Fluid–structure interactions modeling the venous valve

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Abstract

In this study, a fully coupled fluid–structure interaction computational model for a pulsatile flow in the venous valve was developed. An arbitrary Lagrangian–Eulerian formulation is used in the coupled model, considering two domains, specifically the blood flow and the valve leaflets. The effect of the gap width between the valve leaflets (venous valve incompetence) on the valve reverse flow (reflux) has been investigated.

1. Objectives

The incompetence of venous valves is the cause of chronic venous insufficiency, which occurs in 33.2\% of the population [1,2]. The chronic venous insufficiency is manifested by the skin changes or leg ulcers in 6\% of people in developed countries. It occurs more frequently in female obese patients over 50 years old [2,3]. The incomplete closing of valve leaflets arises under the influence of congenital and acquired factors, such as the increased vein volume, loss of elasticity, asymmetric closure, shortening of valve leaflets [1,4]. The venous valve incompetence is accompanied by the retrograde blood flow (reflux) that appears during the diastole. The duplex ultrasound investigation allows setting the reflux characteristics well, while the visualization of the valve itself is not accurate [5]. This pathology can be complicated by the formation of a thrombus behind the venous valve, most often in stagnant zones, where the flow of blood is relatively slow [6].

Due to the level of complexity involved and the difficulty of achieving analytical solutions, different scenarios regarding the venous system are often analyzed using computer simulations. Buxton and Clarke [7] presented a computational simulation focused on the dynamics of a venous valve. They captured the unidirectional nature of blood flow in venous valve and investigated the dynamics of the valve opening area and the blood flow through the valve. In this model, the vein was simulated as a rigid tube and the venous valve dimensions were not based on anatomical data. Furthermore, the applied pressure gradient was not physiological for veins. Zervides [8] reported on a model of the venous valve that focused on the hemodynamics of the opening and closing phases. The results were used to develop a method of measuring blood ‘washout’ from behind the valve leaflets. It was shown that gravity helps removing blood from the locations where flow stasis occurs. However, the sinuses of the valve were not included even though they play an important role in the local fluid dynamics. Recently, Chen et al. [9] presented a biomechanical comparison between mono-, bi- and tricuspid venous valve architectures and the implications of such prosthetic designs on the flow and its
structure mechanics. They found that the mechanical cost, which was defined as the ratio between the internal structural stress and fluid wall shear stress on the leaflets, was lowest for the bicuspid valve. However, the valves dimensions were not described and the designs did not include the sinuses of the bi- and tricuspid valves. The lack of numerical simulation of venous valve insufficiency has motivated us to study this issue.

The aim of the present study is to evaluate the effect of the gap width between valve leaflets (leaflets insufficiency) on the hemodynamics and obtain dependence of the reverse flow duration on the gap width between the valve leaflets.

2. Numerical Method

In this study, ANSYS Fluent and Mechanical solvers were used for the fluid and structure modeling, respectively.

The governing equations are formulated using the Arbitrary Lagrangian-Eulerian (ALE) approach for modeling unsteady, incompressible fluid flow on a deforming mesh. In the ALE formulation, the continuity equation is written as

$$\nabla \cdot \mathbf{u} = 0,$$

where $\mathbf{u}$ is the fluid velocity. For mesh velocity $\mathbf{u}_m$, a convective term $(\mathbf{u}_i - \mathbf{u}_m)$ is introduced, such that the momentum equation in ALE formulation may be given

$$\frac{\partial \mathbf{u}_i}{\partial t} + (\mathbf{u}_i - \mathbf{u}_m) \nabla \cdot \mathbf{u}_j = -\frac{1}{\rho_f} \frac{\partial p_i}{\partial x_j} + \frac{1}{\rho_f} \nabla^2 \mu_i u_i, \quad i, j = 1, 2$$

where $p$ is the pressure and $\mu$ is the fluid dynamic viscosity.

The Structure motion is described by the Lagrangian formulation. Solid with density $\rho_s$ has the displacement $d_s$ which is given by

$$\rho_s \frac{\partial^2 d_s}{\partial t^2} = \nabla \cdot \left( S \cdot F^T \right) + \rho_s f_b,$$

where $f_b$ is the body force and $F$ is the deformation gradient tensor given by

$$F = I + \nabla d_s^T,$$

where $I$ is the identity and $S$ is the Piola-Kirchoff stress tensor.

The Green-Lagrange strain tensor $G$ given by

$$G = \frac{(F^T F - I)}{2}$$

is related to $S$ by the following relation:

$$S = 2\mu G + \lambda \text{tr}(G)I,$$

where $\text{tr}$ is the tensor trace and $\lambda$ and $\mu$ are elastic material Lame constants. In ANSYS Structural, the elastic modulus $E$ and the Poisson ratio $\nu$ are specified as inputs and are related to $\lambda$ and $\mu$ as

$$\lambda = \frac{E\nu}{(1 + \nu)(1 - 2\nu)}, \quad \mu = \frac{E}{2(1 + \nu)}.$$

At the interface $\Gamma$, the following conditions were satisfied:

$$d_s^T = d_f^T, \quad u_s^T = u_f^T, \quad T_s^T = -T_f^T,$$

where $T$ is the traction force at the interface, which is the sum of the pressure and viscous forces.

