COMPUTER-AIDED ANALYSIS OF THE INFLUENCE OF PSEUDOINTIMA FORMATION ON TEXTURED IMPLANT SURFACES

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Introduction

Modifications of the biomaterials surface in medical applications currently offer enormous possibilities for the specialization and functionalization of biomaterial-tissue connections. Appropriate selection of physicochemical properties and topography of the surface allows for a stable connection of the implant with the peri-implant tissue. In the clinic the use of a porous layer of hydroxyapatite in cementless endoprostheses increases the biomechanical potential of contact at the implant-bone interface and affects the rate of protein adsorption. In Mechanical Circulatory Support (MCS) devices textured surfaces has proven that appropriate topography allows controlled scar tissue formation, which results in a reduction of inflammatory processes and limitation of thromboembolic events. The interaction of an implantable biomaterial with living tissue is a very sensitive phenomenon, which in a very short time triggers a cascade of events resulting in cell attachment. The high energy at the implant/tissue interface is stabilized by the adsorption of ions, molecules and/or macromolecules such as proteins. The development of a natural protein biofilm on the surface of the implant allows for increased biocompatibility. The use of porous surfaces in MSC devices in the dynamic blood flow channels allows pseudointima formation, which results in a reduction of shear stresses. Pseudointima is resistant to thrombogenesis and in currently used constructions its formation is promoted by titanium microspheres and a fibrillar texture. The developed neointimal surface is mainly composed of collagen as well as cells derived from circulating progenitors of fibroblasts, myofibroblasts, monocytes, macrophages and endothelial cells. The biological mechanism of pseudointima formation is a complex phenomenon. There are also no reports in the literature describing this phenomenon using computer-aided numerical methods to enable optimization of surface parameters at the device design stage.

Materials and Methods

As part of the project, numerical analyses were performed to assess the impact of pseudointima formation on shear stresses in a simplified blood flow system. The main goal was the development of discrete phase model to simulate the phenomenon of backfilling porous surface by red blood cells (RBC) during blood flow. The blood behaviour in Langrangian view was examined on the basis of the particle tracking of RBC of blood plasma flow. However, the blood plasma behaviour was considered in Eulerian view based on the assumption of a finite volume (FV) element in the fluid flow path. During all analysis, many models of lab-on-chip were developed including three FV models to compare the effect of boundary conditions with and without roughness and their influence on blood velocity and generated shear stress. Moreover, four discrete phase (DP) models were created to compare the roughness effect and irregular morphology of surface on RBCs concentration during blood flow, velocity and time of particles distribution. Simulations were performed in Ansys software. The mesh of FV model of lab-on-chip (μ-Slide I Luer channel, IBIDI) [1] was composed of about 1 milion nodes. The mesh quality parameters - assessed on the basis of skewness, aspect ratio and element quality - were excellent. There were six layers of prism elements near walls of the model. The pressure-based solver and absolute velocity formulation were selected for computational purpose. The pressure-velocity coupling scheme of the solution was selected for computation with spatial discretization using gradient and transient formulation. Discrete phase model [2] was applied in Ansys Fluent and RBCs are able to interact with blood plasma [3]. The diameter of RBCs is assumed from 5 μm to 10 μm using statistical diameter distribution and the average diameter is 7.5 μm [4].

Results and Discussion

The introduction of roughness as a boundary condition in the DP model was preceded by an analysis of its influence on the computed results using FV method model of blood flow applying non-Newtonian power law. The influence of roughness on RBCs flow results using DP models was more visible than in the analysis of blood flow results using FV method models. The values of velocities and shear stress were significantly decreased in DP models of lab-on-chip with roughness. On the other hand, the concentration of RBCs was increased in the case of DP model with roughness near the bottom plane of the middle channel. The comparison of results reached by applying DP lab-on-chip model with cubes and without them indicates the significant decrease in values of shear stress and velocity, as well as the significant increase in values of particle concentration.

Conclusions

The introduction of roughness as a boundary condition in the FV method lab-on-chip model led to a reduction in shear stresses and a slower flow. The introduction of the same roughness parameters as a boundary condition in the DP method lab-on-chip model also led to a reduction in shear stresses and flow limitation, which additionally resulted in an increase of DP model concentration of the RBCs in the bottom part of the model. The arrangement of cubes on the lower surface of the lab-on-chip channel with a height of more than 100 μm organizes the flow of RBCs. The cubes have a strong influence on shear stress, velocity and DP model concentration of particles. The values of shear stress and velocity are decreased, whereas the values of particle concentration increased.

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