Why does the jumping ciliate *Mesodinium rubrum* possess equatorially located propulsive ciliary belt?

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Introduction

***Mesodinium rubrum* Lohman (*Myrionecta rubra* Jankowsky):**
(1) is a ubiquitous marine planktonic ciliate;
(2) has a remarkable unparallelled fast-jumping behavior;
(3) is a primary producer that is able to form red-water blooms.

***Mesodinium rubrum* body morphology:**
(1) Body size ~15-70 μm;
(2) Bifurcated oral tentacles;
(3) A hemispherical oral end, and a conical aboral end;
(4) An equatorial girdle of cirri, and a dense equatorial ciliary belt (ECB) that forms a skirt extending halfway toward the aboral end.

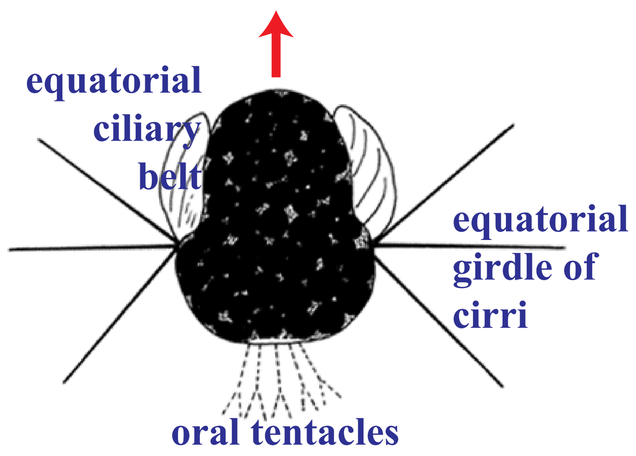


Figure 1

Jumping behavior of *Mesodinium rubrum*:
At the initiation of a jump, the cirri fold to wrap around the oral tentacles, and then the membranelles that form from the cilia of the ECB start to beat from the aboral end toward the oral end; as a result, the ciliate jumps along the direction indicated by the red arrow in Figure 1.

Figure 2 shows an individual *M. rubrum*, ~23 μm in body size, reaches a maximum speed of ~11 mm s^{-1} and covers a distance ~160 μm, all within a single beat of the ECB that lasts ~20 ms. Data from the 1000 fps high-speed video recording by Fenchel & Hansen (2006, *Mar. Bio. Res.* 2:33-40).

