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Review

Acoustically Powered Nano- and Microswimmers: From Individual to Collective Behavior

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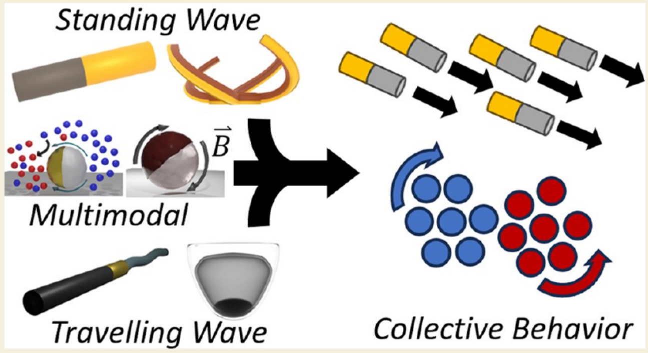
ABSTRACT: Micro- and nanoscopic particles that swim autonomously and self-assemble under the influence of chemical fuels and external fields show promise for realizing systems capable of carrying out large-scale, predetermined tasks. Different behaviors can be realized by tuning swimmer interactions at the individual level in a manner analogous to the emergent collective behavior of bacteria and mammalian cells. However, the limited toolbox of weak forces with which to drive these systems has made it difficult to achieve useful collective functions. Here, we review recent research on driving swimming and particle self-organization using acoustic fields, which offers capabilities complementary to those of the other methods used to power microswimmers. With either chemical or acoustic propulsion (or a combination of the two), understanding individual swimming mechanisms and the forces that arise between individual particles is a prerequisite to harnessing their interactions to realize collective phenomena and macroscopic functionality. We discuss here the ingredients necessary to drive the motion of microscopic particles using ultrasound, the theory that describes that behavior, and the gaps in our understanding. We then cover the combination of acoustically powered systems with other cross-compatible driving forces and the use of ultrasound in generating collective behavior. Finally, we highlight the demonstrated applications of acoustically powered microswimmers, and we offer a perspective on the state of the field, open questions, and opportunities. We hope that this review will serve as a guide to students beginning their work in this area and motivate others to consider research in microswimmers and acoustic fields.



KEYWORDS: *Active Matter, Microswimmers, Micromotor, Nanomotor, Ultrasound, Collective Behavior, Self-Organization, Microbubbles, Acoustic Fields*

Since its experimental beginnings in the early 2000s,[1,2] the field of microrobotics and pumps has been an active and highly interdisciplinary research area, bringing together aspects of biology, chemistry, fluid mechanics, and fundamental physics. The ways in which nano- and microscopic particles can be propelled and controlled by internal fuels and external fields raise basic questions, and it ultimately promises to create tools and systems with useful applications in biology, medicine, physics, and materials science. To achieve these objectives, it is important to understand not only how individual particles can be made to swim autonomously, but also how the interactions between them control the behavior of larger collections of swimmers and their interaction with their environment. The ability to understand and engineer these interactions is vital to creating swarms of particles that are capable of carrying out larger-scale tasks *together,* in a manner analogous to mammalian cells and microbial communities.[3−6] These systems may also serve to mimic biology in ways that help us to better understand and control how living microswimmers grow, communicate, and proliferate. Collective particle interactions are also of great interest to the physics community, who have been predicting and demonstrating fascinating emergent properties that can arise when active particles interact nonreciprocally.[7−11]

In general, propulsion at the micro- and nanoscale is achieved via some sort of symmetry breaking at the particle level coupled with a nonequilibrium driving force. The first chemically powered swimmers were propelled by self-generated chemical gradients that arise due to the catalytic decomposition of hydrogen peroxide,[12] which happens asymmetrically across the body of the particle. This is now a very common method of driving the motion of microscopic swimmers,[13−15] and can be extended to other fuels[16] and photocatalytic mechanisms.[17−19] The motion of particles with

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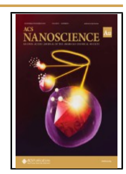

Table 1. Comparisons between Different Microswimmer Propulsion Methods

	Chemophoretic	Electric	Magnetic	Photo-thermal	Acoustic
Speeds	1-200 μm/s	1-500 μm/s,	1-200 μm/s	1-20 μm/s	1-3000 μm/s
Experimental geometries	Open	Confined	Open, close to magnet	Open, optically transparent medium	Open (travelling wave) or confined (standing wave)
Biocompatibility	Generally Low	Low	High	Good	High
Scalability	Typically High	Typically High	Typically High	Good	Low to moderate
Types of Collective Behavior	Chemotaxis, phototaxis, hydrodynamic, predator-prey	Electrokinetic, hydrodynamic	Magnetophoretic, magnetic dipole, hydrodynamic	Phototaxis	Rheotaxis, Bjerknes, acoustophoretic, hydrodynamic

an asymmetry in dielectric polarizability can also be powered by an oscillating external electric field,[20] and via dynamic magnetic fields for particles with a magnetic moment.[21−23] Recently, swimmers powered by self-generated thermal gradients created by laser excitations have also gained attention.[24] Finally, acoustic fields can be used to power swimmers that are asymmetric in their shape or mechanical properties, which is the subject of the current review. These propulsion methods, and the kinds of collective behavior that emerges in each case, are summarized in Table 1.

In addition to simple motion, many types of swimmers have been shown to interact with each other in various ways, leading to collective dynamics. Chemically powered swimmers, for example, can interact with each other weakly through chemical gradients and electrostatics.[25,26] They can also interact with their environment via bulk gradients, which can generate chemotaxis,[27−29] or with features of the environment, such as small pores[30] and microstructures.[31−33] Electric-field-powered swimmers can also interact with each other through dipolar interactions[34,35] and with polarizable features of their environment.[36] In a similar way, magnetically powered swimmers can couple by aligning their magnetic dipoles,[37,38] and can be attracted to bulk magnetic field gradients. The behavior of many magnetically and electrically powered systems can be coupled by hydrodynamics, resulting in the formation of vortices and crystals,[39−43] but it is important to note that, in magnetic systems, the individual particles *are not* driven independently of one another or the field orientation, and they are therefore incapable of carrying out tasks autonomously or of being decoupled from one another. Finally, hydrodynamic interactions with the fluid environment can take place in the form of rheotaxis,[44] or alignment with a static fluid-flow field, which has a number of interesting potential applications.

Acoustic fields that drive the motion of microscopic particles and systems (Figure 1) represent an exciting and emerging aspect of the field, with a number of advantages and opportunities. Acoustic propulsion has created some of the most powerful, tunable, and simple swimmers to date, with individual particles as small as 500 nm that are capable of achieving swimming speeds of hundreds of body lengths per second.[45,46] These swimmers are simple to use in cavity resonators, microfluidic channels, and free fluids with several already demonstrated applications. They are also compatible with many other types of propulsion methods, enabling the design of more complex hybrid systems. Secondary acoustic forces can also be used to navigate difficult environments and obstacles, and can be used to pick up, deliver, and assemble passive particles and swimmers.[47] Acoustically powered swimmers are also capable of generating strong flows that can be used to tune dynamic interactions between swimmers. All of these features make this area rich with opportunities for designing the next generation of microscopic swimmers with interesting individual capabilities as well as intriguing and potentially useful collective properties.

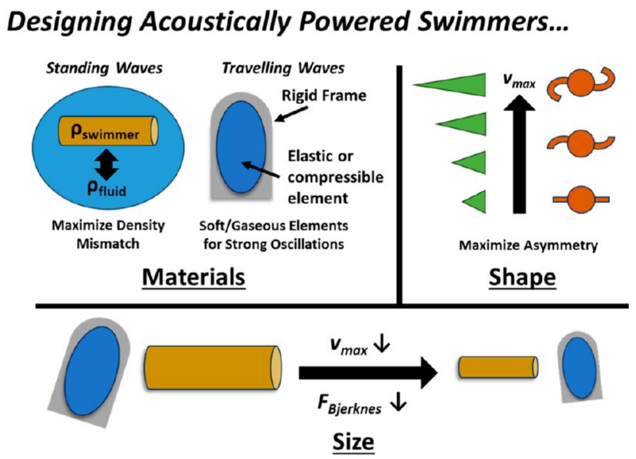

Figure 1. A summary of the design principles for acoustically powered swimmers, including material properties, the shape of the swimmer, and swimmer size.

In this Perspective, we cover recent progress in the development of acoustically powered swimmers, the study of their interactions, and their collective dynamics. The differences between acoustically powered systems and the others mentioned above make acoustic actuation a powerful new tool, but the subfield remains largely underexplored relative to its counterparts. Here, we will discuss the basics of acoustic propulsion, our current understanding of the mechanisms at play, progress in understanding and controlling swimmer interactions, and the potential for future studies and applications. We hope that this article can serve as a starting point for students and those who are initiating research projects in microswimmer research, providing background information for the discovery of new phenomena and engineering of more advanced active matter systems.

