. The graph plotted using the data obtain in table 4.2. The highest percentage can be seen clearly. Stent type 3 has the highest percentage of minimum velocity 10.675% compared to type 1 and type 2 with 10.652 % and 10.455 % respectively.

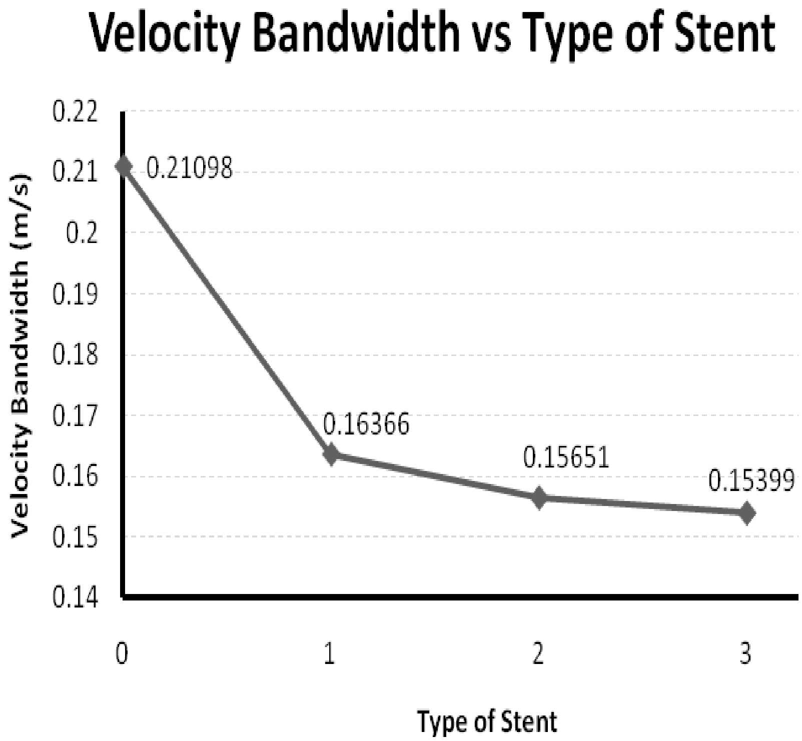
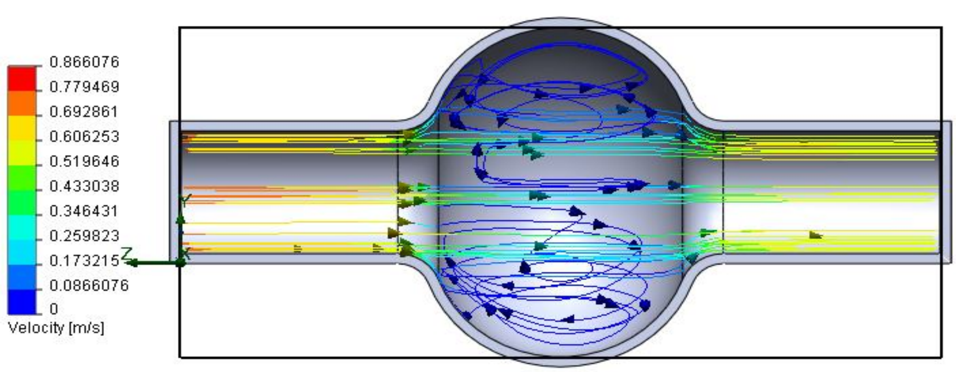
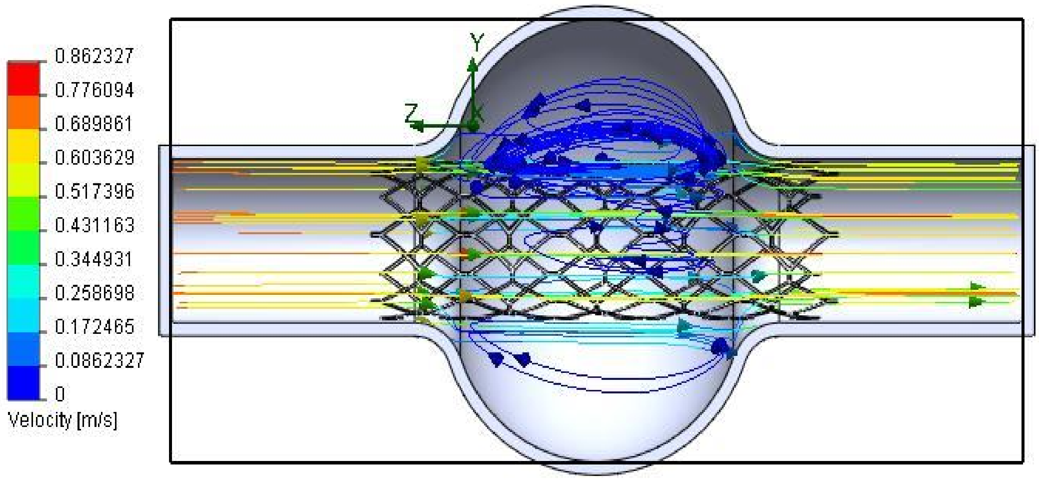


Figure 4.6: Velocity Bandwidth for each stent types

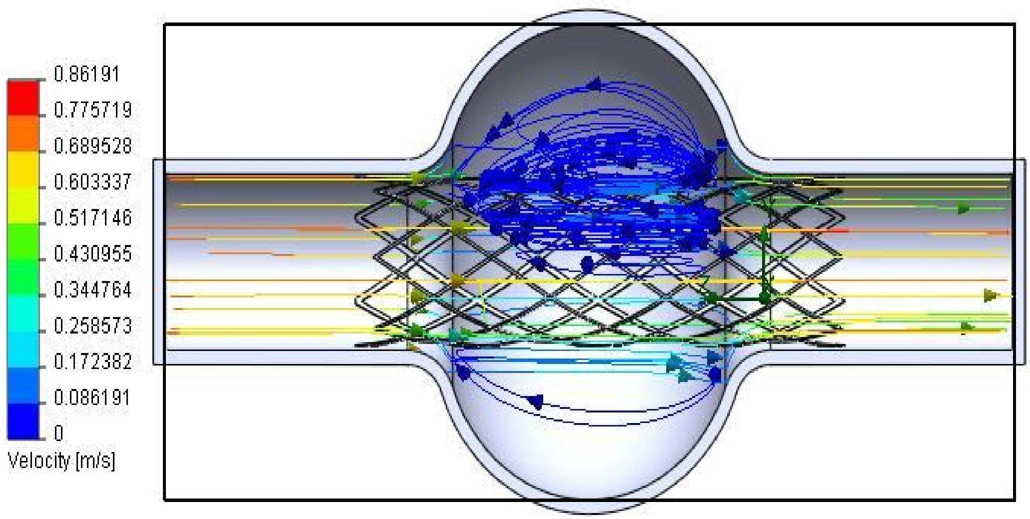
Figure 4.6 shows the graph of velocity bandwidth for each type of stent. Stent type 3 has the lowest velocity bandwidth which 0.15399 m/s compared to stent type 1 with 0.16366 m/s and stent type 2 with 0.15651 m/s.



