Statement of Research Interest

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My research focuses on understanding the physics of fluid dynamics and nutrient transport in microscopic living systems. In particular, I use theoretical and computational approaches to model the flow fields generated by swimming and attached microorganisms and to analyze the spatiotemporal evolution of nutrient concentrations transported by these flows. My previous studies discussed three key research problems: (1) the benefits and limitations of life strategies – swimming versus attached – on nutrient acquisition in oceanic microbes; (2) the constraints imposed by flow physics and nutrient transport on the functional design of ciliated microorganisms; (3) the effects of environmental variations, such as local nutrient gradients, on feeding efficiency. Looking ahead, I am particularly interested in exploring collective phenomena in living systems, investigating how groups of cells or organisms coordinate their behavior to achieve complex emergent outcomes.

Previous Research

1. Benefits and limitations of life strategy – swimming versus attached – on nutrient acquisition in oceanic microbes. Nutrient acquisition is essential and challenging for oceanic microbes due to the patchy distribution of nutrients in their environments. To overcome these challenges, many of these microbes utilize coordinated the motion of cilia or flagella and enhance feeding rates. However, these small protists face an evolutionary trade-off: should they actively swim toward nutrient-rich zones, or remain attached to substrates and generate feeding currents to capture nutrients? Both the ”swim” and ”stay” strategies were independently proposed as the optimal approach in previous studies.

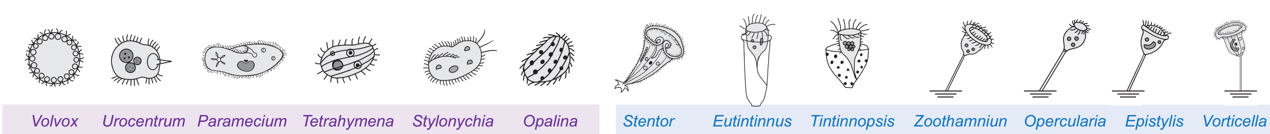

Figure 1: **Collection of** swimming (purple) and attached (blue) ciliates.

To investigate this debate, I developed mathematical models that objectively compare feeding rates in attached and swimming states under equivalent conditions. For attached ciliates, I utilized Blake's envelope model (Fig. 2A), treating cilia tips as a continuous surface. The surrounding flow field was derived by analytically solving the Stokes equation using a spherical harmonics expansion. Nutrient distributions around the ciliate were then modeled by numerically solving the advection-diffusion equation using Legendre spectral method (Fig. 2B). Nutrient intake, quantified by the Sherwood number (Sh), was computed using Fick's law on the model cell surface.

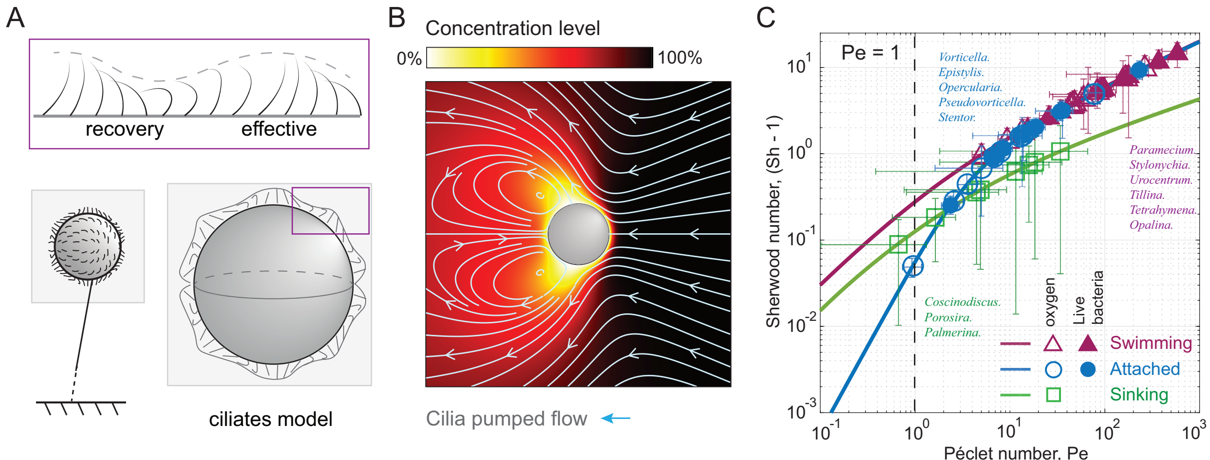

Figure 2: **Ciliate model and comparison of nutrient uptake.** (A) Envelope model applied to attached ciliate. (B) Streamlines (arrow lines) of surrounding fluid flow and the corresponding nutrient concentration field (colormap) by advection-diffusion transport. (C) Computations (solid lines) of shifted Sherwood number (Sh - 1) versus Péclet number in the logarithmic scale for the sinking (green) diatom and the swimming (purple) and attached (blue) ciliates. Pe numbers associated with experimental observations are superimposed in marks, and corresponding Sh numbers are calculated based on the mathematical model. Empty symbols are for oxygen diffusivity and the solid symbols correspond to the diffusivity of live bacteria.