Brief History and the Basics of Acoustic Propulsion

The exploration of ultrasound as a method of propelling microswimmers began around 2012 with the unexpected discovery that asymmetric metal nanorods swam at high speeds when levitated in acoustic resonant cavities.[46] This discovery rapidly led to the development of new swimmer geometries and compositions, the exploration of swimmer mechanics, and

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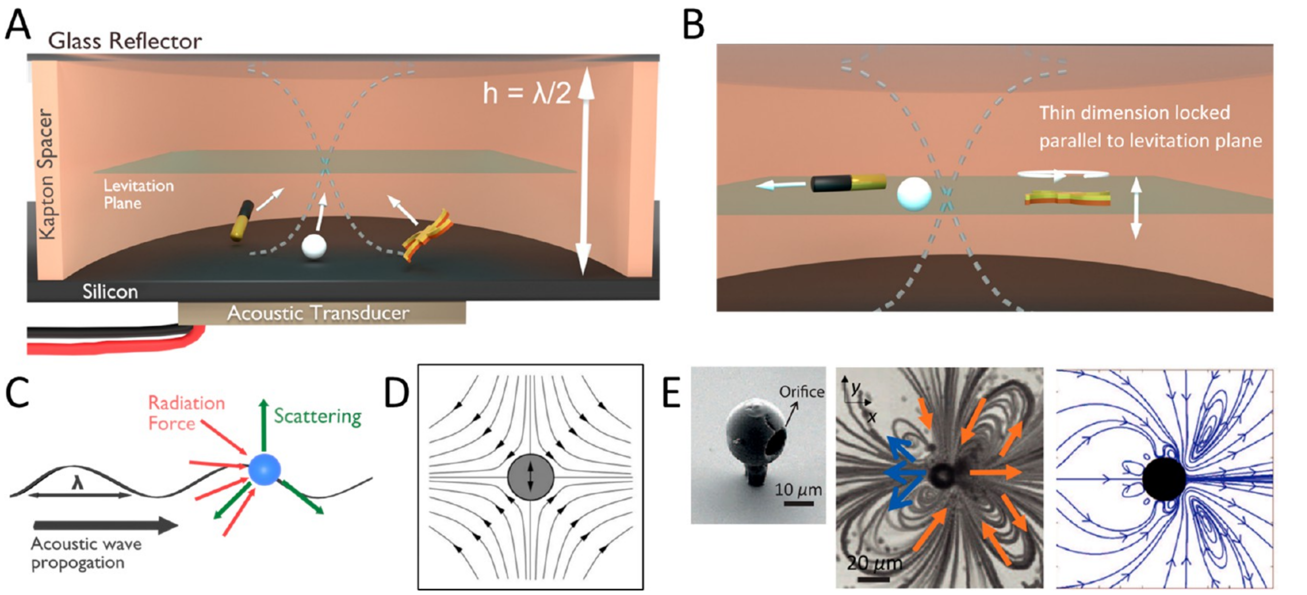

Figure 2. Basics of acoustic propulsion. A) Schematic drawing of a cavity resonator used to levitate and drive the movement of particles via standing waves. B) General behavior of particles at a standing wave, in which they lock themselves parallel to the plan and either translate (in the case of a rod) or rotate (in the case of a spinner). C) Diagram of the acoustic radiation force, in which scattered waves generate a force on a small particle parallel to the direction of wave propagation due to conservation of momentum. D) Numerical simulation of the streamlines around a perfectly symmetric particle oscillating perpendicular to a standing plane wave (indicated by the arrows in the sphere). Flow averages in all directions give no net motion. Reproduced with permission from ref 63, copyright 2014, AIP Publishing. E) Symmetry breaking, in this case a single hole in a sphere containing a microbubble, leads to directional fluid flow that results in pumping at stationary objects and swimming of free objects. Reproduced with permission from ref 57, copyright 2015, American Physical Society.

the study of their applications in diagnostics and intracellular navigation. For example, there are now microswimmers that are powered by standing waves, by oscillating solid structures, and by onboard vibrating bubbles that are excited resonantly by low power fields. The way these particles swim is now fairly well understood with a few open questions, and their collective dynamics has been characterized in some limited cases. Nanorods propelled at standing waves have been explored for some practical "on-chip" applications, i.e., for the detection of small interfering RNAs (siRNAs),[48] and a number of these applications have involved propulsion of nanorods inside living cells.[49] On the other hand, traveling-wave-powered swimmers (e.g., bubble swimmers) may offer more opportunities for applications that require nonconfined geometries. It should also be noted that the development of these applications is nicely complemented by research on acoustic tweezers, which utilize microfluidics, bulk standing waves, and standing surface acoustic waves (SSAWs) to trap and manipulate cells and particles.[50,51]

Soon after the discovery of standing-wave-powered swimmers in cavity resonators, there were the first reports of swimmers powered by bubbles in mobile shells in 2015,[52] swimmers powered by SSAWs in 2017,[53] and several kinds of swimmers powered by high-power traveling waves in 2016[54] and 2021.[55] Much of this work was focused on the goal of developing swimmers for use in biological environments for which ultrasound is well suited. In comparison to other modes of swimming, acoustic fields carry over long distances, especially in solids and semisolids, are biologically safe, provide the opportunity for autonomy (more difficult to achieve with magnetically driven systems), and can generate forces many times larger than those of chemically powered swimmers. We highlight the key differences and compare features in Table 1. In general, we see that acoustically powered swimmers are far more efficient and much faster than any of their counterparts without using toxic fuels or strong light fluences, extremely high electric voltages, or weak, short-range magnetic effects. The reason, as we explore below, is the strong coupling of sound and matter, which transfers energy inertially into the fluid to generate flow directly. Other propulsion methods arise instead from weak diffusive fluxes (as in chemical motors) or heat fluxes (thermophoretic motors), which are subject to unproductive dissipative phenomena. It is for these reasons that many groups have now applied acoustic propulsion to different problems, especially in cellular biology, which is currently an area of intense focus.

As will be examined in greater detail at the end of the next section, generating propulsion using ultrasound requires generally examining three important parameters: material properties, shape, and size (summarized in Figure 1). Sound−matter interactions are strongest at interfaces with the greatest acoustic contrast between the two media, which usually scales with density. This is why bubbles and high-density particles (i.e., gold) make the fastest swimmers. We also want to highlight that throughout this review, we will refer often to bubble-based acoustic swimmers, which are distinct from reaction-induced microtubular swimmers that swim by ejecting bubbles. Unless noted explicitly, "bubble swimmers" and the like refer to those powered by ultrasound. Next, swimming in ultrasound fields relies on acoustic streaming, which is most directional when the particle is asymmetric. Therefore, breaking symmetry as much as possible will lead to faster swimming, although these rules can break down when viscous mechanisms are at play, as published recently.[56] Finally, it has been shown that swimming speed and Bjerknes (attractive) forces scale proportionally with swimmer size. If one wishes to tune these properties, then size may be something to consider.

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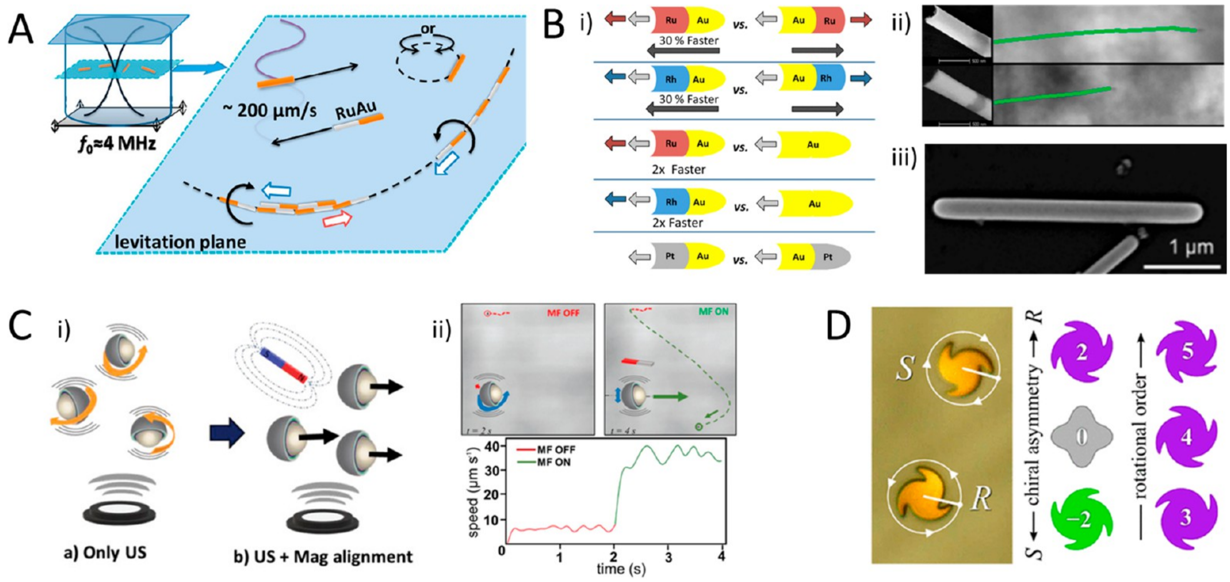

Figure 3. Basic standing-wave-powered systems. A) Nanorods exhibit speeds of about 200 μm/s, orbital motion, and spinning at acoustic levitation planes. Reproduced with permission from ref 46, copyright 2012, American Chemical Society. B) (i) The behavior of bimetallic nanorods is governed by density and shape effects. The concave edge of the rod always moves forward in single-element rods, and the less dense end always moves forward in bimetallic rods. Reproduced with permission from ref 64, copyright 2016, American Chemical Society. (ii) This is demonstrated further by an example where the concavity of the rod end dictates speed. The more asymmetric end leads to faster propulsion. Reproduced with permission from ref 113, copyright 2013, American Chemical Society. (iii) In perfectly symmetric silver rods, there is no evidence of propulsion due to a lack of density or shape asymmetry. Reproduced with permission from ref 70, copyright 2017, American Chemical Society. C) Janus particles coated with a dense cap exhibit motion only with an applied magnetic field due to alignment with the nodal plane. These exhibit speeds that are greater if the particle has more density asymmetry. (ii) Due to reorientation at the acoustic standing wave, there is no propulsion (top-left) unless the rod is constantly oriented using a magnetic field (top-right and bottom). Reproduced with permission from ref 67, copyright 2020, John Wiley and Sons. D) Planar spinners levitated at acoustic standing waves exhibit different spinning directions depending on chirality, and the rotational symmetry can control rotation direction and speed. Reproduced with permission from ref 69, copyright 2018, American Chemical Society.

