CFD Simulation for the Extraction of Blood Clot in the Middle Cerebral Artery Using GP2 Device through a 3 phase flow Model

by

Jeremy Melvin Amboi

Dissertation submitted in partial fulfilment of

the requirements for the

Bachelor of Engineering (Hons)

(Chemical Engineering)

MAY 2013

Universiti Teknologi PETRONAS

Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

CFD Simulation for the Extraction of Blood Clot in the Middle Cerebral Artery Using GP2 Device through a 3 phase flow Model

By

Jeremy Melvin Amboi

A project dissertation submitted to the

Chemical Engineering Programme

Universiti Teknologi PETRONAS

in partial fulfilment of the requirement for the

BACHELOR OF ENGINEERING (Hons)

(CHEMICAL ENGINEERING)

Approved by,

_____

(Dr. Ku Zilati bt. Ku Shaari)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

MAY 2013

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgments, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

_____

JEREMY MELVIN AMBOI

ABSTRACT

Stroke has been considered one of the most fatal disease identified by mankind, killing at least five million people per year. In order to combat this disease, several mitigation measures have been discovered through research, namely thrombolysis drug through consumption or mechanical devices through surgery such as balloon angioplasty, embolectomy and Mechanical Embolus Removal in Cerebral Ischemia (MERCI). Each of these methods have their disadvantages, more prevalently on heavy requirements and potential damage to the artery. However, a proposed device named Gillian-Pearce (GP) device was introduced which claims having lower surgical risks and damage to the patient's artery, through a simple concept of vacuum suction. The device remains untested on a real environment and thus, CFD analysis is done to enable simulation of the device in which it is more cost saving, safe and risk free.

The GP device is designed, modelled and simulated through CFD using ANSYS Design Modeller and FLUENT, using a three phase Volume of Fluid model i.e. air, blood and blood clot. Grid sensitivity study is also done to determine the best meshing size for the model of which the need to balance between the size of mesh and to minimise computational time. Additionally, comparison of two and three phase flow model is done in which to study the difference of extraction rate when additional phase is introduced, i.e. air, into the system. Furthermore, a proposed new GP2 device with different structural tubes is designed that is able to extract blood clot much faster compared to the old previous model.

It was found out that the best meshing size, i.e. between 0.25 mm, 0.20 mm and 0.15 mm, is 0.20 mm which is both fine enough for accuracy of results and short enough for computational time. Next, it was found out that the additional phase into the system will add to more lag time for the extraction process due to the presence of additional viscous fluid, of at least 12% increase in time of removal as compared to the two phase model. Finally, the newly proposed GP2 device is able to remove the blood clot at a rate of 9% much faster as compared to the old GP2 device due to having a larger area of suction for better mass transfer of the blood clot.

ACKNOWLEDGEMENT

First and foremost I would like to praise God for giving me the strength and knowledge in giving me this opportunity to reach up until this level and without His blessings, I will not be able to complete the task. I also would like to thank my family, friends and loved ones for providing the much needed moral support throughout the duration of this project, without them I will surely fall short. I would also would like to thank my FYP supervisor, Dr. Ku Zilati bt. Ku Shaari, for entrusting me in doing this project and without her continuous guidance and advices that I treasure most highly, the project will not be a success. And finally I would like to thank all the GAs for their advice and pointers which has contributed a lot during my research.

TABLE OF CONTENTS

CERTIFICATION i

ABSTRACT iii

ACKNOWLEDGEMENT iv

CHAPTER 1: INTRODUCTION 1

1.1 Background of Study . . . 1

1.2 Problem Statement 3

1.3 Objective and Scope of Study . 4

CHAPTER 2: LITERATURE REVIEW AND THEORY . 7

2.1 Literature Review 7

CHAPTER 3: METHODOLOGY 17

3.1 Grid Size Study 18

3.2 Two Phase versus Three phase flow study . 22

3.3 Proposed new GP2 Device . . . 23

3.4 Software 26

CHAPTER 4: RESULTS AND DISCUSSION . . . 27

4.1 Grid Sensitivity Study . . . 27

4.2 Clot Behaviour Study . . . 28

CHAPTER 5: CONCLUSION AND RECOMMENDATION . 41

5.1 Conclusion 41

5.2 Recommendation 43

APPENDICES 44

REFERENCES 50

LIST OF FIGURES

Figure 1 Thrombus causing blood flow disturbance . . . 2

Figure 2 GP2 device 4

Figure 3 Balloon Angioplasty. 8

Figure 4 Balloon Embolectomy 9

Figure 5 Summary of MERCI Procedure 10

Figure 6 Pulsatile Flow System 11

Figure 7 Interpolation Schemes 15

Figure 8 Isometric view of GP2 Device 18

Figure 9 Front view of GP2 Device 19

Figure 10 Side view of GP2 Device 19

Figure 11 Meshed model of GP2 Device (fine). 20

Figure 12 Meshed model of GP2 Device (coarse). 20

Figure 13 Isometric view of new GP2 Device 24

Figure 14 Front view of new GP2 Device 25

Figure 15 Meshed model of new GP2 Device (coarse). . . . 25

Figure 16 Grid Sensitivity Study under three phase model. . . . 28

Figure 17 Graph of Blood clot volume fraction against Flow Time under three phase model 32

Figure 18 Graph of Blood clot volume fraction against Flow Time under three phase model 38

LIST OF TABLES

Table 1 Dimensions of GP2 Device 5

Table 2 Dimensions of GP2 Device 18

Table 3 Properties of material. 21

Table 4 Boundary conditions at pressure inlet and outlet. . . 21

Table 5 Dimensions of new GP2 Device. 24

Table 6 Two phase versus three phase at 40 kPa . . . 29

Table 7 Two phase versus three phase at 50 kPa . . . 30

Table 8 Two phase versus three phase at 60 kPa . . . 31

Table 9 Validation work with previous model . . . 32

Table 10 Comparison between 2 and 3 phase flow model . . 32

Table 11 Old versus new GP2 device at 40 kPa . . . 36

Table 12 Old versus new GP2 device at 50 kPa . . . 37

Table 13 Old versus new GP2 device at 60 kPa . . . 38

Table 14 Comparison between old and new GP2 device . . 39

ABBREVIATIONS AND NOMENCLATURES

Computational Fluid Dynamics	CFD
Gwen Pearce	GP
Cerebrovascular Accident	CVA
von Willebrand Factor	vWF
Mechanical Embolus Removal in Cerebral Ischemia	MERCI
Thrombus Aspiration Device	TAD
Mechanical Thrombectomy Device	MTD
Tissue Plasminogen Activator	t-PA
National Health Lungs Blood Institute	NHLBI
Balloon Guide Catheter	BGC
American Journal of Neuroradiology	AJNR
Volume of Fluid	VOF
Weber's Number	We
Reynolds' Number	Re
Capillary Number	Ca

CHAPTER 1

INTRODUCTION

1. INTRODUCTION

1.1 Background of Study

The devastating effect of stroke has accounted to nearly fifteen million deaths worldwide every year, of which five million ended up dead while ten million suffered permanent disability (StrokeCenter.org, 2002). In the United States alone, it is by far the third leading cause of death and on average, with a shocking statistics that an American suffers stroke every 40 seconds (StrokeCenter.org, 2013). Stroke or in scientific terms Cerebrovascular Accident (CVA), is an incident whereby the brain suffers disturbance of blood supply which is due to ischemia, which is caused either by means of blockage or haemorrhage, in laymen's term the internal bleeding of the arteries (Sims et al., 2009). As a result, one might lose even the slightest basic ability such as walking, talking or even seeing. Even Jay Humphrey in his book Cardiovascular Solid Mechanics: Cells, Tissues and Organs; agrees that nerve cells die within minutes without enough supply of oxygen in the blood (Humphrey, 2001).

Factors that might induce the occurrence of stroke include elevated cholesterol levels, cigarette smoking, diabetes mellitus, genetic predisposition, social stressors and a sedentary lifestyle such as lack of exercise, consumption of unhealthy foods and unawareness of proper dietary (Humphrey, 2001). Even Donnan et al. and T. B. Martonen agree with Humphrey's statement adding age and high blood pressure to the list of factors contributing to stroke (Donnan et al., 2008), with Martonen supported that the occurrence of stroke increases with age (Martonen, 2000). Stroke occurrence is either ischemic or haemorrhagic, with the initial being the most common by 87% in all the cases around the world (Donnan et al., 2008). Proper study for each of the phenomena should be carried out on why and how it occurs, in order to combat stroke efficiently and successfully, to prolong the lives of mankind.

Ischemic stroke occurs when there is an insufficient supply of blood to the brain, thus causing brain dysfunction. The reasons might be due to presence of thrombosis, which is a blood clot that obstructs blood flow inside the vessel; embolism, which is the formation of embolus that also obstructs the blood flow inside the vessel; and hypoperfusion, which is the decrease in blood supply due to sudden shock in the human body. On the other hand, haemorrhagic occurs mainly due to internal bleeding at the upper section of the human being specifically in the brain. There are two types of internal bleeding in the brain; the intra-axial haemorrhage and the extra-axial haemorrhage. However, this study will only focus on ischemic stroke, which accounts to the most common incident occurred to stroke patients worldwide.

It is a well-known fact that there are millions of arteries within the human body. The mean inner diameter and wall thickness of the artery is around 2.5 cm and 2 mm respectively (Humphrey, 2001). Within the arteries contains a solid section that is primarily composed of elastin, collagen, smooth muscles, endothelium and fluid section that is mainly extracellular water (Humphrey, 2001). The endothelium acts as a smooth lining that separates the wall contents from blood and allows transport of substances through the wall. This part of the human artery is considered the key event in the development of arterial diseases including stroke. Damage to these endothelium walls will trigger the release of pathological quantities of von Willebrand Factor (vWF) that promotes the formation of thrombus within the artery. Figure 1 below shows the formation of blood clot in the artery.

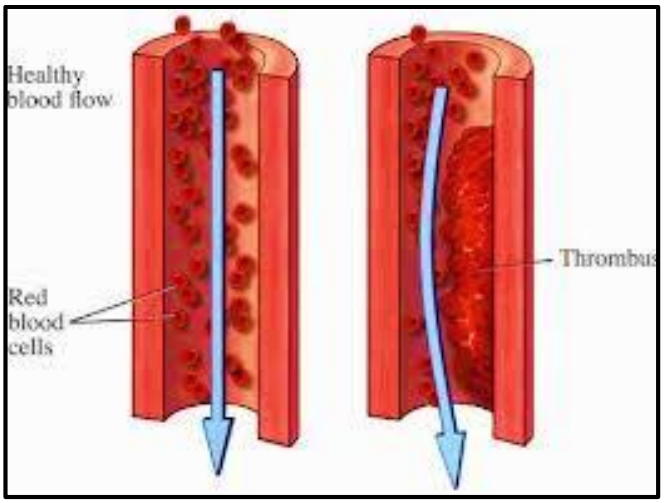


Figure 1: Thrombus causing blood flow disturbance (Masterlife.com, 2013)

There are several devices to cure the occurrence of blood clot namely thrombolysis or the induce of drug to destroy the blood clot, mechanical devices such as angioplasty, balloon embolectomy and MERCI (Mechanical Embolus Removal in Cerebral Ischemia); and also the TAD (Thrombus Aspiration Device) such as the model proposed by Professor Gillian Pearce of Wolverhampton University, United Kingdom or famously known as the GP device (Pearce, Patrick, & Jaegle, 2006).

1.2 Problem Statement

Although mechanical thrombectomy device (MTD) provides an alternative to blood clot removal, it is known that it has its own limitations and risk when conducting such procedure. According to Kwak & Kiris, the devices might cause a highly chaotic or turbulent flow that disrupt and damage red blood cells as it goes through high-shear flows and attempt for such simulation will be a difficult and challenging task to be conducted (Kwak & Kiris, 2011). The recently invented Gwen-Pearce device or 'GP' device counters this problem by not having any mechanical parts on the device, which allows smooth transition phases between insertion of the device, removing the blood clot inside the artery and finally the complete removal of the device from the system.

The GP device uses the concept of vacuum suction whereby it creates a differential pressure within the artery to remove the blood clot solely through suction alone. This will prevent any tissue damage or penetration of arterial wall (Pearce et al., 2006). The initial device involves using a vacuum pump joined to a catheter of 100 cm long and 2 – 5 mm diameter and place approximately 3 mm from the blood clot (Romero et al., 2011). Early experimentation conducted required around 10 kPa to 15 kPa of pressure to extract the blood clot (Romero et al., 2011). Additionally, more and more modifications were done to this GP device that allows faster extraction with increased number of tubes. This has proven an even more efficient procedure, which was modelled by (Rahaman, 2012), through her modified GP2 device, having nine cylindrical tubes, allowing faster suction rate and breaking of the clot fragments into smaller pieces (Rahaman, 2012) (Kuzilati, Rahman, & Pearce, 2012).

Nonetheless, the main goal is to implement and prove that the device is applicable on human beings and does not possess any threat during the removal procedure. Tests and experiments were done to ensure the capability of its safety on the middle cerebral artery and will surely be a breakthrough for mankind in the field of biomedical engineering. Thus, the role of CFD proves to be the most clinical and the safest way to simulate as closely as possible to the real arterial environment, i.e. having blood, blood clot, artery wall, air, and the behaviour of artery upon conducting the procedure.

1.3 Objectives and Scope of Study

The objective of this study is to simulate using 3D ANSYS FLUENT, with a three phase flow model simulating the removal of blood clot in the artery through a GP device. The three phases are blood, blood clot and air present within the system. Simulation will be done to oversee the interaction of each of the phases and to compare the results with previous two phase research and to determine if the presence of air will influence the outcome of the extraction in terms of removal time. Figure 2 shows the sketch done by (Rahaman, 2012), a modification from the initial GP device and table 1 shows the specifications of the device.

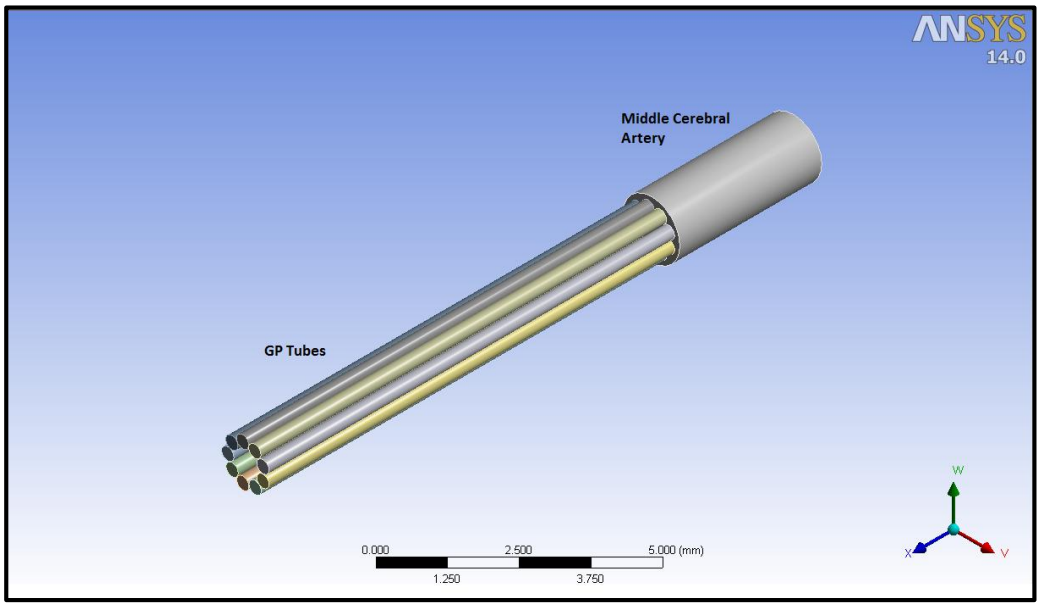


Figure 2: GP2 device (Rahaman, 2012)

Table 1: Dimensions of GP2 Device (Rahaman, 2012)

Criteria	**GP-2**
Number of tubes	9
Diameter of each tube (mm)	0.6
Horizontal length (mm)	20

The model consist of two sections namely the artery section and the tubing section. The blood clot is situated at the artery section together with the blood, whereas the tubing section consist of air phase and both of the fluid, i.e. blood and blood clot, will slowly move towards the tubing section. The GP2 device consists of nine identical tubes of similar diameter of 0.6 mm arranged in a circular manner. The main purpose of having smaller tubes is for breaking the blood clots into fragmentations for better extraction. The length of the tubes will be 20 mm.

