FORCES ON AN ADHERING CELL

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Summary A basic 2D numerical model has been developed to gain insight into the surface deformations and forces experienced by an adhering, elastic cell in flows with negligible inertial effects. When adhering in unbounded uniform flow, the cell experiences a drag force that increases non-linearly with dimensionless velocity. When adhered to a plane wall in linear shear flow, the cell experiences a drag force that increases linearly, and a lift force that increases non-linearly, with dimensionless shear rate.

RESULTS

A critical function of certain blood cells is the ability to adhere to vessel walls. The bonds that form between the cell surface and the vessel wall allow the cell to decelerate from the blood flow and stably attach. Recent studies have utilised volume-of-fluid models or rigid models to study cell adhesion [1],[2]. These methods do not provide accurate representations of surface deformation and surface forces. The present study aims to provide some understanding of these properties during cell adhesion, and to determine the effect of the elasticity of the cell membrane.

As a first approximation, a blood cell is modelled as a neutrally buoyant, two-dimensional, elastic capsule of Newtonian fluid, suspended in a fluid of identical viscosity. In many blood vessels the inertial forces experienced by cells are very small. In this study the inertial effects are assumed to be negligible, facilitating the use of the boundary integral method. The numerical method used in this study is almost identical to that in [3].

The deformation of an initially circular cell is considered, both in uniform unbounded flow and in bounded linear shear flow. The cell is subjected to sudden flow at $t = 0$, with one node fixed to represent the formation of a bond. The cell then deforms until a steady state solution is reached.

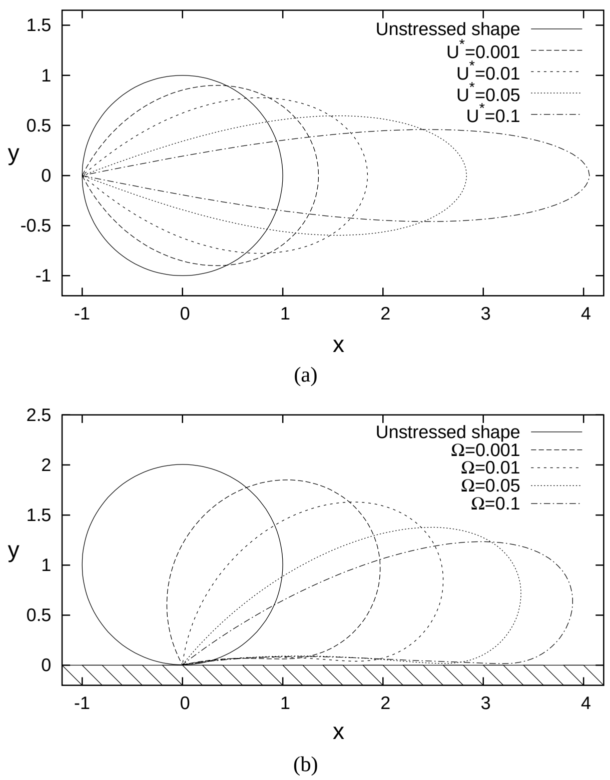


Figure 1. Steady-state profiles of an adhered cell a) in unbounded flow for various values of dimensionless velocity U^*, and b) above a horizontal plane wall at $y = 0$ for various values of dimensionless shear rate Ω.

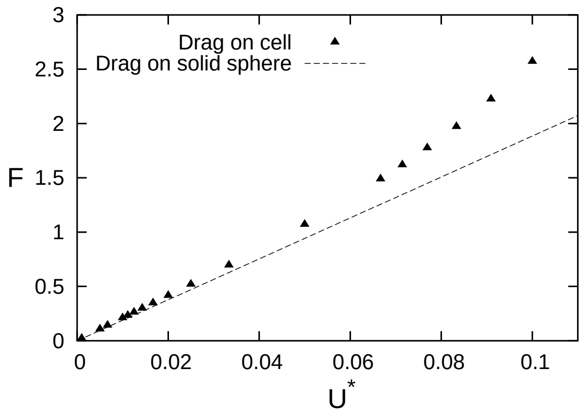
The evolution of the cell shape is governed by the dimensionless velocity U^* for unbounded uniform flow, and the dimensionless shear rate Ω for bounded linear shear flow. These parameters are defined as:

