COMPUTATIONAL FLUID DYNAMICS ANALYSIS OF DEEP VEINS WITH FOCUS ON DEEP VEIN THROMBOSIS (DVT)

UPENDRA PARIMI
Department of Mechanical Engineering

APPROVED:

__________________________________________
Vinod Kumar, Ph.D., Chair

__________________________________________
Ramana Chintalapalle V, Ph.D

__________________________________________
Pennathur ArunKumar, Ph.D.

__________________________________________
Leticia Velazquez, Ph.D

__________________________________________
Herbert F Janseen, Janssen, MEd, PhD

__________________________________________
Patricia D. Witherspoon, Ph.D.
Dean of the Graduate School
COMPUTATIONAL FLUID DYNAMICS ANALYSIS OF DEEP VEINS WITH FOCUS ON DEEP VEIN THROMBOSIS

If you elect to change the title I would suggest including the word "valve" --- but I'm OK if you want to leave it the way it is.

UPENDRA PARIMI, B. Tech

THESIS

Presented to the Faculty of the Graduate School of

The University of Texas at El Paso

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

Department of Mechanical Engineering,

THE UNIVERSITY OF TEXAS AT EL PASO

December, 2010
Acknowledgements

I would like to thank

My advisor Dr Vinod Kumar for his encouragement, guidance and support from the very initial level to the final level in understanding the concept and application of computational fluid dynamics as a tool for multi-disciplinary problems which helped me develop an understanding of the research topic.

Dr Herbert F Janssen for helping me learn the literature on functionality of deep veins and venous valves and for his timely guidance and motivation. I would like to thank him for giving me the opportunity to work and learn.

My colleagues especially Christian and Enrique at the computational lab for maintaining a healthy work environment and being helpful with jobs assigned.

Last but not the least I would like thank my mother, father and sister for understanding me and supporting me during this period.
Abstract

The venous valves in veins carry on the important function of eliminating the retrograde (reverse) flow of blood in veins and help the veins to carry on their work effectively. The aim of our study is to do a computational fluid dynamics analysis on deep veins with the help of the softwares provided by Ansys. We are going to create a geometry which resembles the blood vein containing unidirectional venous valves and are going to create the same flow circumstances which depict the flow undergoing in the blood veins.

It would be interesting to see what happens to the flow when the blood flows past the valves in the blood veins and to learn how the velocity varies in the pocket like structure. We could see the flow patterns in the blood veins and find where the vortices are formed when there are obstructions like the valves acting to stop the flow, this could be helpful in estimating if there is a chance for the clot formation in some specific areas.

Elderly People and pregnant women are the ones who are most likely to develop deep vein thrombosis. It was determined from previous studies that women in their postpartum period are at the highest risk of developing a DVT and even pulmonary embolism in most of the cases. The aid of computational study could help us in improving the prophylaxis given to the elderly and pregnant women, by better understanding the physics involved in the clot formation.

You could also mention cancer, smoking, obesity, people undergoing major surgery, prolonged bed rest, genetic problems that alter clotting conditions, previous history of clotting problems, trauma. I will send you links to a couple articles. I know you are tired of writing on this -- but the addition would make the final document more complete. Please consider, but this is not something you have to do -- OK?
# Contents

Acknowledgements ................................................................................................................. 1
Abstract ..................................................................................................................................... 2
List of Figures ........................................................................................................................... 4
List of Tables ............................................................................................................................. 6
Chapter 1: Introduction ............................................................................................................ 8
Chapter 2: Literature Survey .................................................................................................... 11
  2.1 Veins, Venous valves and Deep vein Thrombosis (DVT): ................................................. 11
  2.2 Complications which might occur apart from a DVT: ................................................... 18
  2.3 Computational Studies: .................................................................................................... 21
  2.4 Blood Flow and Fluid Mechanics ..................................................................................... 24
Chapter 3: Methodology .......................................................................................................... 26
  3.1 Measurements of Deep Veins: ......................................................................................... 26
  3.2 Boundary Conditions: ...................................................................................................... 27
  3.3 Governing Equations: ....................................................................................................... 30
Chapter 4: Results and Discussions ......................................................................................... 34
  4.1 2D model results: ............................................................................................................ 35
  4.2 3D analysis: ..................................................................................................................... 42
Chapter 5: Conclusions ............................................................................................................ 47
Chapter 6: Future Work ........................................................................................................... 49
Bibliography ............................................................................................................................. 50
Appendix ................................................................................................................................... 53
CURRICULUM VITA .................................................................................................................. 77
List of Figures

