

Delivering precision: Medical molecular robotics and the next phase of personalized medicine

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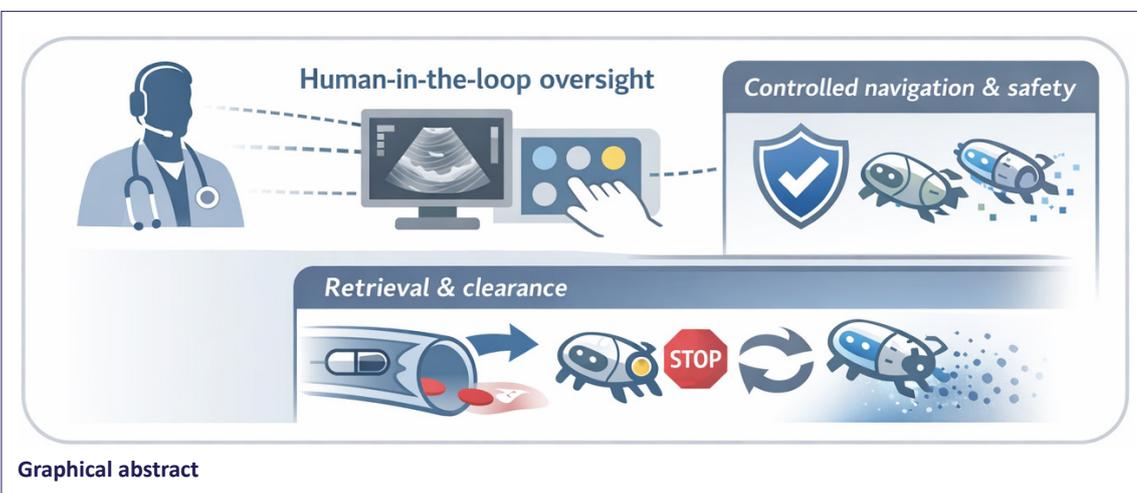
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Abstract

Medical molecular robotics can be seen as the integration of nanotechnology, robotic technology, imaging innovation, and precision medicine that takes minimally invasive robotic surgery forward into the molecular realm. Such approaches include everything from magnetically/sonically activated microrobots through programmable nanostructures that can potentially navigate biological environments with a high degree of accuracy and precision for targeted therapeutic delivery. This editorial article examines the perceived importance of medical molecular robotics in terms of complementing existing medical technology and pushing the boundaries of personalized medicine in the sense that intervention itself becomes a reality in therapeutics. Although the immediate benefits of improved targeting engagement with a low systemic toxicity profile in a theranostic-based paradigm would seem considerable, there would undoubtedly be a multitude of issues in taking these approaches forward that would include biocompatibility issues in terms of control, visualization, regulatory requirements, and so on.



Short commentary

Medical molecular robotics can be defined as the application of mobile micro- and nanoscale robotic systems capable of controlled motion, sensing, and actuation within the human body to perform diagnostic or therapeutic tasks. Unlike passive nanoparticles or static implants, molecular robotic systems are characterized by active navigation, external or field-based control, and the potential for real-time feedback during intervention [1]. Conceptually, the field extends the logic of macroscopic robotic surgery—precision, remote control, and reproducibility—into the intrabody environment, providing continuity between established surgical robotics and emerging molecular-scale medicine (Figure 1) [2,3].

In contemporary clinical practice, targeted drug delivery, interventional radiology, endoscopy, and image-guided surgery already aim to localize therapy and minimize systemic exposure. Medical molecular robotics complements these approaches by enabling intervention at spatial scales that are otherwise inaccessible, including microvasculature, glandular ducts, and localized inflammatory or neoplastic microenvironments [4]. As such, the field is not a replacement for current medical technologies but a functional augmentation of them, particularly relevant to precision and personalized medicine (human-in-the-loop).

Potential clinical advantages

The most prominent advantage of medical molecular robots is their ability to improve spatial and temporal resolution. The mobile microrobots can target a specific area in a body and work towards alleviating some shortcomings associated with diffusion-based or uptake-based approaches [5]. Targeted therapy will be able to decrease pharmacologic doses while limiting systemic side effects that come along with current approaches for treating cancer, immunomodulation, or infection [6].