Transducers, Resonators, and Essential Mechanics

Operationally, the experimental setup for acoustic propulsion was quite simple. The simplest consist of acoustic transducers (inexpensive lead zirconate titanate (PZT) discs) fixed to a flat substrate on which the fluid and microswimmers are placed. Maximum acoustic transmission to the fluid requires using a high-strength ceramic or polymer glue as well as a substrate with a high speed of sound. Silicon wafers combine the advantages of flat surfaces, inert surface chemistry, and high speed of sound, but many experiments are also done with glass or metallic substrates. When the leads of a transducer are connected to a waveform generator and an oscillating voltage is applied, the piezoelectric transducer produces the corresponding frequency of sound and injects energy into the system. For experiments with bubble swimmers, this simple geometry is adequate to observe propulsion, provided that the applied frequency is resonant with the bubble.[57] For bulk standing wave systems, a resonant cavity can be built above the transducer using a ring of known height (e.g., ring-shaped Kapton stickers, thickness ~70 μm) or by stacking thin tape (Figure 2A). Closing the top with a glass slide, which serves as a reflector, completed the resonator. Sweeping the transducer frequency through the resonant region (for one standing wave node in the center of the cavity, we want the half-wave condition, $h = \frac{\lambda}{2}$) should generate a nodal plane that corrals microscopic objects (Figure 2B).[58] The node should be planar if the substrate and reflector are perfectly flat, but in practice, this is rarely achieved over the entire area of the cell. When resonance is achieved, solid objects are levitated to the midplane of the cell, and those with shape or material asymmetry will be propelled within the nodal plane (Figure 2B). While less common, there are many interesting applications that use SSAWs for swimmer propulsion. In this case, the device is fabricated by patterning interdigitated gold electrodes on a piezoelectric substrate, such as $LiNbO_3$.[50]

To better explain swimmer propulsion in these systems, we need to understand what an acoustic field is. In general, sound is a pressure wave, much in the same way that light is an electromagnetic wave, and objects that scatter or are polarized by those pressure waves respond to sound in some way. A simple example is a bubble that is subjected to some oscillating pressure field. Due to the fact that the bubble is compressible (polarizable), it expands on the low-pressure crest of the wave and contracts on the high-pressure crest, leading to a steady pulsation, which is maximized at some resonance frequency. This is an oversimplification when it comes to generating fluid flow and motion using bubbles, but is an easy way to conceptualize sound−matter interactions. For solid objects subjected to strong acoustic fields, scattering of the acoustic waves becomes an important factor. Acoustic waves carry momentum, which can induce motion of objects due to conservation of momentum when scattering occurs, leading to radiation forces and steady oscillations that are maximized at standing wave nodes (Figure 2C) .[59]

Radiation forces lead to migration up or down acoustic pressure gradients, giving rise to acoustic trapping and Bjerknes forces, and steady oscillations lead to fluid flow and propulsion. In the presence of a standing wave field, these radiation forces draw solid particles to the point of lowest pressure in the system, which at the half-wave condition is directly in the center (Figure 2B).[59] For bubbles and other substances that have a lower density lower than water, migration is seen toward regions of highest pressure in the system, which is the walls.[59] This difference in behavior for particles with different densities has been used in the separation of mammalian whole blood, such as blood cells and lipid particles.[60,61] Importantly for propulsion, when an object is trapped at a pressure node (a singular point), a nodal plane (a planar region), or an SSAW (a linear region), it will orient itself to occupy as much of that node as possible. For example, a rod will orient parallel to a nodal plane or SSAW crest, and a disk will lay flat in the nodal plane. Both of these orientations allow the object to maximize contact with the region of the lowest pressure. This locks particles into a single orientation and confines propulsion to the nodal surface, which is important in many contexts (Figure 2B).

The phenomenon that primarily leads to propulsion, apart from the interesting case of bimetallic nanorods,[56] is known as acoustic streaming. Streaming arises from a nonlinear inertial effect governed by the Navier−Stokes equation, which is essentially a perturbation of the viscous boundary layer around a surface or object when vibrated at high frequencies (seen for a sphere in Figure 2D).[62] This occurs when objects oscillate at large amplitudes in acoustic fields, which can be accomplished using standing wave trapping or swimmers with bubbles and soft components capable of large deformations. This effect has been known for decades but has only recently been recognized as a propulsion mode, because only *free* asymmetric objects are propelled directionally by acoustic streaming. Bubbles, for example, oscillate in traveling wave fields and are naturally spherical, and thus, in a free fluid, streaming averages in all directions to give no net propulsion. For early experiments on acoustic levitation and trapping, spherical particles were used, which again gave acoustic streaming flows that were symmetric and led to no net directional motion (Figure 2D). When symmetry is broken (as seen in the case of a shelled microbubble in Figure 2E), streaming becomes directional and can lead to propulsion and pumping. This was first seen by Wang and co-workers when levitated electrodeposited nanorods at levitation planes exhibited fast propulsion (Figure 3A),[46] which, despite initial theoretical debate, can be attributed to density and shape asymmetry (Figure 2B and 2C).[63,64] As mentioned above, it is the combination of asymmetry with a nonequilibrium driving force, i.e., streaming arising from sound−matter interactions, that generates propulsion.

Standing-Wave-Powered Systems

So far, standing-wave-powered systems are the most abundant examples of acoustically powered swimmers, likely due to their simple fabrication and operation. Most of the examples to date are fabricated using the same methods used to generate the first chemically powered swimmers, such as templated electrodeposition to grow wires and tubes,[64−66] and physical vapor deposition onto spheres to generate Janus particles.[67−69] When suspended in the cavity resonators mentioned above at the half-wave resonant condition, swimmers are levitated to the cavity center and self-propelled at high speeds due to acoustic streaming. It has also been shown that, in a similar way, rods can be trapped and propelled in the linear crests of SSAWs, making them useful in “on-chip” platforms.[53] We presume that the mechanism of propulsion in both cavity and SSAW systems is the same, and much work has been done to elucidate them. Understanding these systems at a deeper level is essential to gaining more utility for their use.

The groups of Mallouk, Hoyos, Nadal, and Lauga did preliminary experiments and developed early models to understand propulsion at standing waves, identifying shape and density asymmetry as the essential ingredients.[60,64] Indeed, perfectly symmetric, single-component nanorods show no motion under the same conditions, as demonstrated later (Figure 3B, iii).[70] In most of the particles made by the template electrodeposition method, there is some level of shape asymmetry that leads to net motion. With anodic aluminum oxide (AAO) templates, the metal plating solutions wet the pores during electrodeposition to give a convex tip at the growing end. When the sacrificial cathode is dissolved, the growing end is left convex, and the opposite end is concave.[64] Although this is a small structural asymmetry, it is sufficient to induce swimming speeds of hundreds of micrometers per second at high power. For tubes and rods grown from larger polycarbonate porous membranes, the pores are typically conical and lead to symmetry-broken shapes that exhibit motion at acoustic standing waves.[65,66] It is important also to note that, as mentioned above, objects such as rods *always* orient themselves with their long axis parallel with the plane of levitation or to the SSAW crest. Therefore, the rods never point away from the levitation plane, and their axis of asymmetry is along the length of the rod, leading to net motion parallel to the plane or SSAW trough.

Beyond simple linear motion, other types of microscopic objects have shown complex motion in acoustic standing waves. For example, we recently demonstrated two examples of particles with symmetry breaking about an axis of rotation, which leads to spinning behavior when the particles are trapped at a levitation plane (Figures 3D and 4A).[69,71] Again, the shape of the resonant cavity orients the planar body of the spinners parallel to the nodal plane at all times, confining them into a single plane and creating rafts of autonomous spinners. Spinners that have three-dimensional (3D) shapes can propel themselves to a stationary point above or below the levitation plane due to streaming effects on their 3D arms, forming multiple layers of spinners in parallel planes (Figure 4A). In active matter systems, 3D symmetry breaking can be a way to access more complex systems, as demonstrated by the spontaneous phase separation of oppositely rotating spinners.[68] Additionally, bent or crescent-shaped nanorods become fast-orbiting particles that show similar behavior to spinners,[70] and the same rods can also spin rapidly about their long axis.[72] All of these behaviors can give rise to self-organization, which will be discussed in the collective behavior section.

A number of numerical and computational studies have sought to establish how standing-wave-powered systems work, especially with respect to shape asymmetry. Several foundational examples showed that simple shape asymmetry can lead to asymmetric streaming that in turn results in propulsion and spinning,[63,69,73] and those calculations can roughly reproduce experimental results. However, one question that lacked a sound explanation in early work was the dependence of the propulsion direction on density asymmetry. For example, a half ruthenium (ρ = 12.2 g/cm^3), half gold (ρ = 19.3 g/cm^3) rod is always propelled with the ruthenium end forward, regardless of the direction of shape asymmetry.[64] This was initially explained in a model in which the two sides would oscillate at different amplitudes based on their density, with the gold always dominating. However, in early experiments with rods and

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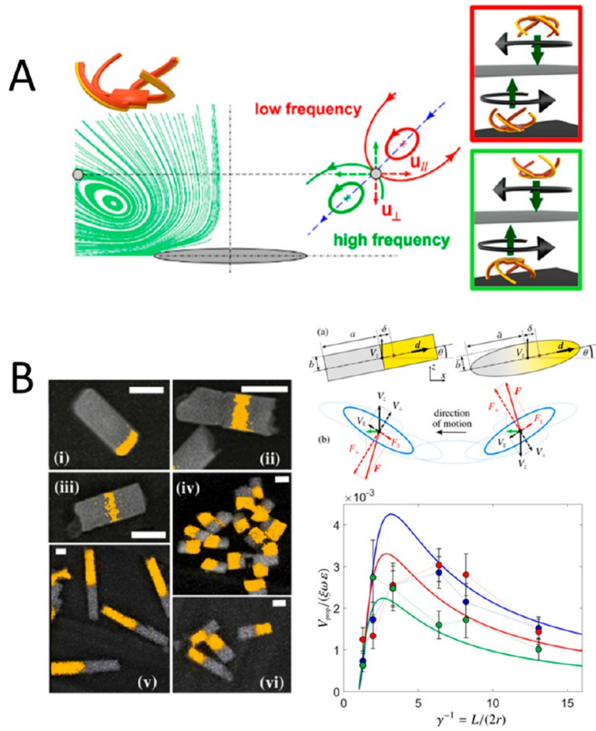

Figure 4. Standing wave swimming mechanics. A) Small, thin spinners modeled as gray discs exhibit rotation due to an acoustic streaming mechanism (left) but also maintain an equilibrium position away from the nodal plane due to their 3D shape (right). This combination of streaming with shape asymmetry is the primary mechanism for more acoustic swimmers at standing waves. Reproduced with permission from ref 71, copyright 2023, American Chemical Society. B) The fast motion of bimetallic rods can be explained using a purely viscous mechanism, whereby the rod changes orientation as a function of time to swim nonreciprocally (top-right). As the rod aspect ratio increases, the maximum speed changes nonmonotonically (left and bottom-right) in agreement with the viscous propulsion model. Reproduced with permission from ref 56, copyright 2021, American Physical Society.