The GP2 device is slightly different as compared to the original GP device. First, it is separated into nine different smaller tubes as compared to one large tube for GP device. It is claimed that the smaller tubes are used to break down the clots into smaller fragments for easier removal. However, a newly proposed GP2 device with a combination features of GP and GP2 device, has a central tube surrounded by smaller tubes will also be deployed to effectively combine a better suction power and at the same time smaller tubes to provide breakdown of the clots into fragments and simulation will be done to determine if the theory is correct that having a larger suction area is much effective in terms of removal time.

Thus, the scope of research for this project would be to carry out grid sensitivity study to determine the best chosen mesh size to be used throughout the simulation. A balance of computational time and accurate results are what the industry requires to effectively understand and in the future, able to implement the simulated results into real life procedure. Secondly, the scope will be to determine the effect of varying pressures, i.e. 40, 50 and 60 kPa to the removal time of the blood clot.

It is theorised that higher pressures will result in faster rate of removal. Therefore, the simulation will determine if the theory is true. Finally, the last job scope would be to propose a better model of GP2 device that is both able to have better suction power and at the same time is able to break fragments of the blood clot so that reoccurrence of clotting will not occur. This will be done during the research whereby a new device will be designed, modelled and finally simulated to prove the theoretical statement.

CHAPTER 2

LITERATURE REVIEW AND THEORY

2.1 Literature Review

Hippocrates, the father of medicine, first recognized stroke over 2400 years ago. Physicians had little knowledge of the anatomy and function of the brain, the cause of stroke, and methods of treatment. It was not until the seventeenth century that Jacob Wepfer found that patients who died with apoplexy had bleeding in the brain. He also discovered that a blockage in one of the brain's blood vessels could be the probable cause of this phenomenon (NewYork-Presbyterian.org, 2008).

Medical science continued to study the cause, symptoms, and treatment of apoplexy and, finally, in 1928, apoplexy was divided into categories based on the cause of the blood vessel problem. This led to the terms stroke or "cerebral vascular accident" (CVA). Stroke is now often referred to as a "brain attack" to denote the fact that it is caused by a lack of blood supply to the brain, very much like a "heart attack" is caused by a lack of blood supply to the heart. There are several methods of removing blood clot that have been discovered by mankind. This process of blood clot removal include thrombolysis, mechanical device (mechanical thrombectomy device) and surgical method.

Thrombolysis is a method through induction of 'clot-busting' drug called tissue plasminogen activator (t-PA) into the human body (Stroke.co.uk, 2013). Unfortunately, thrombolysis can only be given within a four and a half hour time frame only, with which the earlier will be better. Besides this requirement, other patients must comply to other prerequisite that includes not under age of 18 or over 80, must not had major surgery within the past two weeks, must not have bleeding disorder and must not have bleeding in the brain (Stroke.co.uk, 2013). These requirements narrows down the probability of patients to induce the drug thus require other alternatives for stroke recovery.

Angioplasty is one of the mechanical techniques used to combat stroke. A conventional balloon angioplasty uses the principle of a balloon-tipped catheter which is inflated within an atherosclerotic artery to enlarge the lumen and therefore improve blood flow (Vliestra & Holmes, 1987). However, there are several drawbacks from this technique. The arterial wall where the balloon is located might damage the wall, thus becomes more fibrotic due to increase in number of collagen (Zollikofer et al., 1984). Whereas, the long term consequences of balloon angioplasty is the effect of restenosis, with chances of occurrence of about 25% to 50% (Glagov, 1994).

Restenosis is the occurrence of stenosis, a phenomenon whereby the blood vessel will re-narrow itself after receiving treatment. The action of introducing the stent within the artery might cause damage to the walls, thus causing physiological mechanisms to react and counter act the presence of foreign substance within the artery. This is done by sending in immune system response i.e. platelets, which might further lead to the narrowing of the wall. Figure 3 shows how restenosis occurs when angioplasty is introduced to the artery.

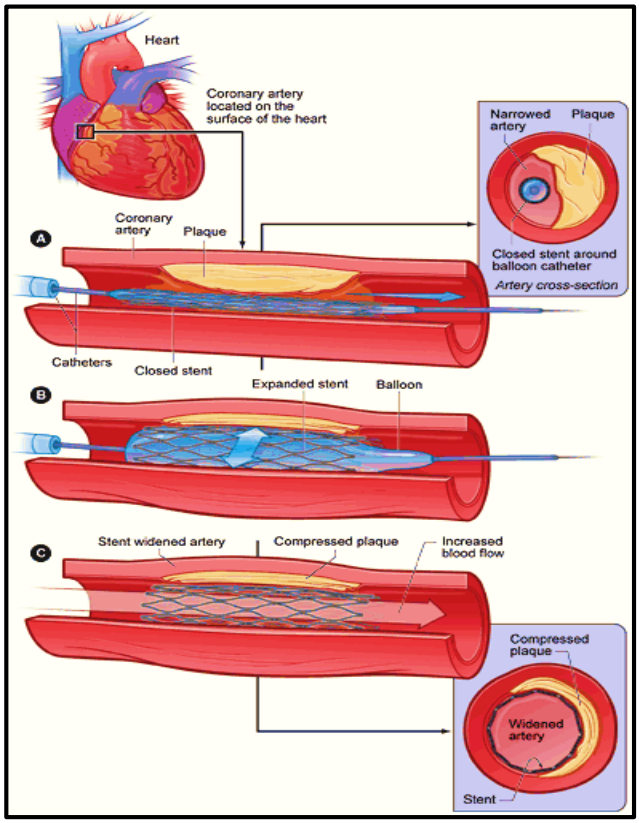


Figure 3: Balloon Angioplasty (NHLBI, 2013)

Balloon embolectomy is another mechanical technique in the removal of thrombus in the human artery. First introduced by Fogarty et al in the year 1963, it uses an inflated intravascular balloon-tipped catheter that extracts emboli and thrombi (Humphrey, 2001). It is found out however, that several risks might occur during the procedure including removal of the endothelium, fracture of atheromatous plaque, fragmentation of the internal elastic lamina, damage to connective tissue and smooth muscle cells and worst case scenario; a complete rupture towards the artery wall (Foster et al., 1970; O'Donnell & Hobson, 1978; Goldberg et al., 1983; Jamal et al., 1992). Figure 4 shows how the balloon embolectomy is used to remove blood clot from the artery.

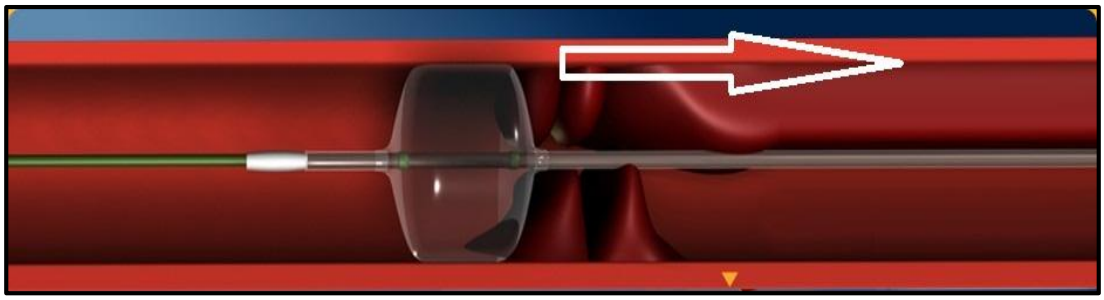


Figure 4: Balloon Embolectomy (HotspurTechnologies, 2013)

Another technique that involves removal of embolus is the Mechanical Embolus Removal in Cerebral Ischemia (MERCI). Gobin et al. conducted an experiment and produced a report regarding the outcome of the procedure (Gobin et al., 2004). He has conducted the experiment on thirty patients throughout the seven US Medical Centres, of which only twenty eight was chosen whereas the remaining two failed to comply with the requirement of procedure. The procedures were performed with the MERCI Retrieval System specially designed for intracranial embolectomy. It consists of the MERCI Retriever itself, a Balloon Guide Catheter (BGC) and MERCI microcatheter. The BGC is a 9-French catheter with a large 2.1 mm lumen and a balloon located at its distal tip. The retriever uses an elastic material made from nickel titanium and tapered with wire of five helical loops of decreasing diameter at the end, which is then connected to the microcatheter.

Upon inducing the MERCI device into the human body, a selective angiogram was performed away from the thrombus to determine the size and tortuosity of the arteries to avoid risk of damaging the arterial wall. The MERCI Retriever is then deployed beyond the thrombus and the BGC was inflated to 'hook' the thrombus within the artery and five clockwise rotations were applied to the MERCI Retriever to further ensnare the thrombus. Finally, the MERCI retriever together with the ensnared thrombus was removed from the artery and continuous aspiration was applied to ensure complete removal. Figure 5 show how the MERCI device captures the blood clot.

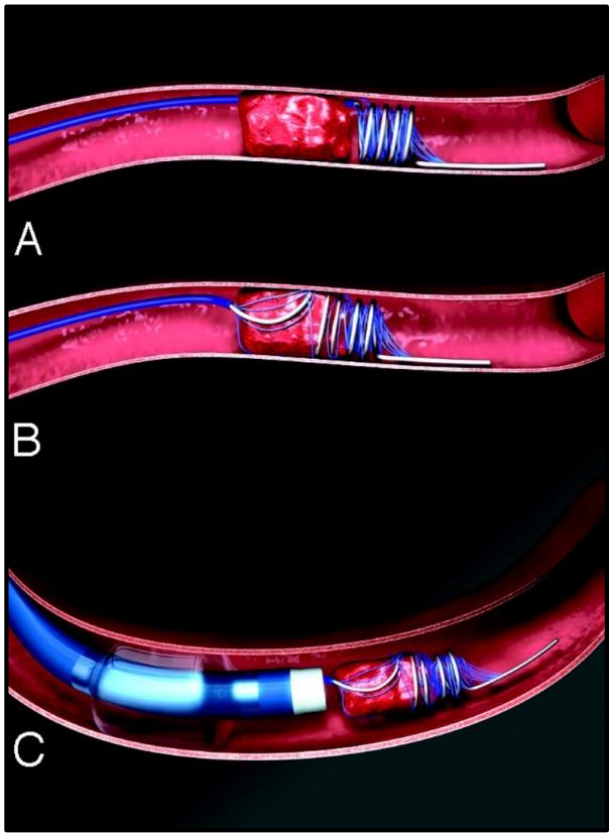


Figure 5: Summary of MERCI Procedure (AJNR, 2006)

Results obtained from the experiment showed that successful recanalisation was achieved in twelve of the patients or accounted to 43% success rate. Eight of the patients (29%) were unsuccessful and were given the intra-arterial t-PA and further recanalisation conducted which resulted to six successful procedures after administrating the drug. However, Gobin et al. confessed that there was technical complication during the procedure when the tip of the retriever detached from the device, and the team used another MERCI retriever to retrieve back the lost tip from the vasculature. They reassured that no clinical consequence was detected, but however there were ten deaths (36%) during the first month after the surgery. They stated that the patients' death was disease related and was not due to the study device (Gobin et al., 2004).

Another study was conducted by Tennuci et al. whereby a comparison of various recanalisation methods were done, namely using thrombus aspiration via 4F catheter, thrombus aspiration using 'GP' thromboaspiration device and mechanical thrombectomy using solitaire thrombectomy device. The experiment was done via simulated human body by creating an artificial human artery. The blood used is the Hartmann's solution and a peristaltic pump was used to create a pulsatile flow of eighty pulses per minute, an average of human heart rate. The thrombus was also created artificially using Hartmann's solution and drip dried. The rest of the apparatus was set as shown in figure 6.

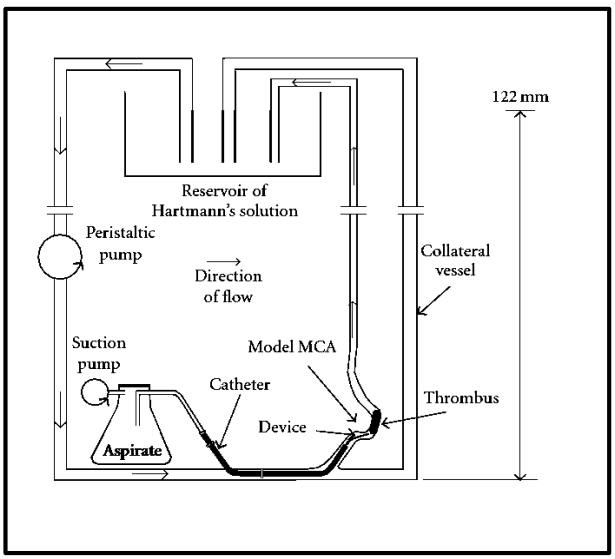


Figure 6: Pulsatile Flow System (Tennuci, et al., 2011)

Results from the experimentation showed that all three methods were successful, with only particular parameters differentiate between these methods namely clot length, recanalisation rate, clot fragmentation, time and device interaction. Cloth length for the 4F was up to 68 mm, 55 mm for the GPTAD and 45 mm for the Solitaire. There was slight difference in terms of recanalisation rates for all devices, at 62%, 77% and 85% respectively. In terms of chances of clot fragmentation, 4F is the most likely to occur at 53%, against GPTAD and Solitaire both at 23%. The time to complete the clot removal process is the fastest for the aspiration devices (4F and GPTAD) and slowest using Solitaire method. It is also showed that the GPTAD grasped the thrombus far more efficient compared to the 4F, thus causing less artery obstruction and ultimately less fragmentation.

Unfortunately, there were several experimental limitations. This test was done in an artificial human body and thus does not reflect in a true human body. The artificial blood, Hartmann's solution, is indeed close to a human blood, but ultimately does not depict true characteristics of the human blood. The middle cerebral artery used was also straight, as compared to reality of bending arteries and the artificial clots might not be exactly how the natural clots are. Tennuci et al. concluded that aspiration devices have much better success rate and might even be better and faster than thrombectomy although they stressed that further research must be done to truly simulate an arterial environment.

