

Numerical Investigation of Blood Flow through a Vein with Two Consecutive Leaflet Valves

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Abstract: Varicose veins and thrombophlebitis are common insufficiencies of leg venous system, which patients suffer from. Leaflet valves play a key role in blood circulation within the veins. In the present work, the blood flow through a portion of a vein, consisting of two consecutive leaflet valves with different opening percentages, is studied numerically. The purpose of this study is to reveal the impact of leaflet valves' function on veins' insufficiency. The blood flow is laminar and the vein wall and leaflet valves are considered to be deformable. Obtained results show details about the blood flow behavior and resultant stresses on vein walls and leaflet valve cusps.

Keywords: **Blood Flow, Leaflet Valve, Numerical Method, Fluid Structure Interaction.**

1 Introduction

Veins are blood vessels which take deoxygenated blood back to the heart, and therefore they have a vital role in blood circulation. Furthermore, there are some leaflet valves on the vein walls which make the blood flow through the veins more complex than arteries. These valves let the blood flow only in one direction towards the heart by opening and closing their twin cusps (fig. 1) [1].

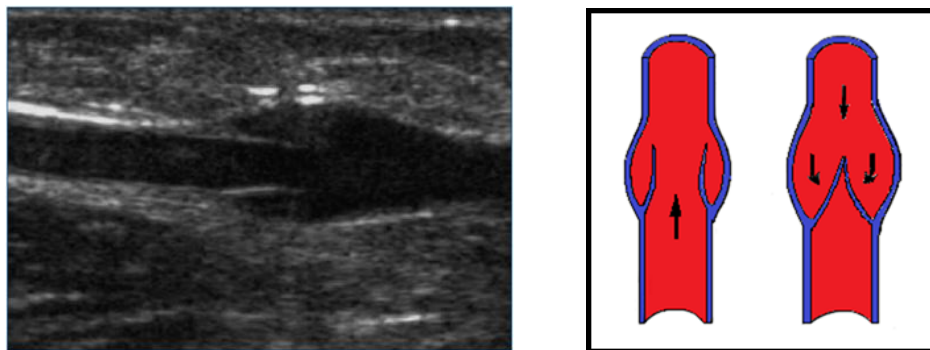


Figure 1: The function of leaflet valves

The insufficiency of leaflet valves causes serious chronic venous disease (CVDs) like varicose veins. Varicose veins are one of the common CVDs which refer to enlarged and deformed veins (fig. 2). Varicose veins disrupt the blood circulation and can be a leading cause of blood clot formation within the veins. Although each of the body veins can become varicose, the lower limb superficial veins, such as great Saphenous vein (GSV) (fig. 3), are the most commonly susceptible regions for this disease. Prolonged standings and sittings are important factors in appearance of the varicose veins, because of increasing veins blood pressure in these cases [2].



Figure 2: Varicose veins

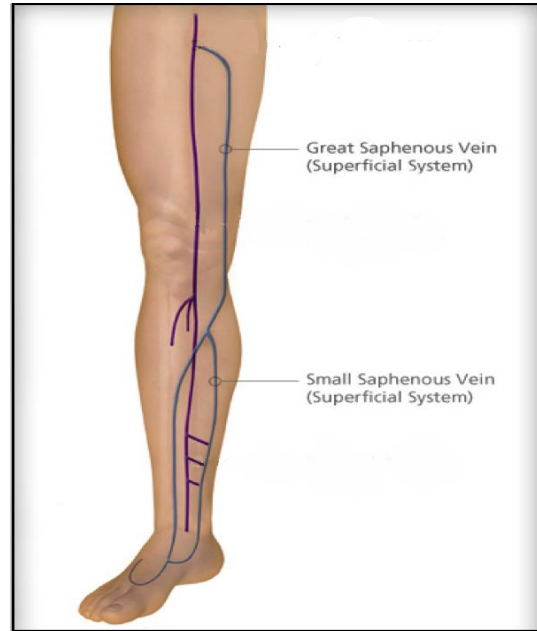


Figure 3: Great Saphenous Vein

Anatomical and functional information about the venous systems will help researchers investigate the blood flow behavior through the venous system properly. Seidel et al. [3] investigated that the relation between body mass index of each individual with GSV diameter is not significant and GSVs in the left and right lower limb have a small difference in diameter. Ochsner et al. [4] have presented that the superficial venous pressure gradients in a man at rest in supine position decrease toward the heart. Stick et al. [5] studies show that the saphenous vein pressure near the ankle increases up to 80 mmHg by changing the recumbent position to the upright position, and then it decreases to 30 mmHg by starting to exercise.

