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USING ACTUATED CILIA TO REGULATE MOTION OF MICROSCOPIC PARTICLES

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INTRODUCTION

Marine animals use microscopic elastic filaments, or cilia, to capture food particles that are suspended in the surrounding solution [1, 2]. In the respiratory tract, active cilial layers facilitate the transport of particulates such as dust or mucous. These motile cilia experience the surrounding fluid as a highly viscous, low Reynolds number environment, where the effects of inertia are negligible [2]. Nevertheless, by oscillating in a periodic, time-irreversible manner, the elastic cilia can generate net currents within the fluid and thereby, effectively transport and direct microscopic particles. The behavior of these biological cilia provides a useful design concept for creating microfluidic devices where actuated "synthetic cilia" would regulate the movement of micrometer-sized particles, such as biological cells and polymeric microcapsules.

COMPUTATIONAL MODEL

To capture the complex fluid-structure interactions in this multi-component system that encompasses oscillating cilia and a suspended particle, which are immersed in a viscous fluid, we employ our hybrid "LBM/LSM" approach [3], which integrates the lattice Boltzmann model (LBM) [4] for hydrodynamics and the lattice spring model (LSM) [5] for the micromechanics of elastic solids. Put succinctly, the LBM is an efficient solver for the Navier-Stokes equation. Via the LSM, we can fashion the cilia and the particle from a network of harmonic "springs", which connect nearest and next-nearest neighbor lattice nodes. To assess the dynamics of the nodes, we integrate the Newton's equation of motion for each node with the velocity Verlet algorithm. The two models are couplet through appropriate boundary conditions [3].

Our simulation box encompasses four elastic cilia attached to a solid surface and a neutrally buoyant particle with a radius R, which is initially placed between the cilia. The length of cilia is L=4R and the inter-cilium separation is 3R. The box is filled with a viscous fluid and has periodical boundaries in the directions parallel to the substrate. The elastic cilia oscillate periodically due to a sinusoidal, horizontal force applied to their free ends.

To characterize the elastohydrodynamic behavior of beating cilia we introduce a sperm number $\mathrm{Sp} = L(\zeta\omega/EI)^{0.25}$, which characterizes the relative importance of the viscous force and the bending rigidity of oscillating cilia [6]. Here, $\zeta = 4\pi\nu\rho$ is the viscous drag coefficient, ω is the angular velocity of the driving force, and EI is the bending rigidity of the cilium. We set the fluid density $\rho = 1$ and kinematic viscosity $\nu = 1/6$ (in LB units), and vary ω to alter Sp. When Sp is relatively large, the dominant viscous effects suppress the wiggling of the elastic cilia, and consequently, no net fluid flow is generated. For relatively small Sp, the dynamic shape of the cilium is governed by its elasticity, leading to time-reversible oscillations that are unable to generate net flows at low Re. Only for intermediate values of Sp, where the effects of cilium elasticity and fluid viscosity are of comparable magnitudes, oscillating elastic filaments create net flows in the low Re environment.

RESULTS AND DISCUSSION

When a periodic force is applied to elastic cilia, the cilia bend back and forth in the oscillation plane and thereby induce the movement of the fluid. The viscous fluid, in turn, imposes a periodic drag on the suspended particle. As a result, the particle follows the oscillatory motion of the beating cilia.

Specific trajectories for the particle's center of mass motion are shown for Sp=3 and Sp=5 in Figs. 1(a) and (b), respectively; as expected, the particles follow oscillatory trajectories. Surprisingly, however, after a short initial transient behavior, the particles steadily migrate in opposite directions across the cilia layer. For Sp=3, the particle moves toward the bottom wall of the microchannel; when we increase the oscillatory

frequency to yield Sp=5, the migration direction is reversed and the particle moves away from the surface. In other words, by simply changing the oscillating frequency, the actuated cilia can direct solid particles to or away from the channel wall, thereby controlling transport processes inside the ciliated layer.

