How Corals Stir Seawater

A new model explains how the microscopic hairs carpeting corals coordinate their beating to shape fluid flow.

By **Vivek N. Prakash**

Motile cilia are microscopic hair-like structures that beat in coordinated patterns on cell surfaces. Ubiquitous in living systems, cilia generate fluid flows that drive transport, feeding, nutrient exchange, and waste removal. On coral surfaces, dense carpets of cilia play a central role in coral physiology. Despite decades of observations, a fundamental question has remained unresolved: How do thousands of microscopic cilia coordinate their motion to generate the complex 3D flows that mediate transport at the coral–water interface? In a new study, Siluvai Selvan of the University of Melbourne in Australia and his colleagues provide an answer by introducing a quantitative framework, validated through experiments, that captures the collective effect of ciliary motion [**1**]. Their work reveals how rotational motions of cilia combine to generate robust 3D flows, filling a long-standing gap in our understanding of how corals interact with their fluid environment.

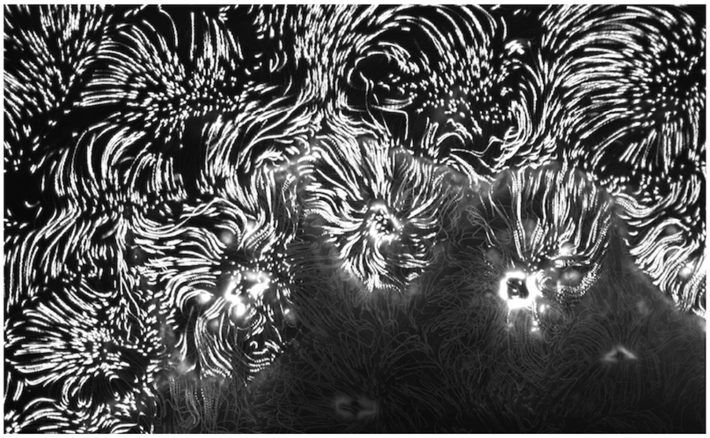

Figure 1: Ciliary flows around corals visualized using tracer-particle path lines. The technique entails seeding the surrounding seawater with neutrally buoyant tracers and illuminating them with a sheet of laser light.
Credit: S. A. Selvan *et al.* [**1**]

At the microscopic scales relevant to cilia, viscosity, rather than inertia, governs fluid motion [**2**]. In this low-Reynolds-number regime, the coordinated beating of cilia generates fluid flows that help a wide range of organisms move, capture food, and exchange metabolites with their environment [**3**]. Corals consist of hundreds to thousands of identical individual animals called polyps. Observational studies in the 1970s first documented organized patterns of ciliary currents on coral surfaces and revealed their dual role in transporting food particles toward the polyp mouths while rejecting sediment and other debris away from them [**4**]. Although these studies provided important qualitative descriptions, it remained unclear how the collective motion of microscopic cilia generates the organized, 3D flows surrounding coral polyps.

Recent experimental studies have begun to quantify these flows and to reveal their physical and biological significance. Ciliary activity generates vortical flows that enhance transport near coral surfaces and disrupt the diffusive boundary layer, increasing nutrient and gas exchange [**5**]. These flows regulate oxygen distributions, redistribute regions of high photosynthetic activity, and help maintain a stable microenvironment at the coral surface [**6**, **7**]. These findings have not filled the gap in our theoretical understanding. Classical theoretical approaches, which approximate ciliary carpets as continuous, moving surfaces, capture averaged features of flow generation but fail to resolve the discrete, localized structure of 3D flows arising from individual ciliary motion at surfaces [**8**].

To resolve this problem, Selvan and colleagues built on their own recent advances. They represented each beating cilium as a localized source of torque, a so-called rotlet, which generates a characteristic swirling flow in the surrounding fluid [**9**, **10**]. Whereas many low-Reynolds-number models of biological flows rely on point forces, or Stokeslets, rotlets instead represent localized torques that generate rotational flow. Rotlets more accurately capture ciliary-driven flows at surfaces, in contrast to force-based push–pull descriptions commonly used for swimming microorganisms [**10**].

Selvan and colleagues' approach was guided by new experimental measurements of ciliary-driven flows over coral surfaces, obtained from corals collected at Australia's Great Barrier Reef (Fig. **1**). By resolving the flows in orthogonal planes, the measurements revealed a recurring spatial structure linked to the underlying hexagonal organization of coral polyps. The researchers constructed a minimal yet predictive model of ciliary carpets by arranging rotlets across a surface in locally hexagonal patterns. Importantly, the model captures multiscale behavior by representing the collective influence of small groups of cilia through effective localized torques, enabling a tractable description of flows across scales.

Using this framework, Selvan and colleagues showed how arrays of ciliary rotations can generate robust 3D flow structures above the coral surface. These flows feature vertical transport and recirculating regions that cannot be captured by 2D or continuum descriptions. What's more, the flows strongly influence how particles are advected and mixed near the coral surface. Transport turns out to be controlled not only by large-scale flow patterns but also by near-field dynamics at the scale of individual cilia. These insights also enable the systematic exploration of how transport depends on ciliary organization and on its coupling to molecular diffusivity and external flow conditions.

By providing a predictive framework that links microscopic ciliary activity to macroscopic transport, Selvan and colleagues close a long-standing gap between observations and mechanistic understanding. Their approach also opens the door to addressing long-standing questions in coral biology, such as those concerning transport-limited processes that are thought to play a central role in growth, metabolism, and response to environmental stress. In turn, this reinforces a broader principle: Across living systems, fluid flows are not incidental but are central to biological function.

Beyond corals, the framework introduced by Selvan and colleagues opens new avenues for studying transport in a wide range of ciliated and active systems. By moving beyond continuum descriptions to discrete, multiscale representations of ciliary forcing, their framework provides a powerful approach for connecting physical processes to biological function. The work is particularly relevant to coral health and resilience, for which transport at the tissue surface plays a key role in mediating environmental stress. More broadly, the work highlights the opportunity for physicists to contribute to pressing biological and ecological challenges by uncovering the physical principles that govern living systems across scales.

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