



## COMPUTATIONAL FLUID DYNAMICS SIMULATION OF EARLY DIAGNOSIS OF DEEP VEIN THROMBOSIS

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### ABSTRACT

This paper presents a validation of *in vivo* experiment of early diagnosis of Deep Vein Thrombosis (DVT) using Computational Fluid Dynamics (CFD) method. This study was focusing on the pressure and also velocity of blood along the popliteal vein distribution. It is important to study the early stage of DVT as it could prevent the fatal injury to the patients. By using Ansys-CFX, the blood movement in the vein can be further analysed. The result of pressure shows that, the highest velocity value was 15.45 cm/s and the lowest velocity recorded was 0.73 cm/s.

**Keywords:** deep vein thrombosis, popliteal vein, computational fluid dynamics.

### INTRODUCTION

Deep vein thrombosis (DVT) is a common disease which effects of 1-2% of Americans. It is a serious condition where it can lead to life threatening condition such as pulmonary embolism (PE). DVT and PE have been reported to cause more than 100,000 deaths each year (Somarouthu, 2010). DVT is a condition where a blood clot forms in deep vein usually at the cuff and the thigh. It may block the flow of blood through the vein partially or completely. Patients usually happened to have pain, swelling and tenderness along the distribution of the vein.

Generally, clinical diagnosis is insensitive and not reliable, therefore screening technique is needed to assist the confirmation of DVT (Khaladkar *et al.*, 2014). Based on the available method, Duplex ultrasound often considered as the gold standard in DVT diagnose. Duplex ultrasound used compression technique where B-Mode images were used and also color-Doppler to visualize the flow or movement of the vessel structure.

In the past decade, the development of 3D simulation has become a promising technique in order to simulate a complex blood flow in vessel. Numerous physicians were reported to have used this technique to simulate blood flow during an operation. Thus, it could prevent a serious complication at region of interest accurately.

In the study of flow behaviour, CFD plays an important role as it allows acquisition of realistic for fields in complex geometries by solving the nonlinear equations of mass and momentum conservation in a discretized form. An accurate reconstruction of the flow and wall shear stress pattern in physiological and pathological conditions can be obtained by using complex geometries and boundary conditions derived from imaging equipment

such as ultrasound, MRI and any other imaging equipment (Botar *et al.* 2010).

This paper presents a 3D simulation of blood flow using computational fluid dynamic (CFD) technique in a popliteal vein for the validation of *in vivo* experiments of the early stage of DVT diagnosis. The early stage of DVT diagnosis is important as it could prevent patient from getting a pulmonary embolism (PE) which could lead them to a sudden death. However, due to the some limitations of the drawing software, only a few parameters could be considered to be used in this experiment.

### METHODOLOGY

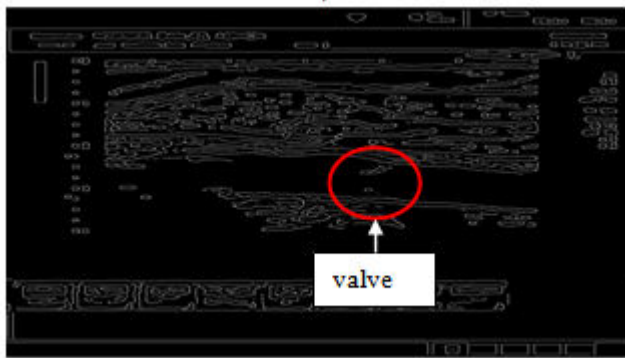
#### Source Data

The medical image of vein was generated from medical imaging equipment which is ultrasound. The popliteal vein geometry and the flow related data was taken from ultrasound machine model Toshiba Xario-200.