Janus particles,[67] the strength of the local pressure field was not measured directly. Accurate measurements of the strength of the acoustic field relative to the swimming speed showed that the predicted speeds in the acoustic streaming model were more than an order of magnitude lower than those that were observed experimentally.[56] By increasing the length of the swimmers, we noticed that the speed was nonmonotonic with aspect ratio (Figure 4B, bottom-left), leading us to develop a new theory based on viscous drag (Figure 4B). This theory predicts a continuous orientational change of the rod (undulatory sperm-like motion) that occurs because of the density asymmetry rather than two-state oscillation. This model, which agrees quantitatively with experimentally measured speeds, is unifying in that it preserves the idea that acoustic streaming is responsible for swimming of particles with shape asymmetry alone, i.e., a pure gold nanorod, whereas density asymmetry generates an undulatory motion that causes the speed to increase with aspect ratio until the drag becomes large and the speed decreases again.

Traveling-Wave-Powered Systems

Traveling waves present a number of advantages to standing wave systems, most notably relaxation of the requirement that the particle be close to the transducer. These systems are, however, less commonly studied due to the complexity associated with the swimmers themselves. Traveling wave swimmers are powered by oscillating bubbles, soft flagella, and soft needles. Effectively, these designs move the resonant cavity into the swimmer itself rather than into the observation cell. Traveling wave power presents a number of useful advantages over standing waves, such as an unlimited choice of environmental geometries, higher propulsion speeds, increased swimmer autonomy, and a greater range of operational frequencies and powers, to name a few. With traveling waves, the user no longer has to establish a standing wave based on the reflection of acoustic waves across a certain length, and without a reliance on radiation forces, the powers used can be much lower. This opens up real opportunities to power autonomous swimmers in free fluids such as in tanks, cell cultures, and living tissues. Bubbles also display interesting and useful secondary forces, called Bjerknes forces, which can be used to steer them (primary Bjerknes), for tweezing small particles and cells, or for climbing surfaces (secondary Bjerknes), adding potential practical utility that we will discuss in more detail below in a small "Bjerknes Forces" subsection.

In general, traveling waves generate motion by inducing large oscillations in the swimmer, which translates to a large streaming force. This is typically accomplished using soft materials such as gas bubbles or polymers that undergo large deformations relative to their hard material counterparts, allowing them to work at lower powers and are independent of standing waves. Bubbles are the most ubiquitous mode of propulsion in the literature and deserve attention for their power and practicality. Fluid streaming generated by gas bubbles at some resonance frequency has been studied for decades, but it was not until they were installed inside asymmetric shells that they could be used to propel swimmers.[52] The first examples of swimmers were lithographically patterned and were hundreds of micrometers in size (Figure 5A). In later reports, swimmers were fabricated at much smaller scales using two-photon polymerization (2PP) to make hollow structures that were a few microns to tens of microns in length (Figure 5B).[47,57,74,75] Making these swimmers hydrophobic or tuning their shape appropriately results in trapping a gas bubble inside the cavity when the swimmer is placed in water. When actuated at their resonance frequency, acoustic streaming generates fluid flow (Figure 5C), and bubble swimmers tend to glide along surfaces at tens to hundreds of microns per second, depending on the input power (Figure 5B, iv). Gliding of swimmers was first observed by Marmottant's group in 2018[75] and was used in a more practical way by Ren et al.,[47] who exploited a magnetic coating that allowed the swimmers to be steered.

Bubble-based swimmers are typically fabricated by photolithographic techniques, as mentioned above, which limit their size to the diffraction limit of light. It also greatly limits the throughput of fabrication because swimmers are typically printed one-by-one in small batches. More recently, techniques have been developed to overcome these limitations, such as fabrication by shadow nanosphere lithography (Figure 5D)[45] and growth of hydrophobic microtubes in polycarbonate templates.[76] The resonant frequency of these bubble swimmers is governed by their size, shape, and surrounding medium (Figure 5B, iii). This frequency is often calculated numerically due to the complexity of many of the shapes, but can be described for cylindrical swimmers by the equation:

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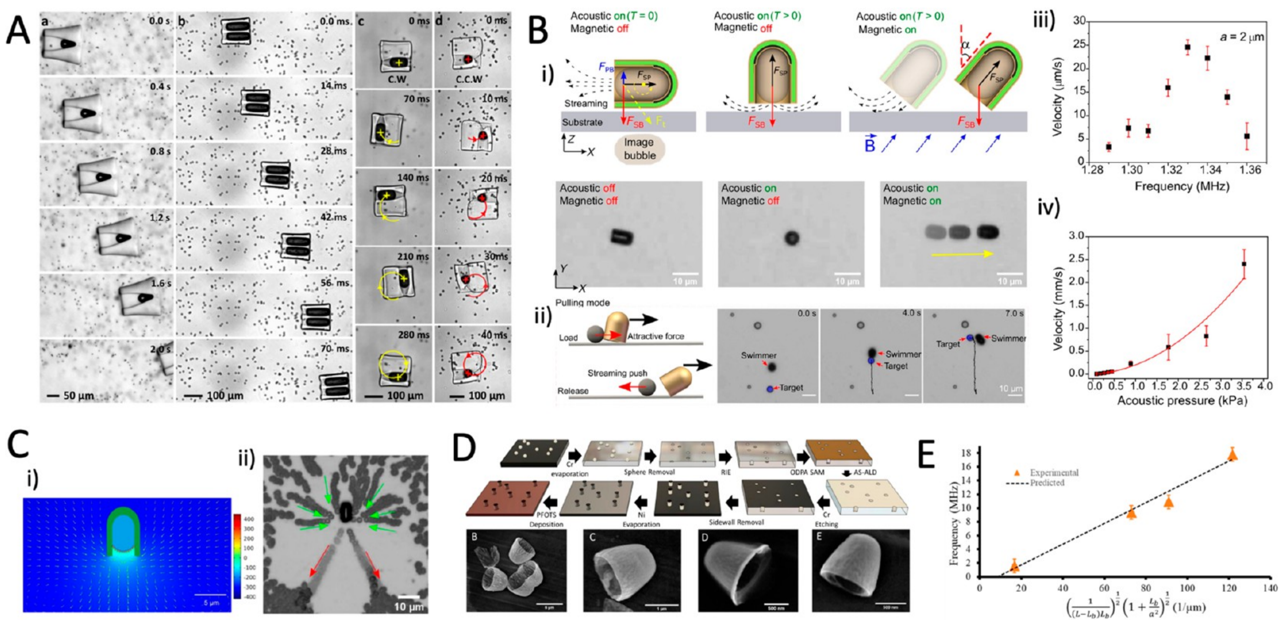

Figure 5. Traveling-wave-powered systems. A) The first bubble swimmers were fabricated using a complex lithographic technique to produce objects that were several hundred micrometers in size and operated at tens of kHz to undergo linear and orbital motion based on their shape. Adapted with permission under a Creative Commons CC-BY 4.0 license from ref 52, copyright 2015, Nature Publishing Group. B) Smaller swimmers are fabricated by two-photon printing and operate in the MHz regime. They are attracted to their image via the secondary Bjerknes force and stand perpendicular to substrate (i). Magnetic tilting enables fast swimmer gliding along the substrate surface and manipulation of passive particles (ii). Their resonance frequency can be extracted from their velocity as a function of frequency (iii), and their speed can be fine-tuned using the acoustic pressure (power) applied to the system (iv). C) Simulations of acoustic streaming (i) can be used to model the behavior and can be demonstrated experimentally (ii) by fixing the swimmer at a location and monitoring the flow with tracer particles. B and C are adapted with permission under a Creative Commons CC-BY 4.0 License from ref 47, copyright 2019, AAAS. D) Bubble swimmers were fabricated at submicron sizes and in large numbers using a shadow nanosphere lithography technique. E) Small swimmers fabricated in (D) match predictions of resonance frequency as a function of size, plotted in terms of the governing equation. D and E are reproduced with permission from ref 45, copyright 2020, American Chemical Society.

$$f_0 = \frac{1}{2\pi}\left(\frac{\kappa P_0}{\rho(L - L_b)L_b}\right)^{1/2} \times M \quad (1)$$

$$M = \left(1 + \frac{4\gamma L_b}{\kappa P_0 a^2}\right)^{1/2}$$

where κ is the adiabatic index (~1.4), P_0 is the resting pressure in the bubble, L_b is the length of the bubble, L is the length of the cavity, ρ is the fluid density, a is the inner radius, and γ is the surface tension (~0.07 N/m in water). Here, M is a correction factor that accounts for the surface tension. It has been found that this equation works well for swimmers with different aspect ratios and sizes from 5×8 μm down to 500×700 nm (Figure 5E).[45,47,76] The resonance frequency, f_0, increases as the size decreases. The strength of the streaming propulsive force can be approximated by the equation:

$$F_{SP} \sim \varepsilon^2 \rho_f a^4 f^2 \quad (2)$$

where ε is the acoustic field amplitude, ρ_f is the density of the fluid, a is the bubble radius, and f is the field frequency. This tells us that velocity will decrease as size decreases (although f goes up, a goes down at a faster rate) and that velocity goes as power squared. There are now many examples of bubble swimmers in the literature,[45,47,52,57,74,75,77,78] and one report of a rotor,[79] all with different applications.