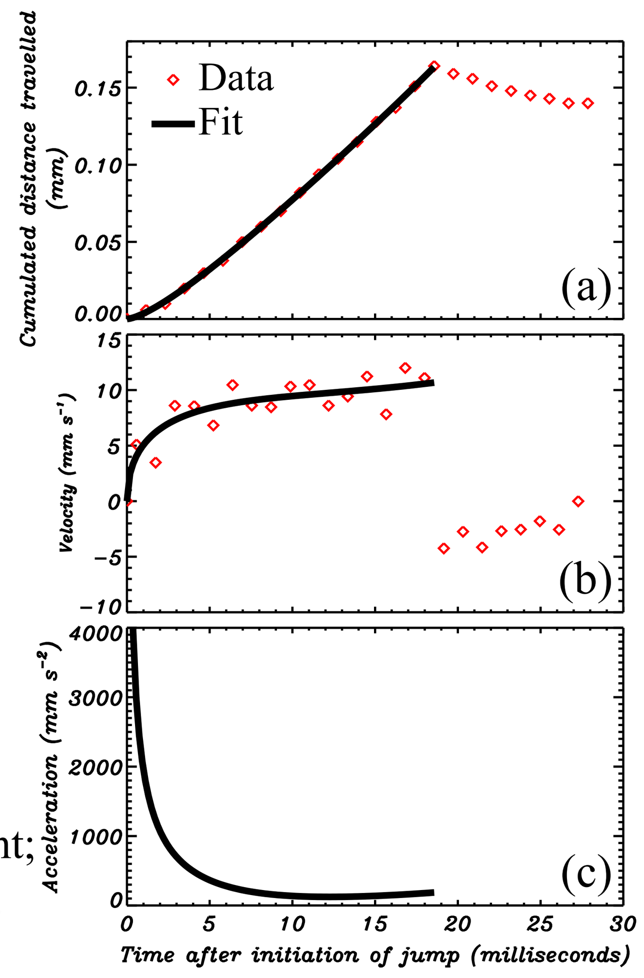


Figure 2

Adaptive significance of fast jumping in *Mesodinium rubrum*:
(1) Jumping enables the ciliate to escape from danger;
(2) Jumping enhances nutrient uptake by steepening nutrient gradient;
(3) Upward-oriented jumping helps in maintaining vertical position;
(4) *M. rubrum* jumping is not for capturing prey.
But, fast jumping may generate stronger hydrodynamic disturbances more easily detectable by rheotactic predators, and be accompanied by higher energy costs.

Comparing propulsive morphology among protists:

	Propulsive morphology	Body size (μm)	Swimming speed (mm s^{-1})
M. rubrum	Equatorial ciliary belt (ECB)	23	11
Flagellates	≥ 1 anterior (posterior) flagella that pull (push)	1-50	< 1
Dinoflagellates	1 longitudinal flagellum, 1 transversal flagellum	10-150	0.01-1.5
Ciliates	Full body surface cilia, or anterior (posterior) ciliary band that pull (push)	15-1000	> 0.5

Hypothesis: *Mesodinium rubrum* using the ECB for fast jumping generates weaker hydrodynamic disturbances and costs less mechanical energy than if other representative protistan propulsive morphologies were used to achieve the same fast jumping.
Empirical data-driven computational fluid dynamics (CFD) is used to test this hypothesis.

Methods

- Solve numerically the Navier-Stokes equations coupled with the dynamic equation of the jumping ciliate (i.e. self-propelled);
- Use deforming mesh (Figure 3b) to describe the observed jump (Figure 2b);
- Consider four realistic protistan propulsive morphologies (Figure 4).

