Modelling of leukocyte motion in hepatic sinusoids using the Volume of Fluid (VOF) method

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Extract from the Supervisor's reference letter

… Leucocytes are hematic cells with a complex internal structure, which determines their mechanical behavior. Viscosity and deformability are key parameters when it comes to the cell dynamic behavior inside the microcirculation system. The Volume of Fluid (VOF) method is a free-surface modelling technique for tracking and locating fluid-fluid interfaces. The main goal of the project is to use the VOF method as a tool to generate a model for the motion of the leukocyte inside hepatic capillaries (sinusoids) - reproducing a totally physiological state - by modelling the hematic compartment as a biphasic fluid.

Starting from a 3D model of a portion of the hepatic micro-circulation system, obtained as a reconstruction from in vivo images, the Poiseuille law was used to define a lumped-parameter (l-p) model of the whole liver microcirculation system (3-Matic, Materialise). Then a simplified model was created, in which only one physical vessel was taken into account and the resistive components were embedded into the previous l-p model. Steady-state CFD simulation were carried out to analyze the hemodynamics behavior in the liver microcirculation (Fluent 16.0, Ansys).

The VOF method was used to investigate the motion of a cell inside hepatic sinusoids. The influence of the characteristic parameters of the model was separately investigated, setting the velocity of the primary phase, the channel diameter, and the viscosity of the cell to their physiological values ($v = 300$ μm/s, $d = 12$ μm, $\mu = 100$ Pa· s). Two different kind of cells were modelled in order to analyze the effect of cellular viscosity on quantitative outputs: red blood cells (RBCs), with cellular viscosity of 0.0045 Pa s in accordance with the computational studies found in literature, and leukocytes, with cellular viscosity of 100Pa s in accordance with the experimental evidences.

The similitude theory (π-theorem) was applied to create a scaled model aiming at reducing the computational cost of the simulations while maintaining the same flow regime as in the case study. Both Reynolds and Capillary numbers were used to characterize the flow regime. The system parameters were modified to guarantee the same values for these characteristic numbers. Once geometric, kinematic and dynamic similitudes are respected, a hemodynamic analysis can legitimately be run on the scaled model.

The outputs of the two models of liver microcirculation were compared both qualitatively and quantitatively. Quantitative outputs of the simplified l-p model are consistent with the physiological ones: the proposed model therefore correctly represents a complete lobular microcirculation system. It can be used to simulate sinusoidal hemodynamics and to study the system response for a number of regime situations.

After the evaluation of the sinusoidal hemodynamics, the applicability of the similitude theory to model biphasic fluids with the VOF method was verified. The outputs of the base model were compared to those of its scaled version: the velocity field of the scaled model is exactly equal to the real one multiplied by the scale factor and the cellular dynamics of the scaled model is identical to the one observed in the base model, at the same dimensionless time T.

The effect of cellular diameter and viscosity and the velocity of the primary phase on the proposed model were investigated; outputs were compared to similar situations from the literature. The results are similar to those found in literature, proving the efficiency of the VOF method to analyze different kinds of situations.

Then, two computational models representing in-vivo conditions were defined, and the effect of the different cell viscosity on quantitative outputs was carefully studied.

In the RBC-model ($\mu = 0.0045$ Pa· s) a low-viscosity cell, dragged by the primary phase, follows a rectilinear trajectory, at a constant distance from the central axis. The cell also warps into a "parachute" configuration, which is consistent with the physiological behavior of red blood cells.

In the Leukocyte model ($\mu = 100$ Pa· s), the cell migrates towards the channel wall, reaching a position of 'quasi-adhesion' and preserving its typical spherical shape. These results are consistent with the physiological behavior: in the case of reasonably large vessel diameter, and in the absence of any inflammatory response, in-vivo leukocytes remain spherical.

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ISBN: 978-88-6296-000-7