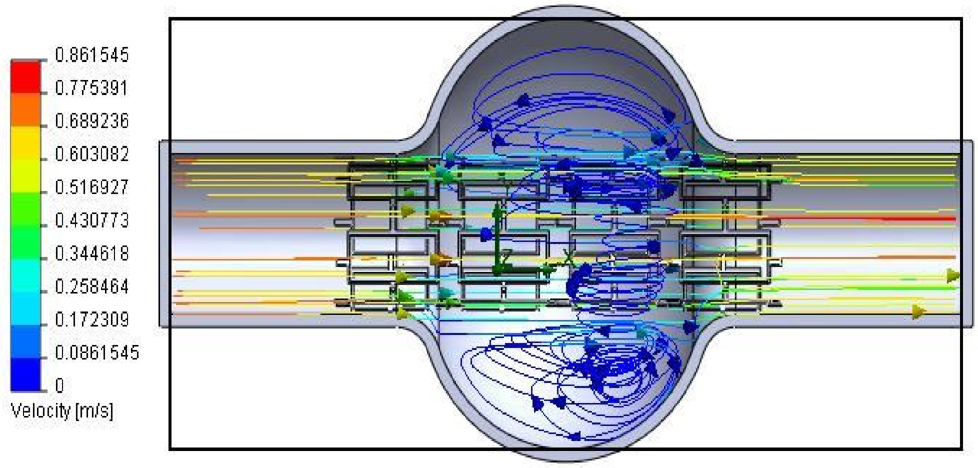
(A)


0.862327
0.776094
0.689861
0.603629
0.517396
0.431163
0.344931
0.258698
0.172465
0.0862327
0
Velocity [m/s]
Y
Z
X

(B)


0.86191
0.775719
0.689528
0.603337
0.517146
0.430955
0.344764
0.258573
0.172382
0.086191
0
Velocity [m/s]

(C)



(D)

Figure 4.7: Velocity streamlines a) Non stented Aneurysms b) Type 1 c) Type 2, d) Type 3

Velocity streamlines before and after the stent was applied is different. It can be seen at figure 4.7. Figure 4.7A is velocity streamlines for the non stented aneurysm. There is many streamlines inside the region compared to others. For figure 4.7B, the amount of vortex inside the region has been reduced compared to figure 4.7A. This is because the blood has been block from entering the aneurysm region and it is the same for figure 4.7C and figure 4.7D. Only the amount of vortex inside the region is different.
The velocity at the center of aneurysm region has been increased and it can be seen in table 4.1. If the velocity at the center of aneurysm is higher, that's mean it will become similar with the normal blood vessel.

4.3 PRESSURE PROFILE

Pressure profile inside the aneurysms region is presented in Figure 4.8 until Figure 4.11. For non stented aneurysms, the high pressure was noted at in Figure 4.8 and the peak pressure occurs before the flow entering the distal neck of aneurysms. The increased of pressure inside the aneurysms area was because of the growth of the aneurysms when the local weakening of the tissue occurred at this area. The effect of stenting can be seen after the stent was applied to the aneurysms region and we can see the stent strut disturbs the blood flow in the aneurysms. It will cause the level of flow activity become higher but the pressure is reduced as shown in Figure 4.9 until Figure 4.11.

According to Bernoulli principle, the exit pressure will be higher than the inlet pressure. Bernoulli principle gives the relationship between velocity and pressure. It is very clear that the pressure for all cases studied follow this principle as shown on Figure 4.8 until Figure 4.11. 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.

The peak pressure has been shows in Table 4.3 after the analysis performed to determine the important parameters in pressure distribution in aneurysms dome. These numerical results revealed some of understanding towards predicting rupture of aneurysms where the local pressure at the distal end found to be critical location. To investigate the role of this weakening wall due to these phenomena.

From table 4.3, it shows that the effect of stent applied. The value of peak pressure is decreased after the stent was applied. The pressure bandwidth also decreased after the stent was applied.

Table 4.3: Peak Pressure and Pressure Bandwidth for all stent types

No	Type	Peak Pressure(Pa)	Pressure Bandwidth(Pa)
1		688	58.616
2	1	607	44.903
3	2	609	46.711
4	3	606	45.327

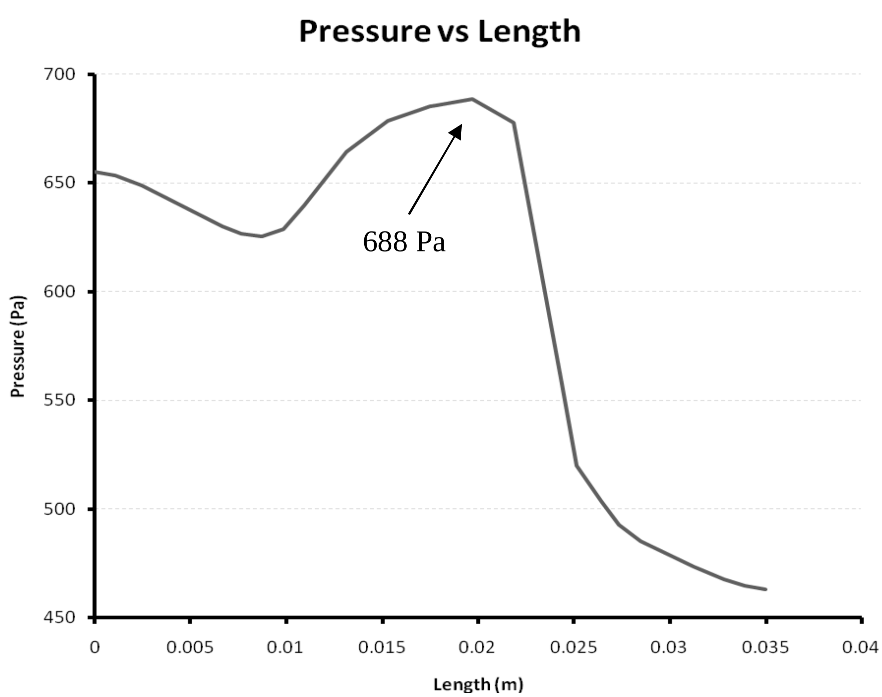


Figure 4.8: Pressure distribution for non stented aneurysms

Figure 4.8 show the pressure distribution for non stented aneurysm. The value of the peak pressure is 688 Pa. The pressure is high because of there is a lot of vortex inside the aneurysm region. The pressure bandwidth for this case is 58.616 Pa as shown in table 4.3. The pressure before the blood flow inside the region is decreased and it suddenly increased when it flow inside the aneurysm region.