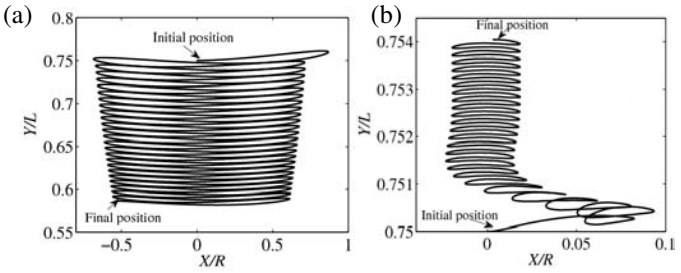

Fig. 1 Trajectory of particles during the first 25 periods of cilium oscillations for (a) Sp=3 and (b) Sp=5.

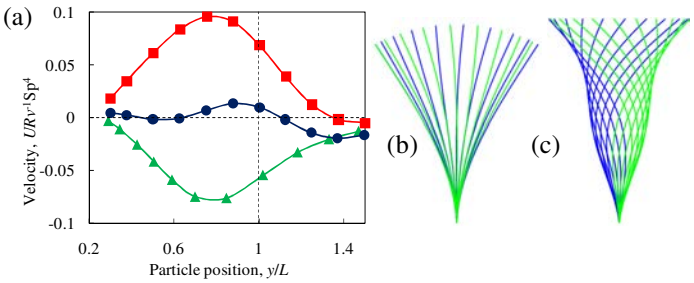

Fig. 2 Panel (a) shows velocity of particles as a function of distance from the bottom wall. The lines with triangles, circles, and squares show the particle velocities for Sp=3, Sp=4, and Sp=5, respectively. Cilium deformation during one beat cycle is presented in panel (b) for Sp=3 and in panel (c) for Sp=5. The blue lines show cilia when the force is directed to the right and the green lines show cilia when the force is directed to the left. For Sp=5, the horizontal deflection is magnified tenfold for clarity.

We characterize the particle migration inside the ciliated layer by measuring *U*, the period averaged velocity normal to the channel wall. In these simulations, we allow the cilia to oscillate up to 20 periods to avoid the effect of the initial transient behavior. The velocity is shown in Fig. 2a as a function of particle distance from the channel wall for different Sp. A positive velocity indicates that the particle is drifting away from the wall. We find that the drift direction indeed depends on the magnitude of Sp. Moreover, for both Sp=3 and Sp=5, the velocities do not change sign inside the layer and even slightly above the cilia tips; this behavior indicates that actuated cilia can transport these particles in a unidirectional manner all the way from the channel wall to the outer stream. Above the ciliated layer the effect of the beating cilia on the fluid flow eventually dissipates and the particle velocity decreases to zero. For Sp=4, the particle velocity is roughly zero across the layer and, thus, no particle migration takes place at this magnitude of Sp.

To gain insight into the effects that control the particle migration, we examined the oscillatory patterns for an individual cilium at both Sp=3 and 5. Figures 2b and c reveal that the cilium exhibits different dynamical behavior at these Sp. In particular, the change in Sp alters the mode of cilium bending. The oscillations for Sp=3 and 5 correspond to the first two oscillatory modes of a beating flagellum [7] and this motion generates traveling waves propagating along elastic cilia [7, 8]. These traveling waves, in turn, generate secondary flows in the fluid that transport the neutrally buoyant particles. Since the direction of the waves depends on the oscillations mode, the particles are transported in opposite direction across the cilial layer for Sp=3 and 5 [9].

SUMMARY

We show that actuated cilia can control the transport of microscopic solid particles near the substrates of microfluidic channels. For low frequency oscillations characterized by a sperm number of Sp=3, the cilia effectively draw particles from outside the layer and deliver these species to the underlying surface. For larger frequencies characterized by Sp=5, the cilia expel the particles and therefore, can be used to clean the ciliated surface from foreign entities and inclusions. Furthermore, our studies indicate that actuated synthetic cilia could be useful for manipulating and directing micrometer-sized particles in lab-on-a-chip applications.

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