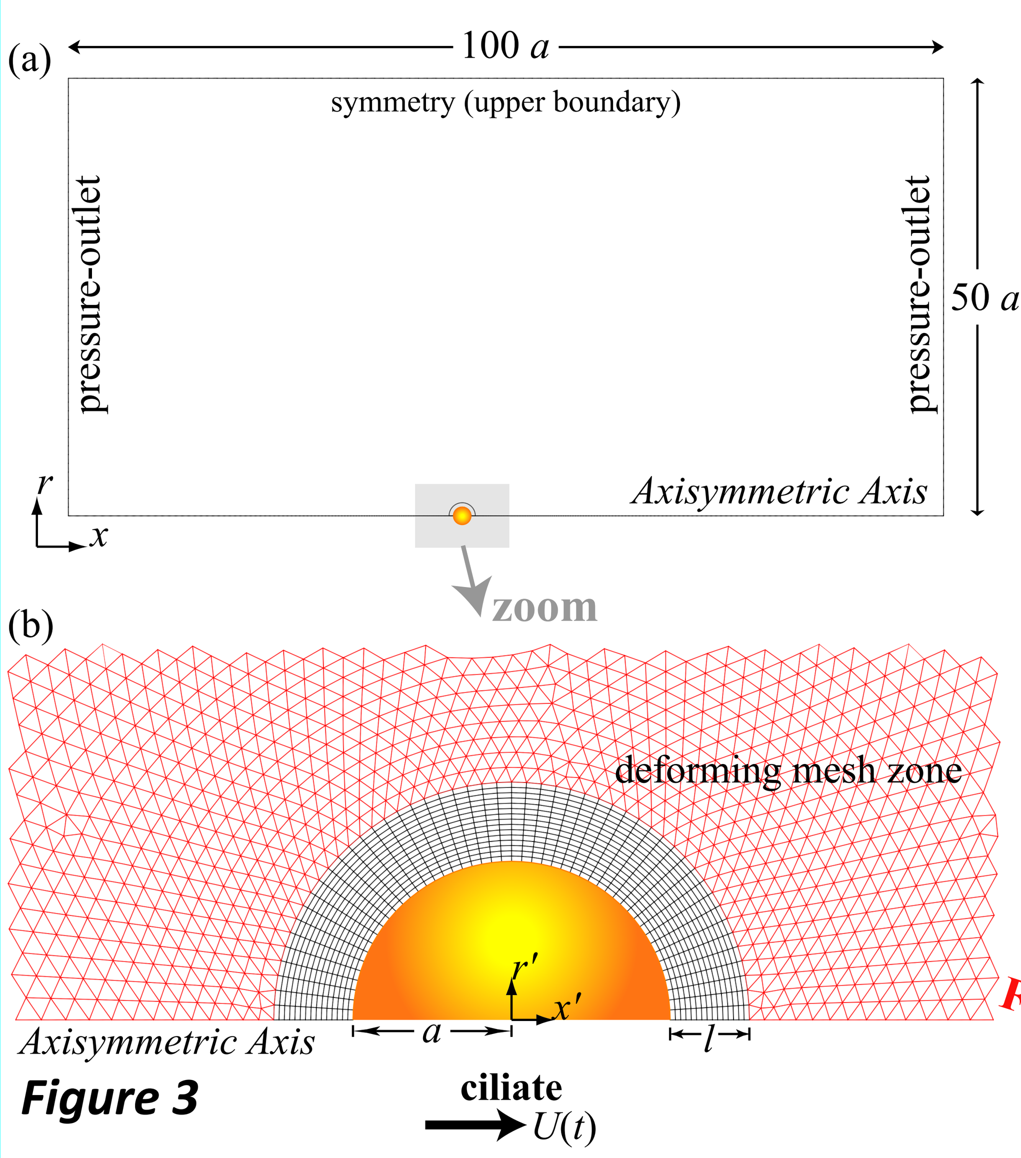


Figure 3

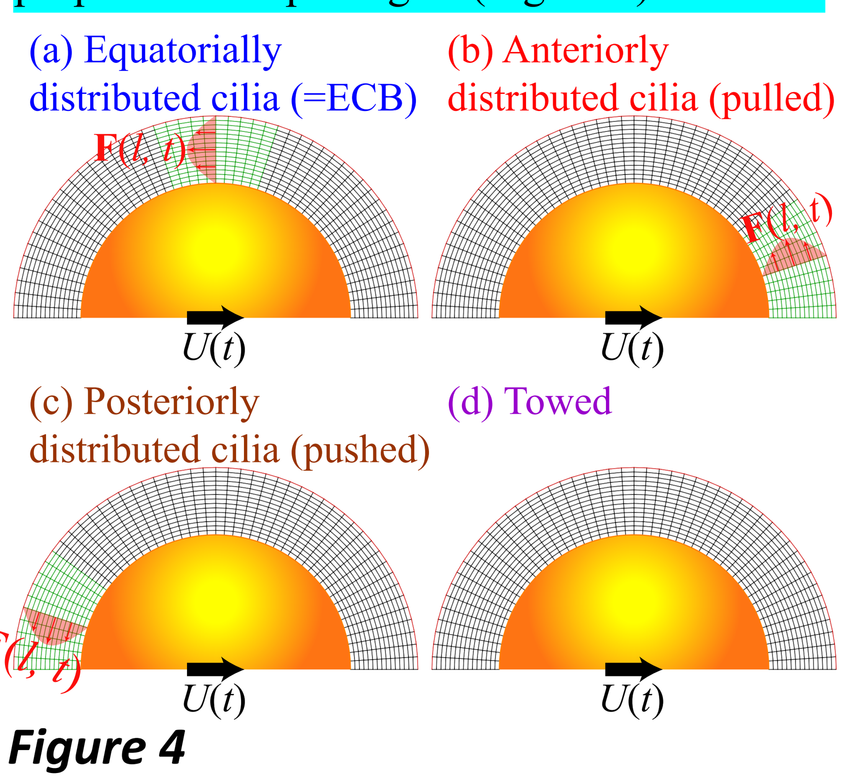


Figure 4

Along with solving for **the jump-imposed flow field**, $\mathbf{u}(x, r, t)$, the advection-diffusion equation governing **a chemical field**, $C(x, r, t)$, of a given diffusivity, D, surrounding the jumping ciliate, is also numerically solved, under suitable boundary and initial conditions.