It is observed that a vortex is appeared just behind of each valve cusp as the blood flows through a leaflet valve (fig. 4) [6]. Ohashi et al. [7] simulated a 2D model of blood flow through a venous valve to show that the size of vortex behind the valve clearly depends on the blood flow Reynolds number.

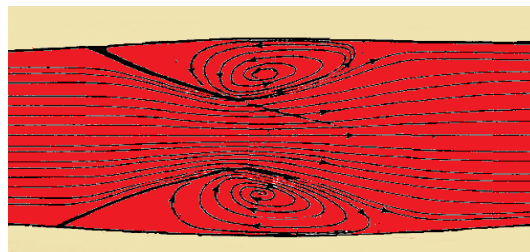


Figure 4: Vortexes behind the valve cusps

It was found that valve pockets are susceptible areas for originating venous thrombi, because of blood flow stagnation in these regions [8-11]. An investigation on the blood flow through a dog saphenous vein valves, carried out by Karino and Motomiya, ascertained that the valve-pocket vortices greatly influence the blood thrombi formation [6]. As significance of valves' function in blood flow, Sheidai et al. [12] numerically studied the blood flow behavior through a rigid perforating vein with different opening percentages of valve cusps.

In the current study, the blood flow behavior through a segment of an elastic GSV, which contains two leaflet valves, is simulated by computational fluid dynamics method. The purpose of this study is to establish the impact of upstream and downstream valve cusps' angel on blood circulation. The results of this investigation clearly identifies the susceptible areas of deformation and the impact of leaflet valves' malfunction on the probability of originating venous thrombi.

2 Problem Statement

In the present study, the blood flow through a segment of vein with two consecutive leaflet valves is investigated in two steps: 1- different angles of downstream leaflet valve cusps, 2- different angles of upstream leaflet valve cusps. The simulated computational 3D geometry is shown in fig. 5.

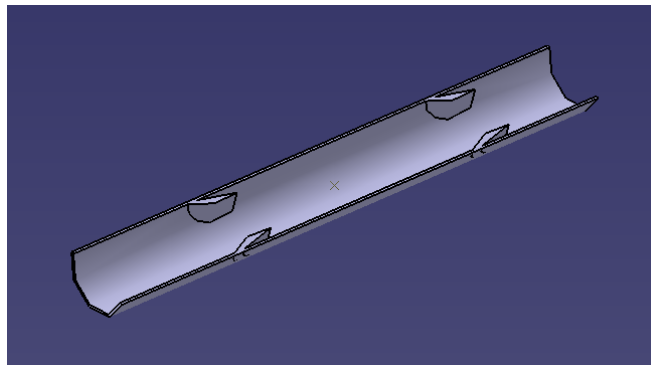


Figure 5: Cross section of computational geometry

The geometry is meshed by nonstructural tetrahedral elements which is shown in fig. 6.

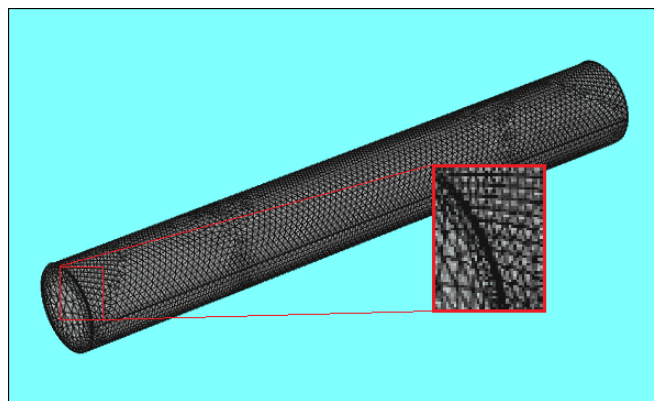


Figure 6: Meshed geometry

Because of the low velocity, the blood flow through the vein is considered to be laminar intrinsically. The governing equations for laminar blood flow through the veins are momentum and continuity equations, which are respectively as:

$$\rho\left(\frac{\partial v}{\partial t} + v \cdot \nabla v\right) = -\nabla p + \mu \nabla^2 v + f \quad (1)$$

$$\nabla \cdot \vec{v} = 0 \quad (2)$$

Where ρ is the density, v is the velocity field, P is the pressure, μ is the dynamic viscosity and f is the body force [13]. The right hand side of equation (1) refers to the total stress applied on vein wall and valves by blood flow. The blood pressure is assumed to be constant at both upstream ($P_i = 90mmHg$) and downstream ($P_o = 80mmHg$) regions of the vein [4]. The blood is assumed to be a Newtonian fluid. The vein wall and leaflet valves are considered to be deformable. The blood flow is presumed to be laminar and steady state. The diameter of the simulated vein is 2.5 mm [14].

The effect of valve cusps opening percentage on blood flow regime is investigated numerically beside the resulted stresses on the vein wall and valve cusps using Finite Element Method (FEM). The continuity equation is discretized by Galerkin method. Furthermore, the Galerkin Least Square Method is used for discretization of the momentum equation in order to stabilize the solution. Blood flow regime through the vein is depicted in fig. 7 and 8.

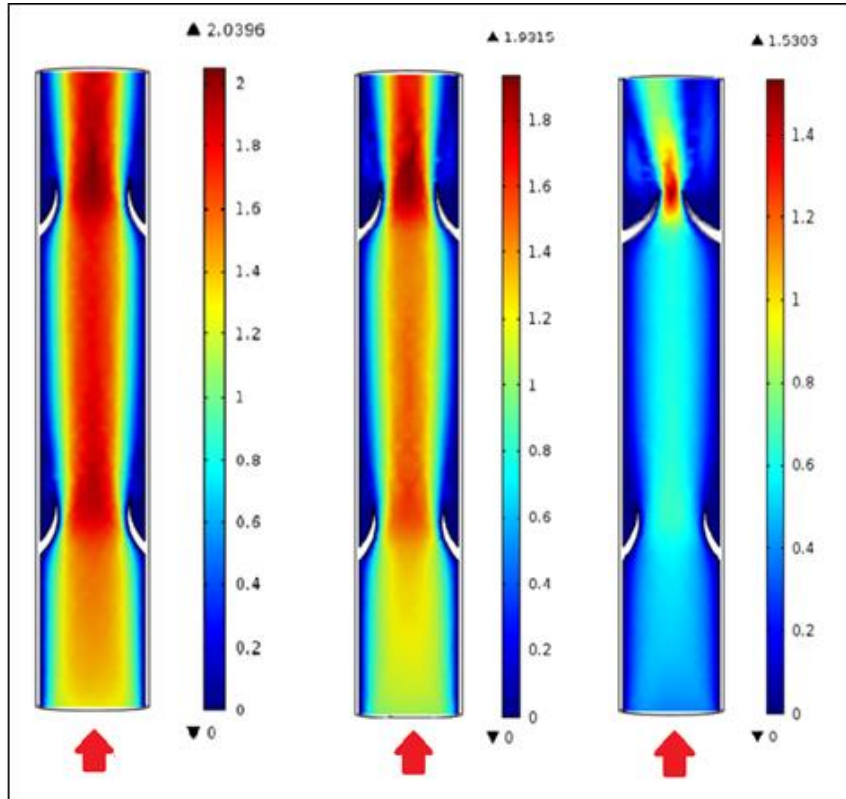


Figure 7: Blood flow regime within a vein with different downstream leaflet valve opening percentages