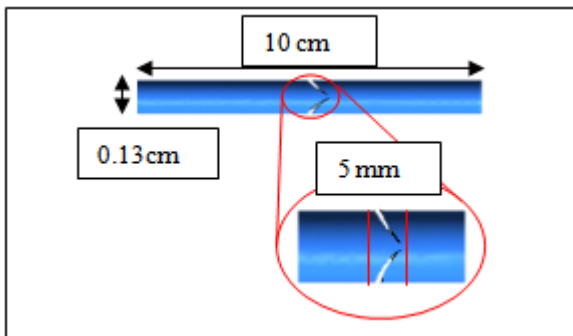
The image of B-mode ultrasound was extracted from Epiphan DVI2 USB 3.0. This device is able to record video at 60 frame per second (fps) and able to capture and saved the image of ultrasound using all type of format. From the Canny-edge detection method, the size of the vein can be determined. Therefore, in the SolidWorks reconstruction image, the length of the vein was set to 10 cm since valve are consistently located at specific location in the veins, and they are usually present in pairs 3-5 cm apart from each other (Muhlberger *et al.*, 2008). While lumen size was set to 0.13 cm (Musil, D. 2008), the vein thickness was set to 1 mm, and the length of vein was set to 5 mm. The size of the valve opening used in this simulation was 3, 5 and 7 mm.



a)



b)



c)

**Figure-1.** The geometry of the popliteal vein a) B-mode ultrasound image. b) Canny-Edge detection (N. Harun *et al.* 2014). c) SolidWorks image reconstruction.

### Blood Flow Modelling

In previous study, blood is considered as Non-Newtonian fluid with both fluid and solid components and completely laminar based on accepted criteria of the Reynolds Number. The thixotropic behaviour of blood not only affects the fluid flow but also the mechanical stress on the vessel wall (J. Chen, 2006).

In this experiment, Navier-stokes formula as shown in (1) was used to define the blood flow within the computational domain.

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

where  $u$  is the flow velocity,  $p$  is the pressure,  $\rho$  is the density of fluid, and  $\mu$  is the dynamic viscosity.

The development of blood flow simulations includes several steps, reconstruction of popliteal vein, meshing, parameters of boundary conditions, fluid behavior, setup of experiments, verification and validation of result (Uus *et al.* 2014). To conduct the CFD, one must know the boundary conditions of the model. This is to ensure the model was following the specification of the real vessel condition. Usually, boundary condition was used to specify the real condition such as flow rate, velocity and also pressure on the inlet and outlet of wall.

In this experiment, the CFD Ansys-CFX analyses was used to study the velocity and pressure distribution along the popliteal vein which is hard to measure *in vivo* experiment (Khaladkar *et al.*, 2014). Therefore, to begin the simulation the initial condition of inlet and outlet of the vessel was set according to N. Harun *et al.* Therefore the pressure was set to 10 mmHg and velocity was  $20 \text{ cm s}^{-1}$ . Based on the reconstructed geometry of popliteal vein model, it consists of 20511 nodes and 101197 tetrahedral elements. For the purpose of this study, blood elements were used to investigate the blood flow movement in the vein especially at the valve region. It is because blood clot usually develops at the back of the valve. Therefore, it is important to study the velocity of the blood at the valve region and along the vein as it can prevent further complication for the DVT patients. Through this simulation, the vessel wall behavior was considered to be rigid with no slip condition.

Table-1 shows the blood parameter and properties that will be used in these simulations. All the parameters need to be declared before setting up the simulations.

