Original Article

Numerical simulations of thrombosis

Abstract

Background: Mathematical approaches for biological events have gained significant importance in development of biomedical research. Deep vein thrombosis (DVT) is caused by blood clot in veins deeply rooted in the body, resulting in loss of blood, pain, and numbness of the body part associated with that vein. This situation can get complicated and can be fatal, when the blood clot travels to other parts of the body which may result in pulmonary embolism (PE). PE causes approximately 300,000 deaths annually in the United States alone. **Materials and Methods:** We are trying to propose a computational approach for understanding venous thrombosis using the theory of fluid mechanics. In our study, we are trying to establish a computational model that mimics the venous blood flow containing unidirectional venous valves and will be depicting the blood flow in the veins. We analyzed the flow patterns in veins, which are included with lump like substances. This lump like substances can be clots, tissue debris, collagen or even cholesterol. Our study will facilitate better understanding of the biophysical process in case of thrombosis. **Results:** The predicted model analyzes the consequences that occur due to the clot formations in veins. Knowledge of Navier–Stokes equations in fluid dynamics along with the computational model of a complex biological system would help in diagnosis of the problem at much faster rate of time. Valves of the deep veins are damaged as a result of DVT, with no valves to prevent deep system reflux, the hydrostatic venous pressure in the lower extremity increases dramatically. **Conclusion:** Our model is used to determine the effects of an interrupted blood flow as a result of thrombin formation, which might result in disturbed systemic circulation. Our results indicated a positive inverse correlation exists between clots and the flow velocity. This would support medical practitioners to recommend faster curing measures.

Key words:
Clots, collagen, pulmonary embolism, systemic circulation, thrombosis, vein

Introduction

Circulatory system is made up of the veins, arteries, capillaries, and muscles that control the blood flow around the body and supplies nutrients to the tissue. The heart is a muscular pump like organ, which regulates the entire blood circulatory system. There are four chambers, two ventricles and two atriums in the heart. The right and left sides are separated by septum, which helps to keep the oxygenated blood and deoxygenated blood separated. Heart also has valves, which distinguish the chambers and connect to the blood vessels.[1] Oxygenated blood come from pulmonary vein, and enters left atrium whereas all other veins in the circulatory system carry deoxygenated blood to the heart from the body tissue.[2] Then blood flows from left atrium to left ventricle; when ventricle is filled up with blood it contracts and blood exits through aorta. There is a valve in atrium and ventricle junction, which closes at this time and prevents the back flow of the blood into atrium. Aorta supply the oxygenated blood to all the branch arteries through systemic circulation and eventually oxygenated blood loses all its oxygen to the tissue and receives carbon dioxide from the cells and tissues. Two large veins names superior vena cava and inferior vena cava collects de-oxygenated blood from systemic circulation and brings to the right atrium of heart. Then the blood passes from right atrium to right ventricle through a one way valve. Eventually, the de-oxygenated blood is carried by pulmonary artery to the

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lung. Blood then returns from lung to the left side of heart after being oxygenated and cleansed of its carbon dioxide content. The circulation is a repeated event, controlled by the contraction and relaxation of heart.[3] The focus of this work is on the properties of vein and its flow regulations. Our present study is focused on blood flow in veins and its modulation during various pathologic conditions. Veins lack elastic property alike the arteries, but they do have valves which keep the blood from pooling and flowing to the reverse direction. Conditions like varicose vein are developed due to breaking down of valves, which appear as large purplish tubes in lower legs.[4]

Blood flow across the vasculature is regulated by pressure across branched network of blood vessels with varying diameters and lengths. The blood flow across the vessel varies with the conditions such as change in diameter or intra-vesicular thickness or formation of lump. Blood viscosity is a regulatory factor for smooth circulation of blood in a healthy body. Thrombin formation or blood clot is an inherent characteristic of blood to protect the person from continuous hemorrhage.[5] Rudolf Ludwig Karl Virchow postulated that damage of vessel wall, alteration in blood flow, and hypercoagulability of the blood are the prime reasons of thrombus formation. Physicians found different associative factors, which could form clots inside the veins leading to an obstruction in blood circulation through the affected veins. Such an obstruction will result into an inflammatory condition of the vein or thrombophlebitis.[6] When the blood clot losses down and travels through the blood flow, it can cause blockage in the pulmonary blood vessel which result into fatal pulmonary embolism (PE).[7]