The study of CFD is essential in any fluid dynamics simulation especially in biomedical engineering such as development of mechanical heart devices, surgical planning, biomedical studies, and areas for analysis and treatment of artery related disease, particularly in determining the effect of the GP device to the arterial wall of the human being (Kwak & Kiris, 2011). Initial simulation conducted by Pearce et al used water to replace blood as the fluid in the experiment (Pearce et al., 2006). According to Kwak & Kiris, blood flows can be assumed to be in continuum and incompressible right up until it reaches the capillaries. Thus, in order to simulate blood flows it is best to use the unsteady, incompressible Navier-Stokes equation with constant density as follow:

$$\frac{\partial ui}{\partial xi} = 0$$

$$\frac{\partial ui}{\partial t} + \frac{\partial (ui * uj)}{\partial xj} = \frac{\partial p}{\partial xi} + \frac{\partial \tau ij}{\partial xj}$$

where,

t = Time

x_i *= Cartesian coordinates*

u_i *= Corresponding velocity components*

P = Pressure

τ_{ij} *= Viscous-stress tensor,*

with,

$\tau_{ij} = 2\nu S_{ij}$ *for Newtonian flow*

$\tau_{ij} = 2\eta S_{ij}$ *for non-Newtonian flow*

$$Sij = \frac{1}{2}\left(\frac{\partial ui}{\partial xj} + \frac{\partial uj}{\partial xi}\right)$$

$$\eta = fcn(\dot{y})$$

$$\dot{y} = shear\ rate = \sqrt{2(Sij * Sij - S^2)}$$

The Volume of Fluid (VOF) model has been chosen to simulate the blood clot phenomena within the arterial wall as it is able to model two or more Eulerian fluids and enables surface-tracking technique. It belongs to the class of Eulerian methods which are characterised by a mesh that is either stationary or is moving in a certain prescribed manner to accommodate the evolving shape of the interface. VOF allows the user to track the shape and position of the interface, but it is not a standalone flow solving algorithm. The Navier–Stokes equations describing the motion of the flow have to be solved separately. The same applies for all other advection algorithms.

However, the VOF formulation requires that those fluids or phases are not interpenetrating. Whenever the model requires addition of phases, a new variable must be introduced to the formulation and the volume fractions of the entire phases sum to unity. Simply put, if the fluid's volume fraction in the cell is denoted by α_q, an empty cell is equals to zero, a full cell is equals to 1 and finally a partially filled cell is in the range between one to none.

The volume fraction can be calculated as below:

$$\frac{1}{\rho_q}\left[\frac{\partial}{\partial t}(\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \vec{v}_q) = S_{\alpha_q} + \sum_{p=1}^{n}(\dot{m}_{pq} - \dot{m}_{qp})\right]$$

where,

$\dot{m}_{qp}$ = *Mass transfer from phase q to p*

$\dot{m}_{pq}$ = *Mass transfer from p to q*

S_α = *equals to zero (Fluent 6.3 Documentation, 2006)*

The primary-phase volume fraction is:

$$\sum_{q=1}^{n} \alpha_q = 1$$

There are two schemes when interpolation near the interface of different phases is done; namely geometric reconstruction and donor-acceptor scheme. Geometric reconstruction uses piecewise-linear approach, accurate and applicable for general unstructured meshes. It assumes the interface between the two phases has a linear slope, and therefore uses this linear shape for calculation of the advection of fluid. Meanwhile, donor-acceptor scheme identifies one cell as a donor and another cell as the acceptor, usually the neighbouring cells. The amount of fluid from a phase is limited to two values: the filled volume in the donor cell or the free volume in the acceptor cell. Figure 7 below shows the difference between the actual interface shape with the geometric reconstruction and donor-acceptor schemes, respectively.

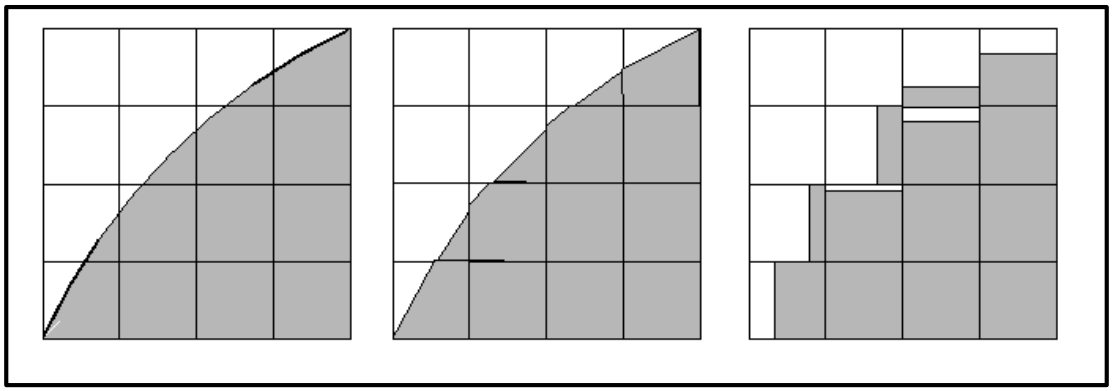


Figure 7: Interpolation schemes (FLUENT, 2007)

In calculating material properties e.g. density, viscosity, the following equation is used (taking example calculation of density):

$$\rho = \sum \alpha_q \rho_q$$

Surface tension and wall adhesion are also important in simulating blood clot in the arterial wall. Surface tension occurs as a result of attractive forces between molecules of, in this case, blood, in the fluid. Surface tension can be written in terms of pressure difference across the surface and the force on the surface can be expressed using divergence theorem, as below:

$$F_{\text{vol}} = \sum_{\text{pairs } ij,\ i<j} \sigma_{ij} \frac{\alpha_i \rho_i \kappa_j \nabla \alpha_j + \alpha_j \rho_j \kappa_i \nabla \alpha_i}{\frac{1}{2}(\rho_i + \rho_j)}$$

The importance of surface tension in the experiment can also be determined through several dimensionless quantities, which are Reynolds number, capillary number and Weber number. Surface tension can be neglected if Ca > 1 or We > 1. For Re < 1, use capillary number which can be determined by:

$$\text{Ca} = \frac{\mu U}{\sigma}$$

For Re > 1, use Weber number which can be determined by:

$$\text{We} = \frac{\rho L U^2}{\sigma}$$

where,

U = Free stream velocity

Another parameter to consider is the wall adhesion on the arterial wall. Rather than impose this boundary condition at the wall itself, the contact angle that the fluid is assumed to make with the wall is used to adjust the surface normal in cells near the wall. The equation involving wall adhesion is as below:

$$\hat{n} = \hat{n}_w \cos\theta_w + \hat{t}_w \sin\theta_w$$

where,

θ_w = *Contact angle at the wall*

$\acute{\eta}_w$ = *Normal*

t_w = *Tangent to the wall.*

CHAPTER 3

METHODOLOGY

There will be in total of three parametric studies to be conducted throughout the project i.e. grid sensitivity study, comparison between two phase and three phase flow model and finally a newly proposed GP2 model that both incorporate the initial design consideration of the original GP device and the design consideration of the GP2 device that is to break fragments of blood clot in the artery.

The entire methodology consists of three major parts, namely pre-processing, simulation and finally post-processing. Pre-processing will be the design and modelling part of the project whereby it is to design according to the given dimensions and structure by (Rahaman, 2012). There are basically two parts of the model, namely for the nine tubes and the middle cerebral artery. In the latter section will place the blood and blood clot to actually simulate that the blood is within the artery in the shape of a cylinder of 3 mm in diameter and 4 mm in length. Next will be the modelling in terms of building a suitable mesh size for the model to allow the model to be run on FLUENT. A mesh size is usually determine using the options available in length value i.e. 0.1 mm, 0.2 mm, and 0.3 mm and so forth.

Next, the model will go through simulation using ANSYS FLUENT with pre-determined sets of options which will be mentioned later. The important parameter to be considered will be the pressures applied to the model i.e. 40, 50 and 60 kPa, the surface monitor for grid sensitivity study and also the volume monitor to determine the removal time for each pressure. Finally, in post-processing the set options i.e. surface monitor and volume monitor will be assessed and analysis together with the movement of the fluids i.e. air, blood and blood clot and to determine if the objective is met.

3.1. Grid Size Study

For the first parameter, grid size study will be done in determining the balance between having a short computational time while at the same time retaining computational accuracy of the results.

3.1.1 Pre-processing

First, geometrical design is done to model the GP2 device using Design Modeller under ANSYS 14.0. The model will consist of two major section namely tubing section and artery section. The tubing section will consist of nine similar diameter tubing of cylinder in shape, and same goes to the artery section having a cylindrical shape to simulate an artery, which is as shown from figure 8 to 10. The dimensions for the model are as follow –

Table 2: Dimensions of GP2 Device

Criteria	**GP-2**
Number of tubes	9
Diameter of each tube (mm)	0.6
Horizontal length (mm)	20

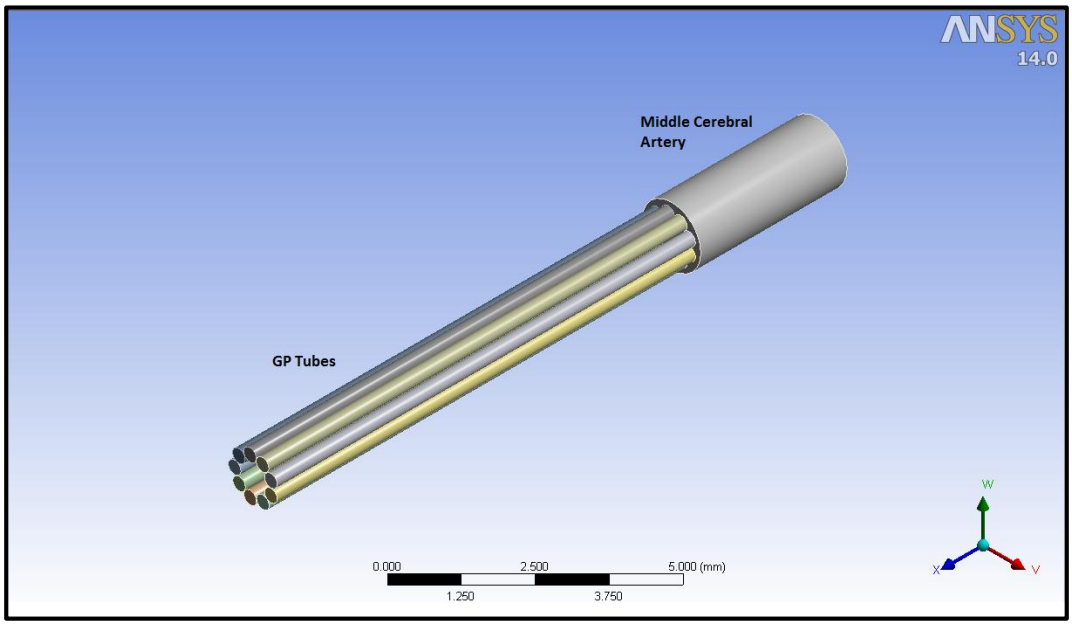


Figure 8: Isometric view of GP2 Device

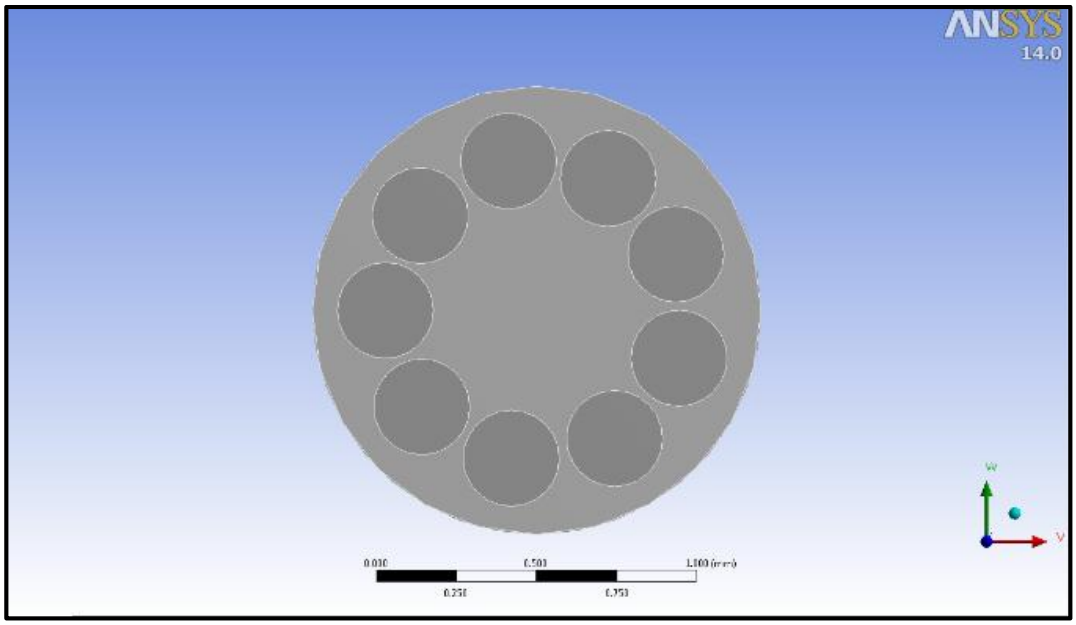


Figure 9: Front view of GP2 Device

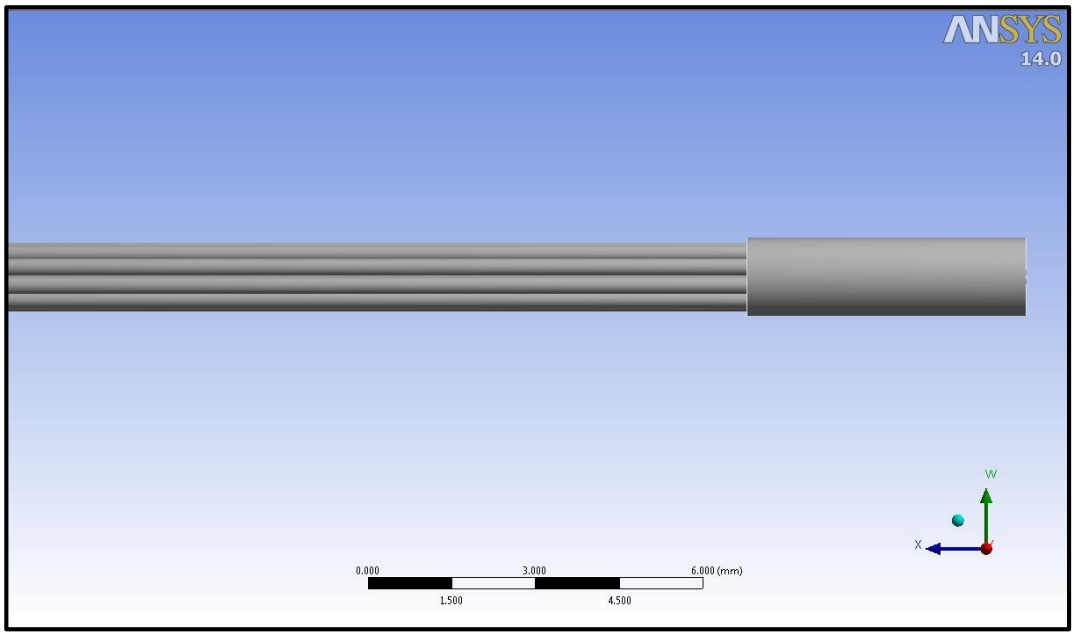


Figure 10: Side view of GP2 Device

Once geometric design is done, meshing is applied on the completed model according to suitable grid size i.e. mesh size of 0.2 mm, 0.15 mm and 0.1 mm respectively as per recommended by (Rahaman, 2012). The different mesh size is to be used for grid sensitivity study to determine the best mesh size to be used throughout the project that has both accuracy and lower computational time, as shown from figure 11 and 12.

