Bioparticle separation in microfluidic devices: a numerical study on the role of viscoelastic properties and inertia

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Over the past few years, the development of diagnostic and therapeutic devices for bioparticle separation was promoted by significant advancements in the field of microfluidics. In the context of multiphase biological flows, inertial microfluidics has become a very attractive separation method because (i) it does not require any external force to sort cells; (2) it reduces the possibility of contamination due to the limited sample handling; (iii) it has a high throughput. The particle migration is affected by competing forces that can induce a particle displacement in the direction of the microchannel centerline or towards the walls. The migration is also strongly influenced by the viscoelastic properties of the bioparticles. In this context, reliable fluid-dynamics models are essential to predict the final equilibrium position of the bioparticles when they flow in microchannels. This is essential to effectively design microfluidic devices able to sort bioparticles or, for instance, distinguish healthy and diseased cells.
In this context, the Lattice-Boltzmann Immersed-Boundary (LB-IB) method has emerged as an effective technique to model the transport of deformable particles in a fluid flow [1]. In the classical LB method, the fluid pressure and density are linked by a linear relationship. When a large pressure difference exists between the inlet and outlet of the separation device, as it is for the flow conditions typical of inertial microfluidics, this linear relationship leads to a non-physical fluid density increase that does not satisfy the fluid continuity equation. To overcome this problem, we implemented a fully-incompressible version of the LB method suitable for the bioparticle transport in microfluidic devices driven by large pressure differences.
The goal of this study is to provide an accurate investigation of bioparticle transport both in Stokes and inertial flow regime and elucidate the role of the bioparticle viscoelastic properties in the migration dynamics. To achieve this goal, we developed a FSI framework in which the BGK-Lattice-Boltzmann (BGK-LB) method was used to solve the Navier-Stokes equations coupled with a Finite-Element (FE) model for structure dynamics to describe the evolution of rigid and deformable bioparticles [1]. The FE model versatility allows to compute the stress tensor starting from any strain energy function, thus bioparticles with different mechanical properties can be modeled, such as red blood cells (RBCs) or cancer cells. The Immersed-Boundary method was used to impose boundary conditions at the fluid-solid interface and the time advancement is performed with a weak-coupling strategy.
The proposed FSI framework was validated by computing the evolution to steady-state of both a purely elastic vesicle and a viscoelastic RBC subjected to a linear shear flow at Stokes regime. The deformation of both bioparticles compared very well with benchmark data present in the literature [2, 3]. Next, we performed a set of simulations to investigate the migration of an off-centered RBC subjected to a bounded shear flow at Stokes flow regime which is a good reference case to model the transport of cells in channels. The final equilibrium position and the time scale of the migration were studied as a function of the RBC membrane deformability, viscosity contrast and RBC membrane viscosity. For the tested parameter space, the RBC migrated close the channel centerline, but the migration time scale was sensitive to the viscoelastic properties of the RBC membrane.
Lastly, we carried out a study to evaluate the influence of flow and structural characteristic parameters to the migration dynamics of vesicles in straight and spiral microchannels. In straight microchannels, softer vesicle migrated in the center of the microchannel, whereas stiffer vesicles found a stable equilibrium position on the diagonals of the microchannel cross-section. This qualitative behavior was enhanced for flows at higher Reynolds number. In curved microchannels, stiff particles showed that same behavior as in straight microchannels, even though the radial migration is slowed down by the centrifugal forces due to the curvature. The equilibrium position is still on the diagonals, but further away from the center of the channel. Instead, the softer vesicle reached an off-centered stable position far from the both the channel center and the diagonals. These preliminary results proved the validity of our framework and provided useful data to design microfluidic devices for cell-sorting applications.

Acknowledgments
The study is part of the project “Tumor Immunotherapy by Nanotechnology (TITAN)”, and it was financially supported by the grant PON ARS01_00906.

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