DEFORMATION OF VESICLES FLOWING THROUGH A CAPILLARY

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Summary Giant vesicles are closed, deformable membranes which can be a useful model when trying to understand the fluid mechanics and rheology of cell suspensions, such as blood. The flow of giant vesicles through cylindrical capillaries is experimentally investigated. Vesicles (20 to 50 microns in diameter) are deflated with reduced volumes between 0.8 and 1. Both interior and exterior fluids are sugar solutions with viscosities close to 1 cP. Vesicles are aspirated into a capillary tube with a diameter close to the vesicle size and a constant flow rate is imposed. Significant deformation of the membrane occurs, with vesicle shapes such as ellipsoids, bullet shapes or parachute shapes. We quantitatively investigate the deformation as a function of velocity, reduced volume and confinement. The mobility of vesicles (ratio of their velocity to the average velocity of the carrier fluid) is also studied and consequences on flow resistance are discussed.

INTRODUCTION

The motion of deformable particles in a flow has led to a considerable amount of work in various contexts. From a mathematical viewpoint, it is a challenging problem because of the non-locality of the problem and the existence of moving boundaries. Deformable objects govern the rheology of various fluids and mixtures, such as emulsions, suspensions of droplets or bubbles, or blood. In addition, the mechanical response of cells to hydrodynamical stresses is potentially important in many biological processes.

Giant Unilamellar Vesicles (GUV) are closed membranes made of a phospholipid bilayer enclosing a fluid. They can be considered a rough model of biological cells, especially red blood cells which do not have a nucleus.

Many studies have been devoted to microchannel flows of objects such as drops or bubbles [1], capsules [2,3], and in-vitro measurements have been made on blood [4]. As opposed to capsules, whose membranes are elastic solids, the vesicle membrane is an almost incompressible bidimensional fluid, with a bending energy that governs its equilibrium shape [6]. Those properties also significantly differ from simple interfaces characterized by a surface tension. We report here an experimental study of vesicles flowing through narrow capillaries.

EXPERIMENT

Giant unilamellar vesicles were prepared by the electroformation method [5] with *L* - α phosphatidylcholine (DOPC) in a 280 mM sucrose solution (interior fluid). We obtained vesicles with diameters between 10 and 70 μm. The vesicle suspension was then diluted in a 320 mM glucose solution (exterior fluid) which has a slightly higher osmolarity than the interior solution. After a while, vesicles are slightly deflated with reduced volumes between 0.9 and 1 (reduced volume v is defined as the ratio of the final volume of a vesicle to the volume of a sphere with the same surface area). Both interior and exterior fluids have viscosities close to 1 cP and densities close to 1 g/cm^3.

The suspension of deflated vesicles was placed in a chamber made of two parallel glass slides separated by teflon spacers (1.5 mm thick). One side of the chamber was kept partly open to allow the introduction and micromanipulation of a glass micropipette (diameter: 40-50 μm) connected to a microsyringe attached to a syringe pump. The experimental chamber was placed on an Olympus IX71 inverted microscope equipped for phase contrast microscopy with a 40x objective lens. A COHU video camera was used to capture images which were analyzed with Scion Image software.

Vesicles were individually sucked up into the pipette and a constant flow rate was set via the pump, leading to a stationary flow of vesicles in the pipette, at speeds up to 300 μm/s.

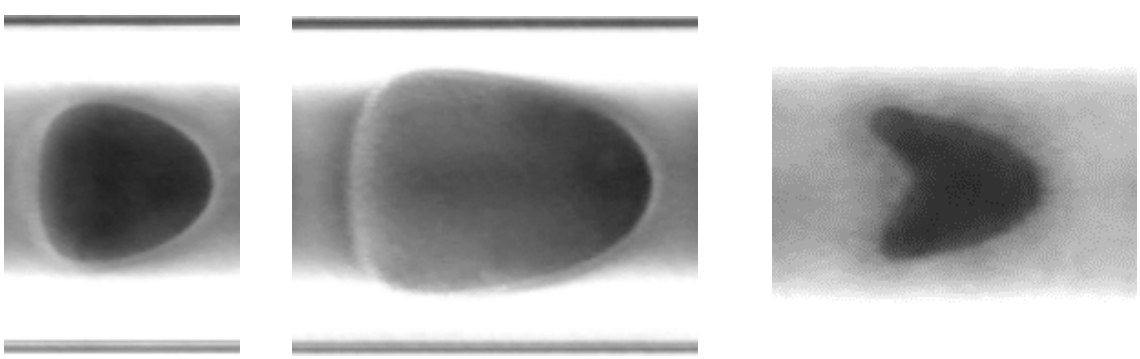

Fig. 1: Vesicles flowing through a capillary (from left to right). Pipette walls are visible on the first two pictures.