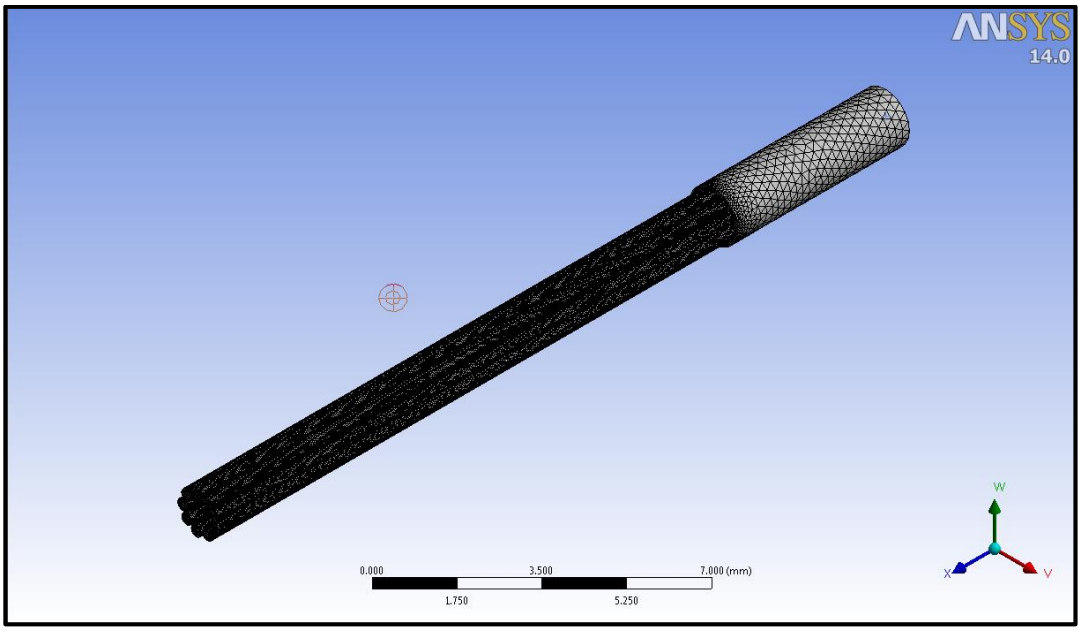


Figure 11: Meshed model of GP2 Device (fine)

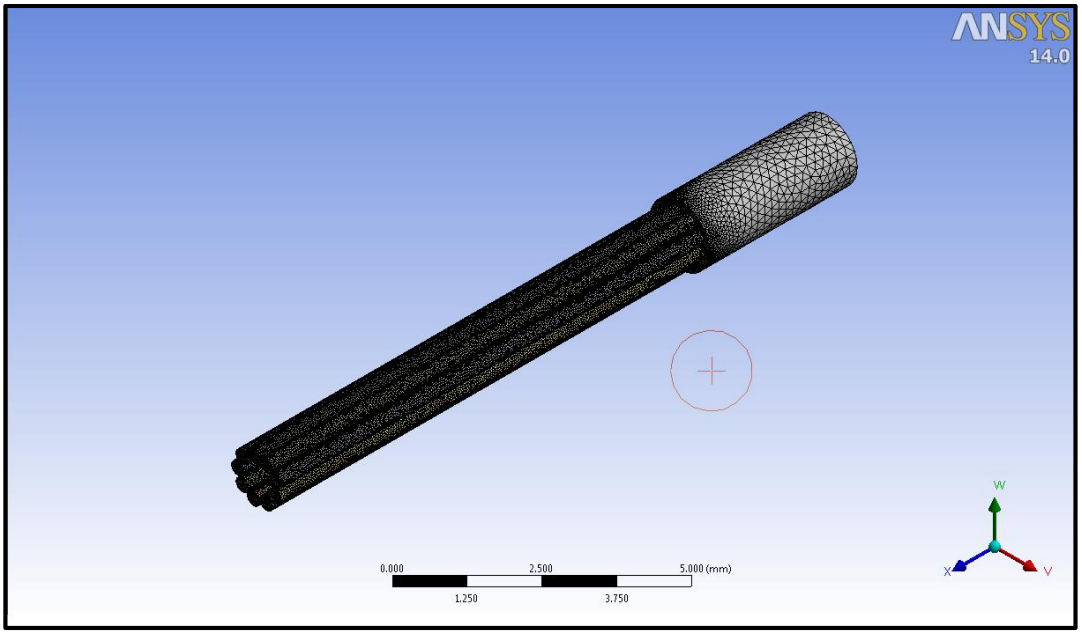


Figure 12: Meshed model of GP2 Device (coarse)

3.1.2 Simulation

Simulation works is under using the FLUENT software to investigate the fluid movement in the model for both the artery section and the tubing section. The Volume of Fluid model will be incorporated, which the model was designed to study the fluid characteristics in an enclosed volume.

Under the General options, solver type chosen is pressure-based and time chosen is transient. Multiphase Volume of Fluid is selected under the Models options and the number of Eulerian Phases selected is 3 namely air, blood and blood clot. The Courant Number is left default at 0.25. Material properties are carefully specified namely for air, blood and blood clot. Table 2 shows the properties of each phases –

Table 3: Properties of material (Rahaman, 2012)

Parameter/Phase	Air	Blood	Blood Clot
Density (g/cm^3)	0.001225	1.06	1.08
Viscosity (poise)	0.00017894	0.035	0.35

Under Phases options, air is chosen as the primary phase, while blood and blood clot are chosen as secondary phases. The interaction between blood and blood clot is also specified under the interaction options, whereby surface tension is set as constant of 0.1 N/m (Rahaman, 2012), and wall & jump adhesion are checked. Boundary conditions for the inlet and outlet is specified under Boundary Conditions, as summarise below. However, for this part of parametric study, only 40 kPa of pressure will be used as on the model –

Table 4: Boundary conditions at pressure inlet and outlet

Location	Value (kPa)
Inlet	40, 50, 60
Outlet	-40, 50, 60

Under the Solution Methods options, scheme selected is PISO and Non-Iterative Time Advancement to reduce calculation time. Solution is initialised, the blood and blood clot's location are identified, adapted and patched into the artery. Both the blood and blood clot are cylindrical shape having radius of 1.5 mm and 3 mm in length and distance of 0.5 mm from the tubes, while the blood fills the entire artery, i.e. 1.5 mm in radius and 4 mm in length.

3.1.3 Post processing

Post processing is finally done to actually investigate how the fluid moves in the model through proper depiction of the fluid. Hence, the data for each iteration is loaded initially. Surface monitor is loaded for analysis of the grid sensitivity study and to be graphed for easier depiction.

3.2 Two phase versus three phase flow study

The second parametric study will be on the comparison between the two phase and three phase flow model. Comparative value will be in terms of removal time of the blood clot to determine if there will be any effect to the removal time should another phase i.e. air is introduced into the model.

3.2.1 Pre-processing

The initially designed model will be used to compare the difference between two phase flow model and three phase flow model, thus the dimensions and design of the model will remain the same from the previous section.

3.2.2 Simulation

Simulation will be conducted in total of six times using the same GP device model, i.e. 40, 50 and 60 kPa for two phase flow model and also 40, 50 and 60 kPa for three phase flow model. Simulation options are also similar to previous section except for step two whereby for two phase flow model, only two Eulerian phases will be chosen i.e. blood and blood clot. Blood will be the primary phase while blood clot will be the secondary phase for this model. As for three phase flow model, the steps are very much similar to the previous section of the method and retaining all the given options. Pressure used will be 40, 50 and 60 kPa for both models.

3.2.3 Post processing

Similarly, the data for each iteration is loaded initially. Contours is chosen under Graphics and Animations option, to visualise the removal of blood clot in the artery into the GP tubing. After the model together with the visualisation of the fluid movement i.e. air, blood and blood clot for three phase model and blood and blood clot for two phase model, is shown, the pictures are saved. Volume monitors are also loaded and graphed to analyse the time taken for the removal of blood clot.

3.3 Proposed New GP2 Device

A new GP2 device is proposed that incorporates features of both the original GP device and the slight modification of the GP2 device. The resultant modification is having the arrangements of the tubes that has a central tube surrounded by eight similar sized tubes which have relatively smaller diameter. It is claimed that having a bigger area of suction will contribute to better mass transfer while at the same time, having the smaller tubes is to break down the blood clot into fragmentations for a more thorough removal of the blood clot.

3.3.1 Pre-processing

First, geometrical design is done to model the new GP2 device using Design Modeller under ANSYS 14.0. The model will consist of two major section namely tubing section and artery section. The tubing section will consist of eight similar diameter tubing of cylinder in shape and a central tube of larger diameter, and same goes to the artery section having a cylindrical shape to simulate an artery, which is as shown from figure 13 and 14. The dimensions for the model are as follow –

Table 5: Dimensions of new GP2 Device

Criteria	**GP-2**
Number of tubes	9
Diameter of major tube (mm)	1.6
Diameter of minor tube (mm)	0.5
Horizontal length (mm)	20

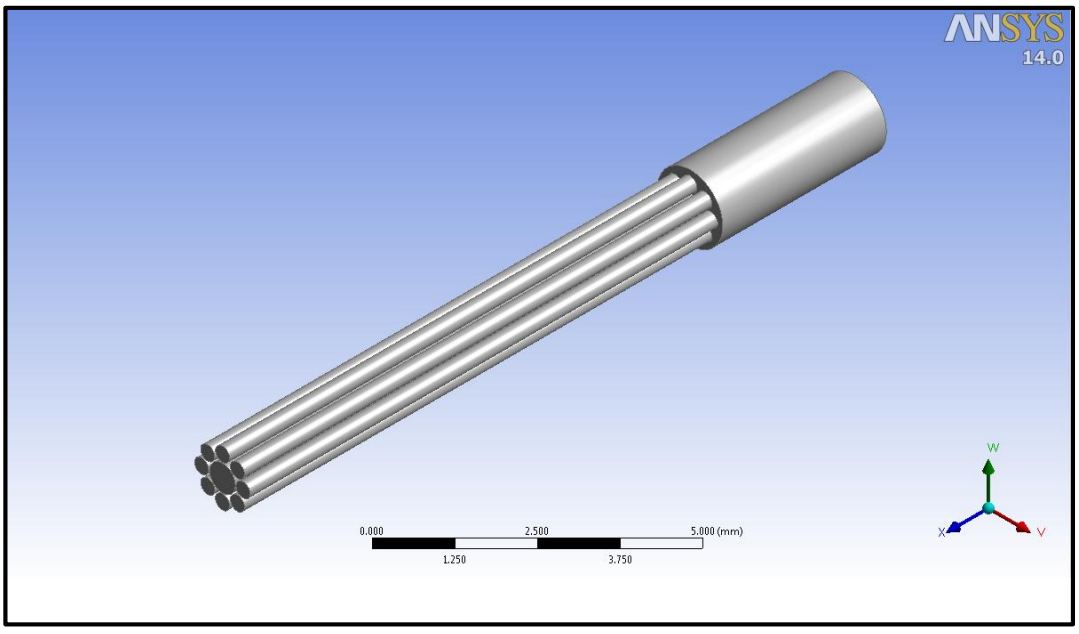


Figure 13: Isometric view of the new GP2 device

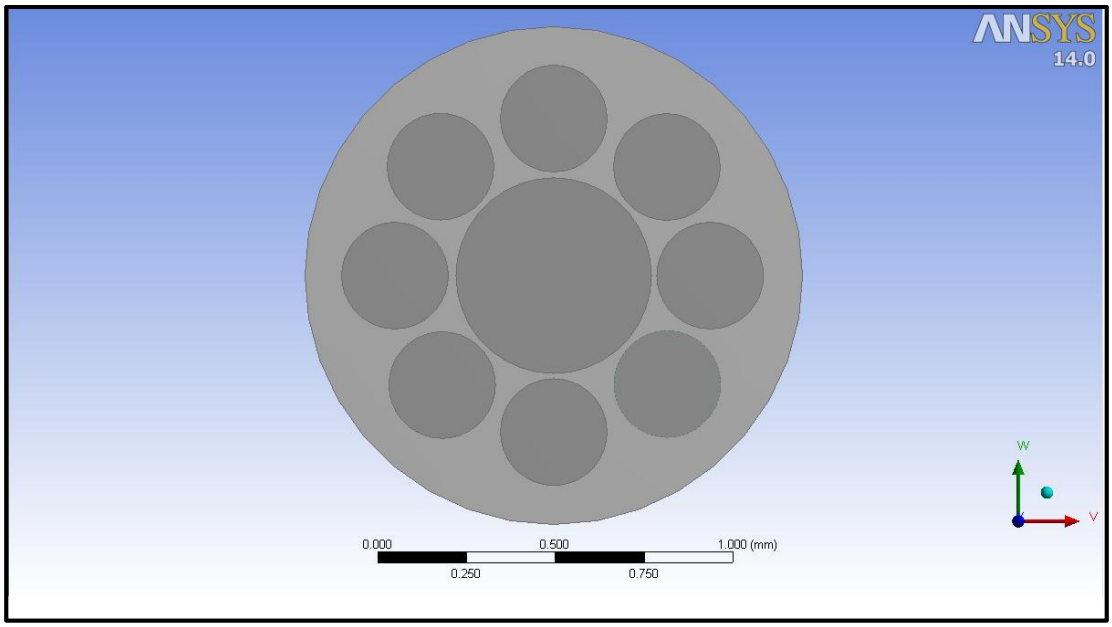


Figure 14: Front view of the new GP2 device

Once geometric design is done, meshing is applied on the completed model according to the selected grid size based on the grid sensitivity study i.e. either mesh size of 0.2 mm, 0.15 mm and 0.1 mm, as shown in figure 15 below –

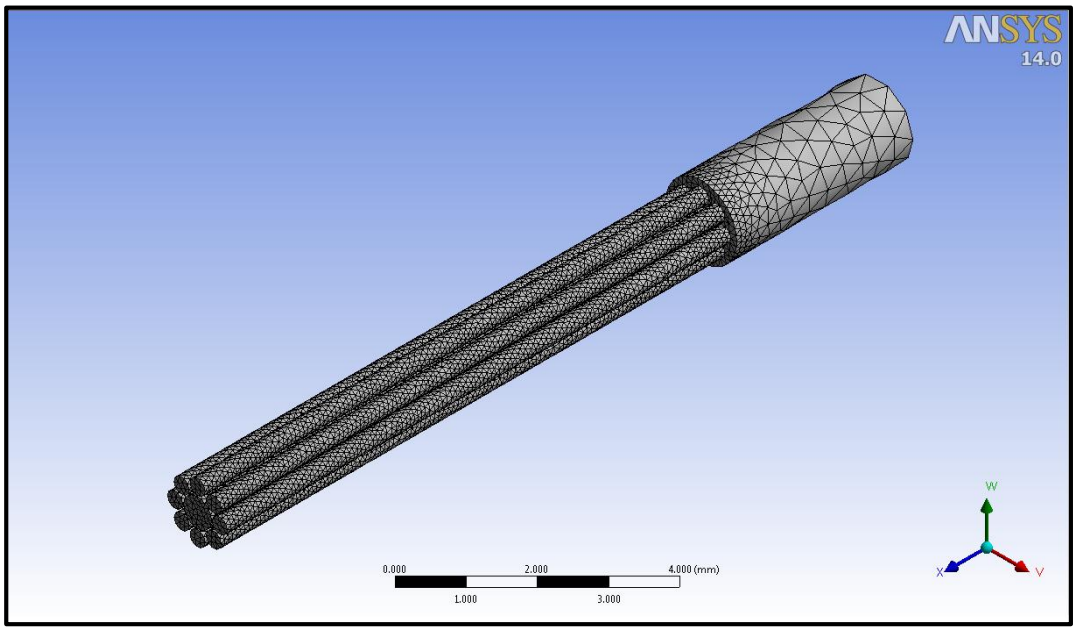


Figure 15: Meshed model of the new GP2 device (coarse)

3.3.2 Simulation

The simulation will be done similarly as section 3.1.2 with three Eulerian phases i.e. air, blood and blood clot. The other simulation options are similar, using the same options i.e. pressures of 40, 50 and 60 kPa.