Figure 1: Arrangement of venous valves (Gottlob and May n.d.) ................................................................. 13
Figure 2: Virchow’s Triad ................................................................................................................................. 18
Figure 3: Flow Physics explaining the fluid flow in the presence of obstacles (Gottlob and May n.d.) ............................................................................................................. 25
Figure 4: A scale kept by the side of a vein ........................................................................................................ 26
Figure 5: Grid or mesh generated for one of the cases .................................................................................... 29
Figure 6: Velocity vs. Position at the center ....................................................................................................... 38
Figure 7: Velocity vs. Position in the pockets .................................................................................................... 39
Figure 8: Pressure vs. position at the center ..................................................................................................... 40
Figure 9: Pressure vs. position in the pocket .................................................................................................. 40
Figure 10: Experimental setup being installed .............................................................................................. 49
Figure 11: Velocity and Pressure Contours (case1) ......................................................................................... 53
Figure 12: Velocity Vectors Colored by Pressure (case1) .............................................................................. 53
Figure 13: Velocity and pressure contours (case2) ......................................................................................... 54
Figure 14: Velocity vectors colored with Pressure (case2) ........................................................................... 54
Figure 15: Velocity Vectors Colored by Pressure (case3) .............................................................................. 55
Figure 16: Velocity vectors colored with Pressure (case3) ........................................................................... 55
Figure 17: Velocity and Pressure Contours (case4) ......................................................................................... 56
Figure 18: Velocity vectors colored with Pressure (case4) ........................................................................... 56
Figure 19: Velocity and Pressure Contours (case5) ......................................................................................... 57
Figure 20: Velocity vectors colored with Pressure (case5) ........................................................................... 57
Figure 21: Velocity and Pressure Contours (case6) ......................................................................................... 58
Figure 22: Velocity vectors colored with Pressure (case6) ........................................................................... 58
Figure 23: Velocity and Pressure Contours (case7) ........................................................................................ 59
Figure 24: Velocity vectors colored with Pressure (case7) ........................................................................... 59
Figure 25: Velocity and Pressure Contours (case8) ........................................................................................ 60
Figure 26: Velocity vectors colored with Pressure (case8) ........................................................................... 60
Figure 27: Velocity and Pressure Contours (case9) ........................................................................................ 61
Figure 28: Velocity vectors colored with Pressure (case9) ........................................................................... 61
Figure 29: Velocity and Pressure Contours (case10) ....................................................................................... 62
Figure 30: Velocity vectors colored with Pressure (case10) ......................................................................... 62
Figure 31: Velocity and Pressure Contours (case11) ....................................................................................... 63
Figure 32: Velocity vectors colored with Pressure (case11) ......................................................................... 63
Figure 33: Velocity and Pressure Contours (case12) ....................................................................................... 64
Figure 34: Velocity vectors colored with Pressure (case12) ......................................................................... 64
Figure 35: Velocity and Pressure Contours (case13) ....................................................................................... 65
Figure 36: Velocity vectors colored with Pressure (case13) ......................................................................... 65
Figure 37: Velocity and Pressure Contours (case14) ....................................................................................... 66
Figure 38: Velocity vectors colored with Pressure (case14) ......................................................................... 66
Figure 39: Velocity and Pressure Contours (case15) ....................................................................................... 67
Figure 40: Velocity vectors colored with Pressure (case15) ......................................................................... 67
Figure 41: Velocity and Pressure Contours (case16) ....................................................................................... 68
Figure 42: Velocity vectors colored with Pressure (case16) ......................................................................... 68
Figure 43: Velocity and Pressure Contours (case17) ....................................................................................... 69
Figure 44: Velocity vectors colored with Pressure (case17) ......................................................................... 69
Figure 45: Velocity and Pressure Contours (case18) .............................................................. 70
Figure 46: Velocity vectors colored with Pressure (case18) ..................................................... 70
Figure 47: Velocity and Pressure Contours (case19) .............................................................. 71
Figure 48: Velocity vectors colored with Pressure (case19) ..................................................... 71
Figure 49: Velocity and Pressure Contours (case20) .............................................................. 72
Figure 50: Velocity vectors colored with Pressure (case20) ..................................................... 72
Figure 51: Velocity and Pressure Contours (case21) .............................................................. 73
Figure 52: Velocity vectors colored with Pressure (case21) ..................................................... 73
Figure 53: Velocity and Pressure Contours (case22) .............................................................. 74
Figure 54: Velocity vectors colored with Pressure (case22) ..................................................... 74
Figure 55: Velocity and Pressure Contours (case23) .............................................................. 75
Figure 56: Velocity vectors colored with Pressure (case23) ..................................................... 75
Figure 57: Velocity and Pressure Contours (case24) .............................................................. 76
Figure 58: Velocity vectors colored with Pressure (case24) ..................................................... 76
List of Tables

Table 1: Scaled Velocity Contours plotted for four cases .......................................................... 35
Table 2: Scaled Pressure Contours plotted for 4 cases ................................................................. 37
Table 3: Scaled velocity contours of 3d cases ............................................................................. 42
Table 4: Scaled Pressure Contours of 3d cases ......................................................................... 45
Chapter 1: Introduction

dependous thrombosis (DVT)

Every year in the United States complications from Deep Vein Thrombosis results in 250,000 hospitalizations and over 50,000 deaths. The general risk of venous thromboembolism (one disease with manifestations of both pulmonary embolism and Deep Vein Thrombosis) in general medical patients ranges from 10 to 30% (Meyer-Michel 2000) (Fredrick and Fredrick 2003). It is the third most prevalent cardiovascular disease and remains the most preventable cause of death in our hospitals. Also, reports suggest that the number of hospital admissions in 1990’s ranged from 300,000 to 600,000 and the death toll was approximately 50,000 per year (Herbert Janssen 1993).

The risk of deep venous thrombosis (DVT) and its associated conditions such as pulmonary emboli (PE) and chronic venous insufficiency (CVI) increase with age (Stein, et al. 2004). It has been demonstrated in previous studies that venous valves in the legs of elderly individuals are often damaged or missing. This damage occurs as a leaflet tears, an ancillary flaps, a leaflet develops or grows into the vein wall, and/or as remnants of the leaflet that appear as only small outgrowths on the vein wall.

These abnormalities generally result in CVI since valve incompetence most frequently exists in these conditions. The damage also inhibits proper valves function, which enhances the risk of blood stasis; one of the major factors that increase the risk of future DVT development. The flow in the deep veins takes place with the help of the muscles and the vein valves.
The muscles squeeze the veins and help the blood to flow against the gravity and vein valves help in restricting the flow from flowing in the opposite direction. When the muscles contract, they pressurize the veins which intern squeezes the blood to flow against the gravity and when this happens the venous valves move away from each other allowing the blood to flow through the valves. When the muscles relax the blood tends to flow back due to gravity so the venous valves come closer to each other and form a seal. Venous valves eliminate the retrograde flow of the blood; hence they are called unidirectional valves.

As blood flows through the arteries and veins, a balance is continuously maintained between factors that induce clots (procoagulants such as fibrin, fibrinogen, prothrombin, etc.) and other factors that prevent clots from forming (anticoagulantants such as antithrombin-III, activated protein C, fibrinolytic enzymes, etc). In such a system an increase in activity (e.g. an increase clotting rate) can be achieved by either increasing the procoagulants or decreasing the anticoagulants. At first glance this seems wasteful; however, in the human body, this assures that the clot forming system is always prepared to respond quickly to an injury that would otherwise produce a life threatening blood loss (Bertina 2009) (Paul and Sabine 2005).

Elderly People and the pregnant women are the ones who are most likely to develop a DVT. From previous studies (Heit, et al. 2005) it was determined that women in their postpartum period are at the highest risk of developing a DVT and even pulmonary embolism in most of the cases. This is because; during pregnancy and postpartum there is an increased level of coagulation or clotting factors in the blood. Also there is an increased venous diameter which intern reduces the flow of blood from the lower extremities (Wee-shian and Jeffrey 2002). Apart from elderly people and the pregnant women, stroke patients are the ones who are at a higher risk of developing a DVT (Georgia, Trevor and Philip 1995).
The aid of computational study could help in improving the prophylaxis given to the old people and pregnant women, by better understanding the physics involved in the clot formation. The modeling will prove to be a valuable resource to better understand this observed condition that has continued to threaten the lives of our elderly. This study would help us know how the flow develops in the deep veins and also how it varies with the varying distance of the valves that is the opening and the closing of the valves. We could get a detailed understanding of where the vortices would be formed for different valve positions.

