Vein mechanism simulation study for deep vein thrombosis early diagnosis using cfd

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Abstract. Using a Computational Fluid Dynamics (CFD) technique, this work focus on the analysis of pressure, velocity, and vorticity of blood flow along the popliteal vein. Since the study of early stage of Deep Vein Thrombosis (DVT) becomes essential to prevent the pulmonary embolism (PE), those three parameters are analysed to assess the effect of different opening between two valves of a normal popliteal vein. When only one valve is simulated, the result of pressure shows that the highest and lowest velocities are 15.45 cm/s and 0.73 cm/s, respectively. From the visualization of observed data, however, the different size of orifice between the first and second valves influencing the velocity and vorticity of the blood flow. The rotational motion of blood particle at the same region increases the probability of blood accumulating which is associated with the development of thrombus. Thus, a series of experiment has been conducted by changing the size of valve orifice for the first and second valves along the vein distribution. The result of the CFD simulation shows a significant variation in blood flow in terms of velocity and vorticity.

1. Introduction

Coagulation of blood in vessel system could lead to heart attack and other cardiovascular disease such as coronary thrombosis, deep vein thrombosis (DVT), pulmonary embolism (PE) and in the worst case is death [1]. DVT is a condition when accumulation of blood or thrombus is attached on the vessel wall which could prevent the movement of blood along the vessel system. Since the probability of thrombus initiates is along the popliteal vein, thus, this work will focus on the site around the valve area. Veins contain valves to prevent the backflow of blood toward the capillary beds. Dysfunctional of valves will lead to obstruction of blood circulation, thus, this could effects the tissue dysfunctional to whole body. Previous *in vitro* study demonstrates the blood progress of antegrade stream on valve geometry, material properties of the vein, and venous valve [1, 2]. Moreover, it is reported that the dramatic change of the three dimensional velocity profile of blood is due to the shape and size of the orifice [3]. Since there were no studies that investigate the valve aperture orientation in relation to blood flow dynamic, this study is performed to address and visualize the asynchronization between two valves in a popliteal vein.

Conventional advanced computational fluid dynamics (CFD) allows complex numerical reenactment of the cardiovascular framework. CFD investigations have been utilized to assess particular parameters in the body such as wall shear stress, velocity of blood flow in vessel stream and pressure of the blood against the wall of the vessel which have complexity to obtain from the *in vivo* experiment [4]. This work employs the CFD technology, a three-dimensional simulation of blood flow in a venous vessel. The model of the vein structure is then, implemented into ANSYS's CFX software package. Two study cases are performed that control the valves orifice size. The effect of the irregularities in the blood flow will cause valve insufficiency which lead to various disease related to venous vessel such as heart attack, and pulmonary embolism.

2. Methodology

As the objective is to simulate the vein mechanism, the geometrical structure of the popliteal vein needs to be constructed. The image of a popliteal vein is generated from medical imaging equipment model TOSHIBA SSA-580A. The image is extracted from Epiphan DVI2 USB 3.0 which is capable of recording a video at 60 frames per second (fps).

2.1. Valve and Vein Structure

Figure 1 shows the ultrasound B-mode image obtained from the medical imaging equipment. The position of the valve in the popliteal vein could be visualized. By employing the canny-edge detection method, figure 2 shows the clearly edges which could determine the size of the vein and valve [5]. Thus, in the SolidWorks reconstruction image, the length of the vein is set to 10 cm as shown in figure 3. Since this study is focusing on the size of leaflets or valve aperture, therefore the structure of the vein was assumed to be in a cylindrical shape. A pair of leaflets attached at a point of vein wall and the red arrow shows the direction of blood flow. Since valve are reliably situated at particular area in the veins, they are normally present in pairs 3-5 cm separated from one another [3]. Furthermore, it is reported that the leaflets position is fix, thus, *a* represents the size of leaflets opening where in this study it will vary from 30% to 70%. In addition, the maximum leaflets opening is 60-70% of the vein diameter [3].