A further benefit for its application in theranostics could be its integrated functionality of sensing, imaging, and therapy. The microrobot guided by ultrasound for imaging shows how treatment can be confirmed in real-time rather than merely through the pharmacodynamic effect (Figure 1) [7,8]. This is very much in line with the emphasis on personalized therapy, in which the differences between individuals could possibly be a result of variation in targets rather than identity itself.

Medical molecular robotics also enables functional adaptability. Soft and reconfigurable microrobots can alter shape or mechanical properties in response to environmental cues, improving navigation through heterogeneous biological media such as mucus, branching vasculature, or interstitial tissue [9]. At the molecular scale, programmable nanostructures such as DNA origami offer the possibility of encoding logical rules for multivalent targeting and conditional payload release, allowing therapeutic activity to be matched to patient-specific molecular signatures [10]. Collectively, these features suggest a future in which personalization is achieved not only through drug selection but through controllable delivery dynamics.

Limitations and translational challenges

Although very promising, there are many translational challenges to the application of medical molecular robotics. The reliable navigation and control in a biological tissue are hard to

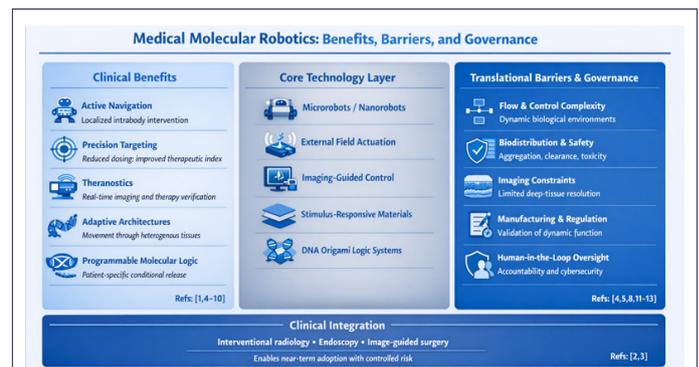


Figure 1: Medical molecular robotics: Clinical benefits, enabling technologies, and translational governance.

This diagram encapsulates the emerging paradigm of medical molecular robotics over the three interrelated areas. The Clinical Benefits area focuses on the core benefits, which include active intracorporeal navigation for targeted therapy, precise targeting permitting reduced systemic dosages and optimized therapeutic ratios, intra-procedural theranostic imaging permitting concomitant imaging and treatment validation, dynamically adaptable designs able to maneuver through inhomogeneous tissue, and programmable molecular logic systems enabling patient-customized, switched therapeutics. The Core Technology Area identifies the core technological building blocks needed for implementing the benefits, which include micro/nanorobot systems, external field control (for example, magnetic, sound, or electric guidance and actuation), image guidance and navigation systems, bioconforming and stimulus-responsive biomaterials, and logical systems enabled through the use of DNA origami platforms. The area on Translational Barriers & Governance identifies the core translational hurdles that must be addressed prior to clinical implementation, such as the challenges posed by the fluid dynamics and control present in living biological systems, biodistribution, bioconformity, and toxicity considerations regarding accumulative nanosizing, as well as the challenges represented by image resolution in deeper biological systems, the scalability and validation (including regulatory approval) process in the use of dynamic systems, and the role of human monitoring systems for implementing controls over safety, security, and medicolegal respect. The third area at the bottom fundamentally focuses on Clinical Integration and finds near-term translational corridors in the use of interventional radiology systems, endoscopy systems, and image-guided surgery systems.

master with regard to biological dynamics of tissue hydration [4]. The high-resolution tracking in a safe way for long interventions would also be a hard task to master [8].

Biocompatibility issues also introduce new restrictions. The potential for the microdevice poses challenges that are quite different from pharmacotherapy, such as mechanical obstruction, unintentional aggregation, vascular occlusion, and unpredictable biodistribution patterns. The ability of microrobots to navigate the sensitive area of the brain's vasculature demonstrates the potential for therapy as well as the need for strict control over the device's behavior, reversibility, and predetermined safety levels [11]. The device's clearance or bioresorption needs to be reliable for regulatory requirements to be met. From regulatory and manufacturing perspectives, molecular robotic systems challenge existing frameworks because their function depends on dynamic behavior rather than material composition alone. Scalable fabrication, rigorous quality control, and validation of performance metrics will be essential prerequisites for widespread clinical adoption [1,5].

