Hunting for Survival: Chemotaxis, Search and Statistical Mechanics

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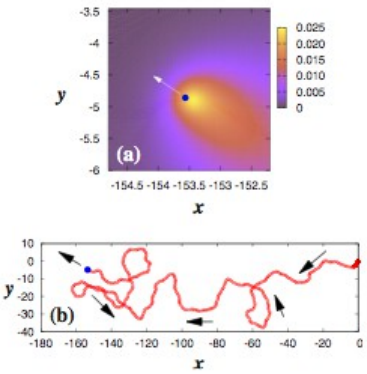
Abstract: Chemotaxis and Brownian Motion belong to the key processes governing the motility of cells and unicellular microorganisms (e.g., bacteria, amoeba and endothelial cells). Self-organization of cells at the collective level under a chemical cue rely on the individual dynamics of chemotactic cells [1] which in turn depends on their ability to probe the chemical concentration field efficiently. Prokaryotes, like most bacteria, being too small to directly sense chemical differences across their body length, chiefly chemotax by temporal comparisons of chemical concentration by a run-and-tumble motion [2]. By contrast, eukaryotes, like amoeba, yeast cells, white blood cells and glial cells, respond to food and toxins by direct spatial sensing of the local gradient. While biological and physical parameters like coupling strength to chemicals, cell motility, secretion rate and diffusion constant of chemicals are crucial to answer important biological questions, like how self-secreted chemicals control steady state dynamics [3], and puzzles, like the outcome of a chemotactic hunt [4], the details of the nature of the motion induced in taxis is crucial to understand individual response itself and classify cells according to their non-trivial dynamics.

Modeling the eukaryotic cell as an Active Brownian Particle self-propelled by a chemical cue we investigate their individual dynamics for the cases when the chemical serves as a chemoattractant or a chemorepellant [3]. Debating an earlier claim that a cell can be eternally trapped in its own chemoattractant cloud in two and lesser dimensions [5], our simulation studies show that the arrest is only transient and sub-diffusive for all dimensions; fluctuations are responsible for ultimate long-time diffusion where the diffusivity scales quadratically with the inverse coupling strength. For chemorepulsion, there is a ballistic motion in the intermediate time window, flanked by diffusive dynamics on either side. Analyzing the chemorepellant distribution around the cell (figure (a)), the cell's trajectory (see figure (b)) can be mapped to a Wormlike chain Model of a polymer to estimate the diffusivity trends. Our studies, extended to a discrete predator-prey model, allow us to understand the conditions necessary for a predator to successfully conclude a hunt, and when search for the prey continues without capture [4]. Eukaryotic cell motility, as biologists understand, is based on the ability of cells to polarize their cytoskeleton, forming biased traction forces that move the cells forward along the direction of polarization. In the presence of a chemotactic signal, the cytoskeleton activity tends to polarize along the direction of larger chemical concentration, leading to chemotactic motion up the gradient. Taking into account the internal dynamics of cytoskeleton polarization coupled to cell motility and the active multiplicative noise in self-propulsion, we study the dynamics of chemotactic eukaryotic cells under an external cue. Comparing the model calculations with in vitro experiments performed in tandem with dendritic cells of mouse, we find clear evidence that the chemical signal applies an effective torque on the cell polarization, reorienting it towards the chemical gradient [6]. Our results set up the stage for a future, more concerted, understanding of the interplay between individual cell migration and emergent order in cell colonies [1,7] and exploration of the scenarios where hydrodynamics is further important [8].



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