The second chapter discusses the literature which explains in detail about the arrangement, functionality and other such properties of the veins, shows what are the different phenomena that occur in deep veins and how they can be handled and in the later part of this chapter shows how computational analysis is being used as an important analysis tool in the field of medicine.

The third chapter discusses in detail the methods used in creating the geometry, the equations solved by the solver, the kind of solvers used, the type of grids created and also how the problem is divided into several cases and solved. It also gives some information about the kind of results being captured.

The fourth chapter discusses the various results of the number of cases into which the problem was divided and also shows the velocity and pressure profiles of each of these cases and explains about these contours in detail.

The fifth and sixth chapters discuss the conclusions made and then discuss scope of future work that can be done in this field of study respectively.
Chapter 2: Literature Survey

This chapter mainly focuses on giving a broader picture of research that was previously done to show how veins function, how the valves work, what are the diseases that could occur in veins and valves and it also explains how the aid of computational tools has helped in bettering the medical industry.

2.1 Veins, Venous valves and Deep vein Thrombosis (DVT):
Blood vessels differ in their architectural structure and they behave differently to handle different tasks (Bader n.d.). The blood vessels which carry the oxygenated blood from the heart to different parts of the body are called arteries and the vessels which carry de-oxygenated blood from body parts to the heart are called veins.

Veins are an integral part of the human body. Also the functioning of the veins is much more complex when compared to the function of the arteries. Veins in the leg can be considered as long thin collapsible tubes containing a series of one-way bicuspid valves (Buescher, et al. 2005). The veins carry on the important function of returning the deoxygenated blood from all the parts of the body back to heart (right side of the heart) (Anne July 2001). There are two major types of veins: the superficial veins and the deep veins. As the name suggests the superficial veins are the ones which are just under the layer of skin and are visible in green color and the deep veins are the one’s which are deep inside the muscle tissue.
There are a third kind of veins called the perforating veins. As their name suggests, they are present in between the superficial veins and the deep veins. The main function of these veins is to connect the superficial veins with the deep veins and to ensure that the flow remains unidirectional within the veins: from the superficial veins to the deep veins. These kind of veins are further classified as direct perforators and the indirect perforators, the direct perforators connects the superficial and the deep veins while the indirect perforators connect the other veins in the muscles to the superficial veins in order to effectively draw blood from the superficial veins.

The deep veins are present in the lower body and they help drain the blood from the lower extremities. The deep veins of the leg are covered well by the muscle and are supported by the tissue surrounding them; these veins produce 90 to 95% of the venous outflow from the leg (Anne July 2001).

Effective venous return from the lower extremities requires the interaction of the heart, a pressure gradient, the peripheral muscle pumps of the leg, and competent venous valves (Mark, et al. 2007). There are several unidirectional valves in the deep veins which function in coordination with the muscles in order to eliminate any retrograde flow of the blood and help the veins to function effectively when pumping the blood against gravity.

Venous Valves: The venous valves are one of the smallest and the most delicate organs present in the human body. They are present in the blood veins and are bicuspid in nature i.e. they have two flaps. When they where first discovered, it was presumed that their function was to form an obstacle to the blood flow.
Later it was found that venous valves carry on the important function of eliminating the retrograde (reverse) flow of the blood in the veins and help the veins to carry on their work effectively. From then onwards, the venous valves where considered important in the concept of the circulatory system. Each valve has a couple of very thin walled cusps which originate at the opposite sides of the wall (vein wall) and meet at the center. They are able to regulate the flow and keep it unidirectional when the pressure above the valves is greater than the pressure below them.

When the muscles contract, these venous valves move apart. Thereby allowing flow of blood towards the heart. When the muscles expand, these valves move close to each other blocking any reverse flow of the blood in the veins. Hence, the greater the pressure of the circulating fluid, the greater will be the opening of the valves. Thus these venous valves are able to eliminate any retrograde flow of blood in the blood veins unless there are any disturbances within veins like the clots (Franklin 1927).

The veins of less than 1 mm diameter do not contain these valves. The distance between the valves in the deep veins is much shorter when compared to that in the superficial veins. Also, the alignment of valves in perforating veins helps ensure the unidirectional flow of blood from the superficial veins to the deep veins.

Figure 1: Arrangement of venous valves (Gottlob and May n.d.)
The valves are of two types namely parietal valves and the ostial valves. The valves which are most frequently encountered are the parietal valves. These parietal valves are otherwise called the pocket valves and contain cusps. The Ostial valves occur less frequently and are placed at the intersection of small veins and large veins especially at the places where the small veins transform into the large veins. The parietal valves consist of cusps, the valvular agger, the valvular cornua and the valvular sinus. The valvular cusps intersect at the valvular agger and are usually half moon sharpened like structures in shape (Franklin 1927).

The venous valves that are found in the Veins have cross sections of elliptical outline at the sites of the venous valves. The formation of these valves takes place very early in the life cycle, in fact the earliest formation of the valves was seen in the embryos that were just 3.5 months old. In a 70 years old adult only 19 to 20 percent of the total valves exist. This reduction in the number of venous valves can be due to thromboses of valvular sinus which occurs more frequently than it actually is taught to occur. Further studies show that these valves just do not disappear but, they become impotent along with the increasing age. This impotence of the venous valves might be due to their over dilation of venous valves as well as massive venous thrombosis or even due to over-dilation of venous wall.

Some experiments were carried out to see how these valves functioned, in one of the experiment a probe was attempted to be passed through the connecting veins to see whether the valve functioning can be studied. The experiment showed that when the probe was passed from the smaller branches of veins to the deep veins it would not be possible to move the probe, and the deep veins always resisted the probe. But when the probe was inserted in the reverse direction i.e. from the deeper veins to the branches, the veins did not offer any resistance. This study showed that the blood flow is regulated in a single direction from superficial veins to deep veins.
Factors like high pressure on valves especially in the persons whose jobs require long time standing, their veins are compressed for long periods of time by the compressed muscles. Also, during pregnancy increased dilatability of vessels was observed. One incompetent valve could lead to the overloading of the other valves i.e. the valves might have to handle increased amount of blood flow, such cases can lead to the dilation of the walls.

When the walls of the veins get dilated the retrograde flow of the veins cannot be stopped. This in turn leads to the over-dilation of the walls which makes the venous valve incompetent (Robert 1980). The over-dilated walls and incompetent valves lead to blood regurgitation and turbulences. These turbulences could cause further complications which render the valve incompetent (Gottlob and May n.d.).

