A novel two-layer, coupled finite element approach for modeling the nonlinear elastic and viscoelastic behavior of human erythrocytes

Abstract:
A novel finite element approach is presented to simulate the mechanical behavior of human red blood cells (RBC, erythrocytes). As the RBC membrane comprises a phospholipid bilayer with an intervening protein network, we propose to model the membrane with two distinct layers. The quite complex characteristics of the very thin lipid bilayer are represented by special incompressible solid shell elements and an anisotropic viscoelastic constitutive model. Properties of the protein network are modeled with an isotropic hyperelastic third-order material. The elastic behavior of the model is validated with optical tweezers studies with quasi-static deformations. Employing material parameters consistent with literature, simulation results are in excellent agreement with experimental data. Available models in literature neglect either the surface area conservation of the RBC membrane or realistic loading conditions for the optical tweezers experiments. The importance of these modeling assumptions, that are both included in this study, are discussed and their influence quantified. For the simulation of
the dynamic motion of RBC the model is extended to incorporate the cytoplasm. This is realized with a monolithic fully coupled fluid-structure interaction simulation, where the fluid is described by the incompressible Navier-Stokes equations in an arbitrary Lagrangian Eulerian framework. It is shown that both membrane viscosity and cytoplasm viscosity have significant influence on simulation results. Characteristic recovery times and energy dissipation for varying strain rates in dynamic laser trap experiments are calculated for the first time and are found to be comparable with experimental data.

Stichworte: Red blood cells; Finite Elements; Cell Membrane; Laser traps; Fluid-structure interaction

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