Figure 1. B-mode ultrasound image of popliteal vein

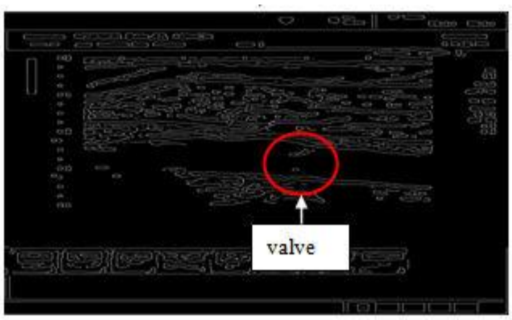

Figure 2. Canny-edge-detection-image of popliteal vein

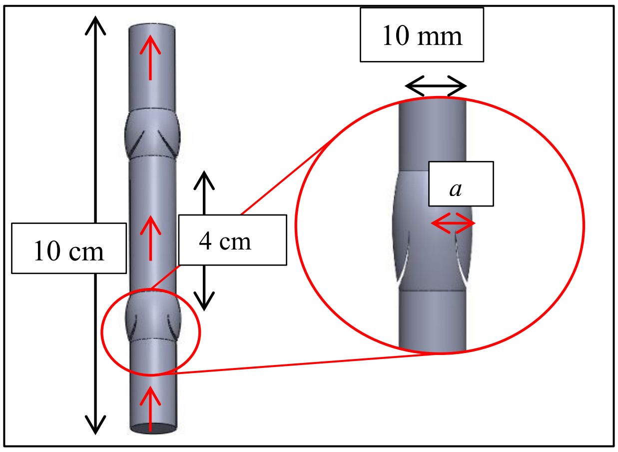

Figure 3. The geometrical structure of popliteal vein

2.2. Designing Popliteal Vein Structure

For the initial step, the boundary condition of the model has to be defined including flow rate, velocity and pressure of the inlet and outlet of the vessel model [6]. Based on the geometrical structure of the vein, a triangle meshes were generated to obtain the optimum grid size for the model. The meshes consist of 65274 nodes and 332503 tetrahedral elements. For the purpose of this study, the blood was assumed as a non-Newtonian fluid flow at isothermal conditions [7], as follows:

$$\begin{cases} \Delta \rho u = 0 \\ \rho\left(\frac{\partial u}{\partial t} + u\nabla u\right) = -\nabla p + \mu\nabla^2 \end{cases} \quad (1)$$

where u is the flow velocity, p is pressure, ρ is density of fluid, and μ is the dynamic viscosity. The parameters used to set up the vein structure are summarized as shown in table 1.

Table 1. Blood parameters

Parameter	Value
Pressure	10 mmHg
Blood Viscosity	0.0035 Pa
Blood Density	1050 kgm^{-3}
Blood Velocity	20 cms^{-1}
Vein Diameter	10 mm
Temperature	37 °C

There are two cases of study in this work. Case A is the set of first valve to 70% orifice size and 50% for the second valve. Meanwhile, for case B, first valve orifice size is set to be 70% and second valve one is 30%. The designated of vein using CFD is shown in figure 4.

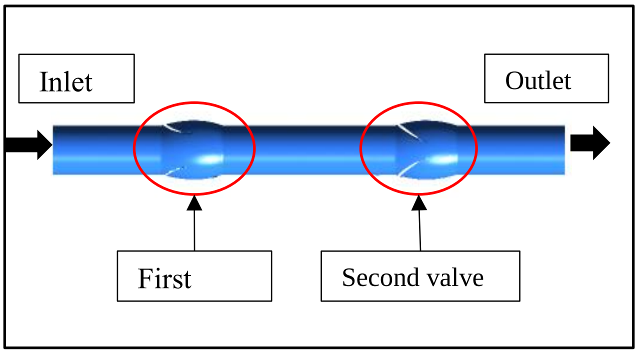

Figure 4. Valve location designated using CFD

2.3. Blood Pressure, velocity, and vorticity

Pressure distribution along the vein is hard to be measured. Therefore, to simulate the initial condition of inlet and outlet, previous in *vivo* experiment has reported the 10 mmHg of pressure and 20 cm/s of velocity [5]. Since the blood clot usually develop at the back of the valve, the region to measure the velocity of vein is focus around the valve along the vein. Thus, three regions of vein is divided to measure the velocity. Vorticity is a condition of rotation fluid elements. The properties of vorticity in blood flow might help in determining the blood particles movement in the body. The observation of vorticity for both cases is conducted to compare the effect of two orifice sizes.