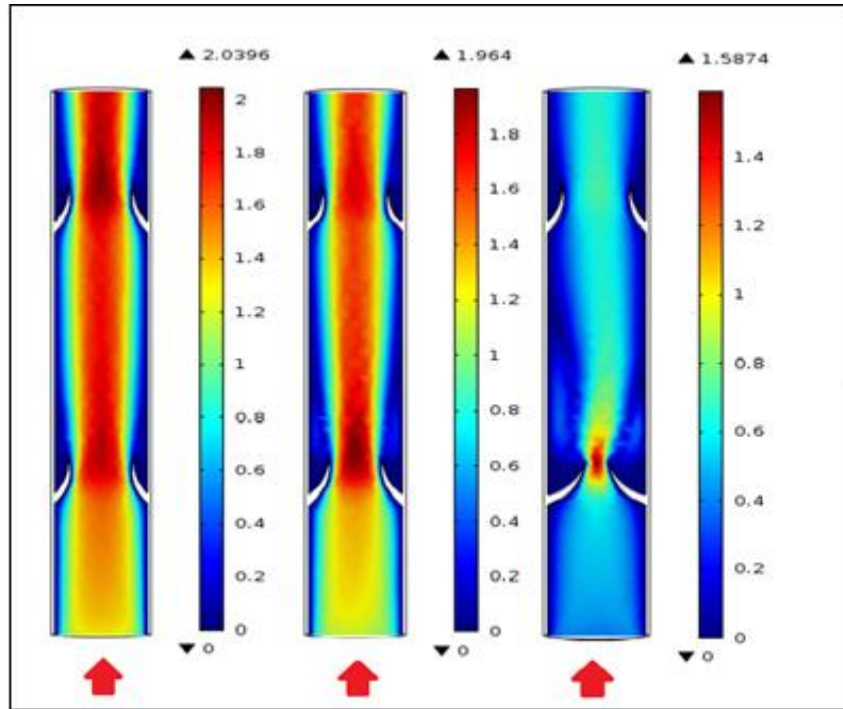


Figure 8: Blood flow regime within a vein with different upstream leaflet valve opening percentages

Obtained results show that as the blood approaches to the valves, it experiences an increase in its velocity, which has a maximum value at the exit point of leaflet valves. It is obvious that as the flow cross section area decreases in the vein, the velocity increases as a result of mass conservation principle. Comparing the velocity magnitude of the blood flow in veins with different opening percentages of the valve cusps shows that the higher the valve opening percentage, the greater the velocity magnitude. At lower valve opening percentages, cusps cause additional resistance against fluid flow and decrease the flow rate and the consequent velocity. Center line blood flow velocity magnitude for three veins with a completely open upstream valve and different opening percentages of downstream valve is shown in fig. 9.

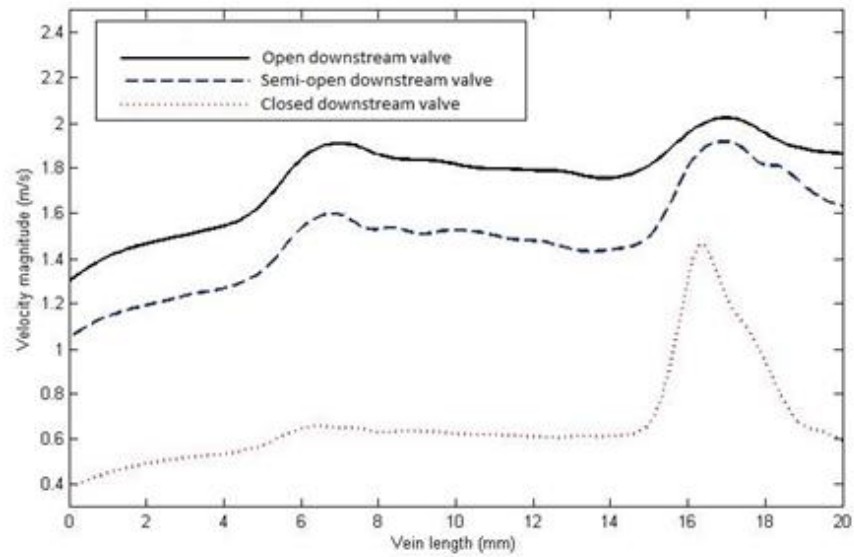


Figure 9: Center line velocity magnitude along a vein with different downstream leaflet valve opening percentages

Center line blood flow velocity magnitude for three veins with a completely open downstream valve and different opening percentages of upstream valve is also depicted in fig. 10.