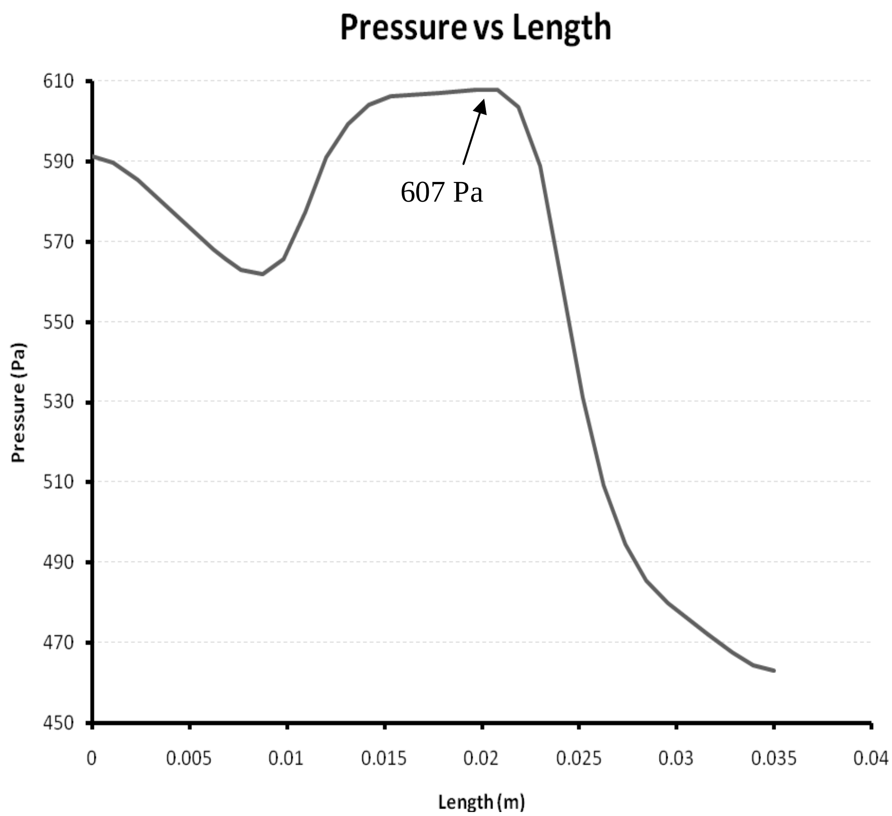


Figure 4.9: Pressure distribution for stented aneurysms for stent Type 1

Figure 4.9 show the pressure distribution for stented aneurysm for stent type 1. The value of the peak pressure is 607 Pa. The pressure is reduced after the stent was applied. It can be seen after making the comparison from the non stented case. The pressure bandwidth also decreased to 44.903 Pa as shown in table 4.3.

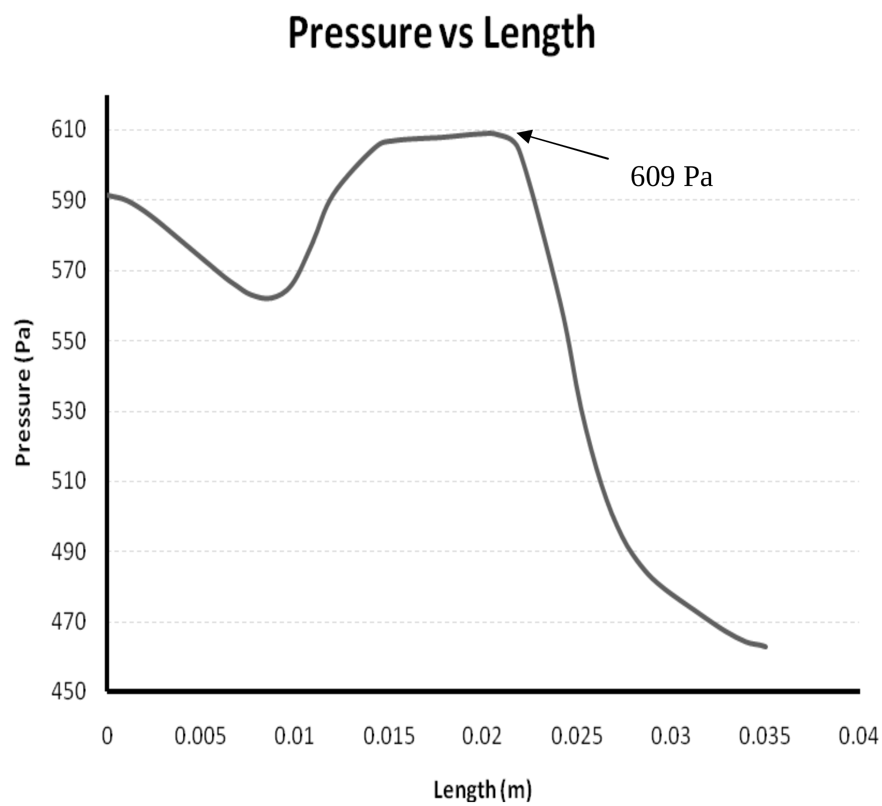


Figure 4.10: Pressure distribution for stented aneurysms for stent Type 2

In figure 4.10, the value of the peak pressure is 609 Pa. The pressure is lower compare when using stent type 1. The pressure bandwidth also decreased to 46.711 Pa as shown in table 4.3. There is a different when using different type of stent. The pressure also lowers than the non stented case.