3.3.3 Post processing

The data for each iteration is loaded initially. Contours is chosen under Graphics and Animations option, to visualise the removal of blood clot in the artery into the GP tubing. After the model together with the visualisation of the fluid movement i.e. air, blood and blood clot is shown, the pictures are saved.

Volume monitors are loaded to analyse the time taken for the removal of blood clot. Solution Animation Playback is also selected to produce an animation of the blood clot removal.

3.4 Software

The software used throughout this project are mainly ANSYS Design Modeller for designing and modelling the GP device with varying design and dimensions i.e. for the old GP2 device and the new GP2 device, ANSYS ICEM CFD for meshing the model into different sizes of mesh i.e. for 0.2 mm, 0.15 mm and 0.10 mm, and finally ANSYS FLUENT to actually simulate the blood clot extraction in the device through different pressures i.e. 40, 50 and 60 kPa and to be used for post processing to analyse results of the simulation using contours, surface monitors and volume monitors to study the fluid movement for the contours, velocity at the outlet tubes through the deployment of surface monitors for grid sensitivity study and fractions of clot left in the artery to determine the removal time.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Grid Sensitivity Study

Grid sensitivity study is conducted to identify the balance between meshing size and the computational time. The accuracy of the results obtained is directly dependant on the meshing size, with which a fine mesh size will result to a more accurate results while coarse mesh will have slightly less accurate results. However, the drawback of having fine mesh would be the longer computational time and thus, the simulation will be more strenuous and long.

Through grid sensitivity study, grid independency can be achieved through selection of a mesh size that is fine enough and at the same time short enough in terms of computational time, when further refinement in the mesh size will only increase the accuracy of the results in a very small amount, or in other words are negligible. Thus, the selected mesh size will be chosen throughout the simulation.

Grid sensitivity study is conducted by applying surface monitor at the outlet of the GP tubes through analysis of the velocity at the outlet of the tube, under the Monitors command in FLUENT. The monitor will detect fluid movement in order to calculate how fast the fluid i.e. air and blood is moving and it is plotted into a graph for easier depiction. Mesh size of 0.15 mm, 0.2 mm and 0.25 mm are chosen as per recommended by (Rahaman, 2012). A graph of velocity against flow time is plotted as shown in figure 15 below.

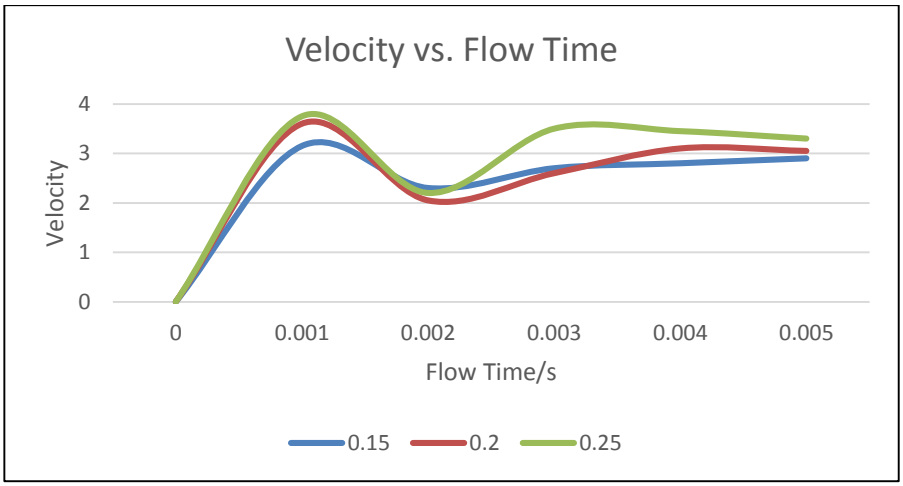


Figure 16: Grid Sensitivity Study under three phase model

From the figure above, it can be seen that all three graphs have quite a similar characteristics in terms of velocity with percentage difference at an average of only 16% and the biggest changes in terms of velocity profile would be at flow time of 0.003 second, whereby mesh size 0.25 mm have the largest gap from 0.15 mm and 0.20 mm. Eventually, the velocity profile achieve stability after approximately 0.005 seconds. After analysis is done for mesh size from 0.25 mm to 0.2 mm to 0.15 mm, it is observed that grid dependency is achieved using mesh size of 0.2 mm which is fine enough as compared to 0.25 mm i.e. velocity profile did not have huge gap, and at the same time accurate enough to compare the results with mesh size of the most fine and accurate meshing i.e. 0.15 mm. This will of course serve the purpose of cutting computational time while at the same time achieving a moderate but acceptable accuracy. Henceforth, the mesh size of 0.2 mm will be chosen to be used for the subsequent simulations.

4.2 Clot Behaviour Study

There are basically two parts for this section, namely the comparison of two phase flow model with the three phase flow model and also the comparison of three phase flow model for the GP2 device done by (Rahaman, 2012) with the newly proposed GP2 device. The phases involved are blood and blood clot and the additional air for the third phase in the three phase flow model.

4.2.1 Two phase versus three phase flow model

Table 6: Two phase versus three phase at 40 kPa

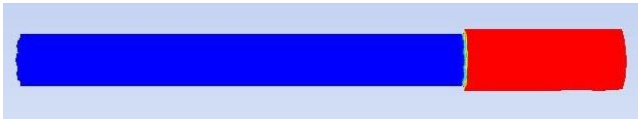
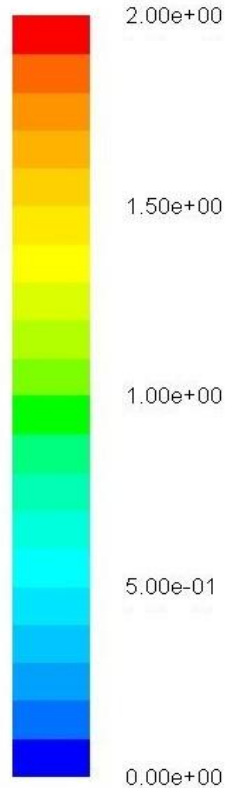
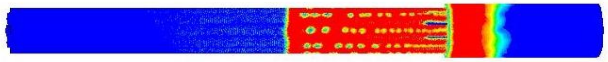
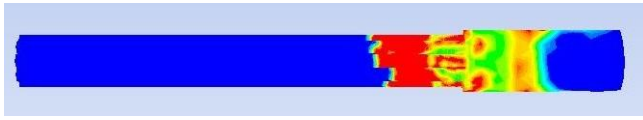
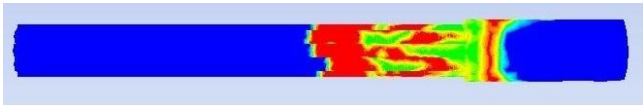
Time	2 phase	3 phase	
0			
0.002			
0.004			
0.006			
0.008			

Table 7: Two phase versus three phase at 50 kPa

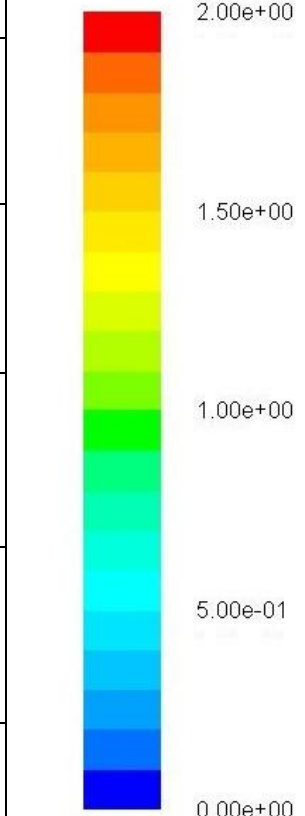
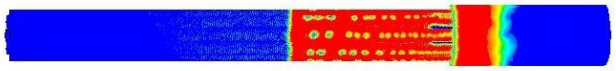
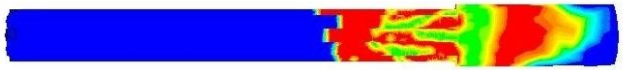
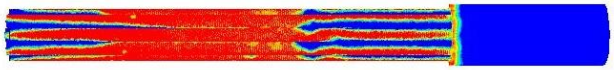
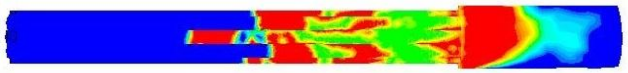
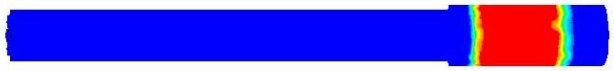
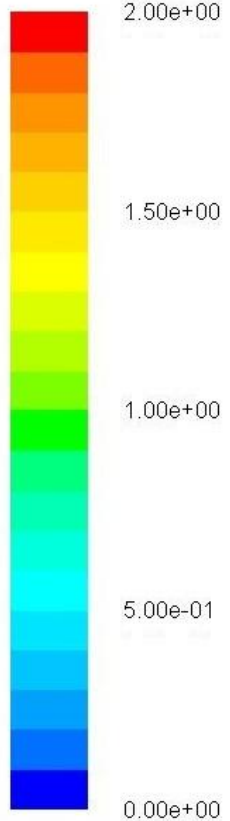
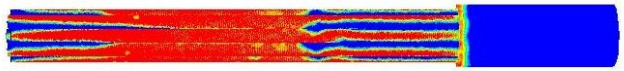
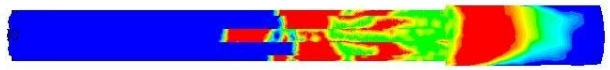
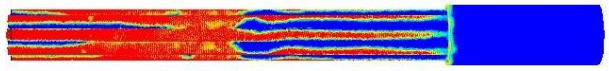
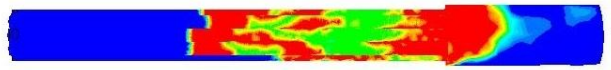
Time	2 phase	3 phase	
0			
0.002			
0.004			
0.006			
0.008			

Table 8: Two phase versus three phase at 60 kPa

Time	2 phase	3 phase	
0			
0.002			
0.004			
0.006			
0.008			

4.2.1.1 Quantitative Analysis of Blood Clot Extraction

A graph is then plotted using the option for volume monitor to generate graph of blood clot fraction against the flow time, which is available under the Monitor options in FLUENT. Validation work is also being done to compare, under 2 phase model, between previous works and the current work. The graph is as shown from figure 17, table 9 and table 10 below –

Table 9: Validation work with previous model

Pressure	Previous work (Rahaman, 2012)	Current work
40	0.0069	0.0072
50	0.0058	0.0061
60	0.0050	0.0054

Table 10: Comparison between 2 and 3 phase flow model

Pressure	2 phase	3 phase
40	0.0072	0.0074
50	0.0061	0.0067
60	0.0054	0.0059

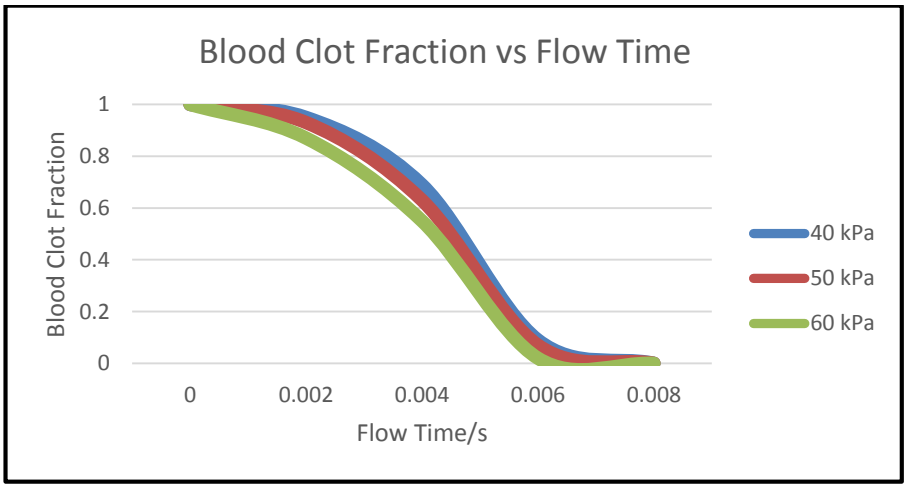


Figure 17: Graph of Blood Clot volume fraction against flow time under three phase model

Validation work have been done by comparing the work between (Rahaman, 2012) and the current work. It can be seen that there are only slight difference in terms of extraction time, i.e. 6.9 with 7.2 ms, 5.8 with 6.1 ms and 5.0 with 5.4 ms, with a calculated average difference of only 5.5%. Thus, it can be said that the current work can be validated and proceed with the subsequent parametric studies, i.e. comparison between two and three phase and the proposal of new GP2 device.

From the graph above, it can be seen that a higher pressure of 60 kPa will extract the blood clot entirely at time of at least 0.0059 second while pressure of 50 kPa will remove the blood clot completely from the artery at time of around 0.0067 second and finally for pressure of 40 kPa the removal time of the blood clot is at around 0.0074 second. This has clearly shown that higher pressure applied on the tube will result in faster extraction of the blood clot, which can be clearly shown from figure above.

From previous research i.e. (Rahaman, 2012), the time required for blood clot removal for two phase flow model are at 6.9 ms, 5.8 ms and 5.0 ms for 40, 50 and 60 kPa respectively. This has clearly shown that a longer time is required for blood clot extraction when air is present within the tube i.e. an increment of 0.5 ms or 6.8% increment, 0.9 ms or 13.4% increment and 0.9 ms or 15% increment for pressures of 40, 50 and 60 kPa respectively. This has clearly shown that the additional phase into the system i.e. air, has slowed down the movement of fluid in the artery and into the tubing.

The reason for the increase in extraction time of at an average of 0.77 ms or 11.7% is due to the fact that another phase i.e. air, is introduced into the system. For the two phase system, the entire system is filled with blood and the only resistive fluid that the applied pressure has to overcome is the blood clot. However for the three phase system, the additional phase of air that is situated at the tubing section will require more time for the fluids to start moving towards the tubing since it needs to invigorate both the blood and blood clot to move towards the tubing section and therefore requires more time.

This phenomenon can be clearly explained using the drag force coefficient and it is related to the Reynolds' Number, which are –

$$Re = \frac{\rho V L}{\mu}$$

$$C_D = \frac{24}{Re}$$

where,

Re = Reynolds' number

ρ = density of fluid

V = velocity of fluid

L = length of travelled fluid

μ = viscosity of fluid

C_D = drag force coefficient

When the cumulative viscosity is high i.e. blood and blood clot, the Reynolds' Number, Re will decrease. When the Re decrease, the drag force coefficient will increase, thus ultimately will have higher drag force and will require more time to move since the force applied is constant throughout the simulation. However, when the cumulative viscosity is low i.e. blood clot only, the Re value will increase. When Re is higher, the drag force coefficient will decrease and therefore the drag force entirely will be much lower. This will ultimately decrease the extraction time of the blood clot since the movement of the fluids are much faster.