To extend the analysis, I performed asymptotic analysis at extreme Péclet numbers, which represents the ratio of advection strength to diffusion strength in nutrients transport. With the analysis, I identified optimal cilia motion that maximizes nutrient intake of the attached ciliate and compared it to the performance of a swimming ciliate. These results were validated through PDE-constraint optimization computations [1]. Finally, by conducting a review of biological data on ciliates shape and flow, I found that, at high Péclet numbers, feeding rates of swimming and attached ciliates converge asymptotically, shown in Fig.2. This finding resolves a long-standing debate by showing that strategies can be hydrodynamically equivalent in their feeding efficiency [2].

2. Constraints imposed by flow physics and nutrient transport on the functional design of ciliated cells. Intracellular transport in unicellular eukaryotes, such as ciliates, is a highly organized and conserved process across diverse cell types. However, the external arrangement of cilia differs significantly between attached and swimming cells: attached cells typically feature a ring-like ciliary arrangement near the oral region, while swimming cells display a broader distribution of cilia across their surfaces (Fig.3A). This distinction raises a fundamental question: do optimal ciliary arrangements depend on a cell's life strategy – swimming or attachment?

To explore this, I extended the mathematical model developed in (1) and employed an inverse optimization approach to computationally examine the optimal configurations of ciliary coverage and oral region placement in model cells. My results reveal that, for a given energy cost, attached cell achieve optimal feeding with a ciliary ring positioned adjacent to the 'mouth', while swimming cells maximize feeding by distributing cilia across all non-oral surfaces (Fig.3C). These findings demonstrate that flow physics play a critical role in shaping the external functional design of cells. Interestingly, they also suggest that phagocytosis, which serves as a link between external and internal nutrient transport, becomes increasingly essential for larger cells [3].

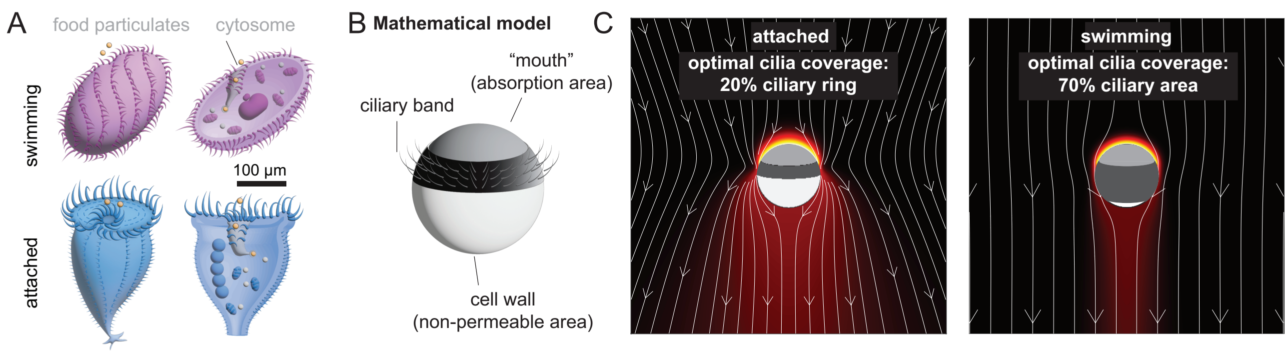

Figure 3: **Model and computational results** for optimal configurations of swimming and attached model ciliates. (A) Example of swimming and attached ciliates. (B) Mathematical model for variation of external design of ciliated cell. (C) Numerical results of optimal design for swimming and attached cells.

3. Effects of environmental variation in nutrient concentration on feeding. Oceanic microbes often inhabit environments with patchy or non-uniform nutrient distributions. To explore how ciliary motion should adapt to such conditions, I extended the nutrient transport model for ciliated cells to account for heterogeneous initial concentration fields (Fig.4). The analysis revealed that optimal nutrient intake requires adaptive orientation adjustments guided by local chemical gradients [4].