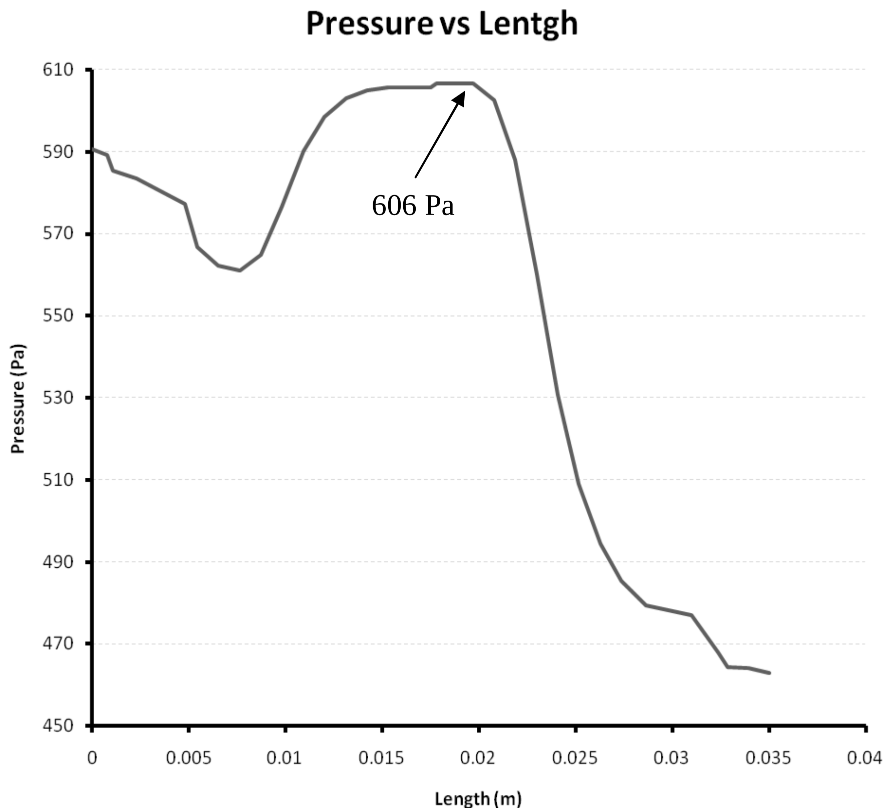


Figure 4.11: Pressure distribution for stented aneurysms for stent Type 3

Figure 4.11 show the pressure distribution for stented aneurysm for stent type 3. The value of the peak pressure is 606 Pa and it is the lowest peak pressure compare to other type of stent. The pressure is reduced after the stent was applied. The pressure bandwidth also decreased to 45.327 Pa as shown in table 4.3.

For example in predicting the exit pressure, consider the sample computational for the stented aneurysm case for stent Type 3. The pressure inlet that been use is 561 Pa at the length of 0.007 m with the velocity of 0.826 m/s. The calculation is to found the value of exit pressure at the length of 0.025 m and at the velocity of 0.736 m/s. The purpose to calculate the exit pressure is to prove the Bernoulli Principle whether exit pressure is higher than inlet pressure.

Table 4.4: Data for two point in streamline

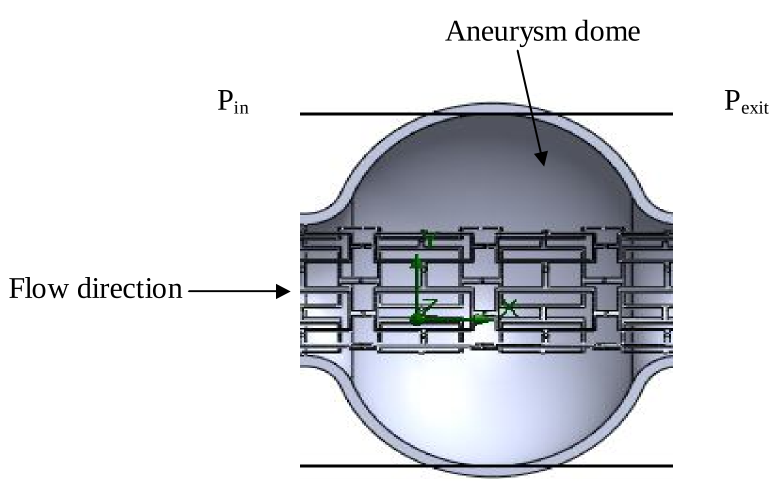
Inlet (*i*)	**Exit(*e*)**
P_{in} = 561 Pa	P_{exit}
X_1=0.007 m	X_2=0.025 m
V_1=0.826 m/s	V_2=0.736 m/s

Calculation:

$$P_{exit} = \frac{(V_1)^2 - (V_2)^2}{2} + P_{in}$$

$$P_{exit} = \frac{(0.826)^2 - (0.736)^2}{2} + 561$$

$$P_{exit} = 561.62 \text{ Pa}$$



Sample calculation above has proved that the exit pressure is higher than inlet pressure. It is agreed the Bernoulli principle because the increase of pressure. According to Bernoulli principle, velocity at exit is lower than the inlet velocity.

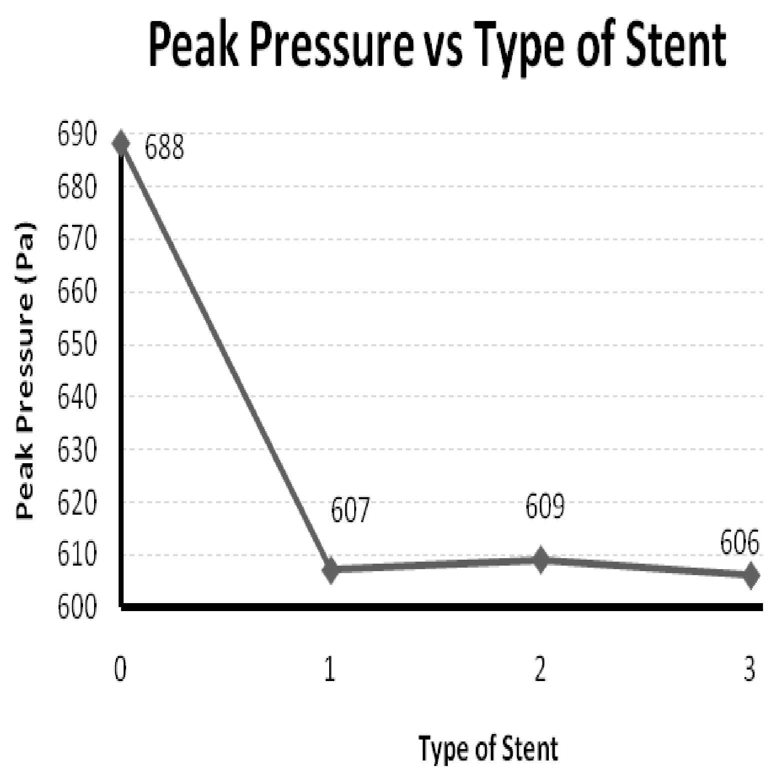
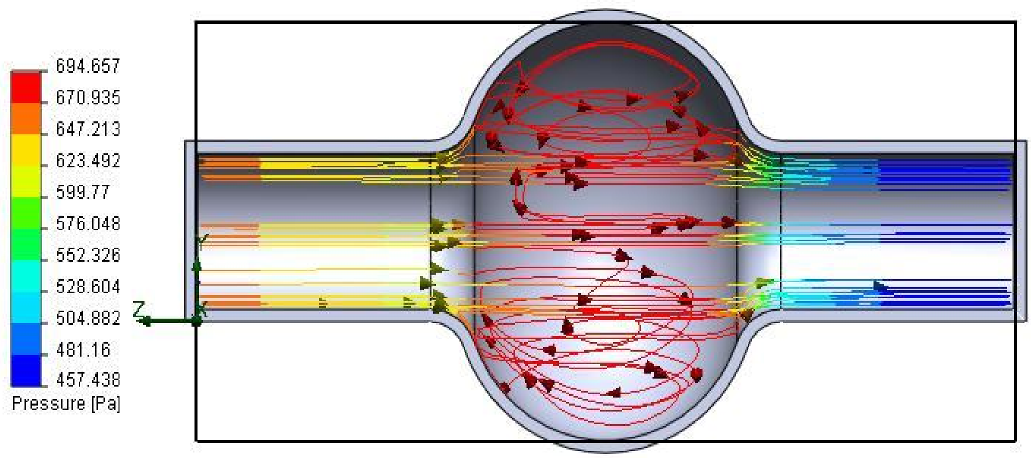