Deep Vein Thrombosis (DVT):

Usually, clots are formed at the places where there are any cuts or wounds. These occur in order to prevent excessive loss of blood which essentially makes them useful clots and without such clots life would be difficult. Thrombus means a clot and the formation of these clots in the deep veins is called the deep vein thrombosis. There is a possibility that these clots block blood from flowing to the heart. Sometimes these clots prevent the one way venous valves from closing this in turn makes the blood flow in the reverse direction. This further leads to the swelling of the legs or the effected parts of the body. As DVT occurs mostly in legs, the elderly and pregnant women are the ones who are most prone to developing it (Heit, et al. 2005).
It is a well accepted that DVT forms in the pockets located behind the venous valve leaflets. These thrombi which are formed in the pockets, progress into larger clots that can break loose and form Pulmonary Emboli (PE). It is also known that the clots in these pockets can damage the leaflets resulting in incompetent valves incapable of closing properly. Increased venous pressure, peripheral edema, and ultimately venous ulcers will result if the condition is allowed to progress. These ulcers are not life threatening, but they significantly reduce the quality of an individual’s life.

Clot formation: The process in which the blood transforms into a clot or thrombi is called a coagulation or hemostasis. When a wound is formed and bleeding starts, a substance called fibrin is released by the action of two clotting factors in the blood called procoagulants and anticoagulants which prevents further bleeding by clotting the blood. This process of clotting of the blood is called hemostasis (Bertina 2009).

Hemostasis of blood occurs in three stages: an initiation phase, a propagation phase and a termination phase. During the initiation phase, the concentration of thrombin tends to increase slowly. During the propagation phase, thrombin activates platelets which in turn support the procoagulants reactions. It is this propagation phase which plays a major role in the regulation of the clot formation. In the termination phase, the hemostatic process (i.e. the formation of clot) occurs.
Clots could form due to:

Inactivity of certain body parts (especially legs), which are absolutely motionless during a long flight journey, could be a potential cause for developing a DVT. This is because when the legs are motionless the leg muscles have to contract more in order to pump the blood from the legs to the heart and the valves have to prevent the retrograde flow of the blood. This takes more effort when the legs are absolutely motionless.

Hypercoagulation is one word in medical literature-

Hyper coagulation and surgeries are a couple of other factors which play a major role in the clot formation. In the case of hyper coagulation, the blood has the tendency to clot more than it is normally expected to. In the case of surgeries, the drugs given to the patient could sometimes alter the clotting factors of the blood. Again, hyper coagulation might occur either hereditarily or by the use of drugs.

Virchow’s Triad:

Rudolph Virchow recognized a triad which is immensely helpful in understanding the clotting system of the human body (Joseph, Edward and Robert 1948). The three factors that contribute to the development of the clot according to the triad of Virchow are (Anthonie, et al. 1999):

Venous stasis

Clotting Factors

Vessel damage
According to Virchow’s Triad there should be a presence of at least two of the three factors in the triad in order for a clot to develop. Virchow’s Triad has laid a path for the clinicians to develop methods that would reduce the clotting of blood (N. S. Wijeratne 2008).

2.2 Complications which might occur apart from a DVT:

Pulmonary Embolism: This is one of the more serious conditions that could occur due to the clots formed in the veins. This occurs when the clot in the blood veins happens to travel along with the blood stream into the heart and then into the lungs. After the clot reaches the lungs it gets deposited in a region of the lungs and makes that particular region of the lung ineffective by blocking the pulmonary artery. Pulmonary embolism is regarded as one of the most common causes of death after a surgery (Kakkar, et al. 1970).

Pulmonary embolism is serious enough to cause death in some of the cases. It causes death in over 100,000 patients each year in the United States and is also a main contributing factor in another 100,000. With this being said, PE might be the most preventable cause of death (especially after surgery) in hospitals (Clagett, Anderson Jr, et al., Prevention of venous Thromboembolism 1992) (Jerry and Wolfgang 2004). Some studies even concluded that the development of DVT and PE are very much interlinked. This was proven by an experiment which resulted in reduced PE with the decrease in the number of DVT (Janseen, et al. 1986).
Chronic Venous Insufficiency: Sometimes the clots formed in the venous valves become so strong that they can easily cause damage to the venous valves rendering them impotent. The damaged venous valves are unable to close properly; as a result, they are unable to carry on their function of eliminating the retrograde flow of the blood effectively: called Chronic Venous Insufficiency (CVI). The prevalence of CVI ranges from 2 to 7% in men and 3 to 7% in women (Abbade and Lastoria 2005).

Venous Ulcers: A venous ulcer is generally an ulcer (wound) which is irregularly shaped and which initially develops superficially, but has the potential to deepen, with well defined borders. These are usually caused due to an ill functioning venous valve, which can arise due to CVI. The venous ulcers are usually very difficult to heal and it is also a common problem in the adult population. The prevalence of venous ulcers ranges from 40 to 50% in males and from 50 to 55% in females (Abbade and Lastoria 2005).

Methods of diagnosing a DVT

Both DVT and PE show few specific symptoms and clinical diagnosis is insensitive and unreliable (Clagett, Anderson Jr, et al., Prevention of venous Thromboembolism 1992). The methods of diagnosing a DVT are of two major types called the invasive techniques and non invasive techniques. In the invasive techniques, an incision is made in order to get to the affected regions. This induces pain and other side effects while the non invasive technique requires no such process for the diagnosis because most of the noninvasive techniques involve imaging the affected area. A study stated that the help of non-invasive diagnostic tests have improved the diagnostic procedures of detecting a suspected DVT in patients (Philips, et al. 1995). A few of the diagnosis methods are discussed below (Eran and Edwin 1994),
Physical Examination: A physical examination is done on the legs; also the blood pressure is checked. This kind of test is not very effective for detecting a DVT but can be used as a screening test in order to determine if any further action is required.

Venography: In this test a dye is introduced into the deep vein, and the x-ray of the vein in which the dye is introduced is taken. The main reason for introducing the dye into the vein is that it makes that particular vein visible under the x-ray. Lower extremity contrast Venography was regarded as a gold standard for the diagnosis of DVT in early 90’s (M.M.W. Van and Ten 1994).

Duplex-Doppler ultrasound Examination: This has become the gold standard method for detecting clotting problems in the lower extremities. It is highly accurate, relatively inexpensive and does not use ionizing radiation.

Ultrasound examination: In this, a transducer is used to detect the clot in leg veins. The sound waves are passed through the veins where the clot is expected and outputs are analyzed to determine whether the clot exists.