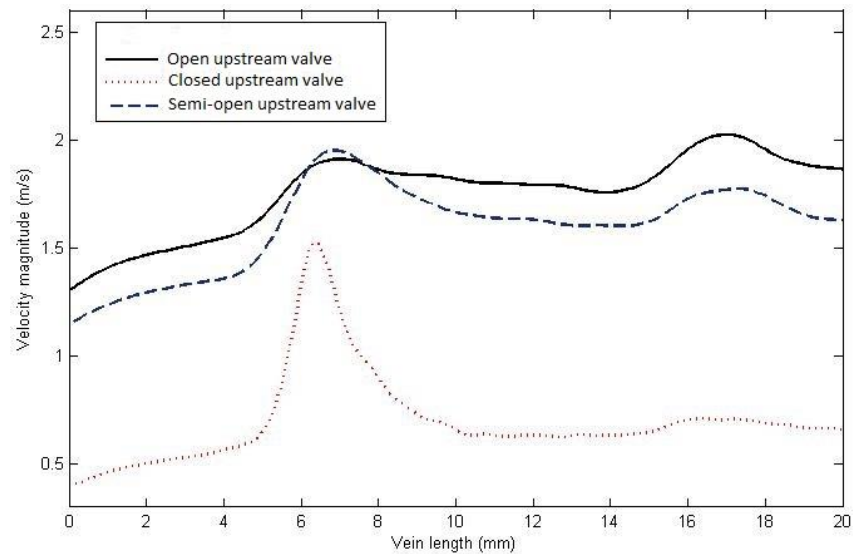


Figure 10: Center line velocity magnitude along a vein with different upstream leaflet valve opening percentages

As shown in fig. 9 and 10, velocity level increases around the leaflet valves. According to Bernoulli's Principle, which is given in equation (3) by some simplification, this rise in the velocity level results in a noticeable decline in blood pressure near the leaflet valves [13].

$$\frac{v^2}{2} + gz + \frac{P}{\rho} = cte \quad (3)$$

Where v is the velocity magnitude at a point on a streamline, g is the value of acceleration due to gravity, z is the elevation of the point above a reference plane, P is the pressure at the chosen point, and ρ is the density of the fluid at all points in the fluid.

Fig. 11 and 12 show the von-Mises stress along the vein walls, exerted from the blood flow, for different valves opening percentages. These results will make it possible to predict, whether if the materials are going to yield.