**Table-1.** Blood parameters and properties.

Pressure	10 mmHg
Blood Viscosity ( $\mu$ )	0.0035 Pa.s
Blood Density ( $\rho$ )	$1050 \text{ kg m}^{-3}$
Blood Velocity ( $u$ )	$20 \text{ cm s}^{-1}$
Vein Diameter	13 mm
Valve aperture	3,5,7 mm

## RESULTS

### Pressure

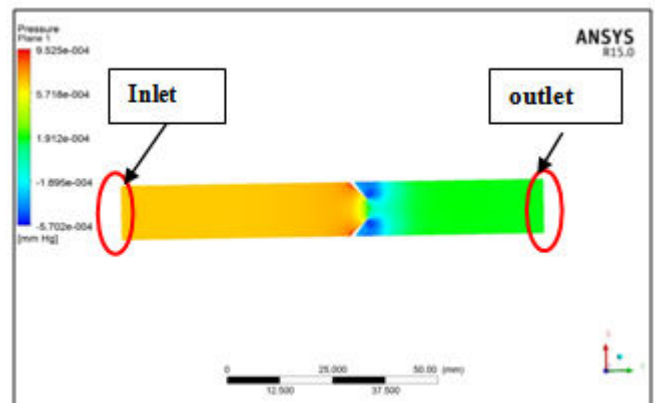
According to N. Harun *et al.*, pressure along the vein distribution in average was 10 mmHg which equals to 1.3 kPa. It is rather lower than artery because vein carry blood from all parts of the body back to the heart. The



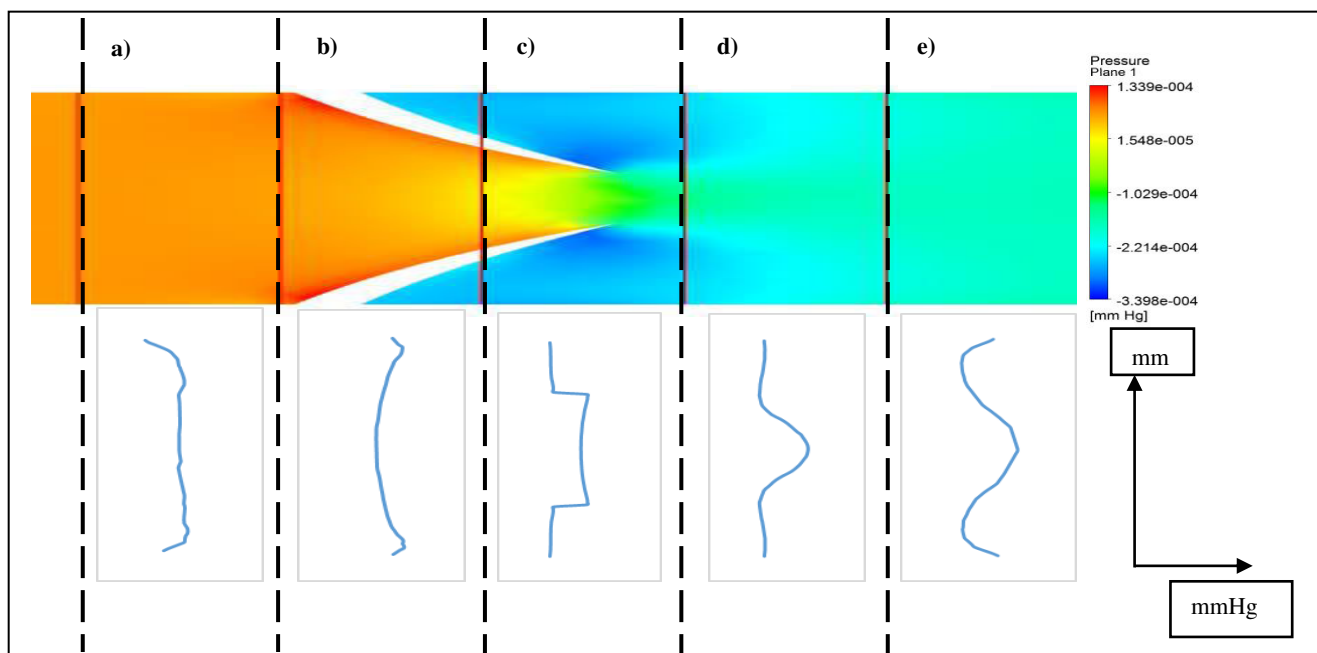
valve actually helps the blood to flow forward by opening and closing it to prevent the blood from moving backward. From the previous research, the pressure of blood before and after the valve was different. However, it is difficult to prove it using *in vivo* method, so that; a simulation technique was proposed to solve the problem. The following shows the result of complete process of the vein simulation.

