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Valve-induced nonlinearity in the lymphatic junctions

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1. Introduction

The lymphatic system is little known and less studied compared to the cardiovascular system. It is only recently that it has attracted the attention of scientists because of its important link with cancer proliferation. The lymphatic system consists of initial lymphatic vessels, which absorb lymph liquid, and collecting lymphatic vessels, which drain the lymph through the lymphatic network and its nodes (Moore and Bertram 2018; Padera et al 2016). Unlike the cardiovascular system, whose heart, acts as the central pump, that circulates blood in our body, the lymphatic network does not have a central pump. The pumping of the lymph is ensured thanks to synchronization between the contractions-relaxations of the walls of the lymphatic vessels and the opening-closing of the lymphatic valves, composed of two leaflets. These valves prevent backflow and ensure the unidirectional motion of the fluid. A malfunction of this system can lead to conditions such as lymphedema, which is a serious bad side effect in some cases of cancer treatment and currently has no cure (Scallan et al 2016; Zawieja 2009).

We are developing a fully coupled fluid-structure computational model using the lattice Boltzmann method to compute the fluid and the immersed boundary method to accomplish the fluid-structure interaction. The results obtained from 2D simulations for the performance of a T-junction are presented in this article.

2. Methods

Several models and numerical methods are used to model and capture the correct mechanics of the valves under flow (Li et al. 2019; Ballard et al. 2018; Wolf et al. 2021; Li et al. 2022; Bertram et al. 2014). In addition to the techniques already proposed in the literature, we suggest the use of bicuspid valves, composed of two leaflets, to prevent reflux. This study is motivated by recovering properly the dynamics of the lymphatic valves and that involves in the pumping of the lymph liquid through the network of the lymphatic vessels.

We are developing a fully coupled two-dimensional fluid-structure computational model to simulate the dynamics of a two-leaflet valve under channel flow. The lattice Boltzmann method (LBM) (Succi 2001) is used to compute the fluid flow using the `lbm2d` library (Kaoui 2024), and the immersed boundary method (IBM) (Peskin 2002) to couple the lymph flow with the mechanics of the valves. The valves are modeled with a spring network, where adjacent points are interconnected with a Hookean spring, with the stretching force and the restoring force.

3. Results and discussion

We focus our study on the fluid behaviour in a complex network of collecting lymphatic vessels. This study aims to understand the nonlinearity in pressure loss due to the presence of the valves and offers insights into their role in vessel mechanics. This helps to better understand the pumping of lymph in the collecting lymphatic vessels, which involve bifurcations and junctions that converge at the drainage channel. To do this, we started with a simple T-junction geometry with two inlets and one outlet with a valve at each inlet and at the outlet. We consider the vessel walls to be rigid, as we are primarily interested in the mechanics of the valve subjected to flow. The valves are deformable structures. Flow rates Q_1 , Q_2 and Q_{out} and pressures P_1 , P_2 and P_{out} are measured respectively at the inlets and at the outlet. We define $\Delta P = P_1 - P_{out}$ for representing the reference pressure difference between the inlets and the outlet of the tested geometry. The Poiseuille law that relates the flow rate Q directly to the pressure drop ΔP by $\Delta P = R Q$ where R is the hydraulic resistance. In figure 1, panel a) shows the pressure field and the velocity's vectors developed in such geometry in presence of the valves. The pressure increases at the inlets where the valves are located. The panel b) shows the variation of the rate flow as a function of the pressure gradient for the two cases: with and without valve in the T-junction geometry and in the channel. In the case of having no valve, the flow rate increases linearly with the pressure. Whereas for the case with the valves, the flow rate increases in a nonlinear way with the pressure gradient, which reflects the effect of the presence of valves. The panel c) shows the distance of the gap between the two leaflets of the valve at the inlets and at the outlet. The gap increases nonlinearly with pressure gradient, similar to the flow rate. Furthermore, the effect of the variation of the elasticity of the valve is also investigated in such geometry, as we can see in panel d). We notice that by increasing the elasticity of the valve, the pressure difference increases. More the valves are rigid, more their resistance is bigger.

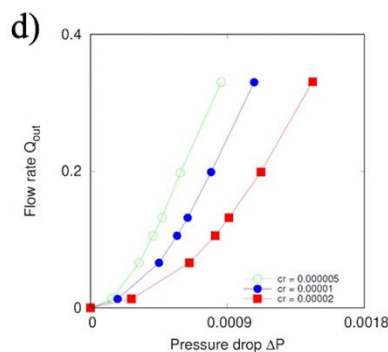
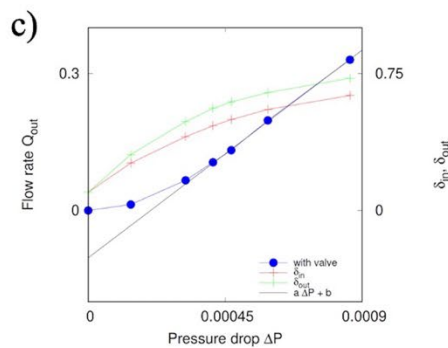
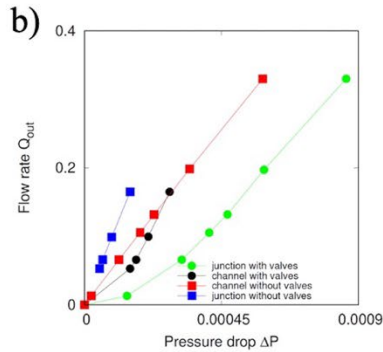
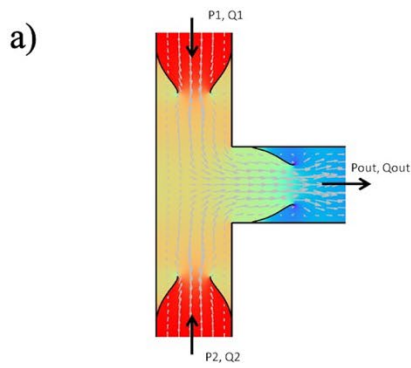


Figure 1: a) pressure and velocity in the T-junction in presence of the valves, b) the flow rate as a function of the applied pressure gradient in the T-junction, and in the channel with and without valves, c) the gap between the two valve's leaflets at the inlets and the outlet, d) effect of the variation of the valve elasticity.

4. Conclusions

We developed a numerical method in 2D that is capable of predicting the dynamics of the valve. These results suggest that the valve stiffness have an effect on overall lymph pumping performance. The outcome of this study will be used to further investigate the lymphatic valves dynamics encountered in the lymph pumping, and to elucidate the causes and emergence of the lymphedema.

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Conflict of Interest Statement

None.

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