Deep vein thrombosis (DVT) is a pathological situation caused by reduced or stagnant blood flow in deep veins, injury to blood vessel or even by an increase in the activity of those substances in the blood that are part of the normal clotting mechanism, a condition called hypercoagulability. Many other conditions associated with the previously stated factors, which can enhance the possibility of DVT are immobilization such as lying in bed following surgery, persons undergoing surgical procedure, persons having major trauma, malignancy, heart failure, and previous experience with thrombosis.[8] Many of the DVT cases produce no specific symptoms, but some of the common symptoms like swelling in legs, pain or tenderness in legs, which may occur while standing or walking, etc.

Diagnosis of a DVT can be done initially by clinical assessment. Different imaging methods such as contrast venography or ultrasonography are widely used for the detection of DVT. Early prevention of a thrombus formation can be achieved by several physical methods such as graduated compression stocking or intermittent pneumatic compression. In some cases, anticoagulant can be applied in low doses to dissolve the thrombus (e.g., low molecular weight heparin, Vitamin-K antagonist, etc).[9]

Epidemiology

Thrombosis involving the deep veins is one of the major health problems around the globe. It has been affecting more than 2.5 million people approximately each year just in United States alone.[10] The most serious complication of a DVT is PE, which is associated to about 50,000-300,000 deaths annually.[11] These problems are often complicated to detect by medical examination. It is important to understand that clinical examination includes attention to patient history, not just physical examination because DVT rarely occurs in the absence of risk factors. Several groups of patients have been identified to have high risk of developing thromboembolic disease.[12] People suffering from orthopedic or post-surgical complications are prone to develop thrombosis.[13]

Materials and Methods

Model study

Blood clots are usually formed at cuts or wounds. Thrombi formed in deep veins can cause a blockage of blood flow. These clots can prevent the functionality of the venous valves, which in turn forces the blood to flow in reverse direction. This further leads to the inflammation of the effected region. As DVT occurs mostly in legs, the elderly and pregnant women are the ones who are most prone to develop it.[14] DVT forms in the pockets located behind the venous valve leaflets, which further aggravates into larger clots that can break loose and form PE. Clots in these pockets can damage the leaflets resulting in inefficient valves.

The process of blood transformation into a clot is called coagulation. Wound formation leads to, a meshy fine thread like structure called fibrin, which is formed by thromboplastin, calcium ions and different blood clotting factors or procoagulants. Blood clots are counteracted by anticoagulants. This process of clotting is called hemostasis.[15] In the initiation phase, the concentration of thrombin tends to increase slowly and during the propagation phase, it activates platelets which in turn support the procoagulant reactions. It is this phase which plays a major role in the regulation of the clot formation. In termination phase, the hemostatic process occurs. DVT is an unlikely event where the blood clots inside the vein and prevents the blood to flow properly. It can be associated with the presence of tissue debris, collagen or fats in the veins which facilitates the coagulation process. Other possibilities include the reduction of naturally occurring anticoagulants in the blood due to a stagnant blood flow.

Virchow's triad

Rudolf Virchow recognized a triad which is immensely helpful in understanding the clotting system of the

human body.[16] The three factors that contribute to the development of the clot according to the triad of Virchow are venous stasis, clotting factors, and vessel damage.[17]

In Figure 1 of 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.[18]

Complications which might occur apart from a DVT *PE*

This is one of the more serious conditions that could occur due to the clots formation in veins. PE occurs when the clot in the veins travels along with the blood stream to 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. PE is regarded as one of the most common causes of death after a surgery.[19] 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 valves would not be able 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 2-7% in men to 3-7% in women.[20] A venous ulcer is generally an ulcer 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.[21]

Methods of diagnosing a DVT

Both DVT and PE show few specific symptoms and clinical diagnosis remain insensitive and unreliable.[22] The method for diagnosing the DVT is of two major types called the invasive techniques and noninvasive techniques. In the invasive techniques, an incision is made in order to get to the affected regions. Noninvasive techniques involve imaging the affected area. These techniques helped the diagnostic procedures for detecting a suspected DVT in patients.[23] Apart from the stated techniques there are other techniques to test a DVT[24] as mentioned below.