Bjerknes Forces

A unique feature of bubble swimmers, relative to all other types of swimmers designed so far, is their ability to glide along surfaces, climb walls, and attract small passive particles.[45,47] This behavior is governed by the secondary Bjerknes force, which is known to occur between pairs of oscillating bubbles.[80] Essentially, a single bubble acts as a point scatterer of acoustic waves, generating a local standing pressure gradient that decays with the distance away from the bubble due to attenuation. Since bubbles migrate toward regions of higher acoustic pressure, they become attracted to each other due to radiation pressure.[81] In the case of bubble swimmers near a surface, the nearby wall acts like an acoustic mirror, generating an "image bubble" that the swimmer is attracted to.[82] This typically manifests as a "standing" behavior due to the fact that the bubble interface is where the attraction is maximized.[47] The attraction between two bubbles, and by relation a bubble and a wall, is described by the equation:

$$F_{SB} = -\frac{\rho_f}{4\pi d^2}\langle \dot{V} \rangle^2 \quad (3)$$

where ρ_f is the density of the fluid, d is the separation distance between bubbles, and V is volume, with ⟨⟩ denoting the time average and the dot representing the time rate of change. This equation works well in a wide range of scenarios, from glass and silicon substrates to SU8 walls and structures, to polystyrene and silica particles, and to mammalian cells. Importantly, we see that the Bjerknes force should become

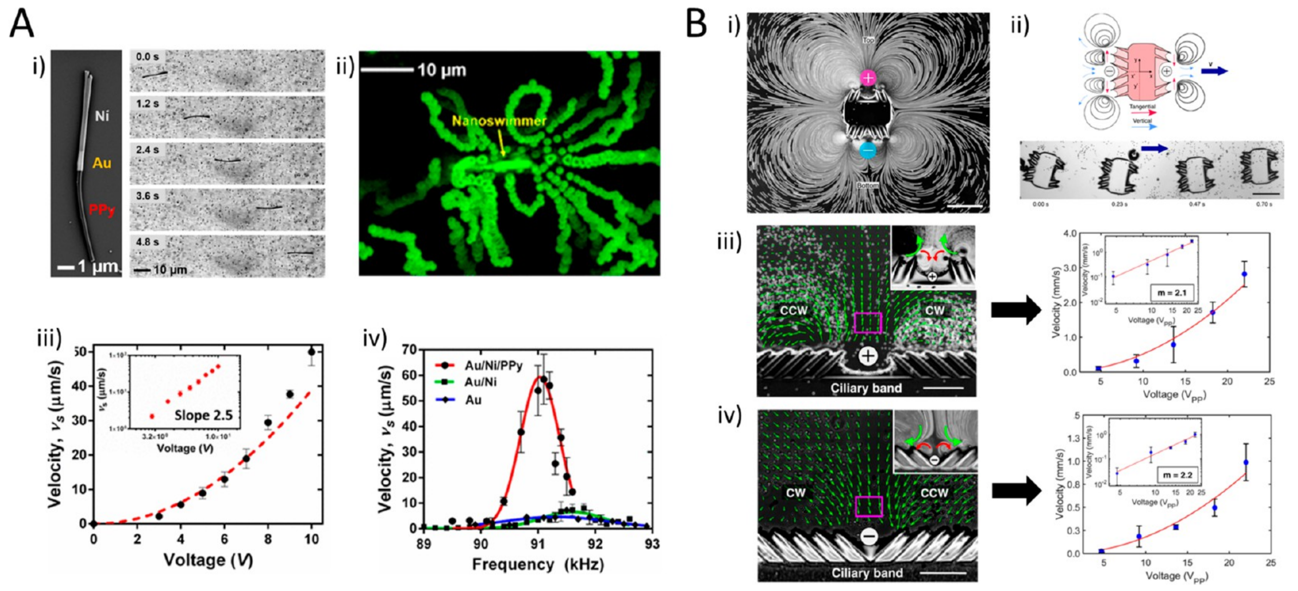

Figure 6. Other traveling wave power systems. A) Nickel−gold−polypyrrole nanorods were fabricated via template electrodeposition and exhibit swimming when actuated by high power traveling waves (i) and (ii). They also exhibit power-dependent speed (iii) and a resonance frequency (iv). Reproduced with permission from ref 54, copyright 2016, American Chemical Society. B) A large polymeric swimmer inspired by starfish ciliary bands exhibits different types of flow in traveling waves depending on the orientation of the edges (i), which can be combined for strong directional propulsion (ii). The speed of both bands also exhibits a strong dependence on acoustic power (iii) and (iv). Adapted with permission under a Creative Commons CC-BY 4.0 license from ref 55, copyright 2021, Nature Publishing Group.

smaller as a function of V, as observed in the very small bubble limit where the swimmers are no longer attracted to surfaces.[45]

Due to the secondary Bjerknes force, tweezing and manipulation of microscopic particles becomes possible. When bubble swimmers are used that are several microns in size, it is apparent that the Bjerknes force is greater than the propulsive force because the swimmers remain at the wall instead of swimming away from it. Similarly, despite fluid flow near the bubble interface, the attraction to particles and cells is greater, leading to a steady attraction when the swimmer is oriented perpendicular to the surface. When the swimmer is reoriented to point the interface directly at the particle (i.e., parallel to the substrate surface), the streaming flow is sufficient to push the particle or cell away from the swimmer, releasing it. This allows the user to pick up, move, and unload particles at a new location by simply using the orientation of the swimmer. Similarly, the swimmers can climb vertical interfaces by reorienting their open end toward the desired surface. This makes this class of swimmers potentially versatile in navigating complex environments such as those that are not perfectly flat. Finally, by designing the shape of the bubble swimmer with elements that separate it physically from the surface (such as fins that protrude from the interface) it is possible to release the particles from the surface to swim freely in 3D.[47] Similarly, one can use off-resonance modes and smaller swimmers to lower the strength of the Bjerknes force relative to streaming to achieve weaker attraction to the surface and particles.[45]

Other Traveling Wave Swimmers

Simple acoustic waves have also been shown to generate propulsion in swimmers with soft flagellae and large structures with needle-like protrusions.[54,55] In both cases, the active material is a soft polymer that oscillates upon absorbing acoustic waves to generate streaming. Soft flagella were demonstrated in a nanorod-based system, where a soft polyaniline tail was grown on a hard, magnetic body composed of nickel and gold (Figure 6A). It is important to note that swimming was fastest when all components were combined into a single structure rather than propelled as individual pieces.[54] Numerical modeling suggests that swimming is due to structural resonances that are excited by the acoustic field, and symmetry breaking in terms of material properties plays an important role in directionality. Ahmed and co-workers have also demonstrated the use of sharp, cilia-like protrusions on a large body to generate acoustic streaming (Figure 6B).[55] This system operates on much the same principles as in many acoustofluidic platforms, where the oscillations of a sharp polymeric feature generates vibration significant enough to give rise to streaming.[83] By controlling the directional orientation of the cilia with respect to the body, they were able to control the direction of streaming, and by combining different directions on either side of the body, they obtained strong directional propulsion. It should be noted, however, that both of these systems require much higher powers than bubble-based swimmers because of the weaker structural response to incident acoustic waves.

Hybrid Systems

Several systems have been developed that combine acoustic driving forces with other modes of propulsion and actuation for enhanced functionality. These systems provide great opportunities to exploit the "best of both worlds" by taking advantage of the compatibility of acoustic fields with essentially every other type of actuation modality in use today. These auxiliary functions include chemically, magnetically, and optically generated forces as well as influence from flow in the surrounding media. So far, despite their usefulness in their own right, electric fields and thermophoretic forces have not been combined with ultrasound but could lead to interesting new hybrids like those described below. These added functionalities can also lead to new scenarios in which

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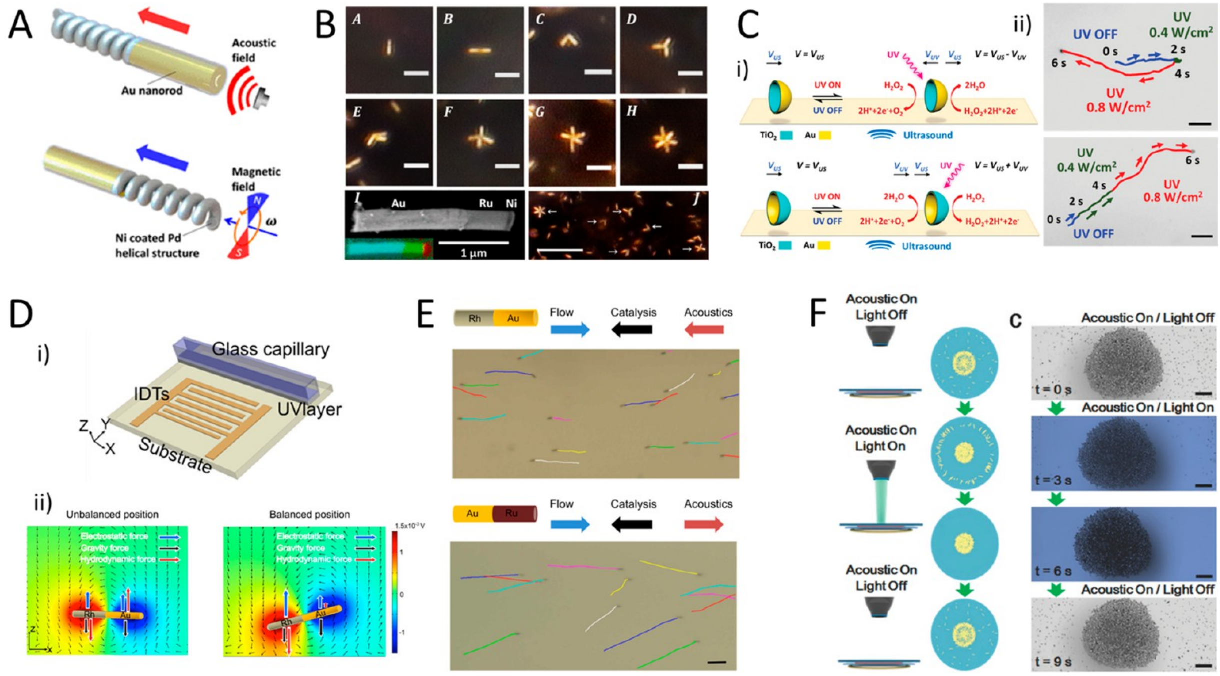