Viscosity is defined as the measure of resistive change or deformation when an external force is applied on to the fluid. In laymen's term, the more viscous the fluid or higher the viscosity, the higher the resistance of the fluid towards movement and thus will require more time or more force to exert for the fluid to start moving. In a much simpler way of explanation, imagine a trolley full of sand as the fluid and we, as the external force, are to push the trolley to a certain distance and at a specified time. When the amount of sand is doubled, i.e. the viscosity increases, we are to double up our force to reach the same distance and time or suffer the consequence of reaching the finish line at a slower pace should the our exerted force remains the same. All in all, the additional phase to the system will increase the removal time of the blood clot entirely.

4.2.2 Proposed new GP2 device

In another parametric study, a newly proposed GP2 device will be utilised to study the theory of the effect of larger suction area to the removal time of the blood clot. Hence for this part of the simulation, the new GP2 device still consist of nine tubes, which consists of eight smaller diameter tubes that surround one central larger diameter tube, i.e. 0.5 mm and 1.6 mm in diameter respectively. This model will be compared with the old GP2 device and to see if it is true that having a larger suction area will result in a larger suction force thus removal time of blood clot will be much faster.

Table 11: Old versus new GP2 device at 40 kPa

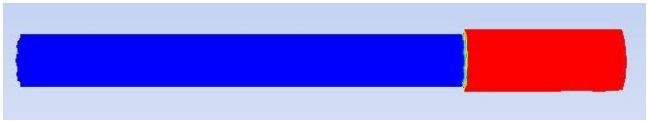
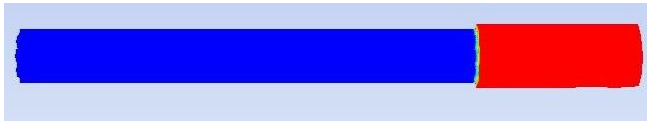
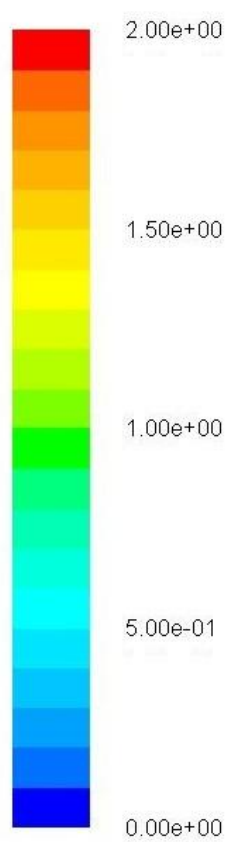
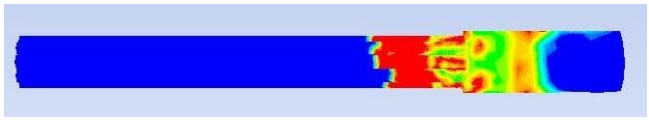
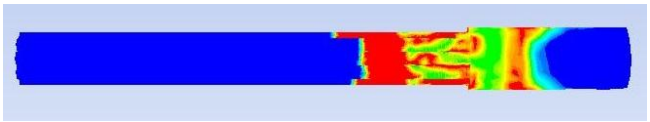
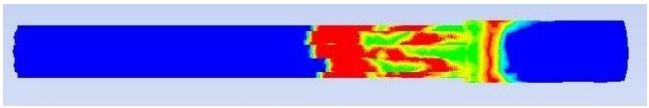
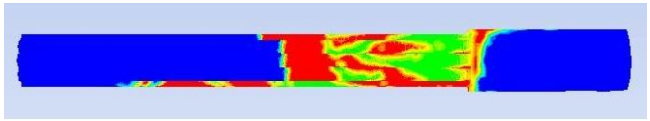
Time	Old GP2 device	New GP2 device	
0			
0.002			
0.004			
0.006			
0.008			

Table 12: Old versus new GP2 device at 50 kPa

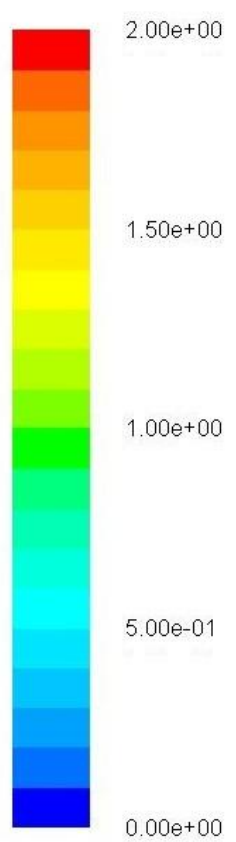
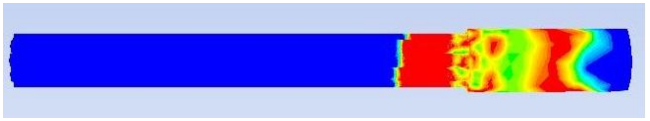
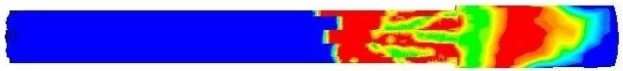
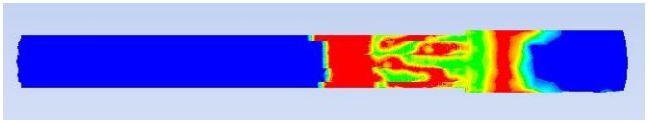
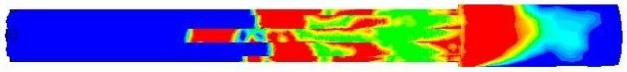
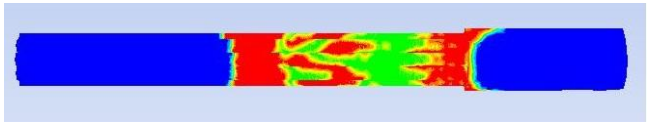
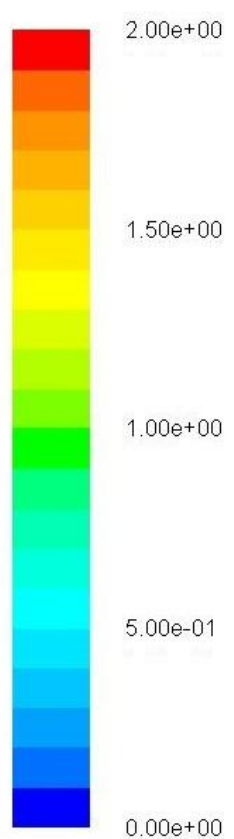
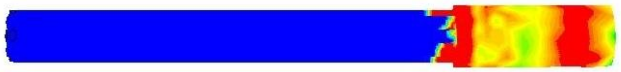
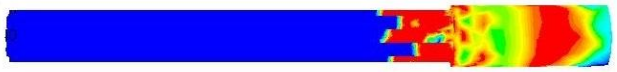
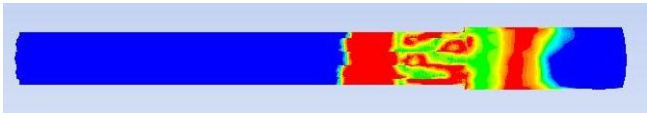
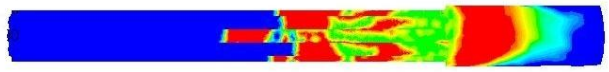
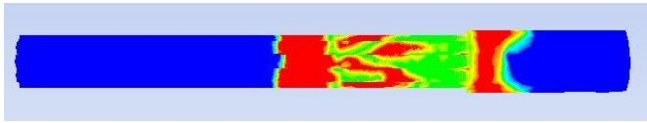
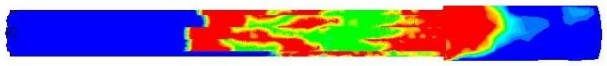
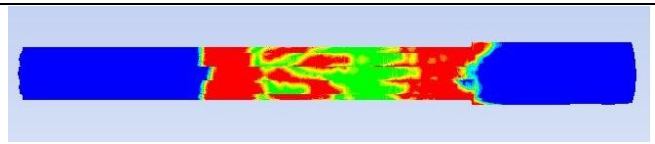
Time	Old GP2 device	New GP2 device	
0			
0.002			
0.004			
0.006			
0.008			

Table 13: Old versus new GP2 device at 60 kPa

Time	Old GP2 device	New GP2 device	
0			
0.002			
0.004			
0.006			
0.008			

4.2.2.1 Quantitative Analysis of Blood Clot Extraction

A graph is again plotted to monitor the volume fraction of blood clot left available in the artery section by utilising the volume monitor under the Monitor options in FLUENT, which is as shown from figure 18 below –

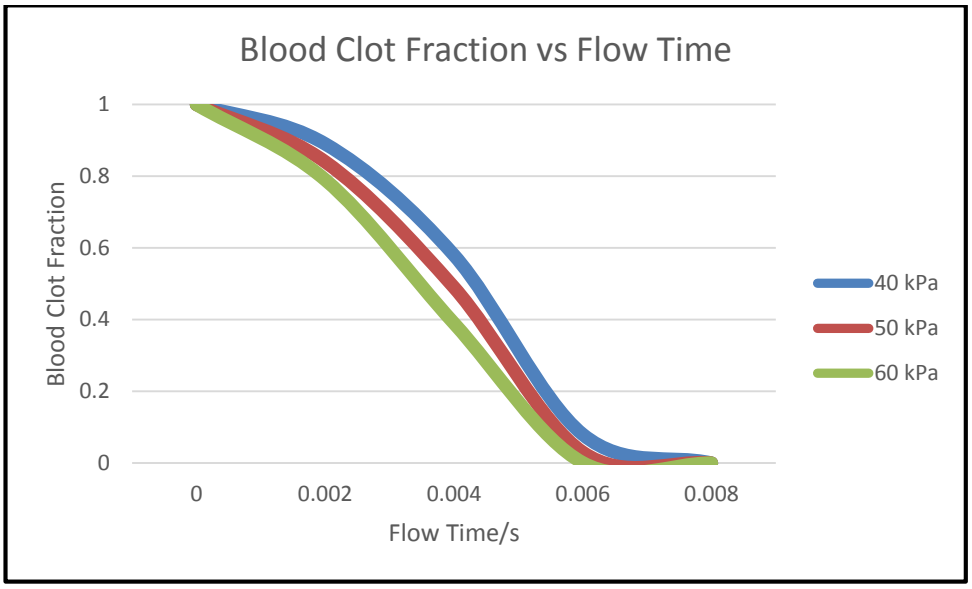


Figure 18: Graph of blood clot volume fraction against flow time under three phase model

A summarise table for the comparison of the extraction time of blood clot between the old GP2 device and the new GP2 device for 3 phase is shown from table 12 below –

Table 14: Comparison between old and new GP2 device

Pressure	Old GP2 Device	New GP2 Device
40	0.0074	0.0071
50	0.0067	0.0061
60	0.0059	0.0057

It can be seen from above that there is a slight increase in terms of the rate of removal of blood clot using the new GP2 device, i.e. removal rate increase by 0.3 ms or 4.1%, 0.6 ms or 9.0% and 0.2 ms or 3.4% for pressures of 40, 50 and 60 kPa respectively. This has clearly shown the influence of bigger area of suction that will increase the removal rate of blood clot in the artery, on average of at least 5.5% increment.

Comparing to the old GP2 device, the time taken to completely remove the blood clot has also significantly decrease i.e. 7.4 ms, 6.7 ms and 5.9 ms for 40, 50 and 60 kPa respectively (Rahaman, 2012), mainly due to the fact that a larger tube is introduced, thus will exert bigger area of extraction for the blood clot when the opening is much bigger. From table 9, 10 and 11 it can also be seen that the artery is almost completely removed from both blood and blood clot, therefore showing that the new GP2 device performs removal works more comprehensive and wholesome as compared to the old GP2 device. The old GP2 device has still remnants of blood remaining in the artery. Although it might be negligible, smaller fragmentations of blood clot might remain in the artery and therefore it is required to completely remove the fluids.

Working side by side with the major tube are the smaller tubes since the remnants of the blood clot might still be present and lurking, therefore the role of the small tubes is to get rid of the remaining minor clots that got separated from the major clot once it is sucked into the main tube. This phenomena can be simply relate to the opening and closing of valves in a tank. Smaller opening of the valve will result in a longer time for the tank to get empty whereas a bigger opening will make the tank empty at a faster rate compared to smaller opening. Although the force exerted will be much smaller when area is enlarged from the pressure equation of the ratio between force and area, the mass transfer will nevertheless will be much higher when the opening is bigger as compared to smaller opening, which is more important to transfer the blood clot from artery to tube as much as possible.

It can be seen from table 9, 10 and 11 that the fluid within the artery section curves inwards for the new GP2 device as compared to outwards for the old GP2 device. This shows that the force is much concentrated towards the central section of the artery as compared to the old GP2 device where the force is concentrated mostly at the outer section of the artery. Some fragments of the blood clot might escape from the opening of the tubing for the old GP2 device, which is not efficient in terms of wholesome removal. However for the new GP2 device, the tubing arrangements are more comprehensive, covering for both central and outer part of the artery so that the wholesome removal efficiency is much better.

An animation is also made on the removal of blood clot using the new GP2 device for 40 kPa pressure as per attached in the disc or can be viewed in the link given (http://www.youtube.com/watch?v=6SR-qWA65U4&feature=youtu.be). From the given video, it can be seen at the top section of the artery and at around 6 seconds in the video, the blood clot starts its breakdown once the major body of the blood clot enters the central tube. And finally at around 13 seconds in the video, the small tube does its job by draining the remnants of the blood clot out from the artery completely. This proves the theory that smaller tubes surrounding the major tube are required for a more comprehensive removal of the blood clot. Of course, the device is not 100% efficient and that even smaller bits of blood clot will pass through the device and remain inside the artery, but can be considered negligible in this research.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Firstly, the simulation of blood clot extraction in the middle cerebral artery using GP2 device was successful, in which the presence of additional phase will lag the removal process to at least 12% and that a higher pressure and bigger surface area of suction will result in better rate of removal of the blood clot, an improvement of around 9% as compared to previous model.

As a conclusion, it can be seen that the simulation of the project was a success. Firstly, the project work was to identify other probable methods of blood clot removal namely thrombolysis drug and mechanical devices such as balloon angioplasty, embolectomy and MERCI device in which both methods have severe consequences and limitations to the patient such as hefty requirements for the usage of thrombolysis drug and damage of the arterial wall should mechanical devices mentioned earlier are deployed into the human artery. Once we have identified each of the limitations from each of the extraction methods, a device was then proposed to counteract the limitations, and thus comes the GP device that is able to prevent internal damage to the arterial wall.

The GP device was modelled according to previous works done by (Rahaman, 2012), in which she uses a slightly better model by having nine smaller but similar tubing in a circular shape of which its' sole purpose is to extract the blood clot at a faster rate. Hence, the device was modelled using ANSYS Design Modeller to basically model the dimensions of the device according to her specifications i.e. each tube having a diameter of 0.6 mm. The mesh sizes used was 0.25 mm, 0.20 mm and 0.15 mm, in which grid sensitivity study was done to determine the best practicable mesh size that is both accurate and low computational time. It was found out that the best mesh size after grid analysis was mesh size of 0.20 mm.

The simulation was done whereby the model was tested using two phase flow of VOF model under different pressures of 40, 50 and 60 kPa and the data was saved for comparison works later. To follow suit, another simulation was done but for three phase flow of VOF model for different pressures of 40, 50 and 60 kPa in which the objective of this simulation is to compare the extraction time of the device when there is the additional phase present in the system, i.e. air. It is found out that the presence of the additional phase has caused the extraction time to be longer than the two phase model, in which the increment was almost around 12% as compared to the previous model. This is mainly due to the fact that pressure needs to move an additional viscous fluid with air as the background phase i.e. blood and blood clot, of which the previous model will only require the movement of one viscous fluid which was blood clot in which blood is the background phase.