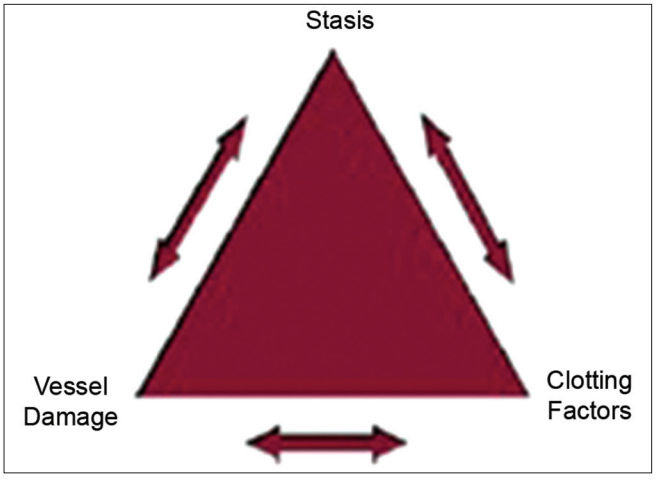

Figure 1: Factors that contribute to the development of the clot

Physical examination

A physical examination is carried out on the effected region; also the blood pressure is checked. This kind of test is not very effective for detecting a DVT, but is 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 is taken. The main reason for introducing the dye into the vein is to make it visible.[25]

Ultrasound examination

In this, a transducer is used to detect the clot in veins. The sound waves are passed through the veins where the clot is expected and outputs are analyzed.

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.

Computed tomography and magnetic resonance imaging scanning

These scanning reports provide pictures which will be helpful for detecting the clot.

Venous occlusion plethysmography

This is a noninvasive technique widely used for the detection of DVT. The presence of major venous outflow obstruction is determined by comparing the rate of venous outflow with the maximum calf volume change.[22]

Computational approach

We are proposing a new computational approach for diagnosing DVT, which can be more efficient and can have a greater impact for having better medical attention in the shorter time period. It is one of the fastest methods to determine the problem and it might be helpful in having a better diagnosing approach. This method helps us to identify the degree of obstruction in any specific vein.

Numerical approach

The purpose of the study is to understand the influence of coagulation in the flow of blood. This analysis of the blood flow is numerically based on Navier–Stokes equation on a two-dimensional (2D) model. It is important to solve a three-dimensional (3D) model for better accuracy, however, currently we employed a 2D model and perform

computation. We are trying to get solutions of this problem by intelligible model.

It is assumed that the fluid in veins is incompressible. In addition, blood exhibits complex characteristics; we simplified the model to handle numerical computation.[23]

A 2D Navier–Stokes equation is expressed in the following equations:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+u\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu\nabla^2 u \quad (1)$$

$$\frac{\partial u}{\partial t}+v\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\nu\nabla^2 u \quad (2)$$

$$\frac{\partial u}{\partial x}+\frac{\partial u}{\partial y}=0 \quad (3)$$

where u and v are velocities of fluid along x and y direction, ρ is density of a fluid, μ is a coefficient of viscosity, $\nu = \mu/\rho$ is a coefficient of kinematic viscosity, and P is pressure of a fluid. Equations of conservation of momentum and continuity are expressed in Eqs. 1-3.

$$u=\frac{\partial \psi}{\partial y} \quad (4)$$

$$v=-\frac{\partial \psi}{\partial x} \quad (5)$$

For a steady flow, we assume that the first term is 0.

$$v=\begin{pmatrix} u \\ v \end{pmatrix} \quad (6)$$

$$\frac{\partial v}{\partial t}+(v\cdot\nabla)v=-\frac{1}{\rho}\nabla P+\nu\nabla^2 u \quad (7)$$

where v is the velocity vector, which is representing Eqs. 1 and 2.