$$U^* = \frac{\mu U}{E}, \qquad \Omega = \frac{\mu k a}{E}, \tag{1}$$

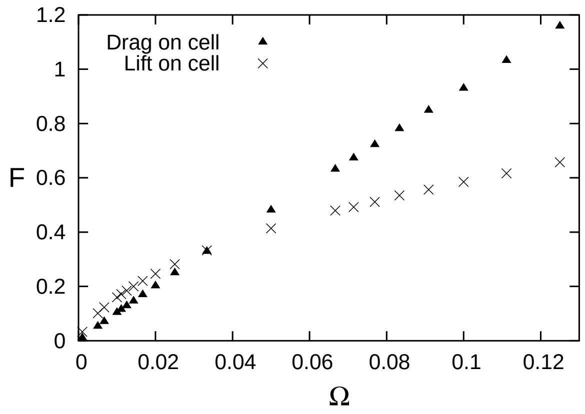
where μ is the fluid viscosity, E is the Young's modulus of the cell membrane, U is the free-stream velocity in the unbounded flow and k is the shear rate in the bounded flow. U^* and Ω are physically equivalent, representing the ratio of viscous forces to elastic forces.

Figure 1 shows a collection of steady-state shapes for various values of U^* and Ω. As U^* increases in the unbounded, uniform flow, the cell adopts a more streamlined, teardrop shape. Above $U^* = 0.12$ no steady-state shape is reached and the cell is assumed to have burst. As Ω increases in the bounded, linear shear flow the cell gets drawn out into a flatter shape along the wall. No evidence of bursting is found over the range of Ω studied.

Figure 2 shows the magnitude of the dimensionless forces acting on the adhered cell for both the unbounded and bounded flows. In unbounded, uniform flow the drag force on the adhered cell increases non-linearly with U^*, in contrast to the



(a)



(b)

Figure 2. Steady-state forces on an adhered cell a) in unbounded flow, and b) above a wall.

drag on a solid sphere which increases linearly. As $U^* \to 0$, the force on the cell in unbounded flow approaches the force on a solid sphere in uniform flow. For $U^* > 0.05$ the drag on the cell is noticeably higher than on a solid body, demonstrating that the elasticity of the cell membrane leads to an increase in drag.

In bounded linear shear flow the adhered cell experiences a lift force away from the wall, and a drag force in the direction of the flow. The drag force increases linearly with Ω, in contrast with the drag force in unbounded flow which increases in a non-linear manner. The lift force acting on the adhered cell in the bounded flow also displays a non-linear increase with Ω. The lift force away from the wall acting on the cell may negate the formation of subsequent bonds with the vessel wall. The presence of a lift force is in contrast to a rigid particle above a wall in Stokes flow, which experiences no forces perpendicular to the wall due to the reversible nature of the linear Stokes equations. Both the presence of a lift force and the non-linear nature of the drag force with Ω can be attributed to the elastic membrane of the cell. For $\Omega < 0.033$, the lift force on the cell is greater than the drag force. When $\Omega > 0.033$, the drag force becomes the dominant force acting on the cell.

This study has demonstrated that the presence of an elastic membrane has a non-trivial effect on the forces acting on an adhering cell. An adhered cell in uniform unbounded flow experiences a drag force which increases non-linearly with dimensionless velocity U^*, due to the elastic membrane. For the cell adhering to a wall in linear shear flow, the effect of the elasticity of the membrane manifests itself in the presence of a lift force, which increases non-linearly with dimensionless shear rate Ω.

Proposed future research includes a more realistic representation of the interior of a cell, and the development of a three-dimensional cell adhesion model.

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