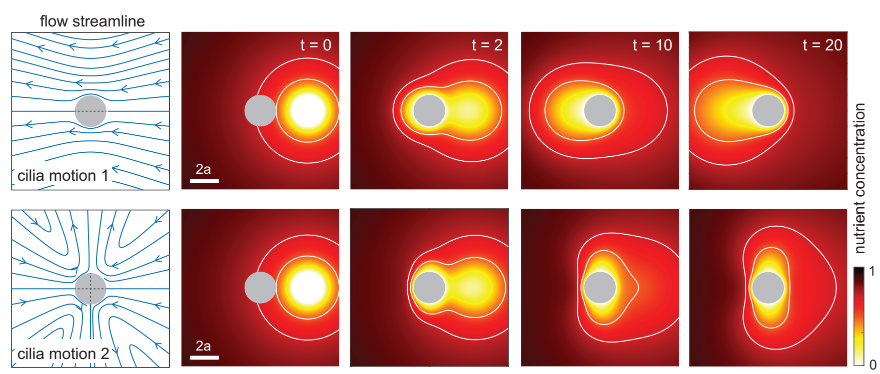

Figure 4: **Flow and nutrient concentration around attached ciliate in non-uniform nutrient background.** Streamlines (arrow lines) of fluid flow due to different cilia motion. Time evolution of nutrient concentration field (colormap) corresponding to each cilia motion.

This finding supports the hypothesis that ciliates may utilize chemical sensing cues to dynamically orient themselves for efficient feeding. Building on this work, I have begun exploring learning and control strategies for microswimmers, focusing on how chemical sensing mechanisms can guide navigation and improve feeding efficiency.

Undergoing Research

Cilia Synchronization and Flow Formation in a Closed Confinement Cilia-driven flows are crucial not only in marine microbes but also in embryonic developmental processes, such as the symmetry-breaking events that lead to formation of asymmetric morphology developments. These phenomena, observed in species like mice, Xenopus, and zebrafish, are closely linked to the directional fluid flow generated by coordinated ciliary motion.

My research focuses on understanding how cilia facilitate directional flow and the robustness of this flow formation in Kupffer's Vesicle of a zebrafish embryo. To model the flow, I consider a mathematical model that represents cilia tips as rotating point forces. The fluid flow was numerically simulated by using randomly distributed rotating Stokeslets within a spherical surface (Fig.5). By simulating cilia as oscillators, I investigated how phase synchronization emerges from hydrodynamic interactions and how this synchronization contributes to directional flow formation. My ultimate goal is to evaluate the robustness of these flows under stochastic variations in cilia placement. This project is currently undergoing detailed analysis and refinement.

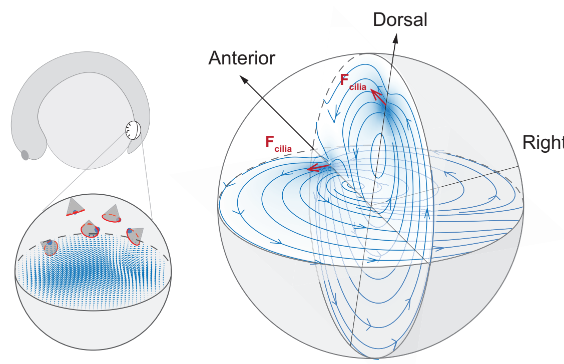

Figure 5: **Model cilia oscillation and cilia-driven flow** in a closed spherical confinement.

Future Plan

The transition of my previous research, from continuous to discrete modeling approaches for studying collective cilia motion, raised my interest in studying collective behavior in living systems. I am interested in investigating how groups of cells or animals coordinate and achieve collective motion, focusing on exploring control policies that enable adaptive behavior. Ultimately, I seek to uncover how group behaviors emerge or how collective decision-making arises from individual interactions. I plan to start with computational modeling, such as agent-based frameworks integrated with experimental observations, and progress toward incorporating theoretical perspectives, such as neuroscience, for a deeper understanding into these systems.

References

[1] Jingyi Liu, Yi Man, John H Costello, and Eva Kanso. (accepted) optimal feeding of swimming and attached ciliates. `https://arxiv.org/abs/2404.13467`, 2024.

[2] Jingyi Liu, Yi Man, John H Costello, and Eva Kanso. Feeding rates in sessile versus motile ciliates are hydrodynamically equivalent. https://elifesciences.org/reviewed-preprints/99003, 2024.

[3] Jingyi Liu, John H Costello, and Eva Kanso. Flow physics of nutrient transport drives functional design of ciliates. (under review).

[4] Jingyi Liu, Yi Man, and Eva Kanso. Nutrient transport in concentration gradients. https://arxiv.org/abs/2412.16408, 2024.