Nano-robot assisted intravascular surgery: engineering design, clinical applications, and future directions

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ABSTRACT

Vascular nanorobotics has emerged as a promising innovation in minimally invasive medicine, overcoming several limitations of conventional catheter-based procedures. Recent advancements in magnetic actuation, biocompatible nanomaterials, and real-time image-guided control have enabled micro- and nanorobots to execute precise intravascular interventions while minimizing tissue damage. This review summarizes recent progress in nanorobot engineering, propulsion techniques, safety considerations, and biocompatibility, highlighting their expanding applications in vascular and oncological therapies. Evidence from preclinical and experimental studies indicates that magnetically controlled nanorobots provide superior targeting efficiency, improved thrombus dissolution, enhanced tumor penetration, and reduced systemic drug exposure when compared with traditional treatment strategies. The development of theranostic nanorobotic platforms allows simultaneous diagnosis and therapy with real-time monitoring and individualized treatment planning. Additionally, artificial intelligence–driven navigation and coordinated swarm behavior further enhance precision and therapeutic effectiveness. Despite existing challenges related to long-term safety, biodegradation, and regulatory pathways, vascular nanorobotics shows considerable potential to reshape precision-based, minimally invasive cardiovascular and cancer care.

Keywords: ***Image-guided therapy, Minimally invasive surgery, Nanorobots, Vascular intervention, Theranostic, Targeted drug delivery.***

INTRODUCTION

Nano-robot assisted surgery within blood vessels represents a novel and rapidly evolving field within minimally invasive medicine. These microscopic devices are designed to navigate intricate vascular networks and perform targeted functions such as clearing blockages, repairing damaged vessels and delivering therapeutic agents directly to diseased sites.[1] By operating at the micro- and nanoscale, they eliminate the need for large incisions and reduce damage to surrounding tissues, improving patient recovery and reducing post-operative complications. Traditional robotic systems such as the da Vinci platform provide enhanced dexterity and visualisation for surgeons; however, their function is limited to external or laparoscopic applications. In contrast, nanorobots function directly within the bloodstream, offering unprecedented micro-manoeuvrability and site-specific treatment. Despite this promise, limitations such as biocompatibility, power generation, navigation control and clinical training remain important challenges.[2,3] Recent advancements in artificial intelligence and material science provide optimism that nanorobot-assisted intravascular surgery will become an important therapeutic option in the near future.

Technical And Design Aspects

Precise navigation of nanorobots is most commonly achieved through magnetic actuation combined with real-time imaging systems such as MRI and ultrasound. This technique ensures controlled movement even in areas of turbulent or high-velocity blood flow. Although alternative propulsion methods such as acoustic, optical, and catalytic propulsion have been explored, magnetic control remains the most promising for clinical application due to its deep tissue penetration and compatibility with medical imaging equipment.[1,4,5] Material design is crucial for successful intravascular application. Recent innovations focus on biocompatible nanocomposite materials that minimise immune activation, resist clot formation, and maintain structural stability against hemodynamic forces. Hybrid nanostructures combining both flexible and rigid elements provide enhanced mobility and durability.[6] In addition, programmable materials capable of altering shape or stiffness in response to external stimuli allow the nanorobots to adapt to variations in vascular diameter and blood flow. These design advancements contribute to improved navigation, stability and therapeutic effectiveness.[7]

Clinical Applications and Therapeutic Efficacy

Nanorobot-assisted therapy is showing remarkable potential in the treatment of cardiovascular and cerebrovascular diseases. Magnetic nanorobots coated with tissue plasminogen activator (tPA) have demonstrated enhanced thrombolytic activity by delivering the drug directly to the clot. This localised approach significantly increases clot dissolution while minimising the risk of systemic bleeding. In ischaemic stroke models, nanorobots have successfully navigated occluded arteries to deliver thrombolytic agents and mechanically disrupt clots.[6,8] This results in improved recanalization rates when compared with conventional catheter-based techniques. Nanorobots also show promise in managing chronic vascular diseases such as atherosclerosis by targeting plaque deposits.[9,10,11] These devices can mechanically interact with plaque, release anti-inflammatory agents and provide real-time imaging guidance. Furthermore, nanorobot platforms are being explored in regenerative medicine. By directly delivering stem cells and growth factors to damaged vascular tissues, they promote regeneration and faster healing with minimal off-target effects.[12]