3. Result Analysis

According to previous *in vivo* study, the pressure distribution along the vein is 10 mmHg [8]. However, the pressure before and after valve has different value. Thus, using this simulated vein structure and decided parameters, the visualization of pressure distribution could be clearly visualized, as shown in figure 5. In this case, only one valve is modelled so that the standard based of pressure for the designed vein could be clarified.

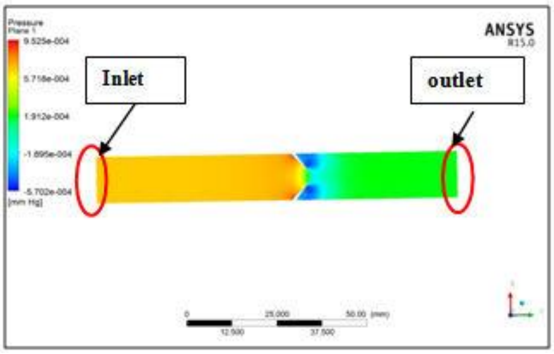

Figure 5. Contour of pressure distribution along the simulated vein

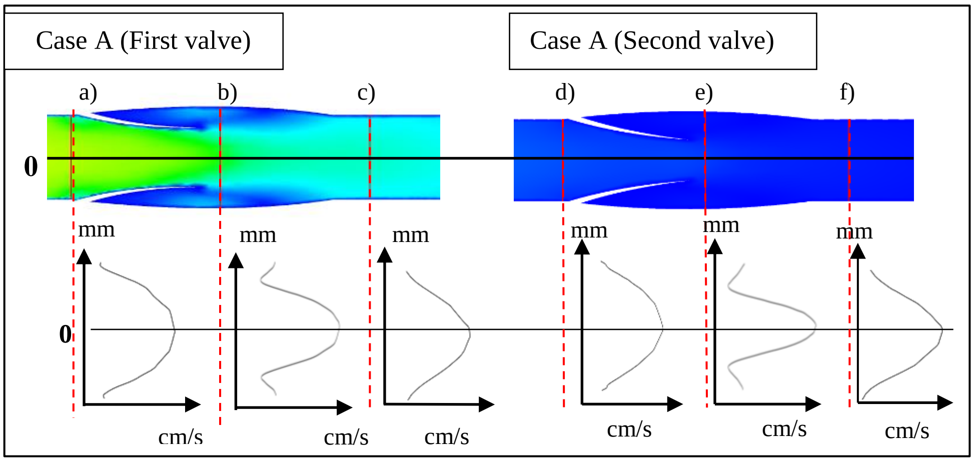

Figure 6. Velocity profile for case A

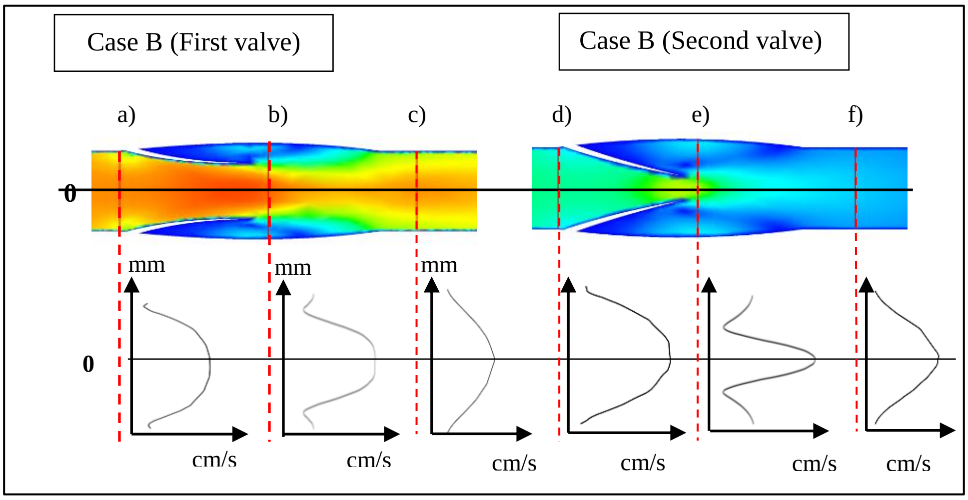

Figure 7. Velocity profile for case B

Figures 6 and 7 show the velocity profile at different locations along the vein distribution, for cases A and B, respectively. The vein was divided into six segments which the three segments for the first valve (a-c) and the other three segments for the second valve (d-f). Every segment was separated by 8 mm. It could be visualized that the red colour represent the regions of high velocity, whereas the blue colour represent the regions of velocity. For case A, obviously, the value of peak velocity decreases after the blood passes through the second valve. Moreover, at the b) segment, the colour contour is green which shows the increasing of velocity as it passing through the leaflets as it following the previous clinical study [7]. Same goes to case B where the pattern of the velocity profile is literally same. However, the velocity range for the both cases is significantly different to one another. This is due to the different second valve orifice size. In addition, the value of the velocity was consistently decreasing after going through the second valve. Since the case B has smaller cross sectional area between the leaflets, therefore, the blood flow could be visualized accelerated in this stenotic area. On the other hand, case A has a large cross sectional area between the leaflets, thus, producing much slower velocity, resulting in reflected stream which against the normal blood flow.

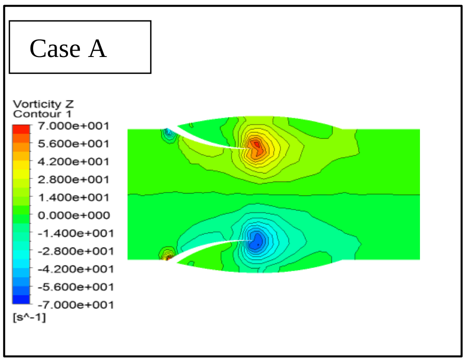

Figure 8. Vorticity contour at the valve area for case A