Figure 7. Hybrid acoustic systems. A) A nanorod with a magnetic, spiral-shaped tail moves in one direction (Ni−Pd forward) when actuated via ultrasound and in the opposite direction under a rotating magnetic field. Reproduced with permission from ref 86, copyright 2015, American Chemical Society. B) Nanorods with magnetic tip features dynamically self-assemble at acoustic standing waves, forming geometrically regular multimers. Reproduced with permission from ref 87, copyright 2014, American Chemical Society. C) Photocatalytic microparticles in hydrogen peroxide can be used to regulate swimming speed at standing waves using UV light. The self-electrophoretic flow generated by photocatalysis can either slow (ii, top) or speed up (ii, bottom) the swimmer, depending on the density asymmetry design of the particle. Reproduced with permission from ref 91, copyright 2019, John Wiley and Sons. D and E) Nanorods can be deliberately propelled with or against an applied flow in a capillary (i) actuated by an SSAW. In hydrogen peroxide solution, one end of the rod experiences an attractive force with the floor (ii), and that end is reoriented by the flow to point upsteam (D). When the ultrasound is turned on (E), the rod swims upstream (in the crest of the SSAW) if the less dense end is pointed upstream (Rh−Au, top) or downstream if the less dense end is pointed downsteam (Au−Ru, bottom). Reproduced with permission from ref 53, copyright 2017, American Chemical Society. F) Suspensions of swimmers and particles levitated at nodal planes become more colloidally dense when they are irradiated by strong UV light, generating patterns. Adapted with permission under a Creative Commons CC-BY 4.0 license from ref 95, copyright 2018, John Wiley and Sons.

individuals interact with each other and their environment via new forces to generate collective behavior.

One of the most ubiquitous and useful added functions to acoustically powered swimmers are those based on magnetic fields. The most popular and simple use is for particles to move in a particular direction instead of diffusively. The magnetic feature (e.g., a single-domain ferromagnet) aligns with an external magnetic field to achieve a change in direction. One of the earliest examples of this was presented by Ahmed et al. in 2016, who added a nickel stripe to bimetallic nanorods,[84] analogous to earlier work by Kline et al. on magnetically oriented catalytic swimmers.[85] The same principle can also be applied to bubble-powered swimmers, either by incorporating magnetic particles into the materials used to print them,[78] or by evaporating a thin layer of magnetic metal onto their shell.[45,47] For Janus particles propelled in standing waves, exerting a torque on the swimmers with a magnetic field is the only way to observe swimming because the most acoustically active part, the metallic cap, autoaligns with the nodal plane to give no net motion (Figure 3C).[67] Beyond a simple steering mechanism, nanorods have been fabricated with a helical magnetic tail that can act as a second "engine" that operates in a direction opposite of the ultrasound propulsion (Figure 7A).[86] Another interesting application of magnetic fields in these systems was achieved by Ahmed et al. in which the mutual attraction of ferromagnetic nickel tips on nanorods were used to drive magnetic assembly (Figure 7B).[87] By levitating the rods in an acoustic field at different strengths, the effective temperature of the system could be tuned to achieve different kinds of regular geometries, such as dimeric, tetrahedral, or octahedral.

Ultrasound combined with chemical and photochemical modes of actuation can also afford useful and unique systems, and have been reviewed in some detail elsewhere.[88,89] These typically involve the fabrication of Janus particles that respond to both ultrasound (by being asymmetric in density or shape) and chemical fuels (by being catalytically asymmetric) to achieve some combined function. There are several examples of chemical fuels being used to tune the propulsion speed and direction of self-electrophoretic motors using catalytic and photocatalytic decomposition of hydrogen peroxide.[90,91] These hybrid motors can travel in one direction when only chemical power is used or in the opposite direction when ultrasound is applied or can change the speed of a particle under a constant acoustic field (Figure 7C). Chemical forces can also orient swimmers, as demonstrated by Ren et al., who utilized the fact that, when bimetallic nanorods consume hydrogen peroxide, the anode (locally positively charged end) is attracted to the negatively charged substrate (Figure 7D).[53] Under forced fluid flow, the greater drag force at the rod "tail" causes it to reorient such that the anode is pointed upstream and the cathode is pointed downstream, a form of rheotaxis. Under an applied

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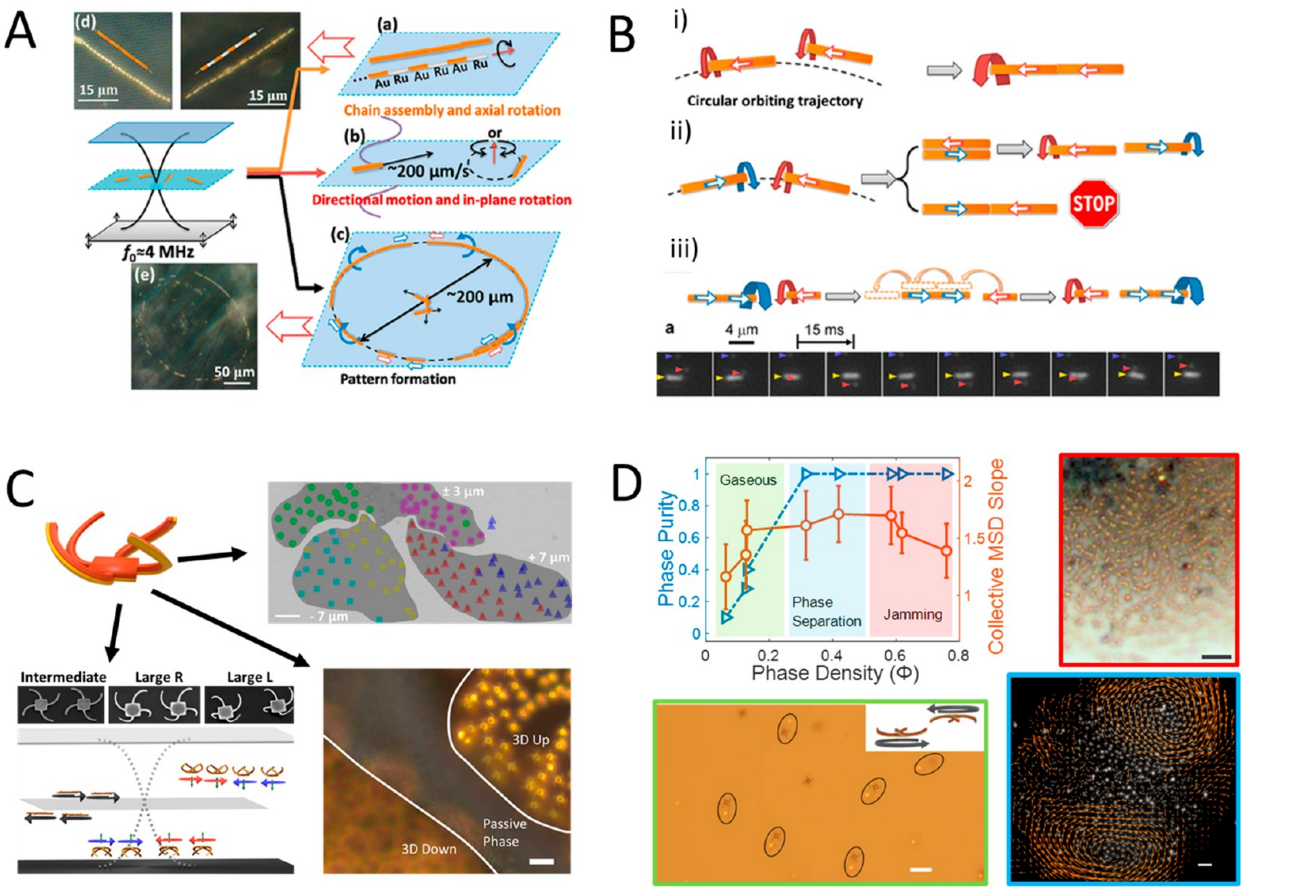

Figure 8. Collective behavior in acoustically powered systems. A) Nanorods powered by ultrasound can self-assemble into spinning chains and rings powered by hydrodynamic coupling, forming patterns. B) Interactions between spinning rods are outlined, showing that bimetallic rods tend to form polar chains by aligning in the same direction (i). Rods aligned antiparallel tend to swim past each other or stop head-to-head (ii). Antiparallel swimmers tend not to add to a growing chain but rather slip past the chain and continue moving independently (iii). Hydrodynamic coupling arising from spinning along the rod's long axis is supported by measurements of nanoparticles rotating around the rods at kilohertz frequencies (bottom). A and B are reproduced with permission from ref 46, copyright 2012, American Chemical Society. C) Microscopic spinners can also self-organize via hydrodynamic coupling at acoustic standing waves. Up to six phases form (top-right) when a mixture of three different spinner types is used (bottom-left). Spinners can also phase separate from passive particles to form active−passive binary mixtures (bottom-right). D) Self-assembly behavior changes as a function of spinner density, from a spin-paired gas at low density to phase-separated liquid at moderate densities to a jammed state at high density (box colors correspond to those in the phase diagram). C and D are reproduced with permission from ref 71, copyright 2023, American Chemical Society.

acoustic field, the rods are propelled with the lower density end forward, allowing the experimenter to select upstream versus downstream motility via rod composition to effect rheotaxis (Figure 7E). Finally, swimming tubes powered by bubble recoil can be modulated by ultrasound because the bubble generates streaming flows and Bjernkes forces.[92,93] This can be used to modulate the speed of swimmers or to self-assemble swimmers around a bubble at a pressure node. It is also worth noting that, while not considered propulsion, acoustic trapping can be a useful tool for spatially confining chemically powered swimmers to generate and study novel behavior, such as oscillating clusters.[94]

Finally, an interesting direction of this field that still remains underexplored involves the influence of strong optical fields on the behavior of acoustically powered swimmers.[95] In general, it has been shown that, when strongly irradiated, swimmers at an acoustic levitation plane tend to gather into a small area or move away from a source of light propagation if it is directional (Figure 7F). This is attributed to an optical radiation force that acts on the swimmers, causing them to move away from the light source. Experiments with charged tracers and at high ionic strength rule out potential phoretic forces generated by the photocatalysis or something similar. Optical contrast of the swimmers or particles seems to play an important role in their response to light. While interesting, it is still unknown whether or not the same effect occurs at other types of standing waves, such as SSAWs, which could answer important questions and potentially inform interesting applications.