In Figure-2, it can be seen that the contour image shows different pressure (mmHg) was obtained along the vein distribution.

Figure-3 shows the pressure profile of the blood flow in the vein where the pressure reference was set to the 10 mmHg.



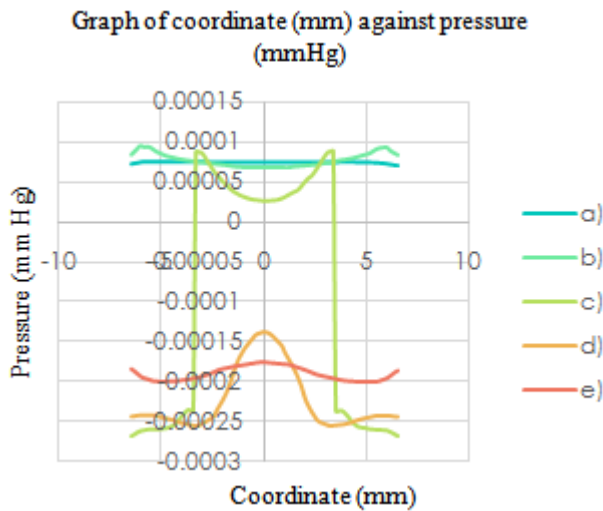
**Figure-2.** Contour of pressure along the vein.



**Figure-3.** Pressure profile of the blood flow in the vein.

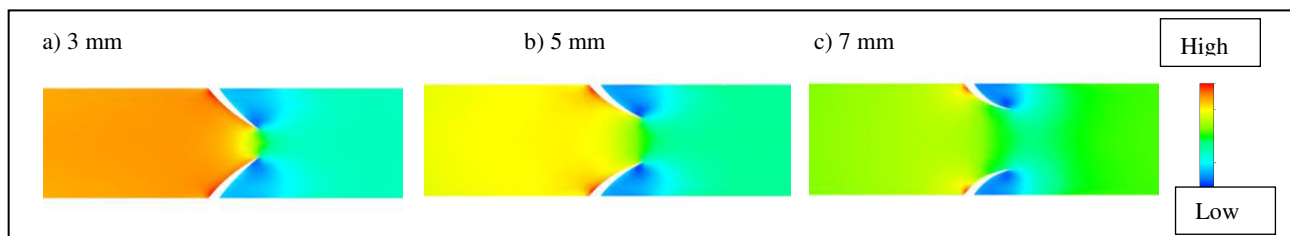
From the figure, the vein was divided into five segment line. It is to monitor the pattern of the pressure flow at every segment. Every line segment was separated by 3 mm. The first segment a), was located before the valve. From that, it can be seen that the pattern of pressure not consistent as it approach the valve area. While b) shows the increment of pressure as it gets closer to the valve. The c) shows the important part of the pressure as the pattern was increase significantly through the valve. The small size of the valve passage cause the high pressure of the blood flow. Whereas d) and e) shows the constant increment of blood pressure along the vein distribution.

Figure-4 above shows the graph of the pressure along the vein distribution. The five lines indicate the location of pressure taken. Line a) to e) indicates the pressure value that was taken from the fives lines as shown in Figure-3. From this experiment, the range of the value taken was  $-3 < x < 3$ , where x is equal to coordinate of the pressure at the c) point.



