

News and Perspectives

Nanorobots Are Using Light and Clever Engineering to Beat Biofilms and Tackle Antimicrobial-Resistant Infections

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Abstract

The scope of the antimicrobial resistance issue is huge—one promising solution may be much, much smaller. In this *News and Perspectives* article, JMIR Correspondent Liam Critchley reports on advances in micro/nanorobotics, which may provide new avenues for treating biofilm infections.

Key Takeaways:

- Antimicrobial biofilms have been preventing therapeutic drugs from being effective, contributing to antimicrobial resistance.
- Advances in micro/nanorobots offer a way to break through these biofilms and treat infections.

Antimicrobial resistance (AMR) is an increasingly critical health challenge and a major global health concern, according to the [World Health Organization \(WHO\)](#). Consistent use and overuse of antibiotics are causing some bacterial pathogens to have multidrug resistance to common medicines and disinfectants.

At the molecular level, one of the main mechanisms contributing to antibiotic resistance is that bacteria can form [biofilms](#) that make it harder for immune cells, like macrophages, to attack the infection; these biofilms reduce the therapeutic efficacy of antibiotics because traditional antibiotic delivery methods struggle to break through them. These biofilms can also complicate treatment and cause recurrent infections. They can also form on implantable medical devices, complicating surgical procedures.

The latest strategies for addressing AMR center around penetrating through these biofilms. Micro/nanorobots (MNRs) offer a way to do this. These tiny machines can be designed or guided to navigate to the infection site, penetrate the biofilm barrier, and deliver a therapeutic load to the bacteria embedded within it.

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A number of MNR systems have emerged, all with different working principles, materials, and locomotion methods. For example, [some](#) MNR systems are designed to have a sort of “spine” that mechanically disrupts the biofilm, and these systems can release zinc ions that then help with tissue repair. [Others](#) can be propelled and controlled using magnetic fields, creating motion that mechanically disrupts the biofilm while delivering antibiotics to the infected site. Still [others](#) are cleverly engineered to undergo a chemical reaction that propels them through the biofilm, where another reaction generates reactive oxygen species (ROS) that damage the bacteria.

The last example reflects one of the most promising MNR avenues—using Janus nanoparticles. A Janus nanoparticle is simply a spherical nanoparticle that has two different sides with distinctly differing properties (think something like [Aero mint chocolate bubbles](#)). One side can be used for stability or propulsion, and the other can be used in chemical or photocatalytic reactions.

Lights, Magnets, Action!

[Research](#) published in *Science Robotics* in 2025, in which researchers tested MNR swarms (numerous microrobots) in a series of controlled laboratory experiments and then in rabbits given a sinus infection, highlights the promise of this approach.

These particular Janus microrobots—copper (Cu) single atom-doped bismuth oxiodide (BiOI) microrobots (CBMRs)—contain a photocatalytic body integrated with a magnetic component.

“Our system combines magnetic actuation, photothermal barrier modulation, photocatalytic sterilization, and image-guided delivery in a single therapeutic platform,” says Yabin Zhang, PhD—one of the lead authors of the study. “An external magnetic field guides the microrobot swarm to the

infected sinus region, while a magnetically responsive optical fiber follows the swarm and provides localized visible-light irradiation.”

Under illumination, these microrobots generate heat that reduces the viscosity of inflammatory secretions—mucous—making it easier for the swarm to penetrate the biological barrier. Magnetic rotation simultaneously provides mechanical shear that disrupts the bacterial biofilms. Once the biofilm structure is weakened, the photocatalytic reaction produces ROS—a process that’s enhanced by the copper atoms in the microrobots’ structure—which then kill the exposed bacteria.

The results are encouraging. According to Zhang, in preclinical studies, this type of MNR “showed favorable biocompatibility, no obvious systemic toxicity or organ injury in a rabbit model, and short-duration treatment [which was effective] did not damage the nasal mucosa.” While therapeutic efficacy and safety have only been demonstrated in a rabbit sinusitis model, there are hopes that these MNRs could move toward clinical trials.