As the structure moves inside the fluid domain, fluid mesh deforms consequently. In this study, the smoothing and remeshing mesh update methods were used. The computational domain was discretized using unstructured triangular mesh. Mesh around the leaflet was refined.

In order to test the accuracy of the coupled fluid–structure solver, the oscillation of a vertical plate in a cavity filled with fluid is investigated.
3. Test case. Oscillation of a vertical plate in a cavity
A thin flexible plate with a length of $L = 10$ m and a width of $W = 0.4$ m is clamped at the lower boundary. The cross-section of the plate and the ambient fluid domain are shown in Fig. 1. The flexible plate has a thickness of $h = 60$ mm; a modulus of elasticity of $E = 2.5$ MPa; a Poisson ratio of $v = 0.35$; and a density of $\rho_s = 2550$ kg/m$^3$. The fluid has a density of $\rho_f = 1$ kg/m$^3$. Three different dynamic viscosities ($\mu_f = 0.2$ ; 1.0; 5.0 Pa s) were examined, being in the laminar range.

A uniformly distributed load of 30 N/m is applied during 0.5 s in order to excite the plate. Then, the plate is loaded by the reacting pressure resulting from the fluid flow. Figure 2 shows the x-coordinate of the moving free end of the flexible plate (point B). Calculated displacements of the free end of the plate for three different viscosities of the fluid are compared with those of Namkoong et al. [10], Gluck et al. [11], Tahereh et al. [12]. Slight discrepancies in the frequency and the amplitude of oscillation can be considered quite acceptable.

![Figure 1. Geometry of the vertical plate oscillation](image1)

![Figure 2. Displacements of the free edge of an oscillating flexible plate for fluid viscosity $\mu=5$ Pa·s](image2)

4. Venous valve with gap
A two-dimensional computational model of the popliteal venous valve geometry was constructed and studied. Abnormal venous valves with insufficiency were modeled with different gap width between leaflets: $r/R=0.06$, 0.08, 0.3 and 0.53, where $r$ is half of the gap width, $R$ is the vein radius. The vein diameter is $D = 10$ mm and the leaflet thickness is $h = 0.4$ mm [13] (Fig.3a).

The valve leaflets were assumed to be isotropic, linear elastic with Poisson ratio $v = 0.45$ and Young modulus $E = 2$ MPa and density $\rho_s = 1200$ kg/m$^3$ [13]. The blood was assumed to be Newtonian fluid with density $\rho_f = 1060$ kg/m$^3$ and viscosity $\mu_f = 0.004$ Pa·s [13]. A uniform velocity profile and a variation in the mean flow velocity during the cycle were specified at the inlet boundary [14] (Fig.3b). The cycle period $T = 1.7$ s. The velocity increase phase makes up 0.23T. The maximum mean flow velocity $V_{b\text{ max}} = 0.07$ m/s. A constant pressure was specified at the outlet boundary. The examined flow is laminar with Reynolds number $Re = \rho_fDV_{b\text{ max}} / \mu_f = 185$.

Numerical calculation results show that the amplitude of leaflet tip oscillations with a gap width $r/R=0.06$ is about 26% of the vein radius. The instant of maximum displacement is approximately in the middle of the cycle ($t / T = 0.48$). The amplitude of oscillations decreases with the gap width increase, and the instant of maximum leaflet displacement moves closer to the beginning of the cycle. There is practically no leaflet movement for the valve with gap width $r/R=0.53$.

An intense forward flow forms between the leaflets. There are two velocity maximums on the centerline of the vein with a small gap width: the first - between the leaflets, the second - between the vortices downstream the leaflets. But there is only one maximum for a big gap between the leaflets.

Figure 4 shows the venous valve vector velocity field at the instance $t = 1.2$ s. The closing leaflet moves with the reverse flow in its vicinity. The recirculation zone is observed behind the leaflet, in the expansion beyond the valve (sinus). The recirculation flow is more intensive for a small gap (Fig. 4a). Reverse flow is observed between the leaflets and along the vein wall. The maximum reverse velocity
is observed in the vicinity of the leaflet tips. In the narrow gap, it can significantly exceed the velocity at the valve inlet.

Figure 5 shows the variation in the maximum reverse velocity, during the cycle time for the valves of different gaps width. Reverse flow duration in the vicinity of the leaflet tip increases with the gap width. The reverse flow duration is the important diagnostic characteristic of venous valve insufficiency measured with ultrasound Doppler diagnoses.

Figure 6 shows an increase in reverse flow duration ($t_{\text{ref}} / T$) with the gap width. A rapid increase in reverse flow duration for a small gap width ($r/R < 0.2$) is replaced by its slow growth at a large gap width ($r/R > 0.2$).

**Figure 3.** Computational domain geometry of the venous valve model with mesh (a); variation in the mean flow velocity during the cycle (b)

**Figure 4.** The vector velocity field in the instance $t = 1.2$ s: $r/R = 0.06$ (a), 0.53 (b)
5. Conclusions
The reverse flow (reflux) duration increases with the gap width. It exceeds the half of the period for the valves with the gap exceeding 5% of its diameter and classified as strong reflux. Defined correlation between the blood flow changes and the valve geometry can contribute to understanding the details of the venous valve mechanics and develop new techniques for surgical correction of its insufficiency. The revealed regularity makes it possible to use reflux characteristics for indirect evaluation of the anatomical defect of the valve when choosing a method of treatment.

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