Calculation methods

Numerical analysis has been performed using these equations and the solution was comparatively stable. Initial values of velocity and pressure are obtained from an initial value of a flow function. We computed the velocity and pressure in the vein along with thrombus. Eq. 7 has been rewritten in the form of a difference equation.

$$\frac{v^{n+1}-v^n}{\Delta t}=-(v^n\cdot\nabla)v^n-\frac{1}{\rho}\nabla P^{(n+1)}+\nu\nabla^2 v^n \quad (8)$$

$$D^{(n+1)}=D^n+\Delta t(-(v^n\cdot\nabla)v^n-\frac{1}{\rho}\nabla P^{(n+1)}+\nu\nabla^2 D^n \quad (9)$$

Here, we define $D = \nabla\cdot v$, in this expression, we substitute $D\ (n)$, an original expression is treated as $D\ (n + 1) =0$. We can calculate pressure by solving Eq. 8.

$$\frac{1}{\rho}\nabla P^{n+1}=\frac{D^n}{\nabla(v^n\cdot\nabla)v^n+v\cdot\nabla^2 D^n-\Delta t} \quad (10)$$

If we substitute the pressure and speed in Eq. 8 and can get speed after Δt. We get pressure from Eq. 11 with a provided velocity.[26]

$$\frac{1}{\rho}\nabla P^{(n+1)}=\frac{D^n}{\nabla(v^n\cdot\nabla)v^n-\Delta t} \quad (11)$$

Computational approach

Computational fluid dynamics (CFD) is used as a tool to study the flow dynamics. Recently tremendous amount of research been taking place on various studies related to blood flow in veins, arteries, as well as analysis of lungs, etc. These studies help in improving the treatment approach given to the patient. It is very convenient in understanding flow physics when it is coupled with numerical simulations. It is supportive in context of patient specific models which are used to have a finer understanding of the problem for a particular patient. CFD can be used as a useful technique to diagnose problems which include, veins, arteries, and cardiac flow. 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.[27] The dynamics of the fluid flow plays an important role in the treatment for thrombosis.[28] The boundary conditions for the finite element CFD model are taken accordingly. The study interprets that image based CFD analysis can be used to provide key information about the hemodynamics.[29,30]

Blood flow and fluid mechanics

Fluids are generally Newtonian and non-Newtonian fluids. In Newtonian fluid the stress to strain rate curve is linear. The dynamic viscosity co-efficient 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 are not linear, that is, when they are non-linear or complex are termed as non-Newtonian fluids. Blood is considered to be a non-Newtonian fluid. The fluid flow through pipes or tubes has similarity to that of fluid flow in veins, arteries, bronchial air ways, vocal cords, etc. Fluid flow is classified into laminar flow and turbulent flow depending upon its behavior. 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.[31] The particles in the laminar flow move in a well-defined path. In turbulent flows, the particles of the fluid move in a random path. One can observe the mixing of the fluid particles, especially in cases with higher velocities. A flow that alternates in between laminar and turbulent flows is called transitional flow. The vertices in the blood flow are said to play a very vital role in the development of clots. Turbulence can be found usually at the junction of smaller veins and larger veins or even at the junction of veins of equal diameters. Collapsed behavior of the flow is observed when an external pressure is applied to the veins. There is a 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.[32] The knowledge of the flow physics involved can play a key role to improve clinical treatment and for future designing and developing artificial valves.[33]

Geometry and boundary conditions

The modeling of the described problem and the related equations have been discussed, which are used to solve the flow in the model. The main challenges involved in solving most of the fluid problems are boundary conditions that are applied and mesh size that is used and if its sufficient to accomplish the best possible result.