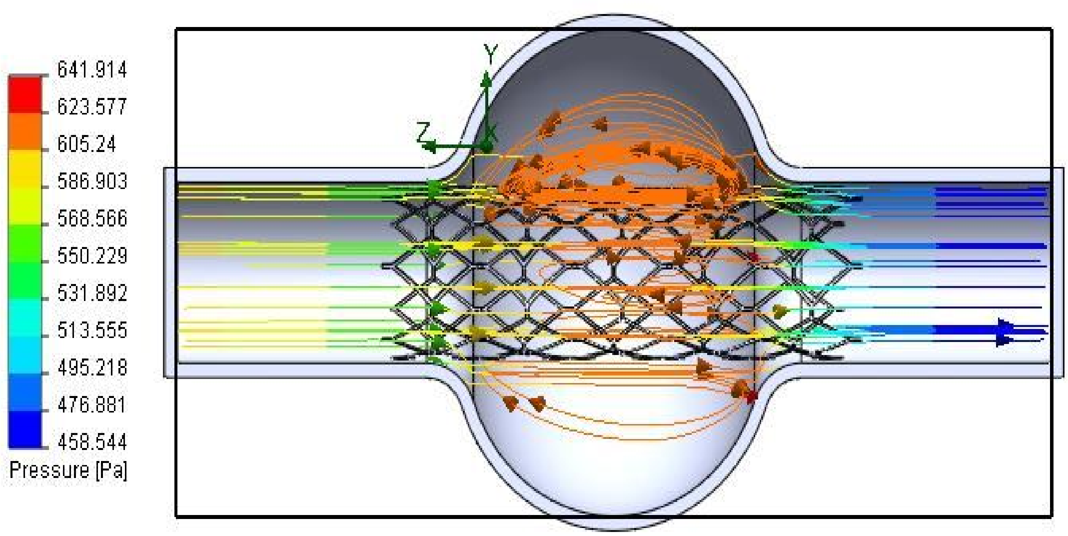
Figure 4.12: Correlation of peak pressure

After graph plotted, stent Type 3 has lowered the down peak pressure. Stent Type 3 has the lower peak pressure compared to Type 1 with 607 Pa and Type 2 with 609 Pa. The lowest peak pressure is 606 Pa. Stent Type 3 also has the most effective minimum velocity as shown in Table 4.1. The application of stent to these aneurysms will result completely different hemodynamic environment. In order to improve the effectiveness of stent, characterization and understanding of the hemodynamic environment in aneurysms after treatment must be strongly correlated.

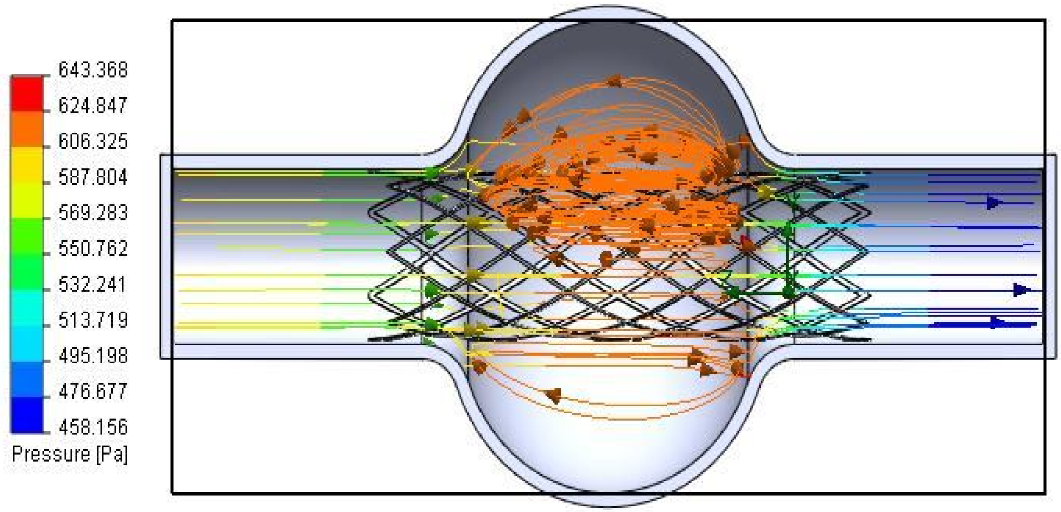
In general, the result can be conclude that the best type of stent can be used is Type 3 because it has the most effective minimum velocity and it also has the lowest peak pressure compared to other type.



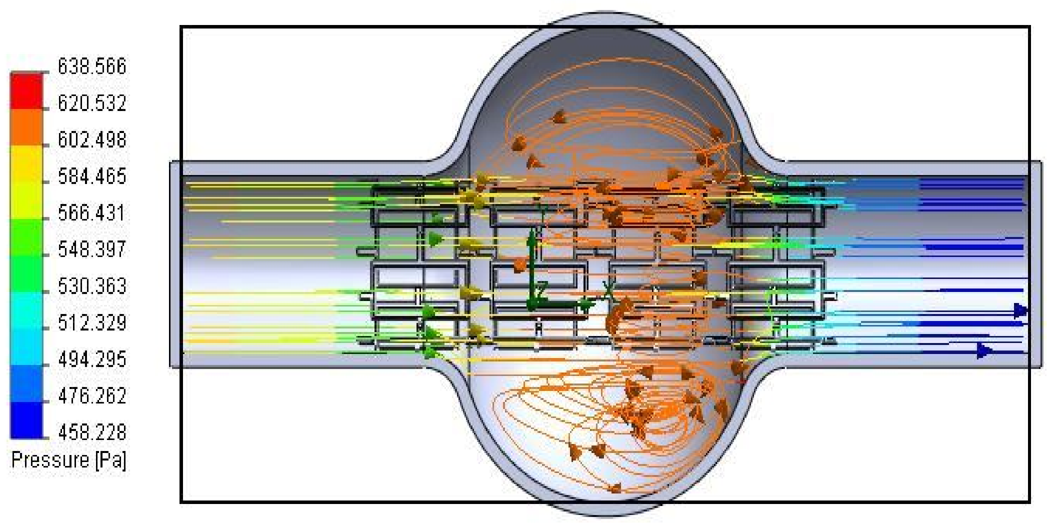
(A)



(B)



(C)



(D)

Figure 4.13: Pressure contour for a) Non stented Aneurysms b) Type 1 c) Type 2 d) Type 3

The study of blood flow behavior is very difficult to measure if it is perform directly in real aneurysms so that we used the numerical simulation method. The result obtained from the analysis provides detailed information on critical local flow parameters such as velocity and pressure near the stent struts. In figure 4.13A, the pressure at the aneurysm region is high compare to other and it is before the stent was applied. While in figure 4.13B, 4.13C and 4.13D, the pressure has been reduced. It can be seen according to the color of the streamlines.