OBSERVATIONS

Since their density is close to that of the surrounding fluid, and because they experience a lift force that pushes them away from the wall, vesicles stay along the centerline of the pipette and an axisymmetric situation is obtained. Depending on various parameters such as reduced volume v, velocity U or ratio λ of vesicle radius to pipette radius, a variety of axisymmetric shapes is obtained as shown on Fig. 1.
At rest, vesicles with reduced volumes in the range 0.9 – 1 have an approximately prolate ellipsoidal shape dominated by Helfrich bending energy [6]. As soon as a flow is imposed, significant deformations of the membranes occur and the fore-aft symmetry is lost, with a decreasing curvature at the trailing end, possibly leading to concave shapes.
We characterize deformations by measuring the displacement of the vesicle's center of mass relative to its middle point on the symmetry axis. The ratio of this displacement to the vesicle's half-length defines an eccentricity a.

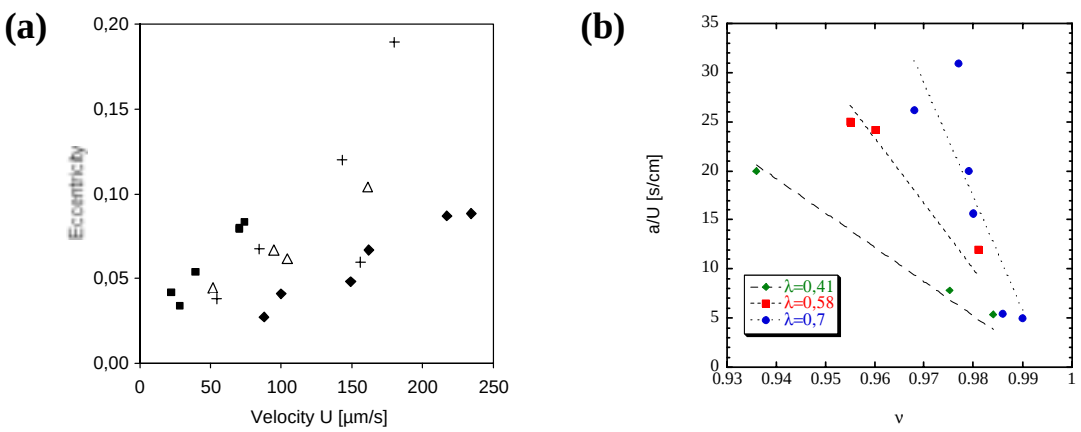

Fig. 2: (a) Eccentricity a vs. Velocity U for various vesicles. (◆): v=0.975, λ=0.397; . (△): v=0.980, λ=0.684; . (+): v=0.971, λ=0.666; . (■): v=0.982, λ=0.604; (b)a/U vs. v for various values of confinement λ.

The influence of velocity U on deformation is directly illustrated on Fig. 2(a). Eccentricity a is a roughly linear increasing function of velocity. Eccentricity is also a decreasing function of v and an increasing function of the confinement λ as shown on Fig. 2(b): vesicles that are more confined and more deflated are significantly more sensitive to shear stresses. If the reduced volume is sufficiently small (around 0.9), vesicles can exhibit a semi-concave shape under flow which is reminiscent of shapes of red blood cells in capillaries.
We also measured the ratio of the vesicle velocity U and average fluid velocity V (as imposed by the pump). As for other systems of particles flowing through tubes, such as drops or capsules [1,2,3], the vesicle velocity is higher than the average velocity V (but lower than the maximum velocity on the axis for a Poiseuille-like pipe flow). We find that the vesicle mobility U/V follows closely an asymptotic result obtained for small, rigid particles [1]:

$$\frac{U}{V} \approx 2 - \frac{4\lambda^2}{3}$$

Because of the axial symmetry of the problem, there cannot be any membrane flow, and thus the vesicle behaves like a solid particle once it has reached its stationary shape. An analysis of relevant dimensionless numbers shows that the membrane bending modulus is very small compared to viscous forces, while the stretching modulus is so large that the surface area of the vesicle must remain constant during the deformation, unlike capsules [2,3] which have a relatively lower elastic modulus. Vesicles appear to be unique objects with a constant volume, constant surface area and very flexible boundary, whose properties cannot be rescaled to be described by a macroscopic system in the same range of dimensionless numbers (Re, Ca…).
The presence of an object in pipe flow is responsible for an additional pressure drop. As a consequence of vesicle deformability, stronger deformations occur upon increasing velocity, which lead to a decrease of the additional pressure drop. A shear-thinning behavior of vesicle suspensions in microchannel flow follows. These phenomena, currently under investigation, are relevant to the rheology of blood in microcirculation.

References

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