Measurements of deep veins

The dimensions of the veins are estimated and the 2D model is created. A finer mesh is used along the boundary of the occlusion and a coarser mesh is used in the areas where it was not exposed to any occlusion. The model has been created using the Gambit software. We have created different models for different conditions. Each model that has been used for analysis is different from other in terms of number of occlusions.

Boundary conditions

Gambit preprocessor is used to generate mesh for these models. The fluid being unidirectional, the boundary from where the fluid is entering the model is the velocity inlet of the model. The top boundary from which the fluid leaves the model is termed as the outlet for the model. All other regions of the model are assigned as walls and the model thus created has assigned velocity inlet, walls, and the outlet. 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 13.87 mm/s. Hence, the bottom boundary is given an inlet velocity of 13.87 mm/s in the positive *Y*-axis. The boundary conditions are assigned 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 values for velocity and pressure are assigned in fluent solver. Mesh generation is one of the most crucial and important process which needs to be done precisely during the analysis procedure. The mesh size depends upon the particularization a region and the flow dynamism is involved at that point of interest.

In the model inputs that, we considered for solving our model in FLUENT software, (which is ANSYS-FLUENT now) and with the triad mesh for meshing the domain are:

- Density: 1025 kg/m^3
- Reference temperature = 37°C
- Minimum viscosity limit = 0.0027 N-s/m^2
- Inlet velocity = 13.87 mm/s.

Governing equations

Incompressible flow equations in domains with moving deformable walls are mainly involved in fluid mechanics. These are differential and integral form of conservation laws. The equation for the 3D flows in one direction is:

$$\underbrace{\frac{\partial}{\partial t}\int_V \rho\phi\, dV}_{\text{Time Derative}} + \underbrace{\int_S \vec{U}\cdot\vec{n}\rho\phi\, dS}_{\text{Advection}} = \underbrace{\int_S \sum \vec{n}\, dS}_{\text{Diffusion}} + \underbrace{\int_V S_\phi\ \rho\, dV}_{\text{Source Term}} \quad (12)$$

The basic conservation laws can be summarized into a general equation. ϕ is the transport and $\vec{U} = \vec{v} - \vec{w}$ is the velocity of the fluid.

In the case of a fixed controlled volume $\vec{w} = 0$, the surface integrals are replaced by the volume integrals using the Green Gauss theorem. The conservation laws in differential form are obtained:

Continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla(\rho\,\vec{v}) = 0 \quad (13)$$

Momentum equation

$$\frac{\partial(\rho\vec{v})}{\partial t} + \nabla[\rho\,(\vec{v}\otimes\vec{u})] = \nabla\cdot\vec{\sigma} + \rho\,\vec{g} \quad (14)$$

Energy equation

$$\frac{\partial}{\partial t}\left[\rho\left(\frac{1}{2}v^2 + e\right)\right] + \nabla\cdot\left(\rho\left(\frac{1}{2}v^2 + e\right)\vec{v}\right) = \nabla\cdot(\vec{\sigma}\cdot\vec{v}) - \nabla\cdot\vec{q} + \rho\vec{g}\cdot\vec{v} \quad (15)$$

For Newtonian fluid behavior of the blood we use linear constitutive relation for incompressible fluid:

$$\vec{\sigma} = -\rho\, I + \mu\, D \quad (16)$$

where ρ is the static pressure and μ the Newtonian limit viscosity for the blood and $\vec{D}$ is the symmetric tensor of rate of deformation, which can be expressed by the tensor gradient of the velocity:

$$\vec{D} = \frac{1}{2}\left[\nabla\cdot\vec{v} + \nabla\cdot\vec{v}^{\,T}\right] \quad (17)$$

Unsteady compressible viscous flow equations are of hyperbolic-parabolic type. Incompressible flow equations are elliptic-parabolic type because of the elliptic character of the equation for pressure predication. The Navier–Stokes equation for an incompressible flow is more difficult to solve, due to their mixed character. For incompressible flows (ρ = constant), the equations of balance for mass and moment can be written in classical conservative form of incompressible Navier–Stokes equation:

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} + \alpha\,\frac{w}{z} = 0 \quad (18)$$

$$\rho\left[\frac{\partial u}{\partial t} + \frac{\partial}{\partial x}\left(u^2 + \frac{p}{\rho}\right) + \frac{\partial}{\partial z}(uw) + \alpha\cdot\frac{uw}{z}\right] = \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xz}}{\partial z} + \alpha\cdot\frac{\tau_{xz}}{z} \quad (19)$$

$$\rho\left[\frac{\partial w}{\partial t}+\frac{\partial}{\partial x}(uw)+\frac{\partial}{\partial z}\left(w^2+\frac{p}{\rho}\right)+\alpha\cdot\frac{w^2}{z}\right]=\frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \tau_{zz}}{\partial z}+\alpha\cdot\frac{\tau_{zz}-\tau_{\phi\phi}}{z} \quad (20)$$

Eqs. 18-20 consists complete system of equations for $\bar{v}$, P and can be solved independently from the energy equation. Where $\bar{v}=(u,w)$ is the velocity vector in is Cartesian coordinates system.[30]

The shear stress (τ) for incompressible fluids is given by

$$\tau=\begin{cases}2\mu\dot{\varepsilon} \text{ for Newtonnian fluids, i.e., } \mu=\text{constant}\\ 2\mu(\dot{\varepsilon})\dot{\varepsilon} \text{ for non-Newtonnian fluids,}\\ \text{i.e., viscosity depends on } \dot{\varepsilon}\end{cases} \quad (21)$$

where strain rate tensor $\dot{\varepsilon}$ of fluid is given by

$$\dot{\varepsilon}(u)=\frac{1}{2}\left((\nabla u)+(\nabla u)^{T}\right) \quad (22)$$

Various relationships for the viscosity approximation have reported in the literatures for the non-Newtonian fluids such as power-law model, Carreau Yasuda model, Bingham model, and Casson model. In order to solve the above equations, we require both Dirichlet ($u = g$), for example, at the surface of arteries where velocities are prescribed by the deformation of the arteries and Neumann ($n\cdot\sigma = h$), for example, inlet and outlet where stress free conditions are good approximations boundary conditions along initial conditions ($u(x, t = 0) = u_0(x)$).[31]

Results and Discussion

We have created 2D computational models mimicking a vein and we incorporated different occlusion bodies inside this artificial venular structure. These occasions are representative of blood clot or thrombus as it is seen in a DVT. The aim of this work is to manipulate the conditions which are responsible for DVT and hence obtain different outcomes in form of flow rate or outlet pressure inside a blood vessel.

Panel A is showing the formation of a vein like structure, which is incorporated with several blood clots across its length in Figure 2. Our computations are carried out using this frame work and therefore, we could modify the degree of obstructions and could get different resultant force as an output. Panel B and panel C is showing the pressure and velocity contour across the total length of the vein. The different colors along the bar represent the effect of the flow caused by the velocity and the pressure at that particular point of location.

This situation can be represented as an early stage of venous thrombosis and therefore the condition could be reversed using physical or early clinical manipulations.

In Figure 2, help in understanding the model represents the vein with fewer clots. The first model (a) represents the geometric model with the fine mesh and the flow acting from bottom to top. The model (b) represents pressure contours for the prescribed flow and model (c) represents the velocity contours.

In Figure 3, we are increasing the degree of occlusions inside the vein by 100% and measuring the resultant force. As the concentration of the clots is increasing, the amount of pressure is also mounting at the particular point, which might result in greater pain for the patient.

We are representing the model in Figure 4 with an 50% increase of clots to model in Figure 3, in comparison to see the effects of pressure and velocity contours.