Volume of influence of the jump-imposed flow: Volume within which the instantaneous flow velocity exceeds a threshold magnitude, u^*;

Instantaneous thrust, $T(t)$: Volume integral of CFD-derived instantaneous ciliary forcing, $\mathbf{F}(x, r, t)$;

Instantaneous mechanical power, $P(t)$: Volume integral of $[\mathbf{F}(x, r, t)\cdot\mathbf{u}(x, r, t)]$ over the volume where the ciliary forcing, $\mathbf{F}(x, r, t)$, is applied;

Total mechanical work, W_{CFD}: Time integral of $P(t)$ over the power stroke duration, τ;

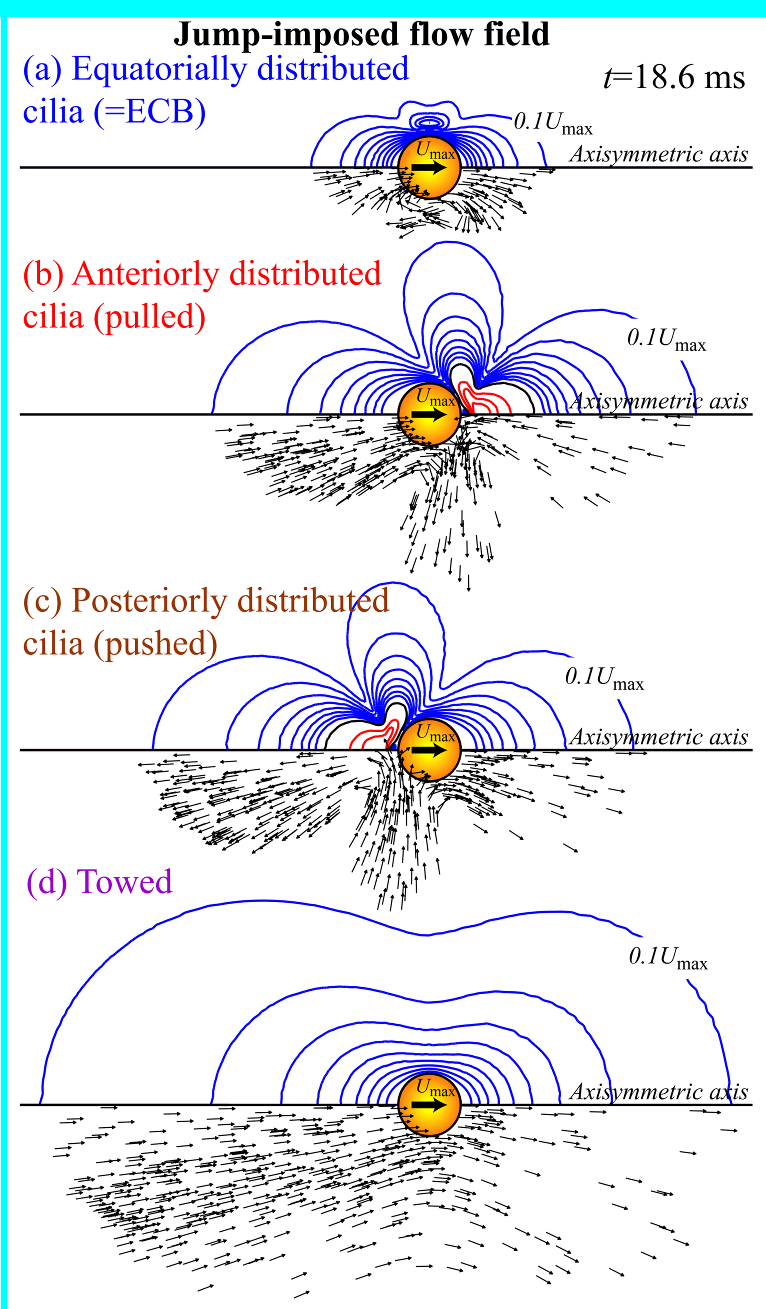
Froude propulsion efficiency: $\xi = \dfrac{\int_0^{\tau} T(t)U(t)\,dt}{W_{CFD}}$;