**Figure-4.** A graph of pressure against coordinate of the vein distribution.

To obtain an accurate result of the pressure, 100 samples of data were distributed along the line for example line **a**). Therefore, there are 500 samples of pressure value was taken along the vein distribution according to the coordinates assigned for each line. From the graph above, it can be concluded that the highest pressure value was taken from the Line **b**) located at the valve which is  $9.51 \times 10^{-5}$  mmHg. The lowest value was taken from the Line **c**) located behind the valve leaflets was  $-2.6 \times 10^{-4}$  mmHg. Line **a**) shows a consistent pattern of the blood pressure before it became negative value. This means that, the pressure was not strong enough to push the blood to go through the valve area. The same condition was also applied to the Line **b**). Whereas Line **c**), shows a significant increment of the pressure value as it is located between the valve. The small passage causes the pressure to be high to allow the blood to move forward and to prevent the backflow of blood. Lines **d**) and **e**) show the positive value of the pressure as it pass the valve region to bring the blood back to the heart.

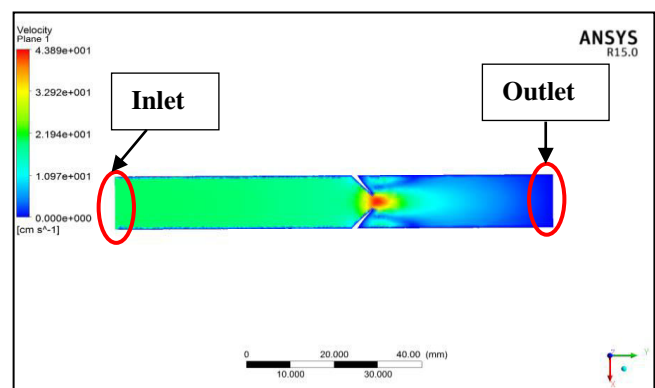


**Figure-5.** Comparison of pressure distribution for different size of valve aperture.

Figure-5 shows the three cases of different size valve aperture in the simulation done. Based on the result obtain, there is significant different in the pressure flow measurement for each cases. For the smallest size of aperture that is 3 mm, shows the increment of pressure before passing through the valve. While for the larger size of aperture that are 5 mm and 7 mm, the pressure flow in the vein is lower than the smallest size of aperture. The blue region at the back of the valve of 3 mm aperture has the largest area compared to the other two sizes. The pressure flow on that particular region is slower than the other part of the vein, this could possibly support the blood clot formation at the back of the valve which could lead to deep vein thrombosis condition.