The project continues with the design of a new GP2 device having a slightly changed structure of the device. The new GP2 device still has nine tubing, of which the ninth tube is located in the central section of the device, surrounded by eight smaller and similar sized tubing of 1.6 mm and 0.5 mm respectively. The model underwent similar processes of design, meshing and simulation as previous works. It was found out that the device has indeed increase the rate of removal of blood clot by as much as 9% as compared to previous model. This is mainly due to the fact that a larger area of suction contributes to the faster mass transfer of the fluid, i.e. the blood clot, from the artery section to the tubing section of the model. Additionally, the smaller tubes are still being deployed to suck out the remaining fragmentations of the blood clot which can be seen from the video that the major body of the blood clot starts to break up once it gets sucked into the tubing.

5.2 Recommendations

The simulation was done assuming that the blood behaves similar to a Newtonian fluid, to simplify calculation methods. Newtonian fluid follows the principle that the relationship between shear stress and shear rate is linear. However in real life, blood actually behaves according to non-Newtonian fluid property, in which the relationship between shear stress and shear rate is non-linear. Simply put, a non-Newtonian fluid will be more viscous when external forces are applied to the fluid, thus will slow down the movement of the fluid in the artery and tubes. In this therefore recommended for future studies that a non-Newtonian fluid is used for the blood properties to simulate an almost real life extraction of the blood clot, since the introduction of air in the tubing has almost simulated to an actual extraction of blood clot during a surgery.

Another recommendation would be a modification on the GP2 device of which the arrangement of the tubing will consist of one cylindrical tube that is separated into several smaller cylindrical tubes, almost similar to the structural arrangement of tubing in a shell and tube heat exchanger. This is mainly to test the sectional force of the tube since from the pressure equation of the ratio of force to area, having a smaller area will result in larger force but at the offset of lower mass transfer of the blood clot. However if the smaller area of tube is combined collectively, each of the tube will exert a much stronger force compared to a large single area, but will still have better mass transfer rate since the arrangement of the tubes are closely packed, and as mentioned similar to the tubes in heat exchanger, and will also promotes breaking of the blood clot into smaller fragmentations.

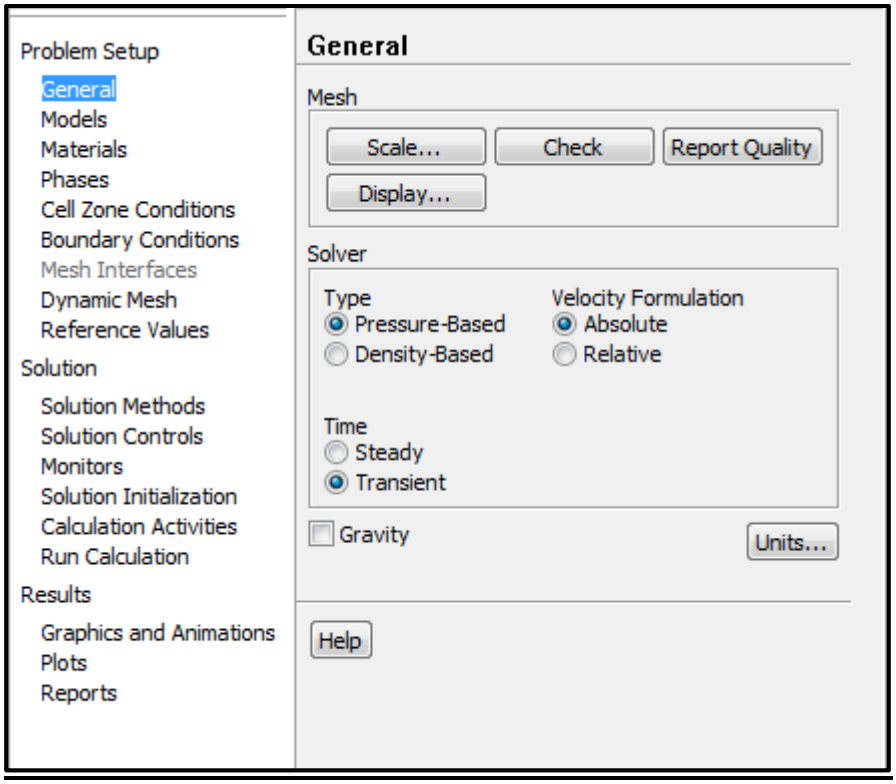
APPENDIX

FYP 2 Gantt chart

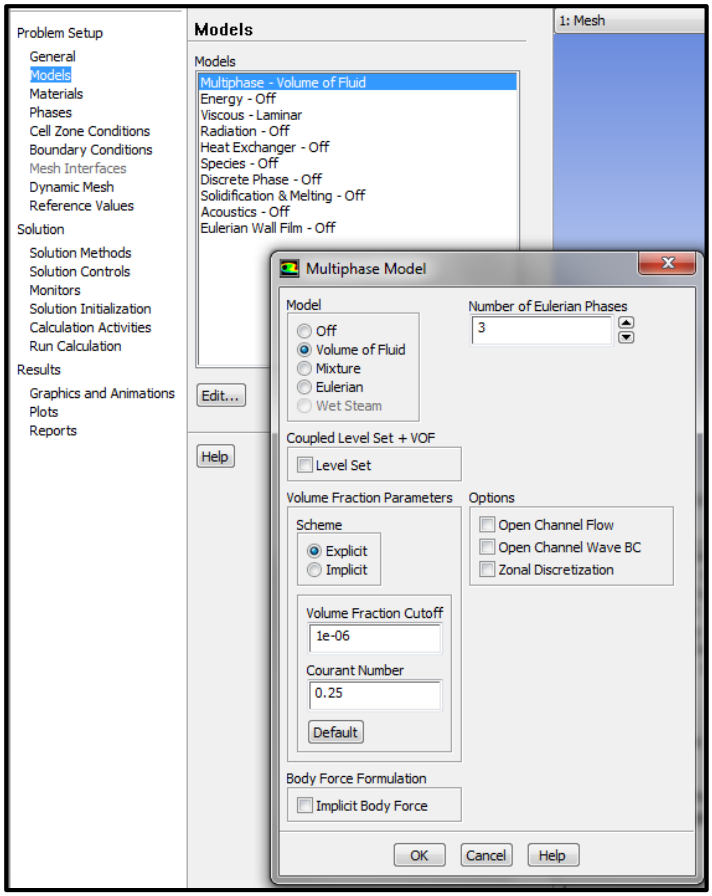
DETAIL/WEEK	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
Project Work Continues																
Submission of Progress Report																
Project Work Continues																
Pre-SEDEX																
Submission of Draft Report																
Submission of Dissertation (soft bound)																
Submission of Technical Paper																
Oral Presentation																
Submission of Project Dissertation (hard bound)																

Mid-Semester break

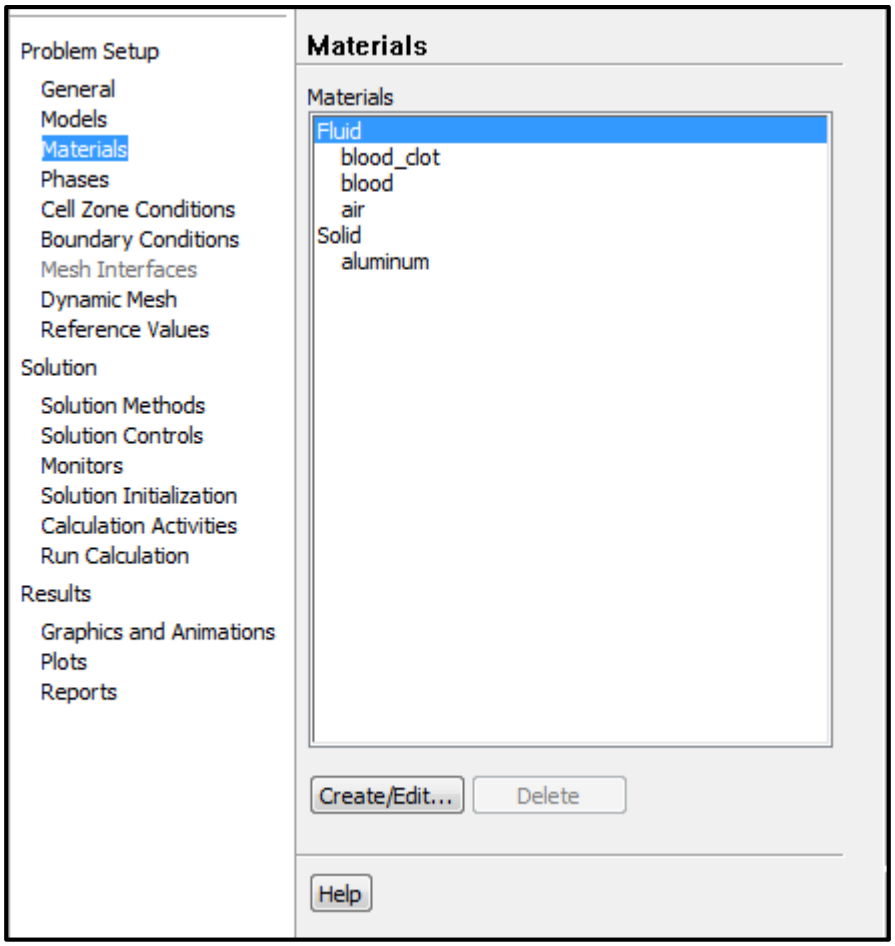
Step 1


Problem Setup
General
Models
Materials
Phases
Cell Zone Conditions
Boundary Conditions
Mesh Interfaces
Dynamic Mesh
Reference Values
Solution
Solution Methods
Solution Controls
Monitors
Solution Initialization
Calculation Activities
Run Calculation
Results
Graphics and Animations
Plots
Reports
General
Mesh
Scale...
Check
Report Quality
Display...
Solver
Type
Pressure-Based
Density-Based
Velocity Formulation
Absolute
Relative
Time
Steady
Transient
Gravity
Units...
Help

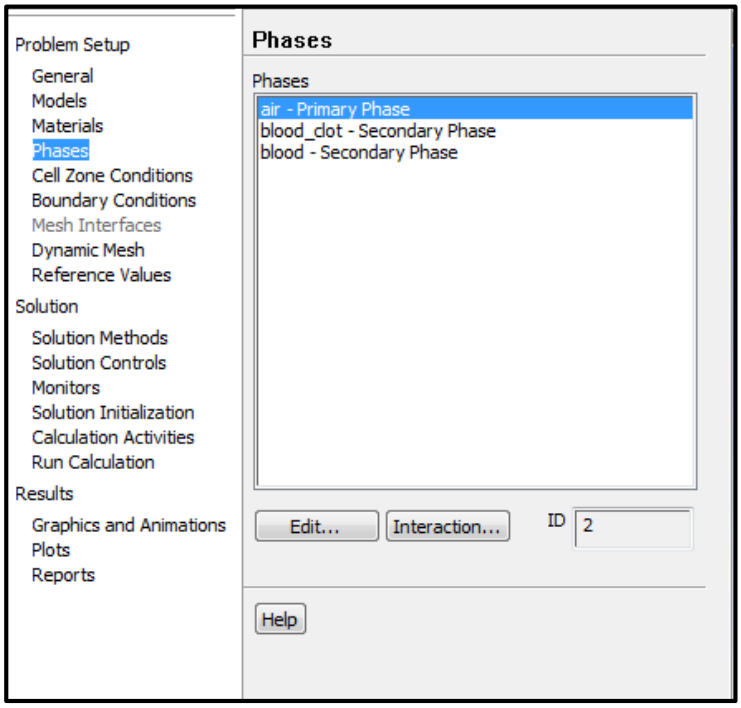
Step 2


Problem Setup
General
Models
Materials
Phases
Cell Zone Conditions
Boundary Conditions
Mesh Interfaces
Dynamic Mesh
Reference Values
Solution
Solution Methods
Solution Controls
Monitors
Solution Initialization
Calculation Activities
Run Calculation
Results
Graphics and Animations
Plots
Reports
Models
Models
Multiphase - Volume of Fluid
Energy - Off
Viscous - Laminar
Radiation - Off
Heat Exchanger - Off
Species - Off
Discrete Phase - Off
Solidification & Melting - Off
Acoustics - Off
Eulerian Wall Film - Off
Edit...
Help
1: Mesh
Multiphase Model
Model
Off
Volume of Fluid
Mixture
Eulerian
Wet Steam
Number of Eulerian Phases
3
Coupled Level Set + VOF
Level Set
Volume Fraction Parameters
Scheme
Explicit
Implicit
Volume Fraction Cutoff
1e-06
Courant Number
0.25
Default
Options
Open Channel Flow
Open Channel Wave BC
Zonal Discretization
Body Force Formulation
Implicit Body Force
OK
Cancel
Help

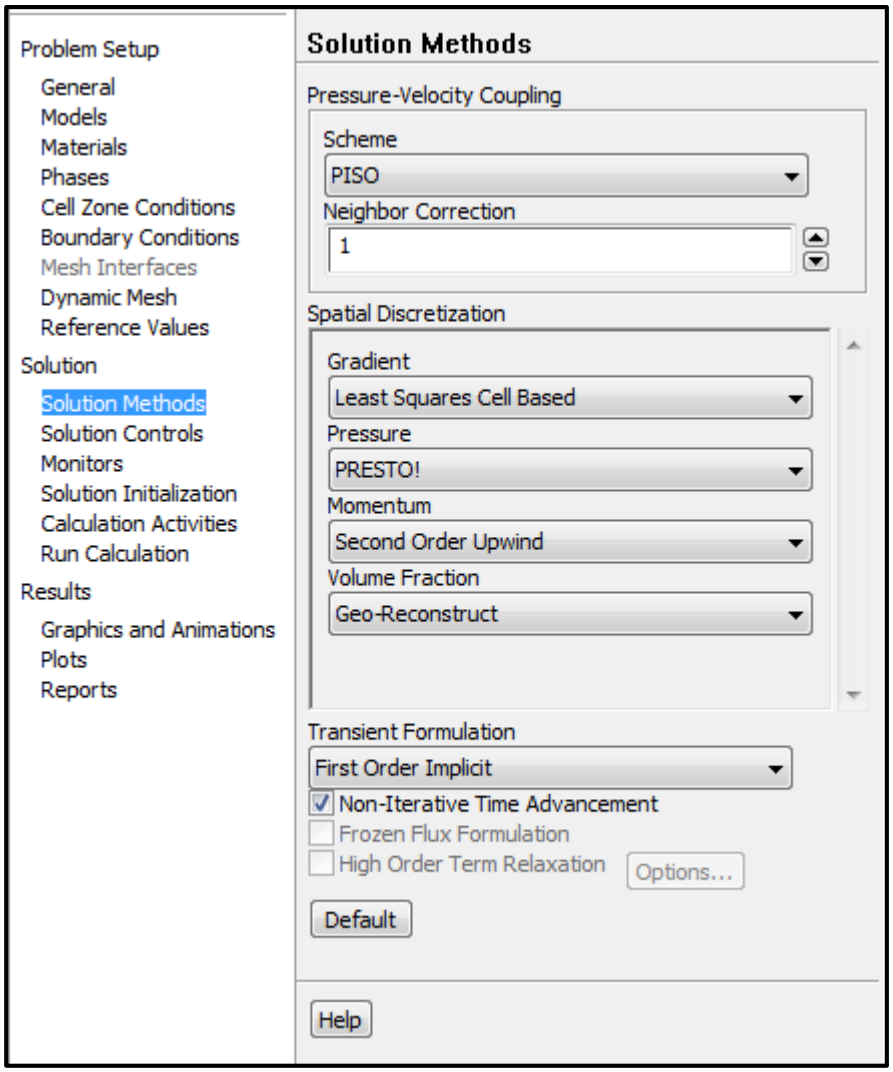
Step 3


Problem Setup
General
Models
Materials
Phases
Cell Zone Conditions
Boundary Conditions
Mesh Interfaces
Dynamic Mesh
Reference Values
Solution
Solution Methods
Solution Controls
Monitors
Solution Initialization
Calculation Activities
Run Calculation
Results
Graphics and Animations
Plots
Reports
Materials
Materials
Fluid
blood_clot
blood
air
Solid
aluminum
Create/Edit...
Delete
Help