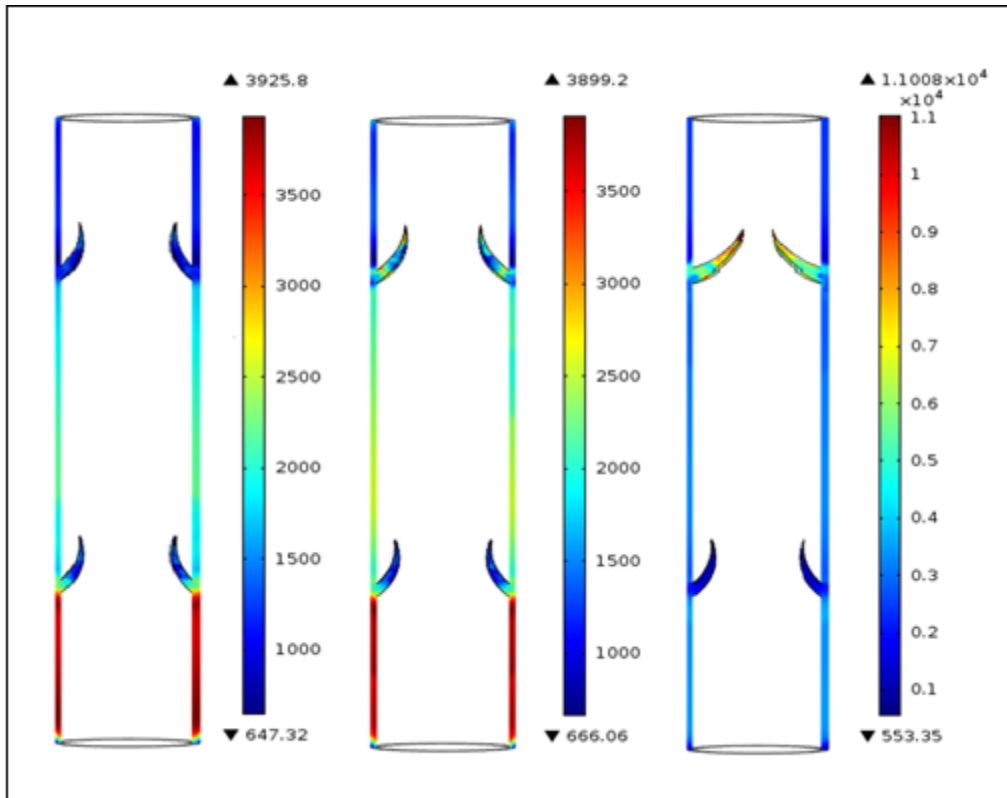


Figure 11: Stress distribution on the vein wall

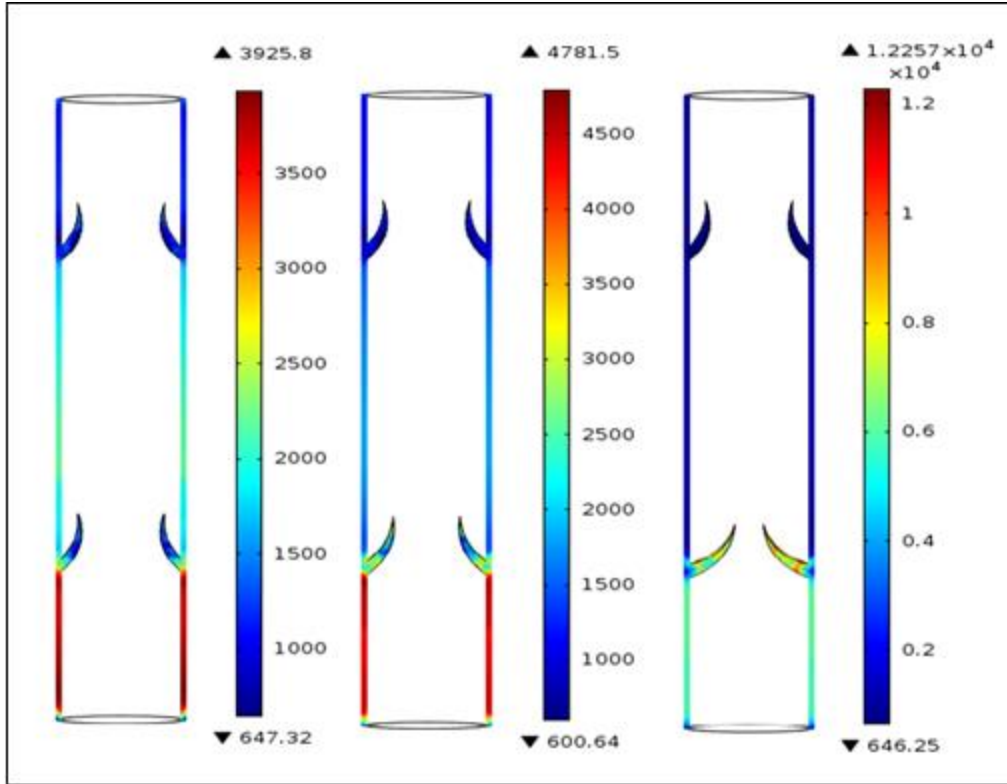


Figure 12: Stress distribution on the vein wall

It is obvious that the wall stress is increased before the valves, especially when the valve cusps opening percentage is high. The tilting angle of downstream valve cusps has a great impact on the wall stress in upstream section of the vein. However, changing the angle of upstream valve cusps slightly influences the downstream wall stress. Fig. 13 and 14 show the von-Mises stress along the vein.