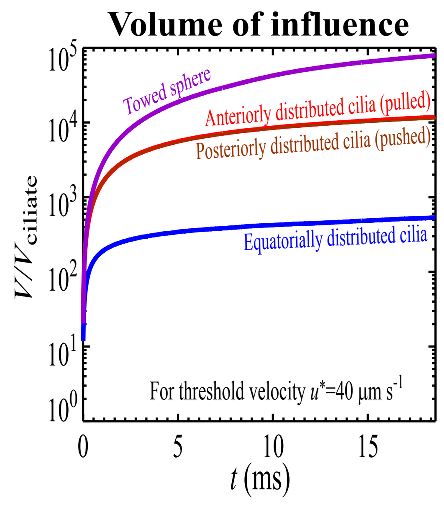
Total flux of the chemical (nutrient) to the ciliate surface: $J = -D\iint_S \mathbf{n}\cdot\nabla C\, dS$;

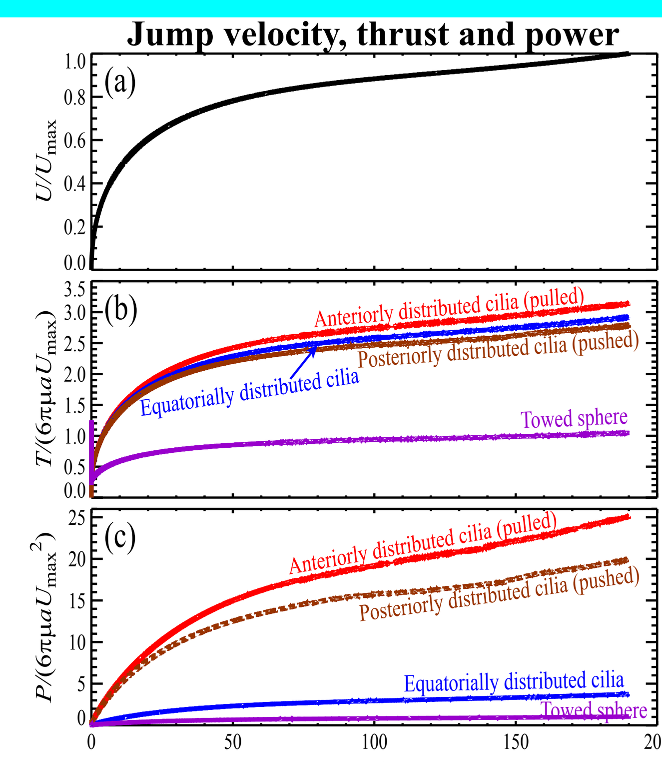
Flux due to diffusion: $J_D = 4\pi a D C_\infty$;

Sherwood number: $Sh = J/J_D$.