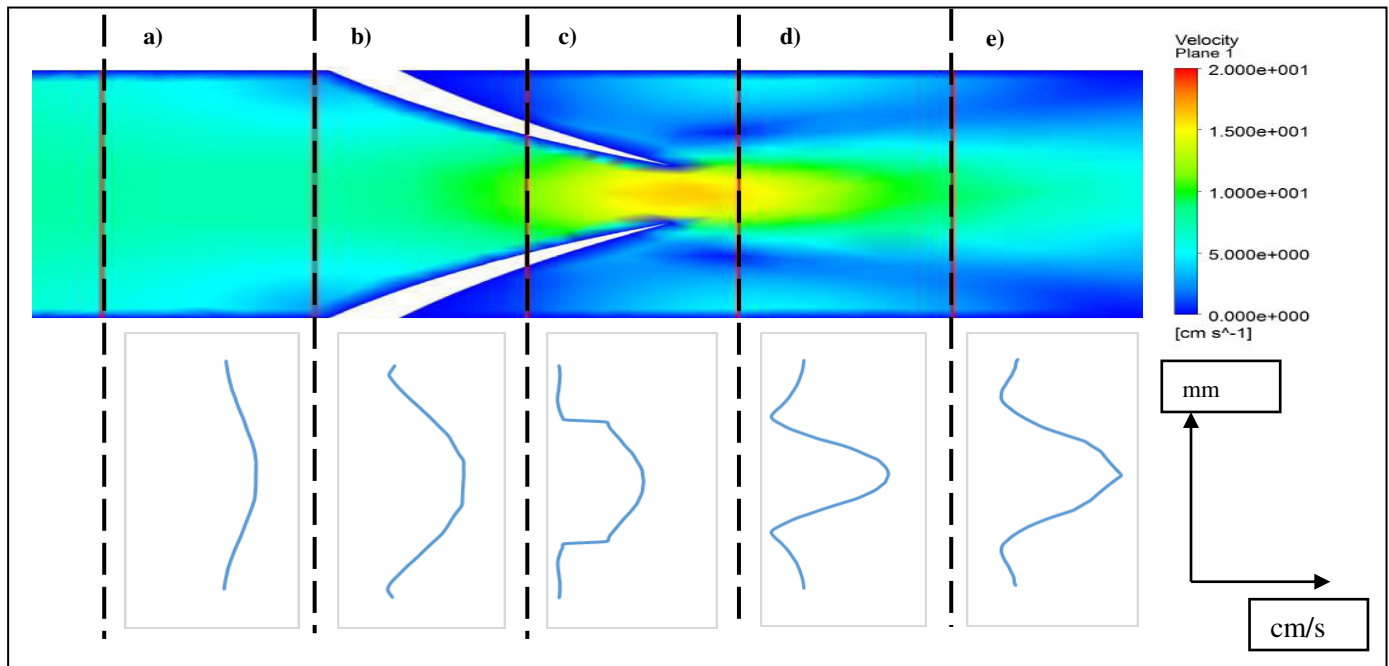
### Velocity

Velocity in blood context means the distance of fluid moves with respect to time. It sometimes can be confused with “flow”. However, flow is the volume of blood that moving per unit time. In this experiment, the velocity of blood was investigated as it can be used to diagnose the early stage of DVT.



**Figure-6.** Contour of velocity along the vein.

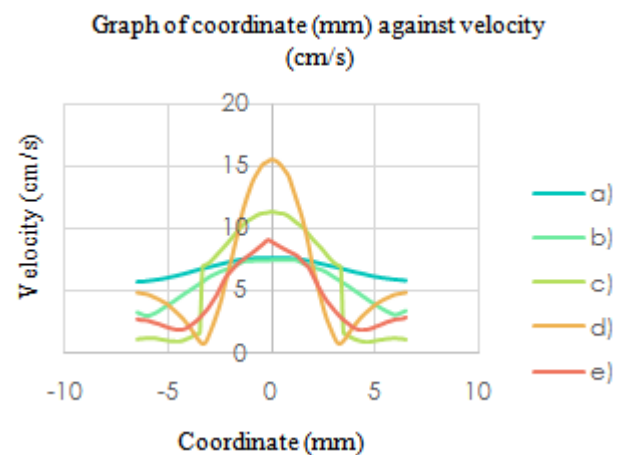
Figure-6 above shows the contour of velocity along the vein. From the figure, it can be seen that there are several value of velocity that lies ahead of the vein. There is obvious formation of contour especially at valve area. This means the value of velocity was changing as they go through the valve.



**Figure-7.** Velocity profile of the blood flow in vein.

Figure-7 shows the velocity profile of the blood flow in the vein. From the figure, the vein was divided into five segment line. It is to discover the pattern of the velocity flow at every segment. Every line segment was separated by 3 mm same with the pressure profile. The first segment a) was located before the valve. From that, it can be seen that the pattern of velocity slowly increase as it go through the valve. While b) shows the increment of velocity profile as it gets closer to the valve. The c) shows the of the velocity as the pattern was increase significantly through the valve. Whereas d) and e) shows the constant increment of blood Velocity along the vein distribution. In previous research, it is reported that the velocity of blood in vein can be in range  $20 \text{ cm s}^{-1}$  or lower (Tokuda *et al*, 2008). From the figure, the red colour indicates the highest velocity that exists in the simulation and the blue colour indicates the lowest value of velocity that had been produced. The red colour contour was bright when it approaches the valve region, this is probably because the value of pressure affect the velocity of blood that passing through the valve.