Targeted Drug Delivery and Oncological Applications

Nanorobots have emerged as a powerful tool in precision oncology. Magnetically guided nanorobots can transport anti-cancer drugs directly to tumour sites with significantly greater accuracy than traditional chemotherapy. Innovative spiked structures can penetrate tumour membranes, improve drug uptake and increase tumour cell destruction.[13] Some advanced designs respond to the hypoxic environment of tumours, releasing their therapeutic cargo only when they reach the target site, reducing systemic toxicity. These systems also help overcome drug resistance mechanisms.[14,15] The development of theranostic nanorobots combining both diagnostic and therapeutic functions allows real-time monitoring of tumour response. Integrated biosensors and contrast agents enable imaging and analysis while delivering drugs, enhancing treatment precision and customisation.[16]

Diagnostic and Monitoring Capabilities

Modern nanorobots are equipped with advanced biosensing technologies capable of monitoring physiological changes in real time. When combined with wireless data transmission and artificial intelligence, these systems can continuously adapt treatment strategies based on real-time patient data. Light-responsive and photonic nanorobots provide high-resolution visualisation, improving surgical accuracy during intravascular procedures.[17,18] In oncology, nanorobots carrying fluorescent markers or SERS nanoparticles accurately differentiate between malignant and healthy tissues, enabling precise tumour margin detection.[19] These advanced diagnostic capabilities improve procedural accuracy, reduce recurrence rates and enhance overall clinical outcomes.

Safety, Biocompatibility and Toxicology

Ensuring the biocompatibility and safety of nanorobots is essential for their clinical use. Materials such as chitosan, gold nanoparticles and silk-derived peptides are being used to minimise immune reactions and inflammation.[20,41] Surface modification techniques like PEGylation help reduce toxicity and prolong circulation time. One major concern is the long-term accumulation of non-biodegradable nanorobots in vital organs such as the liver and kidneys.[21] To address this issue, research is focused on developing biodegradable nanomaterials that safely dissolve or can be externally retrieved after use. Although early studies indicate favourable safety profiles, extensive long-term animal and human studies are still required before widespread medical application.[22,23]

Regulatory And Translational Aspects

Nanorobot-based systems are considered advanced medical technologies and are subjected to strict regulatory guidelines. These devices are typically classified as moderate- to high-risk medical devices, requiring extensive evaluation before approval for clinical use.[9,24,25] Hybrid nanorobots that combine drug delivery and mechanical action may require approval under both medical device and pharmaceutical regulatory pathways.[26,27,42] Ethics committee approval, Good Manufacturing Practices (GMP), and international safety standards are mandatory. Scaling nanorobot production from laboratory prototypes to clinical grade devices also presents technical challenges such as maintaining uniformity, sterility and reliability. Collaboration between scientists, clinicians, and regulatory authorities is essential for successful clinical translation.[11,28,30]

Comparative And Mechanistic Studies

Nanorobots demonstrate enhanced efficiency through a combined mechanical and chemical mechanism. Swarming magnetic nanorobots physically disrupt clot structures while enhancing the penetration of thrombolytic agents.[29,31,43] This dual action significantly improves treatment outcomes while allowing lower drug doses, thereby reducing side effects. Biomimetic surface coatings, inspired by natural cell membranes, allow nanorobots to evade immune detection and remain in circulation longer. These developments create a multifunctional system integrating mechanical action, chemical therapy and immune compatibility.[25,32,33]

Emerging Technologies and Future Directions

Artificial intelligence allows nanorobots to operate autonomously, adapting their movement in response to changes in blood flow and vessel structure.[34,35] Swarm technology enables coordinated action by multiple nanorobots, increasing efficiency and reliability. The integration of exosome-mimetic carriers further enhances targeting accuracy and biocompatibility, especially in cancer treatment.[36,37,44] These next-generation systems represent a new era of intelligent, personalised and minimally invasive therapy.

CONCLUSION

Nanorobot-assisted intravascular surgery represents a revolutionary shift in medical treatment by delivering precision-guided, minimally invasive therapy.[38,45,46] These devices demonstrate significant advantages in cardiovascular and oncologic treatment, offering targeted intervention with reduced tissue damage.[47,48] Challenges such as long-term biocompatibility, controlled biodegradation and regulatory hurdles must still be resolved.[39,40] With continuous advancements in material science, artificial intelligence and biomedical engineering, vascular nanorobotics is set to become a critical component of future precision medicine.[49,50]

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