Results

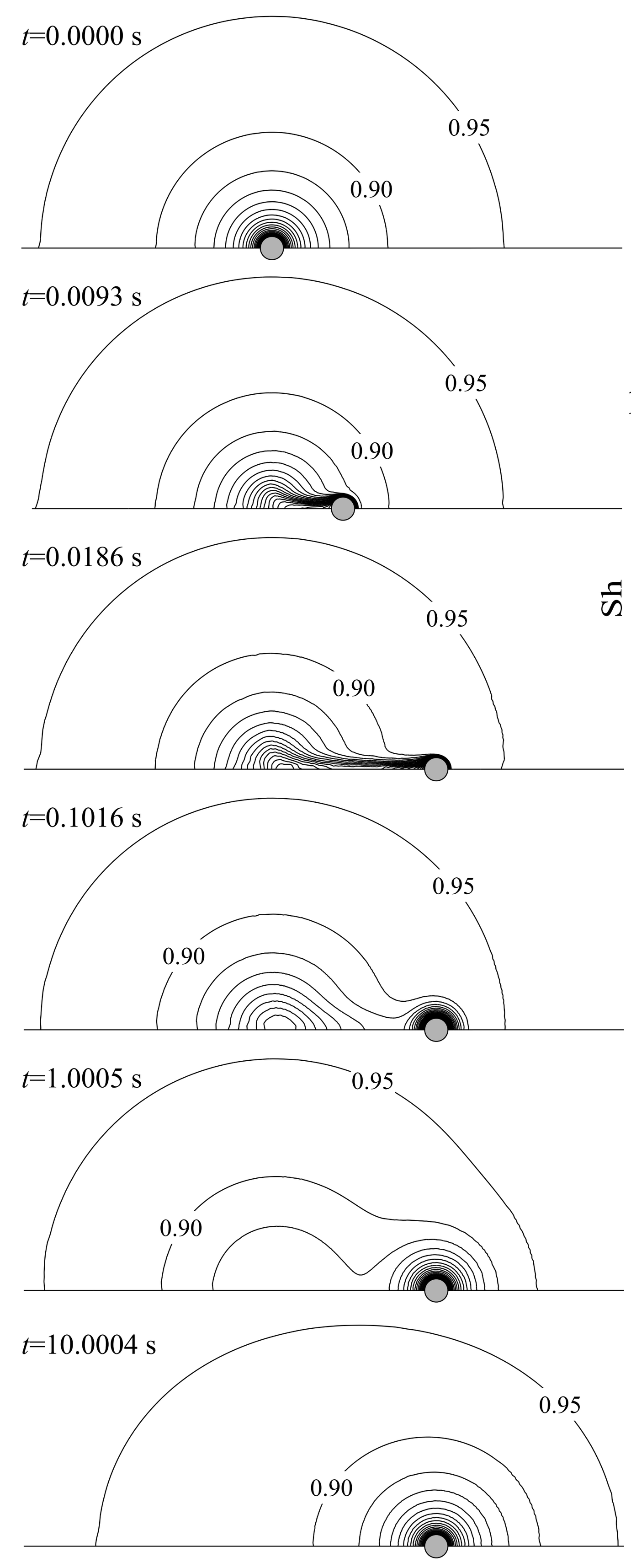


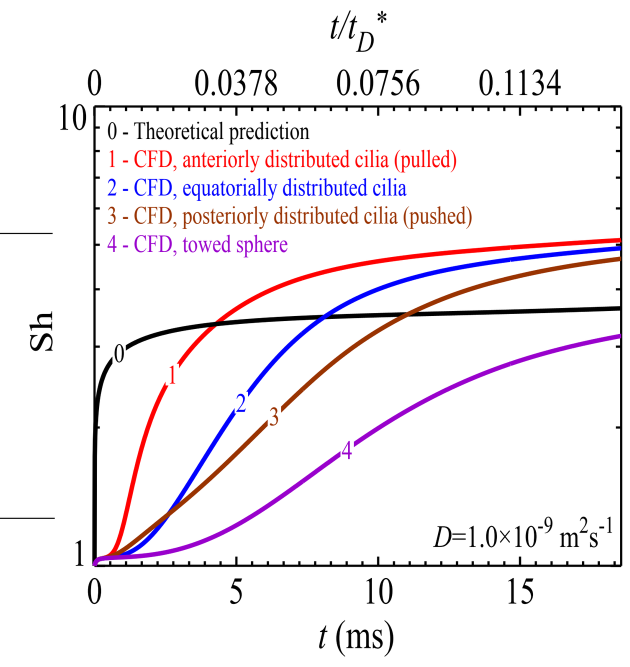


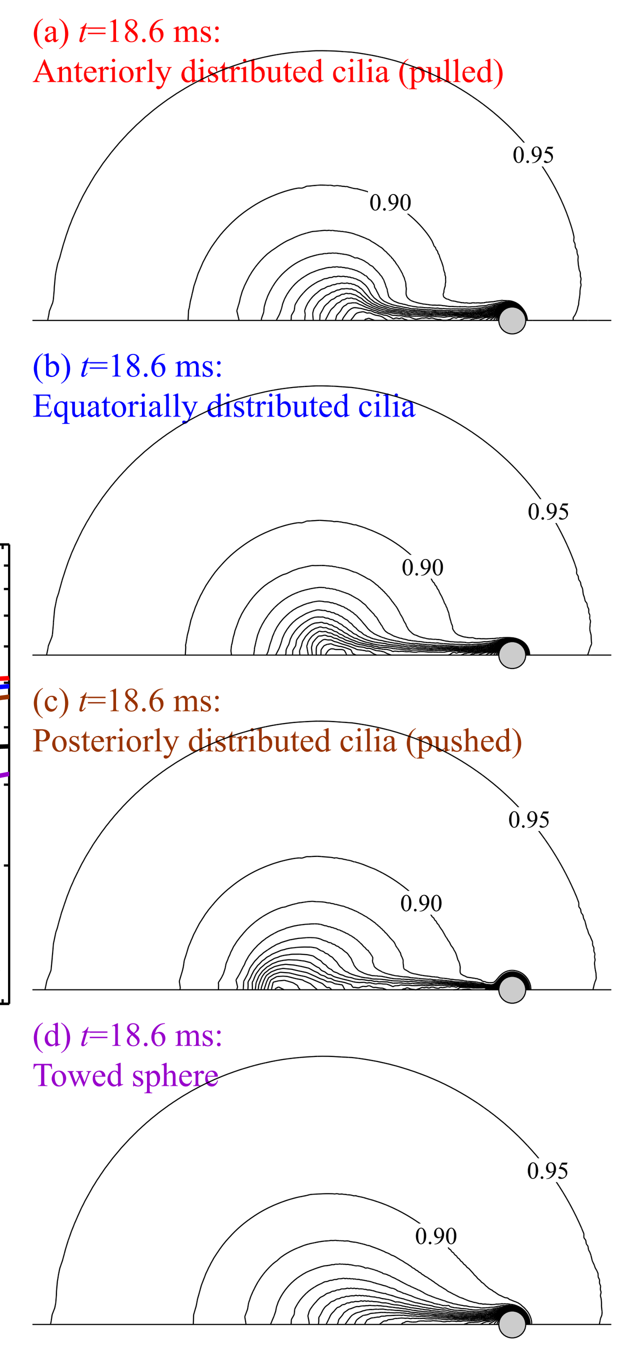


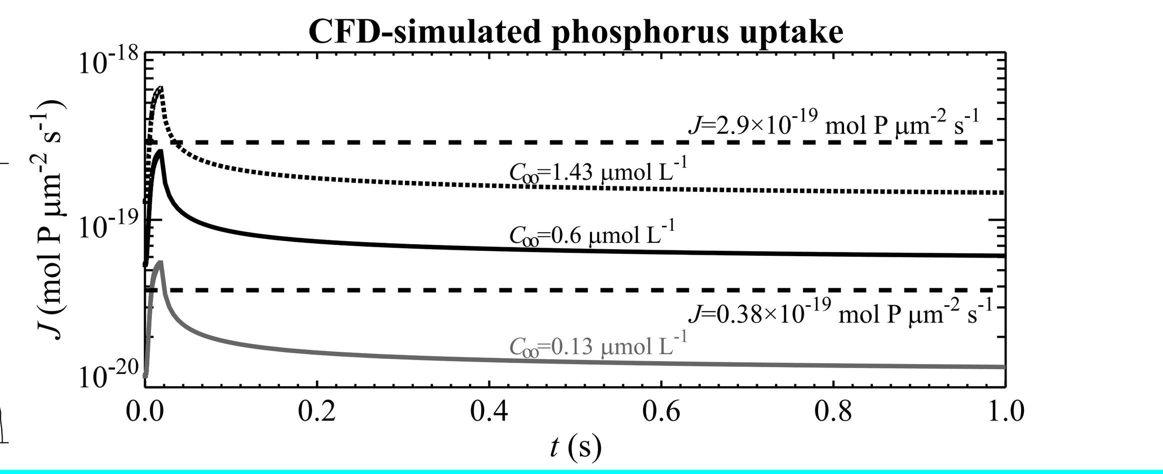
Ciliary forcing schemes	CFD simulated total mechanical work for jump (J)	Froude propulsion efficiency	Cost of jumping estimated for the observed jumping period of ~18.6 ms (% total metabolism)	Cost of jumping estimated for a period of 1 s, based on an assumption of 1 s^{-1} jump frequency (% total metabolism)
Equatorially distributed cilia	1.70×10^{-12}	0.775	28	0.53
Anteriorly distributed cilia	1.11×10^{-11}	0.126	185	3.4
Posteriorly distributed cilia	9.07×10^{-12}	0.139	151	2.8
Towed body	4.81×10^{-13}	1.0	8	0.15