Collective Behavior

Identifying and exploiting collective behavior in swarms of micromotors are keys to unlocking more advanced macroscopic functions. As in bacterial communities and immune responses,[3,4,96,97] communication and coordination between thousands of individuals leads to emergent function and effectiveness, which cannot be achieved with a few individual particles working one at a time. This requires researchers to think carefully about how powered swimmers interact with each other and how to realize large numbers of swimmers to achieve bulk functionality. This has been accomplished in several contexts using other types of swimmers, such as chemically,[19,98−100] electrically,[34,42,43,101] and magnetically actuated systems,[37−39] but it remains very rare for acoustically powered systems. The few examples that have been explored mainly involve standing-wave-powered systems, with a few examples of traveling-wave-based systems.

Collective behavior in ultrasound-powered swimmers has been observed since the first report of this phenomenon in nanorods.[46] Beyond simple swimming, it was also noticed that nanorod-based swimmers align with each other end-to-end in large groups to form chains and rings (Figure 8A and 8B). This behavior is likely caused by hydrodynamic coupling between swimmers as they rotate about their long axis at very high speeds, up to kilohertz as determined by single-particle tracking (Figure 8B, bottom).[72] Hydrodynamic coupling, therefore, can be a powerful type of interaction between acoustic swimmers likely due to the very fast fluid flows that they generate.

Several theoretical studies have predicted that rotors, whether by collisions[102] or hydrodynamics,[103,104] should be capable of phase separation and other emergent phenomena between oppositely spinning populations. Self-organization via rotation is also an important factor in the assembly of biological systems,[5,9] and collections of spinners have been predicted and shown to exhibit exotic nonequilibrium states.[7,8,105] We first attempted to observe this behavior with large, gear-like rotors with a symmetry-broken axis of rotation.[69] However, their large size and subtle asymmetry made them rotate slowly, and their low yield made them difficult to study in large quantities. Additionally, their large size led to strong Bjerknes forces that caused spinners to stick together rather than interact hydrodynamically. Recently, we explored a new fabrication method that gave much smaller swimmers that could be produced in far greater quantities, enabling us to observe collective interactions between particles.[71] The thin arms of these spinners (Figure 8C) exhibit weak Bjerknes forces and maintain the distance between the dense swimmer bodies to prevent strong, irreversible attraction. Changing the number density of spinners enabled us to characterize their phase behavior, with a gas phase at low density, then a phase separated liquid, and finally a jammed state (Figure 8D). 3D shape anisotropy perpendicular to the levitation plane caused spinners that were locked parallel to the nodal plane to propel away from the plane, leading to a three-dimensionally complex placement of the spinners relative to each other in parallel sheets. By mixing different chiralities of spinners, we were able to observe the coexistence of at least 6 distinct domains (Figure 8C, top-right, 3D diagram bottom-left), each corresponding to a particular spinner orientation and chirality combination. Finally, we observed that spinners also phase separated from passive particles (active−passive phase separation, Figure 8C, bottom-right), forming a new type of phase diagram. These observations match nicely with theoretical predictions by Yeo et al., who predicted that rotors should couple hydrodynamically[104] and phase separate from passive particles.[106] We believe that these types of interactions can lead to systems with macroscopically relevant functions, and the system could also be useful in observing new forms of exotic active matter such as fluids with odd viscosity.

Collective behavior in these systems can also be achieved by creating hybrid systems with magnetic fields. Although only demonstrated at small scales, bubble swimmers with magnetically active components are capable of swarming in a given direction dictated by an external magnetic field to steer all swimmers in that direction. Another interesting approach, inspired by the behavior of neutrophils, has been used by Ahmed et al. in which magnetic particles are gathered using a rotating magnetic field.[107] The collection of particles can then be attracted to the walls of an experimental environment, in this case, a microfluidic channel, using an acoustic standing wave (Figure 9A). Once there, they have a surface against

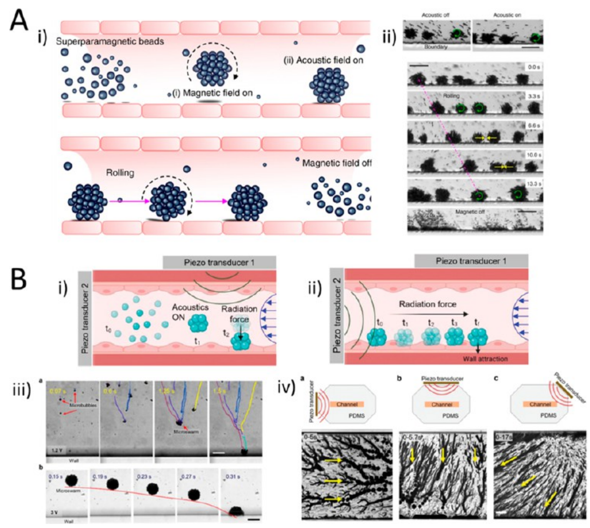

Figure 9. Non-hydrodynamic collective behavior. A) Groups of magnetic particles can be generated using rotating magnetic fields and drawn to the walls of microfluidic channels using acoustic fields. The swarms can be broken when the magnetic field is turned off. (i) and (ii) are schematics and real images, respectively. Adapted with permission under a Creative Commons CC-BY 4.0 license from ref 107, copyright 2017, Nature Publishing Group. B) Swarms can be formed by groups of free, symmetric bubbles that are self-assembled in acoustic fields via Bjerknes forces (i). Bubbles translate as a swarm in the presence of an acoustic field gradient generated by directional propagation of sound (ii−iv). Reproduced with permission from ref 108, copyright 2022, John Wiley and Sons.

which they can rotate, generating more substantial propulsion. In this case, it is the collective magnetic interactions that allow the group of particles to travel faster together than they could as individual particles, and the acoustic field helps to provide an ideal environment for fast propulsion.

Finally, collective phenomena can in principle arise in collections of swimmers powered by traveling waves, especially bubbles, but there are only a few examples in the literature, and they do not describe very large-scale phenomena. This is mostly due to the lack of scalable techniques to fabricate and operate these types of swimmers, limiting them to small-scale studies of their interactions with fields, particles, and other swimmers. One form of collective behavior already observed with bubble swimmers is their response to the direction of traveling waves, in which they typically propagate away from the source of sound, as demonstrated by Louf et al. in hovering swimmers.[75] This is due to the primary Bjerknes force, where the swimmer experiences an acoustic field gradient and moves down that gradient.[80] Although this is a simple phenomenon applied to one or several swimmers at a time, it could be a way of causing many bubbles to swarm toward a single point, especially if the field could be shaped and pointed to a single location. This idea has been utilized by Daniel Ahmed's group to create swarms from free, symmetric microbubbles that are

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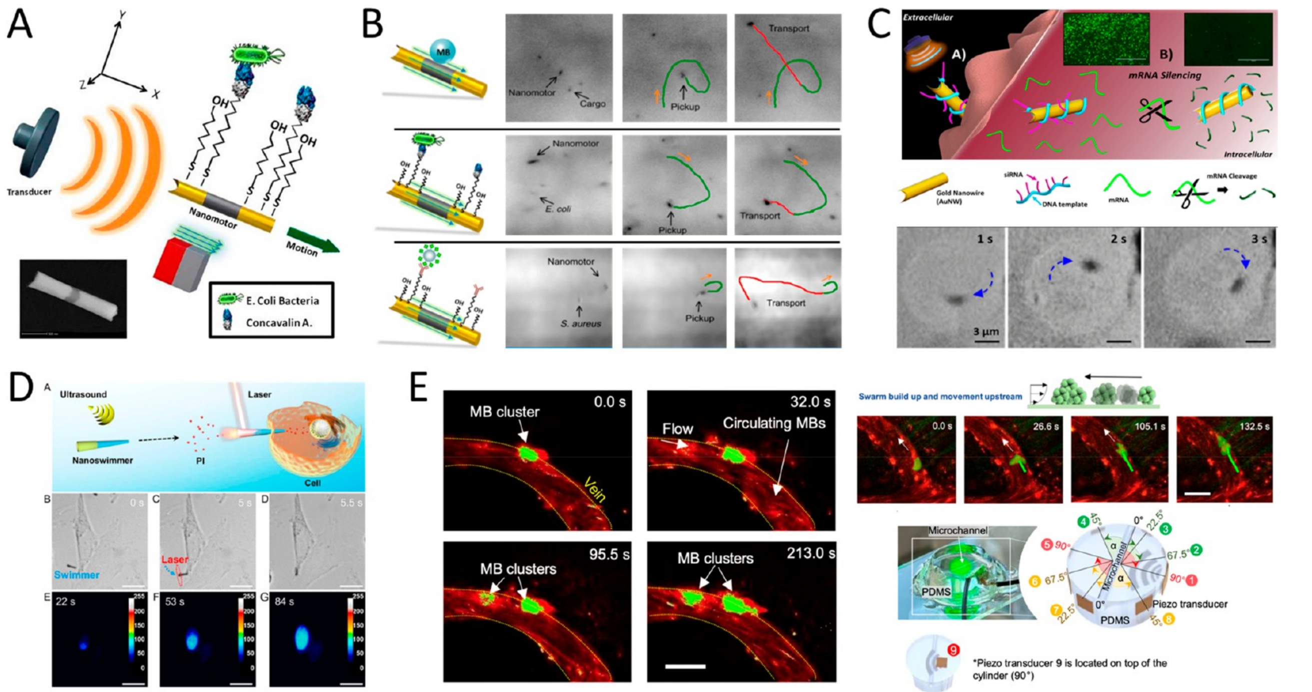