We was increasing the clots by one-third with the total number with respect to the earlier plot in Figure 5. Figures 4 and 5 are just continuation of Figures 1 and 2, where we have increased the load of blood clots. Increased blood clot formation, could impair the complete blood flow in the respective vein

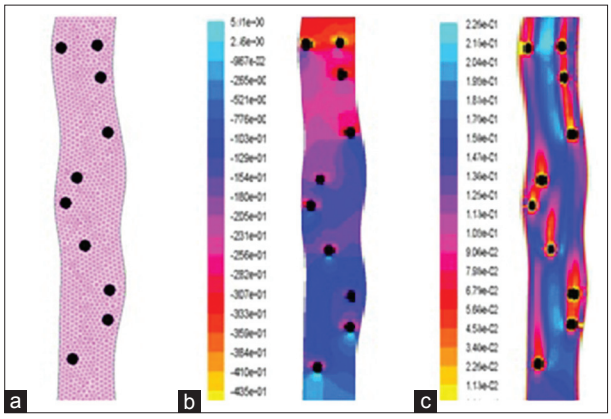

Figure 2: Model representation the vein with fewer clots (a) Geomentry and mesh, (b) Pressure, (c) Velocity

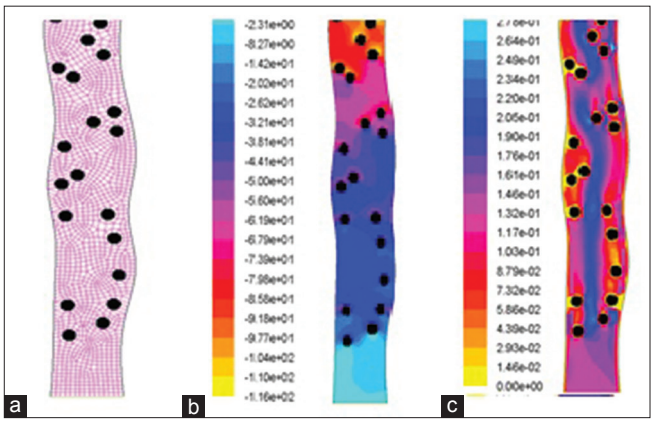

Figure 3: Model representing the vein with 100% increase of clots to model in Figure 2 (a) Geomentry and mesh, (b) Pressure, (c) Velocity

resulting in numbness or even partial paralysis of the organ. This kind of situation can also be responsible for PE which could result into death of the patient.

Figure 6 shows the results obtained from Figures 2-5 in a graphical pattern. In each plot the *X*-axis is representing the position point on the vein (mm) and *Y*-axis representing velocity (mm/s). Panels A-D show the simulation result obtained from Figures 1-4. The plots indicated a positive inverse correlation exists between point distances from the clots to the flow velocity.

We have the different plots representing sign distance influence on the velocity from point distance in vein, which shows the way it behaves at different points with time [Figure 6].

Conclusion

Increased thrombi formation in a deep vein can cause an interrupted blood flow. Our computational model could mimic a DVT like condition *in silico* and provides us with the liberty of manipulating the intensity of blood clots. The purpose was to explore the effects of minimal and maximal clot formation on the flow as well as on the venular blood pressure. The computational modeling and its simulations

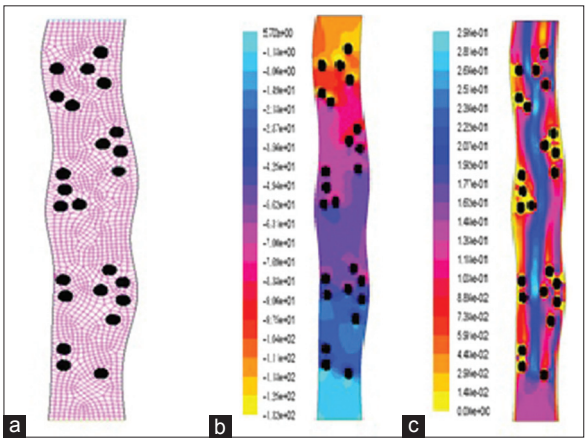

Figure 4: Model representing the vein with 50% increase of clots to model in Figure 3 (a) Geomentry and mesh, (b) Pressure, (c) Velocity