According from the simulation result, stent type 3 given the lowest peak pressure compare to other type. It also given the highest minimum velocity compare to other type of stent. Correlation between the peak pressure, minimum velocity and type of stent has been identified. The effective tool for better understanding of aneurysms flow behavior is by using the numerical flow simulation and it is proved.

4.4 STENT PROPERTIES

All the data obtained is different according to the type of stent. Actually, every type of stent has different properties such as different surface area and volume. That's the factor why the result is different even the double layer stent is applied. If the surface area of the stent is higher, blood flow that will flow into the aneurysms region is less. So, there is a relation between the surface area of stent with velocity and pressure. If the amount of blood flow in aneurysms region is less, the peak pressure will decreased.

When the peak pressure is decreased, the minimum velocity inside the region will increase. There is also a relation between surface area and volume of the stent. If the value of surface area is higher, value of volume also higher. So, stent type 3 is the best stent to apply according to the surface area and volume value. Stent type 3 has surface area 241.06 mm^2 and it's the highest value compared to stent type 1, 192.51 mm^2 and stent type 2, 225.62 mm^2 as shown in Table 4.5. Only the volume is different because stent type 2 has the highest volume compared to others with 3.2 m^3.

Table 4.5: Data for surface area and volume of different stent

Type of Stent	Surface Area (mm²)	Volume (mm³)
1	192.51	3.2
2	225.62	4.24
3	241.06	4.17

Figure 4.14 and figure 4.15 are the graph for surface area and volume for each type of stent. The graphs plotted according to the value obtain from table 4.5. Stent type 3 has the higher surface area of the stent with 241.06 mm² compare to type 1, 192.51 mm² and type 2, 225.62 mm² as shown in figure 4.14. For the volume, stent type 2 has the highest volume with 4.24 mm³ while stent type 1 is the lowest with 3.2 mm³ and stent type 3 with 4.17 mm³ as shown in figure 4.15.

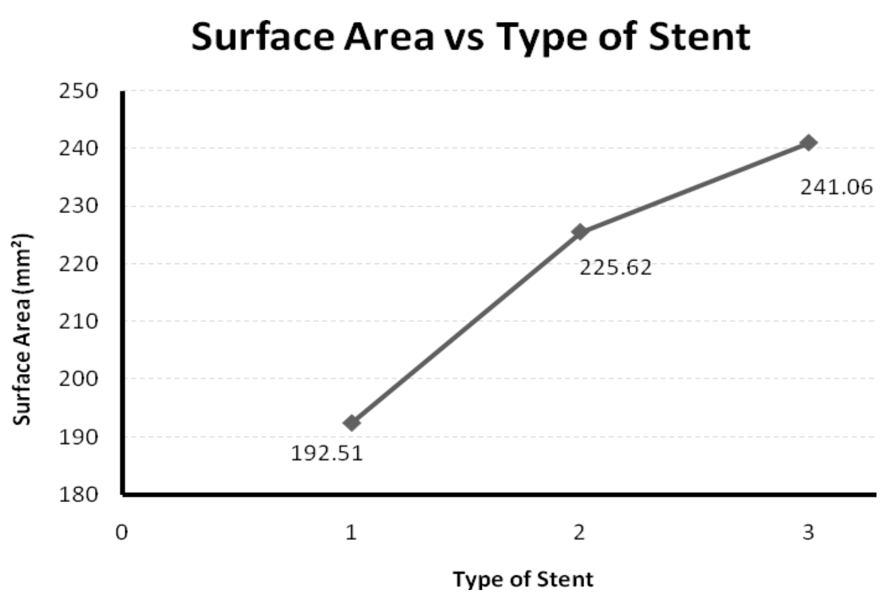


Figure 4.14: Surface area for different type of stent

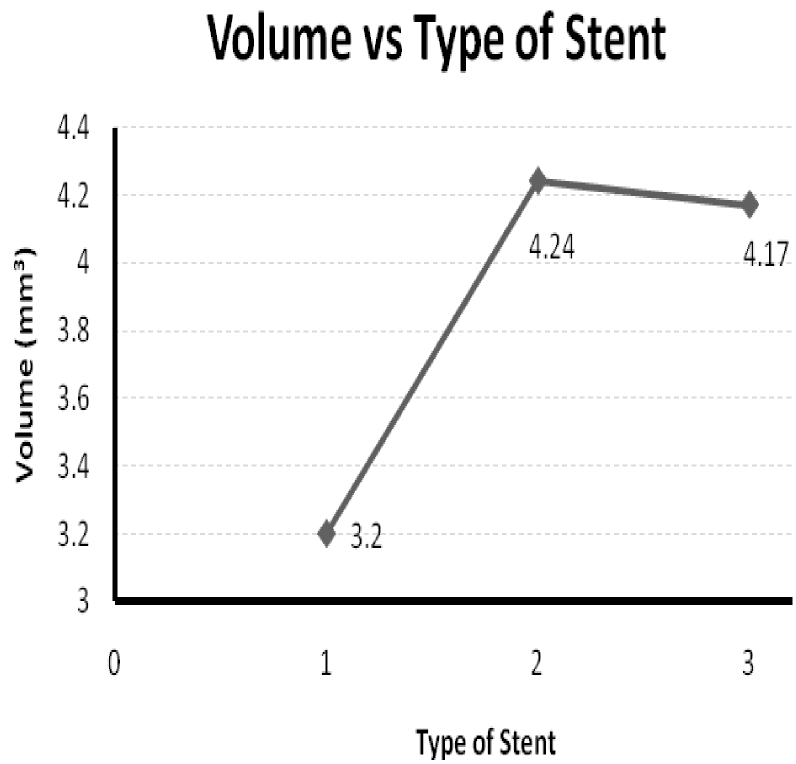


Figure 4.15: Volume for different type of stent

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

In this study, the velocity bandwidth and pressure bandwidth can be known. The best result is to get the lower value for the bandwidth either for velocity or pressure. This is because if the value of bandwidth is lower, that's mean the blood flow in stented aneurysms is similar to a blood flow for a normal person.

