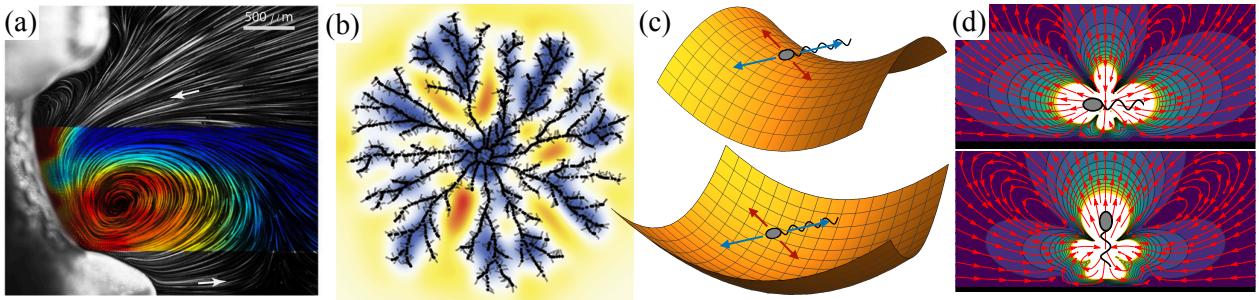
Microscale fluid transport by active surfaces

Most life on Earth involves motion in a fluidic environment, on length scales from subcellular and nanoscopic to oceanic. Although in large-scale systems flows are generally turbulent, in microscopic dynamics, viscosity emerges as the dominant factor that determines the transport processes and dynamics of suspended objects. On the one hand, biological microswimmers are capable of propulsion and therefore stir the fluid around them, inducing local flows that affect their surroundings. At high concentrations, swimmer populations, termed active suspensions, can create large-scale emerging flows. On the other hand, sessile organisms have been found to produce systematic streaming flows to aid the transport of nutrients around them. Collections of such actuators, referred to as active surfaces, often act in synchrony, thus creating complex flow patterns with pronounced fluctuations, as seen e.g. in corals [see Fig. (a)], marine larvae, and bacterial biofilms, also called active carpets [Fig. (b)]. They constitute a class of nonequilibrium transport processes, which lie at the heart of numerous biological functions, such as propulsion or enhanced feeding in microswimmers, or directed transport in higher organisms.



In all cases, microscale biological flows on length scales from individual cilia to multiple cells originate on surfaces, close to which fluid is being pumped, stirred, and streamed. Such motion can be created by individual filaments, arrays of actuated cilia, sessile microorganisms, as well as engineered biomimetic artificial systems, using e.g. chemically generated phoretic flows or external actuation by electric or magnetic fields, for which numerous designs have been proposed. It is well known that the structure and topology of surface-driven active flows in microscale living systems are coupled to their biological function or environmental conditions. However, the role of details of spatiotemporal surface actuation patterns, surface geometry, and hydrodynamics, relevant to cell- and tissue-scale biological flows, remains largely unexplored. The project aims to fill this gap by a combination of theoretical modelling and numerical analysis, in correspondence with experimental data, available from project partners.

The common factor in all such problems is the presence of a fluid, the flow of which is dominated by viscosity. Hydrodynamic interactions in such flows are known to be long-range and have a pronounced effect on transport pathways. The flow depends strongly on the geometry of confining surfaces [e.g. Fig. (c)], which results in a rich diversity of flow patterns [Fig. (d)] and in consequence, different mixing and pumping characteristics of such flows.

We shall address these problems by applying a variety of Stokes flows modelling techniques and concepts from statistical physics to describe the fluctuating flows and characterise their mixing and streaming capabilities. By maintaining a close collaboration with leading experimental groups of international experts, we shall ensure the applicability and relevance of proposed mathematical models.

The primary result of this project will be a set of theoretical and numerical tools, tailored to the multiscale description of active surface flows in diverse flow settings. These tools will then be applied to gain insight into the role of flows in selected biological processes. They will also aid the design of biomimetic artificial flow actuators that can be used in microfluidic and microbiological systems to control the flow structure, particularly its mixing and streaming properties.