There are also, however, some challenges to overcome. “The optical fiber must remain sufficiently close to the microrobot swarm to provide effective illumination, which becomes more difficult in deeper or more tortuous anatomical spaces,” Zhang says, adding that “magnetic navigation currently relies on external permanent magnets and robotic-arm manipulation, so achieving fully automated, closed-loop navigation within complex three-dimensional anatomies remains an important challenge.”

Moving forward, Zhang states that “we aim to further optimize the microrobot itself by developing more efficient single-atom catalytic systems, improving photothermal and ROS generation, and exploring biodegradable materials to enhance therapeutic efficiency and long-term biosafety. We also hope to integrate additional functions, such as local drug delivery, inflammatory biomarker detection, and real-time monitoring of therapeutic response.” Zhang also notes that there are plans to improve navigation and imaging, moving toward a radiation-free design that can undertake automated path planning and be adaptively controlled. It’s hoped that they will be able to adapt the design for different in vivo environments, including the urinary, reproductive, and digestive systems.

“Ultimately,” he says, “the major goal is clinical translation.”

More Active, Efficient Transport

A similarly promising example comes from a recent [study](#) published in *ACS Nano*, which also used photocatalytic Janus nanoparticles, but these had a structure that enabled more active, autonomous motion and additional antibacterial activity. These were mesoporous aminophenol-formaldehyde resin/silica Janus nanoparticles containing metallic silver nanoparticles (mSAR-Ag⁰).

“Our antimicrobial robot combines three functions: photocatalytic production of ROS, the antibacterial activity of silver nanoparticles, and autonomous motion,” says Tianyi Liu,

PhD—one of the lead authors of the study. “The asymmetric structure allows the nanorobots to move in response to both hydrogen peroxide and UV light, and this movement improves their ability to penetrate biofilms, promotes the diffusion of ROS, and increases contact with bacteria.”

“We chose this design because light provides a convenient and non-invasive way to control the system. It can be applied externally and does not require the continuous addition of chemical reagents,” Liu says. As well as light, the robotic system can also use hydrogen peroxide as a fuel source and still move at relatively low fuel concentrations. Hydrogen peroxide is naturally present at elevated levels in infected wounds, so the system could potentially use the wound microenvironment as its fuel source as well.

When tested in rats and with an added compound to accelerate the healing process, the robot proved effective. “Passive diffusion or a single antibacterial mechanism is often insufficient for penetrating dense biofilms and reaching bacteria located deep within them,” Liu explains. “Combining motion, photocatalysis, and the antibacterial effect of silver nanoparticles gives the system a better chance of reaching and eliminating deeply embedded bacteria.”

This system, too, has its limitations. “The main limitation is that the current system is activated by 365 nm UV light. UV light has limited penetration into biological tissue, which restricts the use of this system in deep sites,” Liu says. “Also, more long-term toxicity studies are needed to understand the possible long-term effects of the nanorobots, including degradation behavior and potential accumulation in the body.”

Going forward, the researchers have plans to use molecular engineering to improve the light-harvesting ability of the system and extend its absorption toward the near-infrared (NIR) region, overcoming some of the current limitations with UV light. “NIR light penetrates tissue more effectively than UV light, so this modification could make remote activation in deeper tissues more practical,” explains Liu. “We also plan to introduce biomass-derived materials into the robotic system and carry out more systematic studies on its long-term biocompatibility and toxicity.” These next steps will help the researchers to better assess the MNRs’ potential for biomedical applications and whether the systems are suitable to take to clinical trials.

The Future of AMR: Small and Bright

There is hope that MNRs will be able to address some of the current issues with AMR before they get too difficult to address. Advances in [AI](#), computational modeling, and digital imaging may further improve design, detection, and tracking for better treatment precision and effectiveness.



While still relatively new, MNRs are now moving from controlled lab experiments to animal trials, with the hope that they will eventually be suitable for human trials.

*Ultimately, the major
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Yabin Zhang, PhD

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