After done the simulation, the lowest peak pressure is 606 Pa which is found from the installation of stent type 3. Stent type 3 also gives the highest value for minimum velocity which is 0.67152 m/s. As expected, if the peak pressure is low, the value for minimum velocity will be high.

There is a different that could be seen before and after the stent was applied. The velocity profile inside the stented aneurysms and non stented aneurysms is different because of the stenting effect. After stent type 3 been applied, the large vortex formations that dominate the non stented aneurysms have been reduced.

Stent type 1 has increased the minimum velocity to 10.652% after the stent was applied to the aneurysms compared to stent type 2 with 10.455%. Stent type 3 has the most effective minimum velocity with 10.675%. So, the result of stent type 3 has lowest the velocity bandwidth compared to other.

As a conclusion from the data obtained, stent type 3 satisfy both requirement for the lowest peak pressure and lowest velocity bandwidth.

5.2 RECOMMENDATIONS

There are some recommendations in order to get the better peak pressure and the best velocity bandwidth. They are:

1. Increased the number of stent type. When the number of stent type has been increased, the possibilities to get better result are higher because many data will obtained and it's easy to make a decision.

2. Increased the number of stent layer. If the layer is increased, the total amount of blood flow in aneurysms area will decreased.

3. Use different size of aneurysms from case to case so that this study will be able to predict the effect of dome size to flow behavior.

4. Use other parameters such as strut angle, strut thickness and stent shape design in future studies because these parameters may have significant impact on flow vertices.

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APPENDICES

PRESSURE VS LENGTH DATA FOR NON-STENTED ANEURYSM

Length (m)	Pressure (Pa)
0	655.1209187
0.001060685	653.6003715
0.002469495	648.6856206
0.006696683	629.9846414
0.007636058	626.6478426
0.008731995	625.3779577
0.009827933	628.7223161
0.01092387	639.5982862
0.013115745	664.4879536
0.01530762	678.4333067
0.0175	685.3973601
0.017813053	685.8550204
0.01969137	688.6009821
0.021883245	677.542894
0.024388245	557.7534293
0.025171058	519.9044341
0.026423558	503.6051991
0.027362933	492.6083618
0.02845887	485.0726095
0.031276995	473.4416637
0.03284262	467.6761959
0.03393881	464.7644379
0.034734703	463.6254599
0.035	463.0000003

VELOCITY VS LENGTH DATA FOR NON-STENTED ANEURYSM

Length (m)	Velocity (m/s)
0	0.864240398
0.000530343	0.863015375
0.001060685	0.862645713
0.00215637	0.860083677
0.004504808	0.856115164
0.006853245	0.84850958
0.007636058	0.840184246
0.008731995	0.832001436
0.009827933	0.817734612
0.013115745	0.794323858
0.01530762	0.741853403
0.0175	0.626599335
0.017813053	0.60675492
0.01969137	0.631069317
0.021883245	0.635121803
0.02407512	0.653876639
0.025171058	0.677819233
0.026266995	0.735258457
0.027362933	0.742959515
0.02845887	0.740801246
0.030024495	0.736548057
0.031746683	0.721935787
0.03284262	0.707534924
0.03393881	0.703205935
0.034469405	0.702573714
0.035	0.7

PRESSURE VS LENGTH DATA FOR STENTED ANEURYSM USING STENT TYPE 1

Length (m)	Pressure (Pa)
0	591.2220276
0.001060685	589.6814274
0.002312933	585.3748697
0.003878558	578.4931557
0.006226995	567.9398434
0.006853245	565.5187722
0.007636058	562.8464457
0.008731995	561.8006185
0.009827933	565.5907493
0.01092387	577.3340548
0.012019808	590.9487551
0.013115745	599.3118957
0.014211683	604.0736597
0.01530762	606.1962501
0.016951527	606.8012676
0.017773858	606.9414612
0.01969137	607.8156319
0.020787308	607.7499944
0.021883245	603.621941
0.022979183	588.7875232
0.02407512	560.727142
0.025171058	531.1245509
0.026266995	509.2092665
0.027362933	494.4150546
0.02845887	485.4921379
0.029554808	479.8128433
0.03159012	472.0253519
0.03284262	467.4324872
0.03393881	464.3469461
0.035	463

VELOCITY VS LENGTH DATA FOR STENTED ANEURYSM USING STENT TYPE 1

Length (m)	Velocity (m/s)
0	0.85964687
0.000530343	0.860397493
0.001060685	0.859942418
0.00215637	0.856867227
0.003878558	0.850142941
0.00654012	0.842414572
0.007636058	0.835044762
0.008731995	0.826025516
0.009827933	0.809973168
0.011471839	0.781267407
0.012019808	0.740417052
0.013115745	0.700556776
0.014211683	0.67748717
0.01530762	0.671388286
0.016677542	0.672605176
0.017773858	0.67430105
0.018869417	0.675899407
0.01969137	0.676919359
0.020787308	0.678755181
0.021883245	0.682427621
0.022979183	0.68975121
0.02407512	0.701892894
0.025171058	0.710356744
0.026266995	0.735191427
0.027362933	0.742506044
0.02845887	0.740602919
0.02971137	0.734871168
0.031276995	0.718040864
0.03284262	0.707558896
0.03393881	0.703205755
0.034469405	0.702569617
0.035	0.7

PRESSURE VS LENGTH DATA FOR STENTED ANEURYSM USING STENT TYPE 2

Length (m)	Pressure (Pa)
0	591.6192489
0.001060685	590.0786239
0.002312933	585.7724149
0.003878558	578.8912091
0.006226995	568.3485036
0.006853245	565.9376049
0.007636058	563.2840338
0.008731995	562.3228242
0.009827933	566.223769
0.01092387	578.1508782
0.012019808	591.8526844
0.014211683	605.0466904
0.01530762	607.1758804
0.017773858	608.0713511
0.01969137	609.033644
0.020787308	608.8074508
0.021883245	604.5108674
0.02407512	561.131908
0.025171058	531.1494209
0.026266995	509.1851583
0.027362933	494.4345094
0.02845887	485.5108429
0.029554808	479.7874221
0.031433558	472.594208
0.03284262	467.481738
0.03393881	464.4228751
0.034734702	463.4448477
0.035	463

VELOCITY VS LENGTH DATA FOR STENTED ANEURYSM USING STENT TYPE 2

Length (mm)	Velocity (m/s)
0	0.86006503
0.000530343	0.860853762
0.001060685	0.860422912
0.00215637	0.85746571
0.003878558	0.852951913
0.00654012	0.843626318
0.007636058	0.835603694
0.008731995	0.826704363
0.009827933	0.810756428
0.011471839	0.782058195
0.012019808	0.740832651
0.014211683	0.676358157
0.01530762	0.670194858
0.016677542	0.671247789
0.017773858	0.673314507
0.018869417	0.674857979
0.019965355	0.675784393
0.020787308	0.677568923
0.021883245	0.68159273
0.02407512	0.701437448
0.025171058	0.709943481
0.026266995	0.734956961
0.027362933	0.742341419
0.02845887	0.740529236
0.029867933	0.734851376
0.031746683	0.718040918
0.03284262	0.707558566
0.03393881	0.703205524
0.034469405	0.702569491
0.035	0.7