D dimer blood test: This test is used to determine clotting factors of the blood. This is helpful for understanding the risks of an individual to be affected with a DVT.

Computerized tomography (CT) and magnetic resonance imaging (MRI) scanning:

CT and MRI Scanning: Both of these scanning reports provide pictures which will be helpful for detecting the clot.

Venous Occlusion Plethysmography (VOP) is a noninvasive technique widely used for the detection of deep vein thrombosis. The presence of major venous outflow obstruction is determined by comparing the rate of venous outflow with the maximum calf volume change.

Apart from these techniques there are several other techniques in the present day to test for a DVT.
Studies on pregnant women and their relative risk of venous thromboembolism (Heit, et al. 2005): A population based study in Olmsted County, Minnesota was conducted to study the incidence of venous thromboembolism in pregnant women. The study showed that, 105 cases of DVT or PE were identified in women who were either pregnant or women who were in the postpartum period. These figures were said to be 4 times higher than the expected number of DVT and PEs found in women who were not pregnant. It was also determined that the overall incidence of venous thromboembolism was higher in postpartum period than during the pregnancy. Also the same study states that the incidence of venous thromboembolism in the general population is strongly and directly related to the increasing patient age.

2.3 Computational Studies:

Use of CFD as a tool to study the flow dynamics of the blood has been taking place recently; several studies on blood flow in arteries (David, Image-Based Computational Fluid Dynamics Modeling in Realistic Arterial geometries 2002), as well as analysis of lungs, etc. All these studies help in improving the prophylaxis given to the patient by explaining the flow physics in detail with the help of the simulations. Also, in some cases, patient specific models are being used to carefully analyze the physics involved. It can be said that CFD can be used as a useful noninvasive technique to diagnose the patients of DVT in the future.
One of the studies built a coupled momentum method for the blood flow in the arteries. In this study, the deformation of the artery along with the flow of the blood was studied. The model was created such that the flow of blood at each stroke of the heart came into the arteries at different flow pressures and different flow velocities. The flow inside the arteries for each stroke was studied along with the movement of the artery due to that flow (Alberto, et al. 2006).

The flow dynamics are important in the treatment of the patients with aneurysms (Nurullah, et al. 2005). These aneurysms develop due to the weakening of the valves and usually form balloon like bulges in the arteries. With the help of computational analysis, the blood flow dynamics of these aneurysms can be better understood. A study used computational analysis as a tool for the treatment of cerebral aneurysms. The study used volumetric image data from which they created the lumen geometry. Also, the boundary conditions for the finite element CFD model where taken from the same data.

The analysis thus revealed that vortices were formed due to high velocities at the proximal and distal ends; thus producing elevated wall shear stresses along the sidewalls of the aneurysm. This study concluded that image based CFD analysis can be used to provide key information about the hemodynamics for future studies on aneurysm growth (David, Jaques, et al. 2003).
Computational analysis was also done on a human carotid arterial bifurcation. In this study, the pulsatile flow in human carotid bifurcation was simulated numerically (Juan, et al. 2002). They used non invasive techniques to determine the pressure and mass flow waveforms in these artery bifurcations. The mesh and the geometry of the model were created from the MRI angiograms of the carotid artery. The flow in the carotid arteries was induced primarily by the asymmetry and the curvature of the geometry, thus they carried out the flow simulations by assuming the walls to be rigid. One of the main assumptions that were made in this study was that fluid blood was considered a Newtonian fluid. The results of the analysis showed that, the magnitude of the wall shear stress varied with the location and the cardiac cycle. It also showed that there were regions of low wall shear stress (Zaho, et al. 2000).

The main reasons for using the computational analysis over other conventional techniques are: computational analysis facilitates a detailed understanding of the flow physics involved by solving the flow equations computationally. Also, the conditions can be changed and the results can be analyzed using the computational softwares, which cannot be done physically because it is difficult to predict lot of parameters physically.

If there are any changes to be done in a system, computational analysis can exactly show whether the changes done would be beneficial to the system or not. In other words, computational analysis could make the prophylaxis given to the patients be more efficient and even safer.
2.4 Blood Flow and Fluid Mechanics

Fluids are broadly classified into two main types, namely Newtonian Fluids and Non-Newtonian Fluids. The Newtonian Fluids are the fluids which exhibit a linear relation between stress and strain, hence the dynamic viscosity coefficient of a Newtonian fluid is independent of time or strain measured from any reference state. The fluids in which the relation between the stress and strain is complex are called Non-Newtonian Fluids (James 2006) (N. S. Wijeratne 2008). Blood is considered to be a Non-Newtonian fluid.

The fluid flow through pipes or tubes is of interest due to its similarity to that of fluid flow in veins, arteries, bronchial air ways, vocal cords, etc. Fluid flow is classified into two types based on its behavior. The two types of flows are laminar flow and turbulent flow. The word laminar comes from the movement of adjacent fluid particles together in “laminae” (N. S. Wijeratne 2008) (John and Yunus 2008).

Laminar flow, otherwise called a streamline flow, is the flow in which the particles of fluid flow from a zero velocity at the walls to the maximum velocity in the axial stream (Helps and McDonald 1954). The particles in the laminar flow move in a well defined path and are predictable. In turbulent flows, the particles of the fluid follow a random path. One can observe the mixing of the fluid particles, especially in cases with higher velocities. A flow that alternates between laminar and turbulent flows is called transitional flow.

The turbulences or the vertices in the blood flow are said to play a very decisive role in the development of clots. Some turbulence is found usually at the junction of smaller veins and larger veins or even at the junction of veins of equal diameters.
When there is an obstacle in the fluid flow – three eddies, one in the front and two behind the obstacle will be formed. Also a collapsed behavior of the flow is observed when an external pressure is applied to the veins.

There is lot of similarity between fluid flow through the collapsible channels and the flow of fluid (blood) in the veins. The collapsed behavior can be seen in the flow in veins when an external pressure is applied to the fluid flow in veins (Wijeratne and Hoo 2006). Total irreversible collapse of the system may occur if there is any malfunctioning in the valves, or there are clots (thrombi) in the vessels. The knowledge of the flow physics involved in the venous valve could provide a key to an improved clinical treatment and to the future of designing and developing artificial valves (Yuchen, et al. 1995).
Chapter 3: Methodology

This Chapter discusses in detail about the steps involved in modeling the problem and also about the various equations which the softwares solve for developing the flow in the model. It also focuses in detail about the meshes created, solvers used, boundary conditions applied and the results being captured.