C/C_∞, by ***Mesodinium rubrum* jumping**







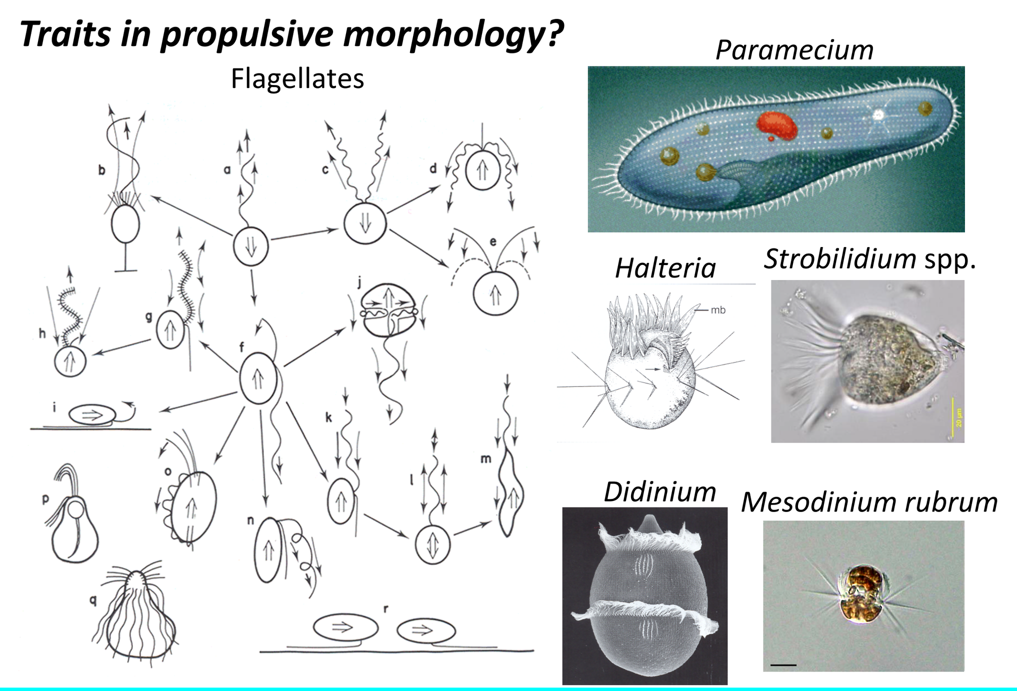


Discussion

- **Jumping enhances phosphorus uptake with simulated values consistent with available field data;**
- **The *Mesodinium rubrum*-like propulsion generates the weakest and spatially most limited hydrodynamic disturbance and therefore may effectively minimize the jump-induced predation risk;**
- **The *Mesodinium rubrum*-like propulsion achieves a high Froude propulsion efficiency (~0.78) and is least costly in mechanical energy expenditure among the three self-propelled strategies considered.**

Thus, using the ECB for propulsion can be essential in ensuring that *Mesodinium rubrum* is a successful 'fast-jumping' primary producer.

Traits in propulsive morphology?



Jiang, H. (2011) Why does the jumping ciliate *Mesodinium rubrum* possess equatorially located propulsive ciliary belt? *Journal of Plankton Research*, 33, 998-1011.