Ethical, operational, and governance considerations

As with macroscopic robotic surgery and telemedicine, increasing autonomy and connectivity raise ethical and governance concerns (Figure 1). These issues are amplified in medical molecular robotics, where decision-making may involve algorithmic navigation, remote actuation, and real-time intrabody data integration. Human-in-the-loop oversight is therefore critical—particularly in early clinical deployment—to ensure accountability, traceability, and rapid intervention in the event of device malfunction or unexpected physiological responses [12,13]. Operationally, the most plausible near-term applications are those that integrate seamlessly into established procedural ecosystems, such as interventional radiology or endoscopy, where imaging, access routes, and emergency protocols are already defined—mirroring the historical adoption trajectory of robotic surgery [2,3].

Conclusion

Medical molecular robotics represents a natural and potentially transformative extension of precision medicine and robot-assisted therapies. Its defining advantages—localized drug delivery, integrated theranostics, and adaptive functionality—address long-standing limitations of systemic treatments and passive targeting strategies (Figure 1). Nevertheless, the field faces substantial challenges related to safety, controllability, visualization, manufacturability, and regulation. If these constraints are addressed systematically, medical molecular robotics may progress from experimental innovation to a clinically meaningful adjunct, enhancing personalization, efficacy, and safety across multiple medical disciplines.

Declarations

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References

1. Iacovacci V, Diller E, Ahmed D, Menciassi A. Medical microrobots. *Annu Rev Biomed Eng.* 2024; 26: 561–591.
2. Stefano GB. Robotic surgery: fast forward to telemedicine. *Med Sci Monit.* 2017; 23: 1856–1861.
3. Stefano GB. How quantum computing could rewire medical robotics. *J Artif Intell Robot.* 2025; 2: 1031–1032.
4. Bozuyuk U, Wrede P, Yildiz E, Sitti M. Roadmap for clinical translation of mobile microrobotics. *Adv Mater.* 2024; 36: 2311462.
5. Lee JG, Raj RR, Day NB, Shields CW IV. Microrobots for biomedicine: unsolved challenges and opportunities for translation. *ACS Nano.* 2023; 17: 15427–15455.
6. Lin J, Cong Q, Zhang D, Li Y, Li H. Magnetic microrobots for in vivo cargo delivery: a review. *Micromachines.* 2024; 5: 664.
7. Han H, Kim Y, Lee S, Park J, Ahmed D. Imaging-guided bioresorbable acoustic hydrogel microrobots. *Sci Robot.* 2024; 9: eadp3593.
8. Dillinger C, Chatzipirpiridis L, Bozuyuk U, Hoop M, Nelson BJ. Real-time color flow mapping of ultrasound microrobots. *Sci Adv.* 2025; 11: eadt8887.
9. Gao Q, Zhang Y, Li J, Xu H, Zhang L. Soft magnetic microrobots with remote sensing and communication. *Nat Commun.* 2025; 16: 945.
10. Zhan P, Li Y, Wang X, Liu J. Recent advances in DNA origami-engineered nanomaterials. *Chem Rev.* 2023; 123: 12345–12432.
11. Del Campo Fonseca A, Glück C, Droux J, Ferry Y, Frei C, Wegener S, Weber B, El Amki M, Ahmed D. Ultrasound trapping and navigation of microrobots in the mouse brain vasculature. *Nat Commun.* 2023; 14: 5889.
12. Naik N, Hameed BMZ, Shetty DK, Swain D, Shah M, Paul R, Aggarwal K, Ibrahim S, Patil V, Smriti K, Shetty S, Rai BP, Chlosta P, Somani BK. Legal and ethical consideration in artificial intelligence in healthcare: who takes responsibility? *Front Surg.* 2022; 9: 862322.
13. Saadat A, Siddiqui T, Taseen S, Mughal S. Revolutionizing impacts of artificial intelligence on health care systems and medical in-transparencies. *Ann Biomed Eng.* 2024; 52: 1546–1548.