3.1 Measurements of Deep Veins:

To get the dimensions of a human vein, the vein was cut longitudinally at the junction where the two leaflets intersect at the vein wall and was kept beside a scale to get the measurements. These measurements where used to approximate the distances at each points and also the distances between the vein valves when the valves where at different positions. The dimensions which were thus measured and approximated were incorporated in the model.
Based on the above diagram the dimensions of the veins are estimated and the model is created. The co-ordinates are created, which are then connected with the help of lines and curves wherever required. A 2-d model was first created which resembles the above picture in dimensions. The position of the valve was estimated and different models were created for each position of the valves right from the valves at the fully open position to the valves almost trying to close.

Each of the case (different position of the distance between the valves) is meshed based on the complexity of the geometry. A boundary layer is added at the valves in order to capture the flow physics at the valves more effectively. Similarly a finer mesh is obtained at the areas in between the valves and a coarser mesh is made at the entrance and the exit region. An extension channel was added at the top and the bottom. The reason for doing this at the bottom was to ensure that the flow is fully developed before it enters into the model and at the top was to eradicate any possible reverse flows and ensure that the flow flows out of the system.

3.2 Boundary Conditions:
The gambit preprocessor software is the tool used to create the geometry and also to create the mesh (grid) for each case. The lower boundary or the line from which the fluid is desired to be entering the model is determined to be the velocity inlet of the model. The top boundary or the top line is the boundary from which the fluid leaves the model; hence it is determined to be the outlet. All the remaining regions of the model are assigned to be walls.

The model thus created has assigned velocity inlet, walls and the pressure outlet using the gambit preprocessor. However the values of the velocities and pressure at the boundaries are assigned using the fluent solver.
The fluid is considered to be entering from the bottom boundary with a velocity of 0.25 m/s. Hence the bottom boundary is given an inlet velocity of 0.25 m/s in the Y-direction.

All the interiors are not having any fluid velocity, hence the interior parts, i.e. the walls and the valves of the veins are considered as walls or in other words a no-slip (velocity zero in both X and Y-directions) boundary condition is applied.

Also the fluid coming into the model is desired to exit with zero pressure, hence the outlet i.e. the top boundary is applied with zero pressure outlet boundary condition.

The boundary conditions are assigned (to tell the system where the inlet or outlet is or where the walls are) using gambit after the completion of desired grid generation. This ensures that the solver knows where exactly the inlet, outlet and the walls of the system are before the solver initializes. The specific values of the velocities or pressures are assigned when setting up the problem in fluent solver.

Grids or Meshes Generated: Grid/mesh generation is one of the most important step in the analysis procedure. The mesh intensity is based upon the detail required at particular regions and the physics involved. The meshed are usually quadrilateral, triangle or a combination of both. Triangular elements have been used to generate the meshes for our models.
A total of 24 cases were made each at a different positioning of the valves with case 1 starting at the fully opened position to the case 24 in which the valves are almost about to close. A finer mesh is desired in the areas in between the valves and a coarser mesh is needed in the other regions. We have also added an extension channel to the top and the bottom of the model and to mesh these regions triangle elements were used as well, these elements coarse as there is no significant change occurring in the flow physics. A coarse mesh in such areas where the flow field is not significant helps us in reducing the computation time.

Figure 5: Grid or mesh generated for one of the cases
The above figure shows how a combination of fine and coarse elements is used in order to reduce the computation time. Also it shows the meshed extension channels and fine boundary layer elements used at the walls i.e. the valves.

One can find that a finer mesh is obtained at the areas of the valves and a coarser mesh is obtained at the extension channels, and by closer inspection we can see that the area in between the valves is given more focus by having more elements between the valves and in the pockets. The fine boundary layer elements at the valves help us to get the detail of the physics involved when fluid passes near the walls.

### 3.3 Governing Equations:

Fluid Dynamics (FD): Fluid dynamics is governed by the conservation of mass (or continuity; equation (2)) and momentum (equation (1)) principles. With continuum and incompressible fluid approximations, these principles result in partial differential equations (PDEs) and popularly known as Navier-Stokes equations (V 2005).

Let \( \Omega_t \subset R^{n_{sd}} \) be the spatial domain with boundary \( \Gamma_t \) at any instant of time \( t \in (0, T) \) where \( n_{sd} \) is the number of spatial dimensions (= 4 for 3D incompressible fluid i.e. pressure and three components of velocity vectors) and \( T \) is the total time of computations. The spatial coordinates and time are denoted by \( x \) and \( t \), respectively.

\[
\rho \left( \frac{\partial u}{\partial t} + u \cdot \nabla u - f \right) - \nabla \cdot \sigma = 0 \quad \text{on} \quad \Omega_t \quad \forall \ t \in (0, T),
\]

EQN(1)
The Navier-Stokes equations of incompressible flows are:

\[ \nabla \cdot \mathbf{u} = 0 \text{ on } \Omega_t \quad \forall \ t \in (0, T) \]  

EQN(2)

Where \( \rho, \mathbf{u} \) and \( \mathbf{f} \) are the density (constant for incompressible flows), velocity, and the external force, respectively. With \( \mathbf{I} \) as the identity matrix, the stress tensor is related to the pressure (\( p \)) and shear stress tensor (\( \tau \)) by:

\[ \sigma(\rho, \mathbf{u}) = -p\mathbf{I} + \tau \]  

EQN(3)

The shear stress (\( \tau \)) for incompressible fluids is given by:

\[ \tau = \begin{cases} 2\mu\dot{\varepsilon} & \text{for Newtonian fluids i.e. } \mu = \text{constant} \\ 2\mu(\dot{\varepsilon})\dot{\varepsilon} & \text{for non-Newtonian fluids i.e. viscosity depends on } \dot{\varepsilon} \end{cases} \]

Where strain rate tensor (\( \dot{\varepsilon} \)) of fluid is given by:

\[ \dot{\varepsilon}(\mathbf{u}) = \frac{1}{2} \left( (\nabla \mathbf{u}) + (\nabla \mathbf{u})^T \right) \]  

EQN(4)
Various relationships for the viscosity approximation have reported in the literatures for the non-Newtonian fluids (e.g. “power-law” model – Ostwald & deWaele, Carreau-Yasuda model, Bingham model, Casson model, etc.). In order to solve the equations (1) & (2), we require both Dirichlet - \( u = g \) on \( \Gamma_g \), e.g. at the surface of arteries where velocities are prescribed by the deformation of the arteries) and Neumann – \( n \sigma = h \) on \( \Gamma_h \), e.g. inlet and outlet where stress free conditions are good approximations) boundary conditions (BCs) along with initial conditions \( u(x, t = 0) = u_0(x) \).