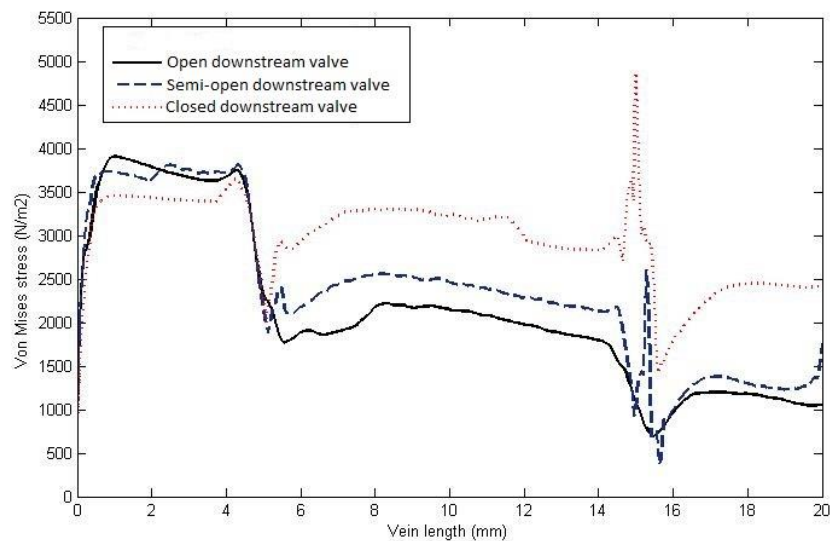


Figure 13: Von Mises stress along the vein wall

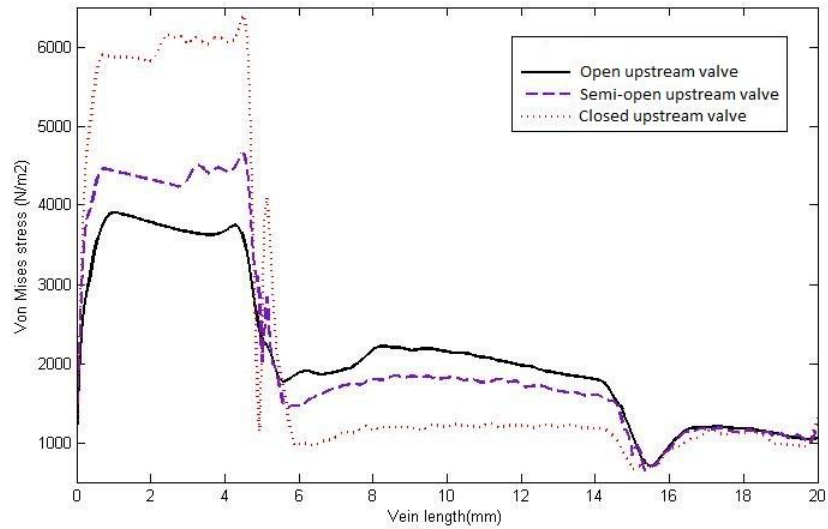


Figure 14: Von Mises stress along the vein wall

The advent of thrombi in a vein has a close relationship with the blood flow shear rate [8]. Because of the special significance of blood clot formation hazard in human body, studying the blood flow shear rate is considered in this study. Regions with low shear rate are more susceptible to blood clotting. Fig. 15 and 16 refer to flow shear rate on the vein walls with different opening percentage of valve cusps. The value of shear rate decreases near the valve flaps and almost reaches to zero in the valve pockets. As a result, blood clots seem more likely to be created in junction regions, where the valves are attached to the vein wall, and especially within the valve pockets.

