Magnetobiology: Beyond attraction

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Jinxing Li and Christopher H. Contag delve into the emerging field of magnetobiology, which utilizes magnetic fields to manipulate and control living systems, while reflecting on its potential to surpass the limitations of other modalities

Magnetobiology: drawing biologists to magnetic control of living systems

Magnetobiology is emerging as a transformative discipline defined by the use of magnetic fields to manipulate and control living systems. Techniques such as magnetic resonance imaging (MRI) and magnetic particle imaging (MPI) have already revolutionized biomedical research and clinical practice, enabling non-invasive visualization of anatomy, physiology, and molecular processes with unprecedented resolution. Building on this legacy, magnetobiology moves beyond merely observing biology to actively controlling it, leveraging magnetic fields to interrogate, engineer, and actuate biomolecules, cells, tissues, and whole organisms.

Historically, magnetism was considered peripheral to biological research, overshadowed by optical, chemical, and electrical modalities. Today, magnetic technologies are gaining traction for their unique combination of capabilities: they penetrate deep into tissue without attenuation, deliver forces and torques at cellular and subcellular scales, actuate micro- and nanoscale devices, and remotely regulate genetic and cellular functions. These properties allow researchers to not only monitor biological processes but precisely manipulate these functions in real time.

The field has expanded far beyond simple magnetic interactions. Researchers across disciplines are drawn to magnetobiology because it offers a powerful toolkit for non- invasive, spatially precise, and spatiotemporally controlled biological intervention. By integrating magnetogenetics, magnetically actuated micro- and nano-robots, magnetic hyperthermia, magnetoelectric energy transmission and harvesting, and magnetic control of neural and immune circuits, magnetobiology positions itself at the frontier of both fundamental research and translational applications, transforming magnetic fields from passive imaging tools into active instruments for controlling life.

Why magnetism matters

Magnetic fields are uniquely suited to biological control. Unlike light, they pass through tissue without scattering or attenuation; unlike chemical modulators, they can be applied locally without requiring systemic distribution. Alternatively, the fields can be applied over the entire body, and only where engineered nanomagnets are located is the biology affected, offering the potential to affect biology with magnetic targeting. Magnetic control can be non-invasive, eliminating the need for surgical access or chronic interfaces required by implants or electrodes. Magnetic fields can be shaped, pulsed, rotated, or focused with millimeter precision and can exert mechanical force, torque, thermal energy, or navigational control.

These capabilities make magnetism a compelling platform for a wide range of biological applications. Magnetic fields can manipulate signaling pathways, stimulate the nervous systems, remotely trigger gene expression, guide therapeutic agents, activate drug release, and navigate micro- and nano-robots within complex tissue environments. They also enable modulation of neural and immune functions without implants, providing spatial precision, temporal control, and deep-tissue access that few other modalities can achieve. For biologists seeking minimally invasive tools that scale from single cells to whole organisms, magnetism is increasingly impossible to ignore. Its rapid adoption reflects a new ‘attraction’ – the recognition that magnetic systems combine biophysical clarity with translational potential.

In vivo magnetic actuation with molecular imaging

Our teams have designed and characterized magnetically responsive systems capable of actuating intracellular pathways via magnetothermal energy. [1,2] Magnetotactic bacteria are naturally occurring microorganisms that biomineralize iron into nanoscale magnets, or magnetosomes, which can be targeted for imaging, [3,4] as well as locally warming cells when exposed to alternating magnetic fields in vivo. [2] We have used natural magnetotactic bacteria or mimicked these bacteria by coating bacteria with iron oxide nanoparticles, and demonstrated that this enables imaging, heating, and precise control of biological processes. [1-4] Using in vivo bioluminescence imaging and intravital imaging, we demonstrated quantitative spatial and temporal activation of genetic pathways. Magnetothermal energy generated by applying alternating magnetic fields to tissues containing magnetic bacteria guided the release of repressors from bacterial promoters, turning gene pathways on via magnetic fields. [2] These studies confirmed that magnetic fields can modulate biology without off-target heating or tissue damage.

This work lays the groundwork for magnetogenetic platforms capable of remotely regulating gene expression, immune programs, and regenerative pathways, directly linking magnetism to synthetic biology and gene therapy. By enabling deep-body biological modulation without invasive interventions, this approach attracts biologists seeking alternatives to optogenetics or chemogenetics. These strategies build on and will interface with transcranial magnetic stimulation (TMS) and will provide non-invasive neural modulation at depths and scales inaccessible to light-based methods. Combining cellular magnetogenetics with external field delivery enables precise neural control with translational potential for neurotherapeutics.

Pioneering magnetic micro- and nano-robotics

Complementing magnetogenetics, our teams have developed 3D-printed magnetic swimmers, biohybrid microrobots based on magnetotactic bacteria, and biodegradable magnetic robots capable of navigating through biological fluids and gastrointestinal environments. [5,6] These miniaturized, untethered devices can access previously unreachable locations in the body, enabling cellular-level procedures with remarkable precision and efficiency. Magnetic microrobots will enable delivery of drugs directly to tumors, disrupt biofilms, clear blockages, ablate tumor cells, stimulate neurons, and enhance tissue barrier penetration. Integrating magnetic materials with living cells or scaffolds enables programmable tissue formation, immune modulation, and organ-level intervention.

Magnetic fields can also provide both individual and collective control of microrobots. 3D-printed microrobots with three integrated magnetic functionalities – magnetic actuation, magnetic particle imaging, and magnetic hyperthermia – can potentially enable closed-loop, autonomous navigation inside the body to perform targeted delivery or precision procedures, [(6)] as envisioned in the 1966 movie Fantastic Voyage. These advances attract bioengineers and mechanobiologists interested in spatially precise, non-invasive interventions within living organisms.

Attracting the broader life sciences community

Magnetobiology offers capabilities that neither optical nor chemical tools can match. That is, precise signal modulation, remote control of gene expression, guided therapeutic delivery, and non-invasive neural and immune regulation. Its unique combination of spatial precision, temporal responsiveness, and deep-tissue access positions magnetic control as a transformative platform across biology and medicine. By connecting molecular and cellular actuation (magnetogenetics) with tissue- and organism-level interventions (micro- robotics and TMS-inspired neuromodulation), magnetobiology is drawing a diverse community of researchers, including neuroscientists, immunologists, cancer biologists, regenerative medicine specialists, and translational engineers, into this emerging field.

Magnetobiology goes beyond the physical attraction of magnets; its strength lies in programmable control over diverse biological functions. Foundational work from our research teams and others demonstrates that magnetic technologies enable precise, non-invasive actuation across scales from single cells to organs. By integrating molecular magnetogenetics, magnetic micro-robotics, and non-invasive neural modulation, the field is moving from conceptual promise to practical impact.

With continued investment, magnetobiology can become a defining discipline of the next decade that will move decisively beyond attraction toward precise, transformative control of life while attracting biologists and engineers to a dynamic, interdisciplinary frontier.

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