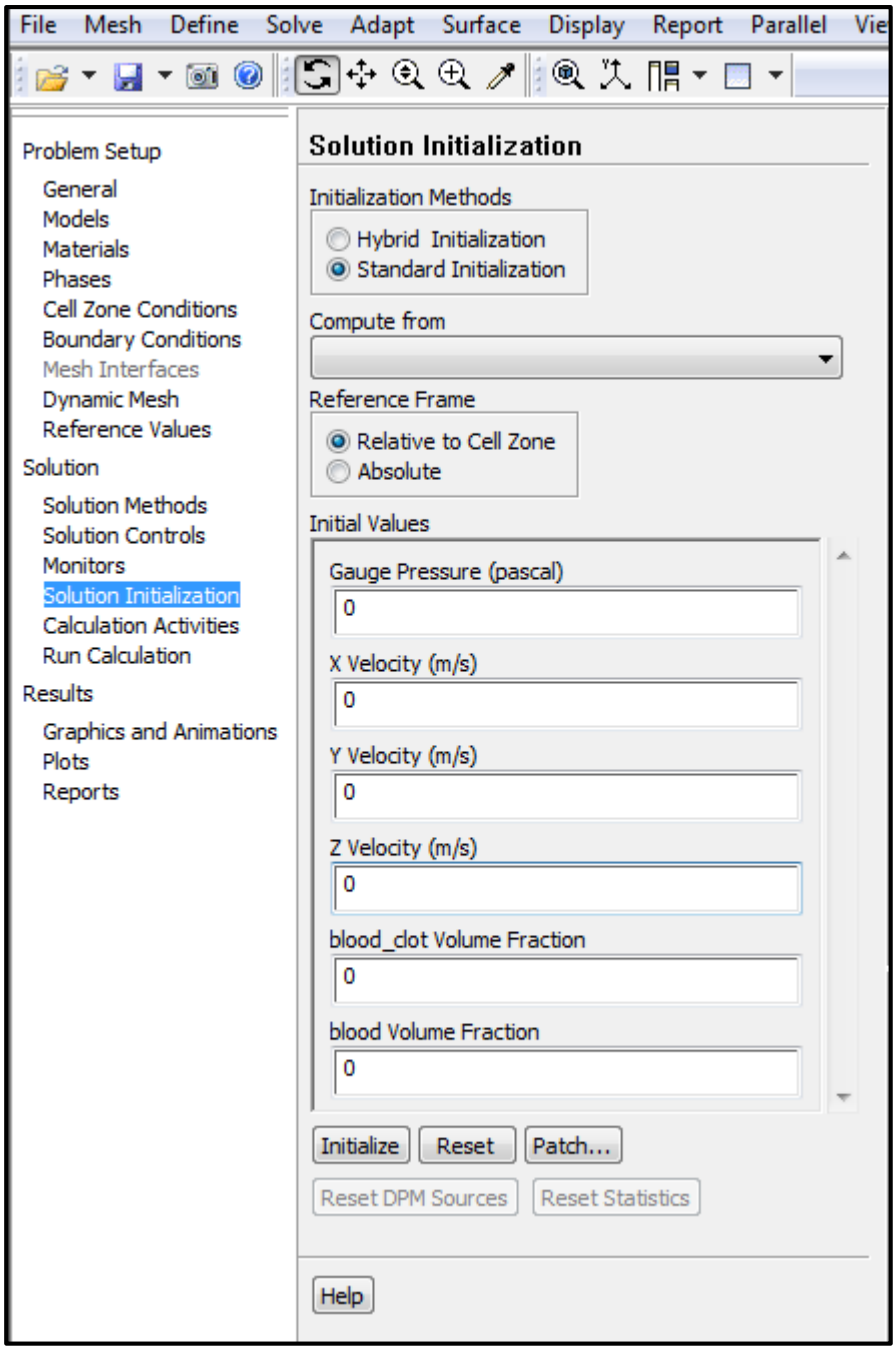
Step 4


Problem Setup
General
Models
Materials
Phases
Cell Zone Conditions
Boundary Conditions
Mesh Interfaces
Dynamic Mesh
Reference Values
Solution
Solution Methods
Solution Controls
Monitors
Solution Initialization
Calculation Activities
Run Calculation
Results
Graphics and Animations
Plots
Reports
Phases
Phases
air - Primary Phase
blood_clot - Secondary Phase
blood - Secondary Phase
Edit...
Interaction...
ID
2
Help

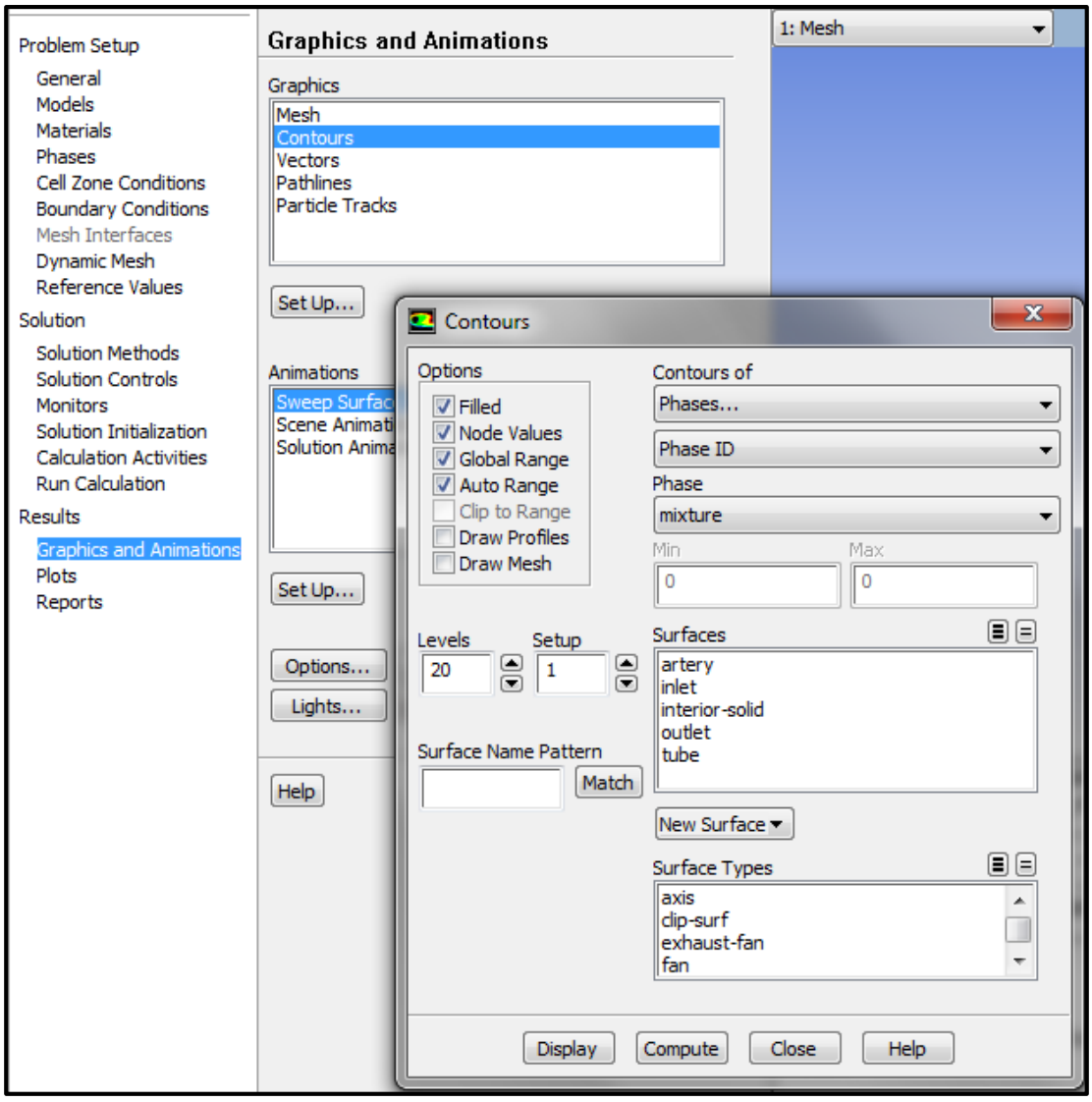
Step 5


Problem Setup
General
Models
Materials
Phases
Cell Zone Conditions
Boundary Conditions
Mesh Interfaces
Dynamic Mesh
Reference Values
Solution
Solution Methods
Solution Controls
Monitors
Solution Initialization
Calculation Activities
Run Calculation
Results
Graphics and Animations
Plots
Reports
Solution Methods
Pressure-Velocity Coupling
Scheme
PISO
Neighbor Correction
1
Spatial Discretization
Gradient
Least Squares Cell Based
Pressure
PRESTO!
Momentum
Second Order Upwind
Volume Fraction
Geo-Reconstruct
Transient Formulation
First Order Implicit
Non-Iterative Time Advancement
Frozen Flux Formulation
High Order Term Relaxation
Options...
Default
Help

Step 6


File Mesh Define Solve Adapt Surface Display Report Parallel Vie
Problem Setup
General
Models
Materials
Phases
Cell Zone Conditions
Boundary Conditions
Mesh Interfaces
Dynamic Mesh
Reference Values
Solution
Solution Methods
Solution Controls
Monitors
Solution Initialization
Calculation Activities
Run Calculation
Results
Graphics and Animations
Plots
Reports
Solution Initialization
Initialization Methods
Hybrid Initialization
Standard Initialization
Compute from
Reference Frame
Relative to Cell Zone
Absolute
Initial Values
Gauge Pressure (pascal)
0
X Velocity (m/s)
0
Y Velocity (m/s)
0
Z Velocity (m/s)
0
blood_clot Volume Fraction
0
blood Volume Fraction
0
Initialize
Reset
Patch...
Reset DPM Sources
Reset Statistics
Help

Step 1 (post processing)



REFERENCE

About Stroke. (2013). Retrieved from Stroke Association: http://www.stroke.org.uk/about/thrombolysis

AJNR. (2006, June 27). *Safety of Mechanical Thrombectomy and Intravenous Tissue Plasminogen Activator in Acute Ischemic Stroke*. Retrieved from American Journal of Neuroradiology: http://www.ajnr.org/content/27/6/1177/F1.expansion.html

Donnan, G., Fisher, M., M., M., & Davis, S. (May 2008). Emergency and comprehensive care for stroke needed. *The Lancet*, 1612-1623.

FLUENT, A. (2007). *FLUENT 6.3 Documentation*. Retrieved from http://cdlab2.fluid.tuwien.ac.at/LEHRE/TURB/Fluent.Inc/fluent6.3.26/help/index.htm

Foster, J., Carter, J., Graham, L., & Edwards, W. (1970). Arterial injuries secondary to the use of the Fogarty catheter. 971-978.

Glagov, S. (1994). Intimal hyperplasia, vascular modeling and the restenosis problem. *Circulation 89*, pp. 2888-2891.

Gobin, Y., Starkman, S., Duckwiler, G., Grobelny, T., Kidwell, C., Jahan, R., . . . Saver, J. (2004). MERCI 1: A Phase 1 Study of Mechanical Embolus Removal in Cerebral Ischemia. *Stroke by American Stroke Association*.

Goldberg, E., Goldberg, M., Chowdhury, L., & Gould, S. (1983). The effects of embolectomy-thrombectomy catheter on vascular architecture. *J Cardiovasc Surg*, 74-80.

Hirt, C. W., & Nichols, B. D. (1981). Volume of Fluid (VOF) Method for the dynamics of free boundaries. *Journal of Computational Physics*, 204-206.

HotspurTechnologies. (2013). *Balloon Embolectomy*. Retrieved from Hotspur Incorporated: http://www.hotspur-inc.com/

Humphrey, J. (2001). *Cardiovascular Solids Mechanics: Cells, Tissues and Organs.* Springer.

Jamal, A., Bendeck, M., & Langille, B. (1992). Structural changes and recovery of function after arterial injury. *Arterioscl Thromb*, 307-317.

Kuzilati, K., Rahman, A., & Pearce, G. (2012). *CFD Simulation of Blood Clot Behaviour using GP Device.* United Kingdom: 2012 14th International Conference on Modelling and Simulation.

Kwak, D., & Kiris, C. (2011). *Computation of Viscous Incompressible Flow.* Springer.

Martonen, T. (2000). *Medical Applications of Computer Modelling: Cardiovascular and Ocular Systems.* WIT Press.

Masterlife.com. (2013). *Medical illustrations of normal blood flow and blood flow through an artery with a thrombus*. Retrieved from MasterLife: http://www.masterfile.com/stock-photography/image/861-03348304/Medical-illustrations-of-normal-blood-flow-and-blood-flow-through-an-artery-with-a-thrombus.

NewYork-Presbyterian.org. (2008, Nobember 30). Retrieved from History of Stroke: http://nyp.org/health/stroke-history.html

NHLBI. (2013). *Coronary Angioplasty*. Retrieved from National Heart, Lung and Blood Institute: http://www.nhlbi.nih.gov/health//dci/Diseases/Angioplasty/Angioplasty_All.html

O'Donnell, J., & Hobson, R. (1978). Balloon and lateral wall pressures during use of balloon embolectomy catheters. *Surgery*, 583-587.

Pearce, G., Patrick, J., & Jaegle, F. (2006). The Design, implementation and testing of a new revolutionary device for the removal of blood clots in the arterial system. *UKSim*, (pp. 6-9). Oriel College, Oxford, England.

Pearce, J. M. (1997). Johann Jakob Wepfer and cerebral haemorrhage. *J Neurol Neurosurg Psychiatry*, 387-388.

Rahaman, N. (2012). *CFD simulation for extraction of blood clot in MCA using GP 2 device.* UTP.

Romero, G., Martinez, M., Felez, J., Pearce, G., & Perkinson, N. (2011). Analysis and design of a thrombectomy device by using simulation techniques. *IMProVe 2011*, 720-725.

Sims, N., & Muyderman, H. (September 2009). Mitochondria, oxidative metabolism and cell death in stroke. In *Biochimica et Biophysica Acta* (pp. 80-91). Australia: Flinders University.

Stroke Statistics. (2002). Retrieved from The Internet Stoke Center: http://www.strokecenter.org/patients/about-stroke/stroke-statistics/

Tennuci, C., Pearce, G., Wong, J., Nayak, S., Jones, T., Lally, F., & Roffe, C. (2011). Comparison of the Effectiveness of 3 Methods of Recanalisation in a Model of Middle Cerebral Artery. *Stroke Research and Treatment*.

Vliestra, R., & Holmes, D. (1987). *PTCA.* Philadelphia.

Zollikofer, C., Chain, J., & Salomonowitz, E. (1984). Percutaneous transluminal angioplasty of the aorta. In *Radiology* (pp. 355-363).