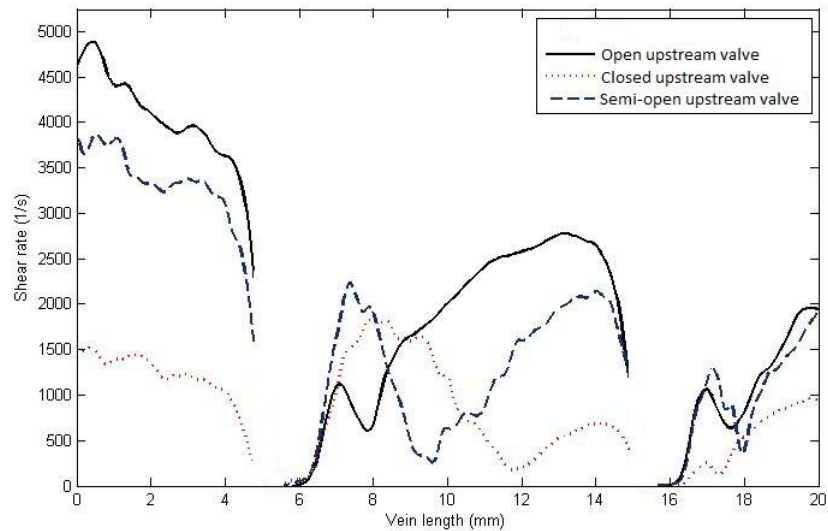


Figure 15: Blood flow shear rate along the vein wall

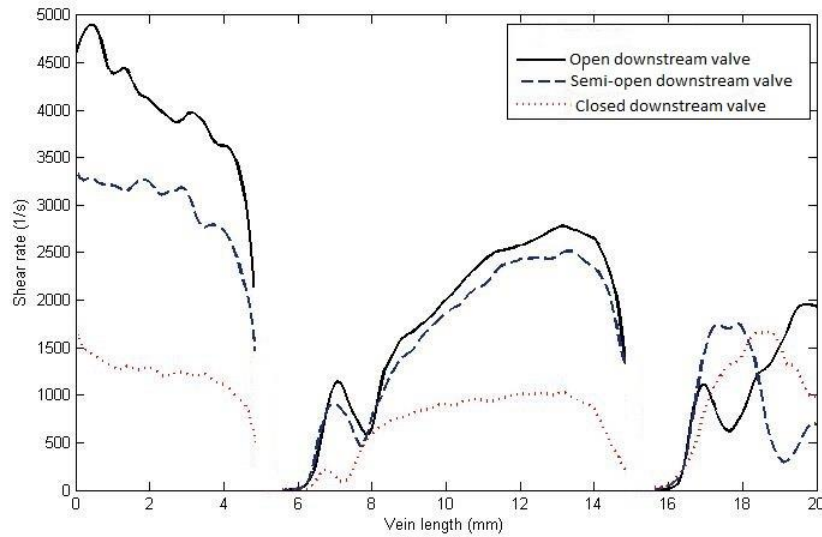


Figure 16: Blood flow shear rate along the vein wall

3 Conclusion

Varicose veins are very common and hazardous venous disease. In varicose veins, the vein walls become enlarged and deformed which consequently results in malformed leaflet valve cusps. Leaflet valve cusps play a key role in blood circulation.

In the current study, the blood flow behavior through a section of Saphenous Vein containing two consecutive leaflet valves is investigated. Different opening percentages of downstream and upstream valve cusps is considered to study the blood flow regime. The blood flow velocity diagram, which is depicted in fig. 9 and 10, clearly ascertains that the velocity experiences an increase as the blood approaches to the valves. It is obvious that this growth in velocity level even rises when the valves shut off. Furthermore, the maximum value of the flow velocity is captured at the exit point of leaflet valves.

The significance of studying the vein wall stress beside the blood flow velocity becomes clearer, as the vein wall can easily deform and loose its function over the time, if the stress on it exceeds its material's strength. This is also true about the leaflet valves. Therefore, studying the von-Mises stress along the vein wall for different valve opening percentages is involved in this research. According to fig. 13 and 14, it is witnessed that the wall stress increases before the meeting point of the wall and leaflet valves, especially when the valve cusps opening percentage is high. It is also clear that a change in the tilting angle of downstream valve cusps greatly influences the wall stress in upstream section, while the impact of upstream valve cusps angle is not much sensible on the downstream wall stress.

In addition, evidence suggests that the risk of thrombi forming increases within a segment of vein, where the blood flow shear rate is low. Accordingly, studying the blood flow shear rate is considered in this study. Fig. 15 and 16 illustrate that the blood flow shear rate decreases near the valve flaps. Thus, the junction points, and specially valve pockets, are the most susceptible regions for appearance and development of blood clots.

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