Figure-8 above shows the graph of the velocity against coordinate of the vein. As we can see, there are five lines that indicate where the value of pressure was taken. The value of the line a) to e), was taken from the location of a) to e) from the Figure-7 above. From this experiment, the range of the value taken was  $-3 < x < 3$  where, x equal to coordinate of the pressure at the c) point. In this simulation, point c) was considered as origin that is why there is two more line at the left and the right side of point c); this is to indicate that point c) is actually origin.



**Figure-8.** A graph of velocity against coordinate of the vein distribution.

From the figure, the highest value of velocity which is from Line d) was  $15.45 \text{ cm/s}$ . While the lowest also from Line d) which is  $0.73 \text{ cm/s}$ . There are no values showing the negative value, this means that the velocity was enough to transport the blood through valve. Line d), shows the most significant velocity profile of the blood. This shows that the velocity of the blood at that point is the highest among any other line segment. It was then followed by the Line c) and Line e). While Line a) and b), shows the constant increment value of velocity profile as they get closer to the valve passage.

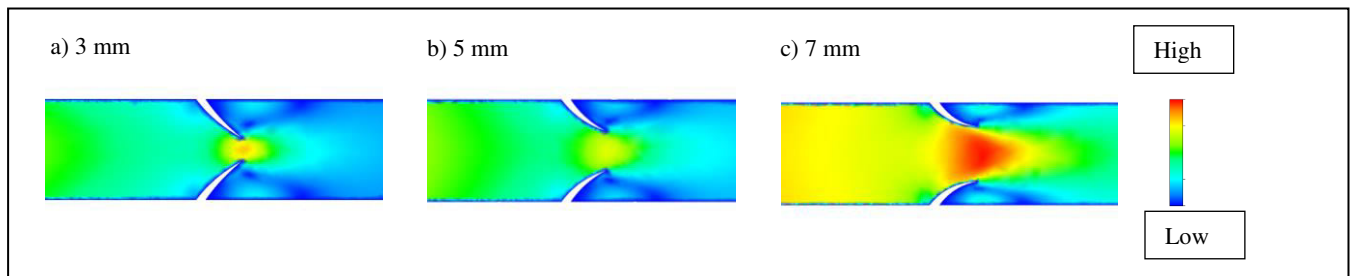
Figure-9 shows the three cases of different size valve aperture in the simulation done. Based on the results





obtained, there is some difference in the velocity measurement for each cases. For the smallest size of aperture that is 3 mm, shows the higher velocity at the valve aperture. However, at the 5 mm valve aperture, there is no red colour at the valve area. While for the larger size of aperture that are 7 mm, the velocity in the vein is highest at the valve opening. Meaning that the bigger the

opening, the higher the velocity flows. Besides that, the light blue at the back of the valve is bigger than the other size of valve aperture. The velocity flow on that particular region is slower than the other part of the vein. Thus, it is possibly support the blood clot formation at the back of the valve which could lead to deep vein thrombosis condition.



**Figure-9.** Comparison of velocity distribution for different size of valve aperture.

## CONCLUSIONS

In conclusion, the purpose of this study is to diagnose the early stage of DVT. From the simulation result, it can be seen that, the value of velocity will excite as they go through the valve. That is shows how the blood actually flows in our body. To get more accurate result, more simulation was needed to create a velocity chart to predict when the thrombus will exist at the valve based on the velocity of blood. As the *in vivo* experiment was difficult to investigate. Therefore, the early diagnosis actually will assist physician in order to prevent the development of pulmonary embolism (PE).

## ACKNOWLEDGEMENTS

The authors would like to thank Research Acculturation Grant Scheme (RAGS R031) for the funding of this project. They would also like to thank Universiti Tun Hussein Onn Malaysia (UTHM) for having the space of Medical Imaging laboratory and also MiNT SRC laboratory doing the experiment.

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