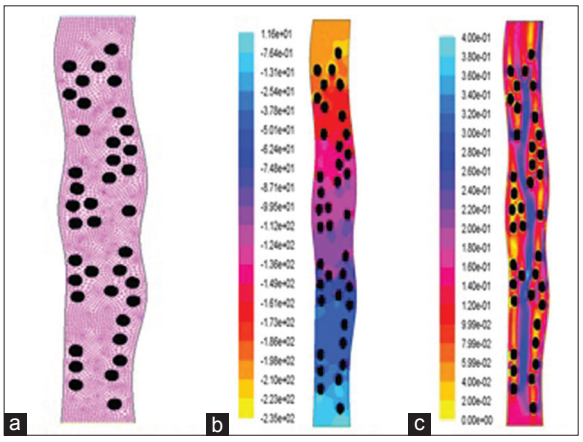

Figure 5: Model representing the vein with 33% increase of clots to model in Figure 4 (a) Geomentry and mesh, (b) Pressure, (c) Velocity

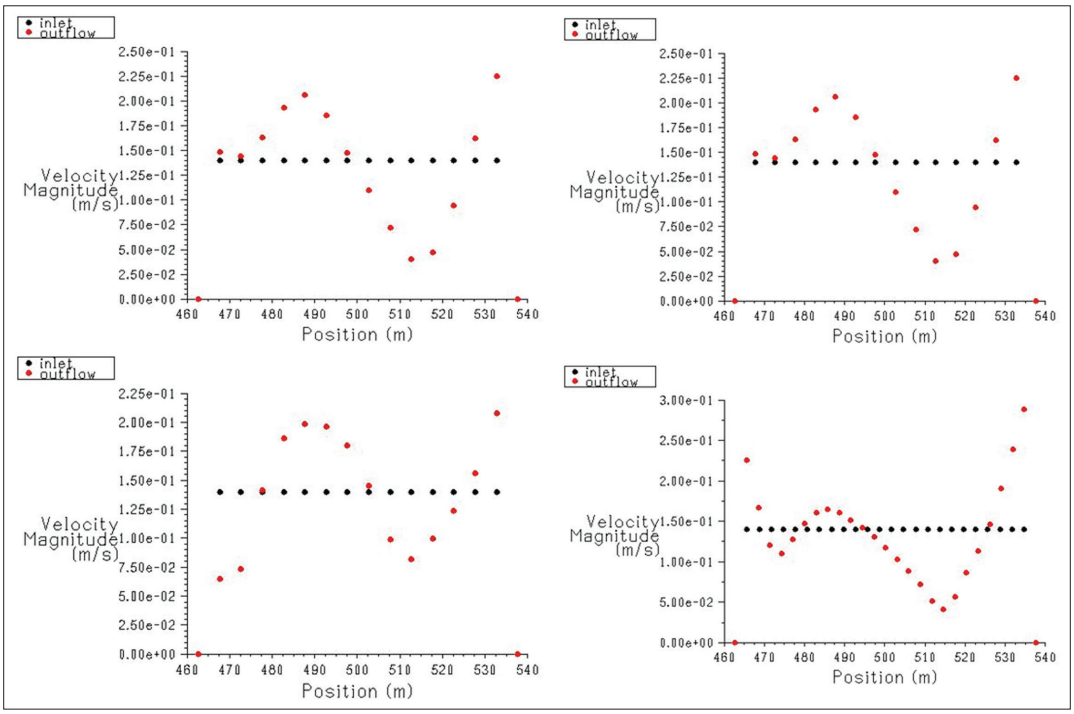

Figure 6: Plots representing sign distance influence on the velocity from point distance in vein

are very convenient method to understand the mechanics associated with the DVT. The better understanding of the aftereffects of clot formation would enable the physicians and the scientists to take a better preventive measure.

We believe that, our predicted model can be helpful to diagnosis. The present model is comprised of basic characters of a vein, whereas we can apply more inputs such as gender and age to make the model more logical and less error prone.

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