The physics of cilia driven flows: efficiency, synchronization and flow sensing

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Cilia are hair-like cellular appendages that transport fluid by beating in an asymmetric fashion. They are responsible for the swimming and feeding of microorganisms, for mucous clearance in airways, left-right asymmetry establishment and many other physiological processes.

Energetic efficiency of swimming has long been considered a non-issue in microorganisms, but newer studies show that ciliates like Paramecium can use more than half of their energy for propulsion. In absolute terms their efficiency appears low, but the actually relevant question is how close they are to the theoretical efficiency limit. The theoretically optimal beating patterns, which we determined, show remarkable similarity with those observed in ciliated microorganisms. We can show that Paramecium has a propulsion efficiency that is within a factor of 2 of the theoretical optimum.

Knowing that metachronal waves represent an energetically optimal state, however, does not yet explain the mechanism of their coordination. A simple model with two spheres on tilted trajectories can reproduce the different synchronization regimes, but the generalization to a ciliated surface is still largely an open problem.

On a larger scale, ciliary flows are central in transferring the molecular scale chirality to the macroscopic asymmetry of the developing embryo. The detection mechanism, however, is not yet understood. We combined experimental data with flow calculations to assess the viability of the proposed mechanisms (chemical and mechanical detection). The low intensity and high spatial variability of the flow preclude mechanical detection with the observed robustness. Particle-based flow detection, on the other hand, is a viable mechanism if the particles are above a certain size.

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