Computational Modeling of Bio-Fluid Mechanics of White Blood Cells

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Abstract

The white blood cell is a soft biomaterial that exhibits unique behavior when exposed to the action of a flowing fluid. This behavior often determines the structure-function relationships of the cell-fluid system and gives information on many important processes taking place in living systems. The equilibrium behavior of leukocytes in solvent is relatively well known, but their dynamics is not yet investigated extensively. In the present paper, the cell is modeled as a viscous fluid that moves in a surrounding less viscous fluid. The dynamics of large-scale deformations of the leukocytes in a given flow field is investigated. In particular; the micro-pipette aspiration of leukocytes is analyzed; and the adhesion dynamics of leukocytes to ligand-coated surfaces is modeled and simulated within the framework of finite-difference/front-tracking methodology developed by Unverdi and Tryggvason[1]. To solve the Navier-Stokes equations we use a fixed, regular, staggered grid and discretized the momentum equations using a second-order central difference scheme for the spatial variables and an explicit predictor-corrector, second-order projection time-integration scheme.

The first test case concerns with aspiration of a two dimensional leukocyte into a micro-pipette. Blockages are inserted into computational domain by treating the selected grid cells as solid body to model the micro-pipette walls.The evolution of the shape of the leukocyte during aspiration into the micro-pipette in a pressure driven shear flow and the corresponding pressure contours are shown in Fig.(1). In this test case the suction pressure is set to 2 kPa. The density of the cytoplasm and the surrounding fluid are set to $10^{12} kg/m^3$ in order to relax the stability constraint for time step. Although this density value is unrealistically large, it doesn't have any significant effect on the flow dynamics since care is taken to keep the effective Reynolds number sufficiently small so that flow is always in the Stokes' limit. Many researchers have studied micro-pipette aspiration cases; and the present results are found to be in good agreement with those of Agresar[3].

Next the events such as attachment, detachment, and rolling of leukocytes in shear flow are studied. In this case, the nucleus of the white blood cell is also modeled as a compound drop to improve the present model.The detachment and following rolling of the leukocyte (modeled as a compound drop) on the enodthelium in a pressure driven shear flow is demonstrated in Fig.(2). At the receptor-ligand level, the kinetic model proposed by Dembo[2] is used in which a bond molecule is mechanically represented by a spring and a reversible kinetic approach is used to describe the association and dissociation of bonds.

The final version of the paper will also present an improved version of the compound drop model which includes linear springs between the nucleus and cortex in order to better represent the response of the leukocyte to deformation.

References

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[3] G. Agresar, J. J. Linderman, G. Tryggvason, and K. G. Powell An Adaptive, Cartesian, Front-Tracking Method for the Motion, Deformation and Adhesion of Circulating Cells. *J. Comp. Phys.*, 143:346–380, (1998).

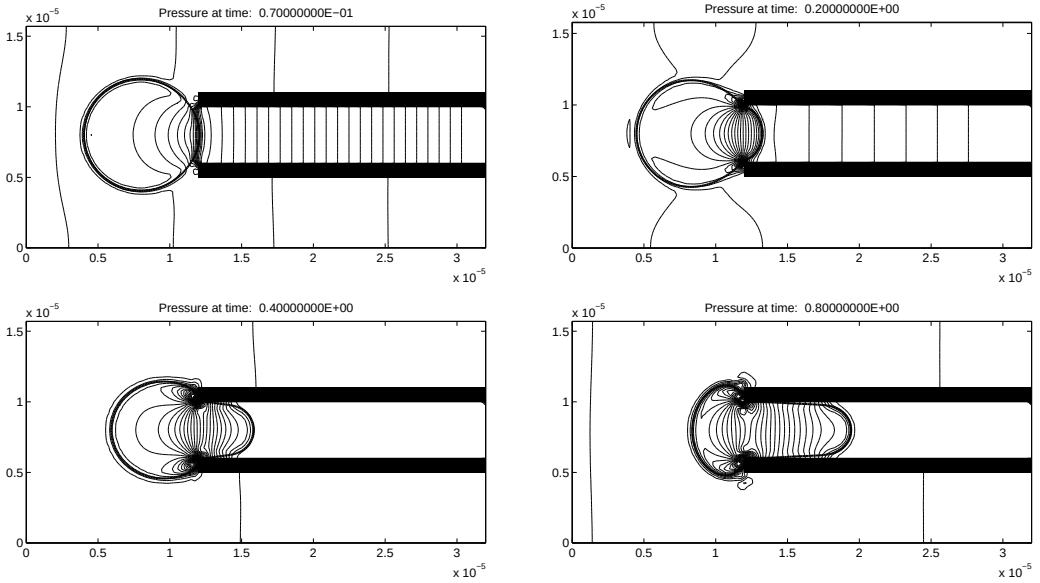

Figure 1: Pressure contours of leukocyte modeled as a Newtonian drop entering a micro-pipette with a suction pressure of 2kPa.

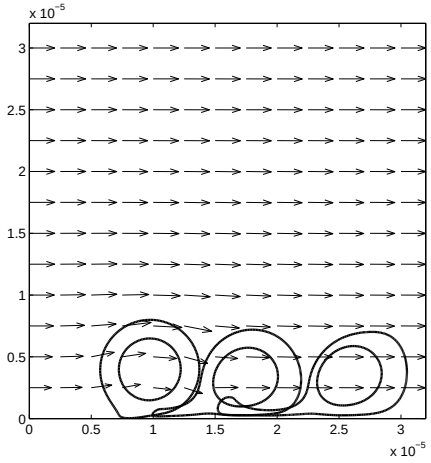

Figure 2: Snapshots of the detachment and following rolling of the leukocyte modeled as a compound drop on the endothelium in a pressure driven shear flow. The arrows show the velocity vectors plotted at every 10 grid points