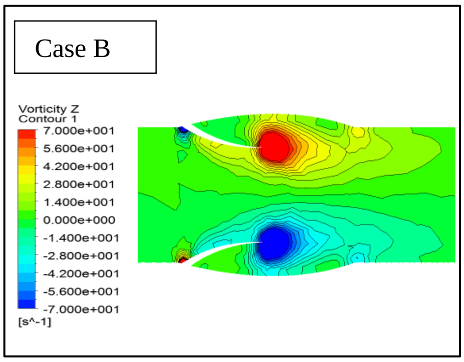

Figure 9. Vorticity contour at the valve area for case B

Figures 8 and 9 indicate the vorticity contour for case A and B, respectively. The blue colour indicate the blood particles which in the clockwise rotation and the red colour indicates the opposite direction. Even though the size of the orifice for the first valve is the same for both case, however the velocity contour shows a significant different in size of the contour from one another. This is due the size of the orifice for the second valve which affecting the blood particle movement at that particular area. The magnitude of vorticity for case B is slightly larger than that of case A, which appear as a larger rotation particles. Furthermore, case B would be one of the factor that affect the accumulating of blood, thus, could lead to the formation of thrombus. In addition, the blood particles can be observed rotating significantly at the valve area since the valve was obstructing the flow of the blood. Hence, once the blood passing through the valve, some of the particles will be entering the valve cusps. That particular particles will rotating in the same area, thus, increasing the contact time of the particles of blood with the vessel wall and the probability of blood clot formation.

4. Conclusion

Two valves were simulated along the designed popliteal vein. The different size of orifice between the first and second valves shows the variation of the velocity and vorticity of the blood flow is signification. For case A which the first valve opened 70% and the second valve opened 50%, the velocity value indicate lower than that of case B, due to the smaller orifice of second valve in case B (30%). In observation of vorticity movement, case B could be seen with a higher vorticity around the second valve which could be assumed has an effect to blood accumulating possibility. In summary, the biomechanics event of the fluid is dependent on the mechanical properties of the valve orifice. In fact, to prevent the reflux of the blood, the valve functions as flow modulator in helping the blood movement in the venous vessel.

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