Problem definition and parameters: The deep veins of the human body are modeled and solved for the fluid equations in order to better understand the flow physics involved in the deep veins. The main focus is laid on the velocity distribution and the pressure variations in order to learn about the pressure differences occurring and also to see the flow recirculation’s in the velocity vector profiles. Emphasis is laid flow occurring in the two pockets and the area between the two valves.

A two dimensional double precision solver is used in fluent in order to solve the flow equations. The energy equation is turned off, so we are not going to be solving the energy equation because we have no interest in the temperature of the flow.

The power law has been used in the model and the following values were assigned (Svelta, et al. 2003):

Power law index \( (n) = 0.4851 \)

Consistency index \( k=0.2073 \) kg-s^n-2/m

Reference temperature=310K
Minimum viscosity limit=0.00125 kg/m-s

Maximum viscosity limit=0.003 kg/m-s.

Each case is run for 500 time dependent iterations with a time step of 0.01 seconds and each time step is run for 20 iterations. We were able to get converged results for flows in all the cases in 2d models. The results of these models are discussed in the following chapter.
Chapter 4: Results and Discussions

This Chapter discusses about the physics captured by creating the vein models and running the simulations using fluent solver. It mainly focuses on the velocity profiles and the pressure contours and tries to justify about the velocity and pressure profiles.

A two dimensional computational analysis is done on the deep veins. The cases are named from case1 to case 27 where the valves are very close to each other. The velocity profiles, the pressure contours, the velocity vectors and the plot of velocity vectors colored by pressure for each case are captured and a table was created for each of them. These tables give us an interface to see how each of the character varies with the cases. In the velocity profiles, the dark red color represents the maximum value of velocity while the dark ink blue kind of color represents the minimum value of the velocities which is zero in most of the cases. A more detail of the exact values can be found in the appendix where in the scale with exact values is shown for each of the cases. Similarly the colors in the pressure contours in red represent the high pressures and the ones represented by the blue color pertain to the low values of the pressure. The values of the contours vary with red being the maximum followed by orange, yellow, green and blue being the minimum for both velocities and pressures, also the respective values of the colors are shown beside them. The color bars (colored scales) seen beside the velocity contours are in meters per second and the ones next to the pressure contours are in Pascal’s.
4.1 2D model results:

Velocity Contours:

Table 1: Scaled Velocity Contours plotted for four cases
The above table shows the contours of the velocity and pressure within a fixed range, this helps us see the variation in the velocities and pressures from one case to the other. We can see the maximum value of the velocity in case 16 and as we go on to case 24 we find a white region which shows that the velocity in case 24 is out of bound i.e. more than the maximum velocity. This illustrates that the velocity increases as we move from case 1 to case 24 due to the decrease in the area between the valves.

One can see the light blue region developing as we progress from case 1 and case 8, into red which is maximum at case 16 and finally to white in case 24 which is out of the scaled range. Also an important thing to be observed in these cases is even though the maximum velocity changes drastically from case 1 to case 24, the pockets (or the regions between the valves and the walls) have zero velocity almost irrespective of the cases.
Pressure Contours:

Table 2: Scaled Pressure Contours plotted for 4 cases

<table>
<thead>
<tr>
<th>Scaled Pressure Contours</th>
<th>Case-1</th>
<th>Case-8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.55e+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.30e+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.04e+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.92e-01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.40e-01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.87e-01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.50e-02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-2.16e-01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-4.70e-01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-7.23e-01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-9.75e-01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-1.23e+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-1.68e+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-1.73e+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-1.98e+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-2.24e+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-2.49e+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-2.74e+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-2.99e+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-3.26e+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-3.50e+00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scaled Pressure Contours</th>
<th>Case-16</th>
<th>Case-24</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The pressure contours plotted the variation of the pressures from one case to the other and also the pressure difference between the regions above and below the valves. As we see the pressure varies a lot from one case to the other, one important observation made is that the pressure behind the valves increases as the area between the valves decreases, hence we see a white region which is out of the plotted scale in case 24.

Graphs plotted based on 2d results:

A line was made from the center of the valves to the veins walls, and the velocity values on that line where plotted with respect to the position. A total of seven cases where picked and the velocities on the line joining the center and the vein walls were plotted for each of the cases, and a graph was plotted.

Figure 6: Velocity vs. Position at the center
In order to better understand the velocities in the pocket, the velocities and the pressures on the line plotted on the pockets were obtained.

The above graph shows that the velocity in the regions of the pockets always tends to reduce, also as the area between the valves decreases the velocity tends to further decrease in these pockets. Also not only is there an initial decrease in the velocities from case to case but also we can see that the velocities are further decreasing as we progress towards the vein valves.

Figure 7: Velocity vs. Position in the pockets
Similarly the pressures were plotted for all the cases at the center and in the pockets.

Figure 8: Pressure vs. position at the center

Figure 9: Pressure vs. position in the pocket
The graphs show that the pressure is always positive or zero in most of the cases in the center and increases when the valves are coming closer to each other, but on the other hand, in the pockets the pressure is always negative (with respect to atmosphere) and tends to drop excessively as the valves approach each other. One can predict that it is this pressure difference in the pressures between the two regions which makes the valves function.
4.2 3D analysis:

Velocity Contours:

Table 3: Scaled velocity contours of 3d cases

<table>
<thead>
<tr>
<th>Velocity Contours</th>
<th>Case-2</th>
<th>Case-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.18e+00</td>
<td><img src="Case-2" alt="Image" /></td>
<td><img src="Case-5" alt="Image" /></td>
</tr>
<tr>
<td>2.05e+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.94e+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.84e+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.73e+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.62e+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.51e+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.40e+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.30e+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.20e+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.09e+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.72e-01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.64e-01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.56e-01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.48e-01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.40e-01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.32e-01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.24e-01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.16e-01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.08e-01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00e+00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
A total of eight cases where constructed similarly in 3d and the fully developed velocity profiles for each of the cases are captured. The above table shows the scaled velocity which is same as the velocity range in the 2d cases and even the 3d cases show similar kind of behavior as we can see the flow to be developing into the maximum range as we move from case 2 to case 9.

The bottom picture for each of the cases shows the plane which is cut in the centre of the model and velocity contours are plotted on that plane, these picture show the top view and show a new prospective of area between the valves. In both 2D and 3D the velocities and pressures exhibit same kind of features. The reason for selecting a scaling range is to see how the maximum values develop as the valves try to close.
Pressure Contours:

Table 4: Scaled Pressure Contours of 3d cases
The scaled pressure contours of 3d cases show the variation of pressure on a scale which is the same as the one shown in the 2d cases, this shows that the pressure variations in each cases. The contours were taken on two planes which are perpendicular to each other.