Figure 10. Demonstrated applications of acoustic motors. A and B) Magnetic nanorods functionalized with antibodies (A) are attracted to bacteria and can pick them up and carry them when levitated and steered at acoustic standing waves (B, middle and bottom). The nanorods can also capture magnetic particles attracted to the magnetic stripe (B, top). A and B are reproduced with permission from ref 113, copyright 2013, American Chemical Society. C) Swimmers functionalized with siRNAs can penetrate the body of the cell at standing waves to deliver siRNA and silence genes (top). Swimmers can even be seen swimming around the inside of mammalian cells (bottom). Reproduced with permission from ref 48, copyright 2016, American Chemical Society. D) Tubular swimmers powered by acoustic waves and equipped with a photothermal element can embed themselves in cells (top and middle) and porate them using lasers to kill them, as seen in the fluorescence images at the bottom. Reproduced with permission from ref 66, copyright 2019, American Chemical Society. E) Swarms of microbubbles can be generated and steered inside the vasculature (including upstream, top-right) of a mouse brain using a complex system of transducers (bottom-right) that create gradients to dictate migration patterns. Fluorescence tagging of bubble membranes and vasculature highlights images. Adapted with permission under a Creative Commons CC-BY 4.0 license from ref 114, copyright 2023, Nature Publishing Group.

attracted to each other via the secondary Bjerknes force and move down acoustic gradients to achieve directional motion (Figure 9B).[108] Swimmers fabricated by templated electrodeposition of microtubes offer a unique solution to the scalability problem, and it is observed that they interact with each other to swim cooperatively, but not on a large scale.[76]

DEMONSTRATED APPLICATIONS

There is a growing number of demonstrated applications for acoustically powered particles and a wealth of potential areas for improvement and utilization. Many of these involve swimmers working in biological environments due to the biocompatibility of sound waves and the speed and selectivity of propulsion relative to other methods. For example, acoustic fields can be used to levitate cells at relatively high powers (comparable to that used in medical ultrasonic imaging) with little to no effect on viability.[109,110] Moreover, if it becomes possible to use them in vivo, ultrasound is already clinically mature and can achieve deep penetration into tissues as compared to the centimeters of penetration achievable through the near-infrared (NIR) window. Ultrasound avoids the need for the toxic or complex fuels, or bright illumination, required by chemical swimmers (which also struggle to work in high-ionic-strength environments), the electrodes and high voltages required by electrically driven swimmers, and the strong and complex magnetic fields needed for magnetically controlled swimmers.

Of the two types of acoustic propulsion, we envision that standing wave power will remain largely confined to "on-chip" applications, whereas traveling waves have many more opportunities for use in vivo. So far, there have been many reports of using nanorod- and nanotube-based systems with cavity and surface standing waves to probe or interact with cells in interesting ways. In several studies, Joseph Wang and co-workers leveraged the high velocities and diffusivity of nanorods in cavity standing waves, as well as their ability to be functionalized at gold surfaces for bioanalytical applications.[48,111−113] In one study, the gold was functionalized with a lectin to capture *E. coli*, and with antiprotein A antibodies for the capture of *S. aureus*, which were both then able to travel along with the motor (Figure 10A and 10B).[113] Similar motors were also coated with siRNA, and under an applied acoustic field, the motion helped the cells internalize the motors, leading to intracellular delivery (Figure 10C).[48] The siRNA was shown to silence the expression of GFP, leading to a loss of fluorescence in two different cell lines, verifying the viability of the approach. Finally, the directed propulsion of cone-shaped swimmers was used to lodge the sharp edge of the particle into cells, and photoactive components, such as gold, could be used to porate the membrane (Figure 10D).[66] These are all examples of "on-chip" systems since they are small-scale analytical techniques performed on fabricated devices.

Applications with traveling-wave-powered swimmers tend to avoid the complex experimental geometries required for standing-wave-powered systems (i.e., no need for cavity or surface standing waves), but they are then limited by the fabrication of more complex swimmers. Moreover, the slow speeds and large size of particles that are not bubble-based tend to limit their usefulness. One interesting way to overcome this problem, developed by Daniel Ahmed and co-workers, is to utilize the swarming behavior of simple, spherical microbubbles, and their response to the direction of an acoustic field, as mentioned above.[108] Their team has demonstrated the ability to operate in real physiological environments such as in flows similar to those found in the bloodstream. They have even tagged the membrane of the microbubbles with fluorescent dyes and observed their swarming behavior and navigation inside of the brains of living mice (Figure 10E).[114] The swarms can grow and merge with one another and move with or against the flow inside the vessels. Although this method requires complex systems of transducers, it holds great promise for accelerating the development of acoustically powered motors for in vivo applications, and it underscores the importance of collective interactions in achieving new function.

Future Directions

The number of new research directions and potential applications of acoustically powered microswimmers is abundant, and we provide here our thoughts on areas that deserve particular attention. These include exploring the mechanism and rules of propulsion in more detail, studying the interactions between swimmers to unlock new types of collective behavior, and building new types of hybrid systems that will also allow for swarming and the realization of useful properties in vivo. Additionally, the necessity of large-scale fabrication, coupled with combined imaging and actuation methods, is apparent. We also make some suggestions on how the community might improve the reporting of quantitative results in order to create a more well-rounded picture of mechanics so the field can advance more quickly.

Building complex systems capable of carrying out meaningful tasks starts with an understanding of individual behavior and the forces at play. Open questions in this area include several aspects of scaling and the role of shape in different types of acoustically powered swimmers. This will be important for engineering the ideal swimmer for any application, especially in traveling wave systems. For example, in standing wave systems, the range of particles that has been tested is very narrow, mostly confined to 300 nm diameter nanorods and microscopic Janus particles. Studying these systems with larger particles or those with significantly different shapes could open up new capabilities, create faster and more efficient motors, and offer more insight into the rules that govern propulsion. In traveling wave swimmers, it is important to tackle several problems and issues that plague their use. First and foremost, bubble swimmers have not been studied in the limit of extreme shapes, either at very high aspect ratios or with asymmetric and nonpseudospherical shapes that could lead to interesting new behavior. Moreover, bubble swimmers are plagued by issues of fidelity, such as how to reliably generate bubbles in every single swimmer and how to keep the bubble stable over long time scales and under harsh operating conditions. The ability to generate bubbles on demand inside a shell when needed or to replace a popped bubble would be very useful to the community.

One area where large strides could be made is in the development of nonbubble-based traveling-wave-powered swimmers. These systems could be free of some of the prevailing issues of bubbles outlined above but suffer currently from issues related to their efficiency, size, scalability, and maneuverability. Therefore, it would be useful for the community to begin exploring the parameters that govern the behavior of this class of acoustic swimmers. For example, in flagellar nanorod swimmers, what is the role of tail length or body length, the material properties of either of those pieces, and the general shape and diameter of the swimmer? There are also a few recent studies that suggest cone-shaped objects could be powered by traveling waves, and these ideas have yet to be validated experimentally.[73,115] We are curious to learn whether, with enough work, these swimmers could begin to approach the speeds and powers achievable with bubble-based acoustic swimmers.

The combination of acoustically powered swimmers with other forms of actuation could also be very powerful. This will require fabrication methods that can integrate new functional moieties into structures capable of swimming in acoustic fields. For example, several studies have shown that chemotaxis can be used to reorient swimmers along a chemical gradient for autonomous navigation,[27,116,117] but chemical modes of propulsion are inefficient. As an example, it may be possible to use chemical forces to orient a traveling-wave swimmer parallel to a chemical gradient and use the acoustic field to drive swimming up that gradient much more efficiently than can be done with chemical power alone. This, along with other chemically complex systems, could find interesting applications in sensing, separation, and particle delivery. Electric-field-powered systems might also be interesting, since they are likely compatible with acoustic swimmers and could be used to generate and tune interactions between other swimmers and their environments. Although magnetic−acoustic hybrids have already been studied, it might be possible to use them to orient swimmer swarms and generate new types of hydrodynamic interactions. Finally, interactions between swimmers and their environment should be studied in greater detail to learn how to program them to be more autonomous. Concepts from work on the collective dynamics of chemically and electrically powered swarms could be applied here.[30,33,118] Swarms of bubbles, for example, tend to gather at walls and can migrate down acoustic field gradients, but a host of new behaviors, such as rheotaxis, could be realized if asymmetric swimmers were used instead of symmetric bubbles.

Finally, we emphasize that the field will be able to advance more quickly if proper steps are taken in reporting the results of experiments. First, the frequency and power used in every experiment, in hertz and peak-to-peak voltage (V_{pp}), should be described. Similarly, the precise geometry of the setup used to run the experiments and the resonance frequency of the transducer used can have a substantial impact on the development of standing waves that cause artifacts and should be described in as much detail as possible. Due to inhomogeneities in the transducer and environment, the ideal case would be to also report the acoustic pressure in the cavity during each experiment, but this requires expensive equipment and difficult experiments. We suggest that, especially in the case of standing wave swimmers, and where mechanisms are being explored in detail, the pressure can be estimated from the drift of tracer particles, as we reported recently.[56] Otherwise, assumptions can lead to oversights and the assignment of erroneous mechanisms. Another very useful experiment that should be included in every report of a new swimmer is to experiment with tracer particles (with the swimmer stationary if possible) in order to visualize the shape of the flow field around the swimmer.

By reliably exploring the physics and mechanics of new and old kinds of microscopic swimmers, both in the presence of acoustic fields and in hybrid systems, it should soon be possible to create powerful autonomous swarms capable of carrying out tasks that have been envisioned for several decades. These systems, with the help of ultrasonics, have the potential to work in environments that other microswimmers struggle with and on length scales that are relevant to biomedicine. This is enabled by the powerful forces that acoustic swimmers generate to move upward of hundreds of body lengths per second and by their ability to work far from a transducer in traveling wave systems. They are compatible with all of the other types of microscale actuation modalities and remain relatively underexplored even by themselves, making them rife with opportunities for improvement and exploration. Designing and characterizing their individual behaviors, tuning their interactions with each other, and understanding how they couple to their environment will all be essential to creating systems that can carry out large-scale tasks autonomously and efficiently. The realization of these systems will likely lead to a generation of powerful bioanalytical tools and to the observation of complex active matter systems with interesting physical properties.

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