PRESSURE VS LENGTH DATA FOR STENTED ANEURYSM USING STENT TYPE 3

Length (m)	Pressure (Pa)
0	590.5902395
0.000795445	589.0432591
0.001060593	585.39825
0.002312749	583.4066177
0.004817749	577.1258744
0.005443999	566.5927429
0.006539937	562.1424911
0.007635874	561.1000386
0.008731812	564.861017
0.009827749	576.46191
0.010923687	590.0130886
0.012019624	598.3729846
0.013115562	602.9777066
0.014211499	604.8893385
0.015307437	605.5743724
0.0175	605.630116
0.017773812	606.5164599
0.019691187	606.4265793
0.020787124	602.4793338
0.021883062	587.914098
0.022978999	560.1183806
0.024074937	530.7783842
0.025170874	509.0763495
0.026266812	494.3860467
0.027362749	485.329122
0.028615249	479.5320068
0.030963687	477.0934857
0.032372749	468.0257157
0.032842436	464.4262176
0.033938718	464.153885
0.035	463.0000004

VELOCITY VS LENGTH DATA FOR STENTED ANEURYSM USING STENT TYPE 3

Length (m)	Velocity (m/s)
0	0.859020293
0.000530297	0.860139054
0.001060593	0.859681582
0.002156187	0.856591524
0.003721812	0.849654427
0.005443999	0.840964056
0.006539937	0.834463001
0.007635874	0.825511099
0.008731812	0.809253462
0.009827749	0.780171921
0.010923687	0.739669259
0.012019624	0.700428826
0.013115562	0.677333655
0.014211499	0.671528314
0.015581421	0.674108389
0.016403374	0.676058558
0.017773812	0.677231496
0.018595249	0.677448895
0.019691187	0.67897197
0.020787124	0.68309748
0.021883062	0.690550126
0.022978999	0.702359905
0.02489689	0.731467963
0.025170874	0.735567676
0.026266812	0.742737321
0.027362749	0.740710554
0.028615249	0.73395311
0.032216186	0.71128063
0.032842436	0.707559608
0.033938718	0.7032012
0.034469359	0.702564931
0.035	0.7

BALLOON-EXPANDABLE STENT CHART

Company Name	Product Name	Indicated Use	Material Used	Maximum Guidewire Size (in)	Introducer Size (F)	Stent Diameter (mm)	Stent Length (mm)	Delivery System Length (cm)
Abbott Vascular Devices	Wavemax	Biliary (US)	316L Stainless Steel	0.035	6	5-7	12, 17, 28, 38	75, 135
					7	8-9	12, 17, 28, 38, 58	
					8	10	28, 38	75
					8	12	38	
Angiodynamics	OmniFlex	Biliary (US)	Platinum	0.035	6	5-6	15	75, 100
					7	7		
	VistaFlex	Biliary (US)	Platinum	0.035	7	5-6	35, 55	75, 100
					8	7-9		
					9	10		
Atrium Medical	iCast Covered Stent	Tracheobronchial (US)	316L Stainless Steel	0.035	6, 7	5-12	16, 22, 38, 59	80, 120
	Advanta V12 Covered Stent	Iliac (Europe)	316L Stainless Steel	0.035	6, 7	5-12	16, 22, 38, 59	80, 120
Boston Scientific	Express Biliary LD	Biliary	316L Stainless Steel	0.035	6	5-8	17, 27, 37	75, 135
					7	8	57	
					7	9, 10	25, 37, 57	
	Express Biliary SD	Biliary	316L Stainless Steel	0.018	5	4, 5	15, 19	90, 150
					5	6	14, 18	
					6	7	15, 19	
	Express Vascular LD	Peripheral Vascular Lesions (available outside US)	316L Stainless Steel	0.035	6	5-8	17, 27, 37	75, 135
					7	8	57	
					7	9, 10	25, 37, 57	
	Express Vascular SD	Peripheral Vascular Lesions (available outside US)	316L Stainless Steel	0.018	5	4, 5	15, 19	90, 150
					5	6	14, 18	
					6	7	15, 19	
Cordis Endovascular	Palmaz	Iliac, Renal, Biliary	316L Stainless Steel	N/A (unmounted)	6, 7	4-8	10, 15, 20, 29, 39	N/A (unmounted)
	Palmaz Blue	Biliary (US) Peripheral (Europe)	Cobalt-Chromium With Tungsten (L605)	0.018	5	4-7	12, 15, 18, 24	80, 135
	Palmaz Genesis	Biliary (US) Peripheral (Europe)	316L Stainless Steel	0.014	4-6	4-7	12, 15, 18, 24	75, 135
				0.018	5, 6	3-8	12, 15, 18, 24, 29, 39	80, 135
				0.035	6, 7	4-10	12, 15, 18, 24, 29, 39, 59, 79	80, 135
Edwards Lifesciences	LifeStent SDS	Biliary (US) Peripheral (Europe)	316L Stainless Steel	0.035	6, 7	6-10	18, 26, 36, 56	75, 120
	LifeStent Turbo	Biliary (US)	316L Stainless Steel	0.018	5	5-6	15, 18	80, 120
ev3	ParaMount Mini GPS	Biliary	316L Stainless Steel	0.014, 0.018	5	5, 6	14, 18, 21	80
					6	7		
	Primus GPS	Biliary	316L Stainless Steel	0.035	6	5, 6, 7, 8	12 (except 8 mm diameter), 17, 27, 37, 57	75, 120
					7	9, 10	17, 27, 37, 57 (and 8 X 57)	
Guidant	Omnilink	Biliary (US) Peripheral (Europe)	316L Stainless Steel	0.018	5, 6, 7, 8	4-10	12, 16, 18, 28, 38, 58	80, 135
				0.035	6, 6.5, 7, 7.5			
	RX Herculink Plus	Biliary (US) Peripheral (Europe)	316L Stainless Steel	0.014	5, 6	4, 4.5	12, 15, 18	80, 135
						5, 5.5		
						6, 6.5, 7		
Medtronic Vascular	Racer	Biliary	Cobalt Alloy (MP35N)	0.014, 0.018	5, 6	4-7	12, 18	80, 130
	Bridge Extra Support	Renal	316L Stainless Steel	0.035	7	5-7	10, 17	75, 120
	Bridge Assurant	Biliary	316L Stainless Steel	0.035	6	6-10	20, 30, 40, 60	80, 130