The pressure builds up gradually as we move from case1 to case9; the values show that maximum pressure is seen in case 9. Also the pressure in the regions above the valves in the pockets is mostly negative.
Chapter 5: Conclusions

We observe that the larger the opening of the venous valve, the smaller the flow acceleration through the valve. Vortices are formed after crossing the valves at different places for each different position of the valves. The round blue regions are the ones where the flow is recirculating. This can also be seen in the velocity profile as we see the vectors forming a circular profile in these regions.

Irrespective of the area between the valves (cases), there are significant amount of particles which are at zero velocity, this shows us that the possibility of these stagnant velocity particles is very high making them susceptible to clot formation.

We believe that the areas where vortices are trapped in the pockets with low velocities or the areas with almost stagnant velocities are more susceptible to clot formation. These areas are mainly the areas between vein valves and the vein wall.

One can observe that the pressures in the regions behind the valves and in the regions of the pockets are never the same (in most of the cases the pressures are maximum at the bottom and almost negative in the pockets); it is this pressure difference between the two regions which allows the blood to flow and the valves to open when the muscles contract and squeeze the veins.
We can observe that there is always a pressure being build up in the regions behind the valves, this is due to the reducing area between the valves, but if observed carefully we can see that the variations of pressure is more at the regions nearing the tips of the valves. One can say that it is these pressure variations, which intern are the cause of fluttering kind of phenomena seen in the valves when there is blood flowing through them.
Chapter 6: Future Work

An experiment is being set up at the lab, in order to measure velocities and pressures of the venous valves. Experimental subjects with different geometries will be used in the place of veins, the setup simulates flow environment of the deep veins. Cameras are going to be used to capture the motion of the particles which will in turn be illuminated by the Particle Image Velocimetry (PIV) system. A motor is used to pump the fluid to the system and pressure transducers are going to be used to measure the drops in pressure of the experimental subjects. Glycerin and sodium chloride solutions are going to be used as the experimental fluid, because of their physical properties.

Figure 10: Experimental setup being installed
Bibliography

Bader, Hermann. "The Anatomy and physiology of the vascular wall." In Handbook of Physiology – circulationII.


Appendix

Case 1:

Figure 11: Velocity and Pressure Contours (case 1)

Figure 12: Velocity Vectors Colored by Pressure (case 1)
Case2:

Figure 13: Velocity and pressure contours (case2)

Figure 14: Velocity vectors colored with Pressure (case2)
Case 3:

Figure 15: Velocity Vectors Colored by Pressure (case3)

Figure 16: Velocity vectors colored with Pressure (case3)
Case4:

Figure 17: Velocity and Pressure Contours (case4)

Figure 18: Velocity vectors colored with Pressure (case4)
Case 5:

Figure 19: Velocity and Pressure Contours (case 5)

Figure 20: Velocity vectors colored with Pressure (case 5)
Case 6:

Figure 21: Velocity and Pressure Contours (case 6)

Figure 22: Velocity vectors colored with Pressure (case 6)
Case7:

Figure 23: Velocity and Pressure Contours (case7)

Figure 24: Velocity vectors colored with Pressure (case7)
Case 8:

Figure 25: Velocity and Pressure Contours (case8)

Figure 26: Velocity vectors colored with Pressure (case8)
Case9:

Figure 27: Velocity and Pressure Contours (case9)

Figure 28: Velocity vectors colored with Pressure (case9)
Figure 29: Velocity and Pressure Contours (case10)

Figure 30: Velocity vectors colored with Pressure (case10)
Case 11:

Figure 31: Velocity and Pressure Contours (case 11)

Figure 32: Velocity vectors colored with Pressure (case 11)
Case12:

Figure 33: Velocity and Pressure Contours (case12)

Figure 34: Velocity vectors colored with Pressure (case12)
Case13:

Figure 35: Velocity and Pressure Contours (case13)

Figure 36: Velocity vectors colored with Pressure (case13)
Case 14:

Figure 37: Velocity and Pressure Contours (case 14)

Figure 38: Velocity vectors colored with Pressure (case 14)
Case15:

Figure 39: Velocity and Pressure Contours (case15)

Figure 40: Velocity vectors colored with Pressure (case15)
Case16:

Figure 41: Velocity and Pressure Contours (case16)

Figure 42: Velocity vectors colored with Pressure (case16)
Case 17:

Figure 43: Velocity and Pressure Contours (case17)

Figure 44: Velocity vectors colored with Pressure (case17)
Case 18:

Figure 45: Velocity and Pressure Contours (case18)

Figure 46: Velocity vectors colored with Pressure (case18)
Case19:

Figure 47: Velocity and Pressure Contours (case19)

Figure 48: Velocity vectors colored with Pressure (case19)
Case20:

Figure 49: Velocity and Pressure Contours (case20)

Figure 50: Velocity vectors colored with Pressure (case20)
Case21:

Figure 51: Velocity and Pressure Contours (case21)

Figure 52: Velocity vectors colored with Pressure (case21)
Case 22:

Figure 53: Velocity and Pressure Contours (case 22)

Figure 54: Velocity vectors colored with Pressure (case 22)
Case 23:

Figure 55: Velocity and Pressure Contours (case 23)

Figure 56: Velocity vectors colored with Pressure (case 23)
Case24:

Figure 57: Velocity and Pressure Contours (case24)

Figure 58: Velocity vectors colored with Pressure (case24)
CURRICULUM VITA

Upendra Parimi was born in Hyderabad, Andhra Pradesh, India. The only son of Raghuram Parimi and Lakshmi Kumari Rajanala, he graduated from St.Patrick’s High School, Hyderabad, India. He then entered Guru Nanak Engineering College and affiliation of Jawaharlal Nehru Technological University in September 2004 and earned his Bachelor of Technology degree in Mechanical Engineering. He then joined the graduate school at The University of Texas at El Paso (UTEP) to pursue his masters in Mechanical Engineering in Fall 2008, as a student at UTEP he got opportunity to research in the field of Computational Fluid Dynamics. He presented a poster at the 5th frontiers in biomedical conference held by American Society of Mechanical Engineers in September 2010.

Permanent Address: Plot no 135, Road no 1, Anantha Saraswathi nagar, East anandbagh, Malkajgiri, Hyderabad-500047, Andhra Pradesh, India.