

**INJECTABLE NANOROBOTS: EMERGING FRONTIERS IN PRECISION DRUG
DELIVERY, DISEASE, DIAGNOSIS, AND TARGETED THERAPEUTICS –A
COMPREHENSIVE REVIEW**

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DOI: <https://doi.org/10.5281/zenodo.23804814>

How to cite this Article: Esther Puli*, Kedareshwari Athikinasetti, Gayathri Naga Sai Lakshmi Merla, Lakshmi Ganesha Surya Durga Tummalapalli, Sourya Satya Deepak Talari, Naga Durga Yarakala, Dr. Bhaskara Raju Vatchavi, Mr. Ajay Ratnam Mulaparthi, Dr. Y.b. Manjulatha. (2026). Injectable Nanorobots: Emerging Frontiers In Precision Drug Delivery, Disease, Diagnosis, And Targeted Therapeutics -A Comprehensive Review. World Journal of Pharmaceutical and Medical Research, 12(11), 26–36.

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Article Received on 17/09/2026

Article Revised on 07/10/2026

Article Published on 01/11/2026

ABSTRACT

The most exciting development in nanomedicine is the injectable nanorobots that combine nanotechnology, robotics, biotechnology, materials science, and artificial intelligence for extremely accurate illness detection and treatment. In contrast to conventional drug delivery systems that disperse medication throughout the body, injectable nanorobots are engineered to navigate bodily fluids, detect disease-specific biomarkers, and release therapeutic agents selectively at the target site. These systems have demonstrated significant potential in areas such as cancer, cardiovascular disease, neurological conditions, infectious diseases, regenerative medicine, and precision diagnostics. Recent advancements in enzyme-powered, magnetic, ultrasound-driven, and biohybrid nanorobots have expedited the transfer of these technologies from lab research to preclinical and early translational investigations. Biocompatibility, biodegradability, large-scale production, real-time navigation, regulatory approval, and long-term biosafety are some of the issues that still need to be resolved despite the tremendous advancements. The present understanding of injectable nanorobots, including their historical evolution, classification, structural elements, fabrication techniques, propulsion mechanisms, targeting tactics, biological applications, safety issues, and potential future clinical uses, is compiled in this review. A thorough overview of this quickly developing topic discusses recent developments and new trends.

KEYWORDS: Injectable nanorobots, Nanorobotics, Targeted drug delivery, Precision therapeutics, Nanomedicine, controlled drug release, Active targeting, nanocarriers, biohybrid nanorobots, magnetic guidance, biosensors, theranostics, Biocompatibility, Bio distribution, pharmacokinetics, toxicity and biosafety, artificial intelligence, stimuli -responsive drug delivery.

INTRODUCTION

Over the last few decades, modern medicine has made major advances in the diagnosis and treatment of disease.^[10] However, traditional treatment methods still have certain disadvantages, such as insufficient accumulation of therapeutic agents in diseased tissues, frequent dosing, rapid degradation of drugs, poor drug selectivity, and systemic toxicity.^[17] These disadvantages often increase side effects and reduce the efficacy of the therapy.^[10] This is the reason why

scientists are working on the development of smart drug delivery networks, which can minimize the damage to healthy tissues and deliver the therapeutic molecules to the disease site.^[25]

Nanotechnology has evolved as a revolutionary platform to overcome these limitations.^[22] The first nanoparticles were developed for better stability, controlled release and solubility of drugs.^[9] The combination of robotics with nanotechnology has resulted in the creation of injectable

nanorobots, that is, microscopic machines capable of carrying out controlled therapeutic and diagnostic operations inside the human body.^[22] These systems show functionalities beyond passive drug carriers, such as active mobility, target recognition, controlled drug release, biosensing and image-guided navigation, although many of them are still at the experimental stage.^[19]

The most common administration methods for injectable nanorobots are intravenous, intratumoral, or localized injections.^[25] Once delivered, they move in body fluids using biohybrid propulsion systems, chemical gradients, magnetic fields, ultrasound, or enzymes.^[17] These nanorobots have sophisticated surface modifications that enable them to recognize specific molecular biomarkers expressed on sick cells and improve the targeted precision and the treatment efficacy.^[25] Such accuracy could reduce systemic toxicity and doses of medicine.^[4]

Nanorobotics has developed from a theoretical concept into an interdisciplinary research area combining nanotechnology, materials science, molecular biology, biomedical engineering, robotics, artificial intelligence, and clinical medicine.^[3] Fully autonomous nanorobots are not yet a reality for routine clinical applications but injectable micro- and nanorobotic platforms have been successfully demonstrated in many experimental studies.^[9] For targeted drug delivery, clot removal, bacterial killing and localized cancer therapy. The successes suggest that injectable nanorobots could be central to the future of precision medicine.^[4] Physicist Richard Feynman first proposed the idea of controlling matter at the nanoscale in 1959 in his fundamental lecture —The bottom has plenty of space.^[27] Future generations of researchers have been motivated by his ideas to explore the possibility of creating microscopic machines capable of carrying out intricate tasks at the molecular scale.^[24] Feynman established the theoretical foundation for contemporary nanotechnology, despite the lack of technology to immediately implement his concepts.^[27] Rapid progress in nanomaterials, molecular engineering and microfabrication in the 1980s and 1990s enabled scientists to develop nanoscale carriers for controlled drug delivery.^[24] Although they greatly enhanced pharmaceutical formulations, liposomes, polymeric nanoparticles, dendrimers, and metallic nanoparticles remained passive systems that mostly depended on physiological transport mechanisms.^[6]

Recent development has concentrated on biodegradable and biohybrid injectable nanorobots made of biological cells, hydrogels, polymers, or extracellular vesicles.^[36] These solutions are designed to decrease long-term toxicity while increasing biocompatibility.^[36] Simultaneously, artificial intelligence and medical imaging technologies are being researched to enable more accurate navigation and therapeutic decision-making.^[22]

INJECTABLE NANOROBOTS

Injectable nanorobots are nanoscale or microscale engineered devices that are administered into the body through injection and designed to perform controlled diagnostic or therapeutic functions.^[1] Unlike conventional nanoparticles, injectable nanorobots possess active or externally controlled movement, enabling them to navigate biological environments, recognize disease-specific targets, and perform localized interventions such as drug release, biosensing, or tissue repair.^[3]

Classification

Injectable nanorobots can be categorized into

1. Based on how they propel themselves

- Magnetic nanorobots
- Ultrasound-driven nanorobots
- Chemically propelled nanorobots
- Enzyme-powered nanorobots
- Light-responsive nanorobots,
- Biohybrid nanorobots

2. Depending on the desired biomedical use, each group has unique benefits and drawbacks According to biomedical function, injectable nanorobots may also be categorized as

- Drug-delivery nanorobots
- Diagnostic nanorobots
- Biosensing nanorobots
- Surgical nanorobots
- Regenerative nanorobots
- Antimicrobial nanorobots
- Multifunctionaltheranosticnanorobots

3. Depending on the structural type of injectable nanorobots

- Nano particle based nanorobots,
- Helical nanorobots,
- Injectable nanorobots,
- Tubular nanorobots,
- DNA based nanorobots,
- Biomimetic nanorobots,

Multifunctional platforms that can diagnose and treat patients simultaneously are attracting more and more attention due to their potential to enable individualized treatment strategies and reduce the number of clinical procedures.^[9]

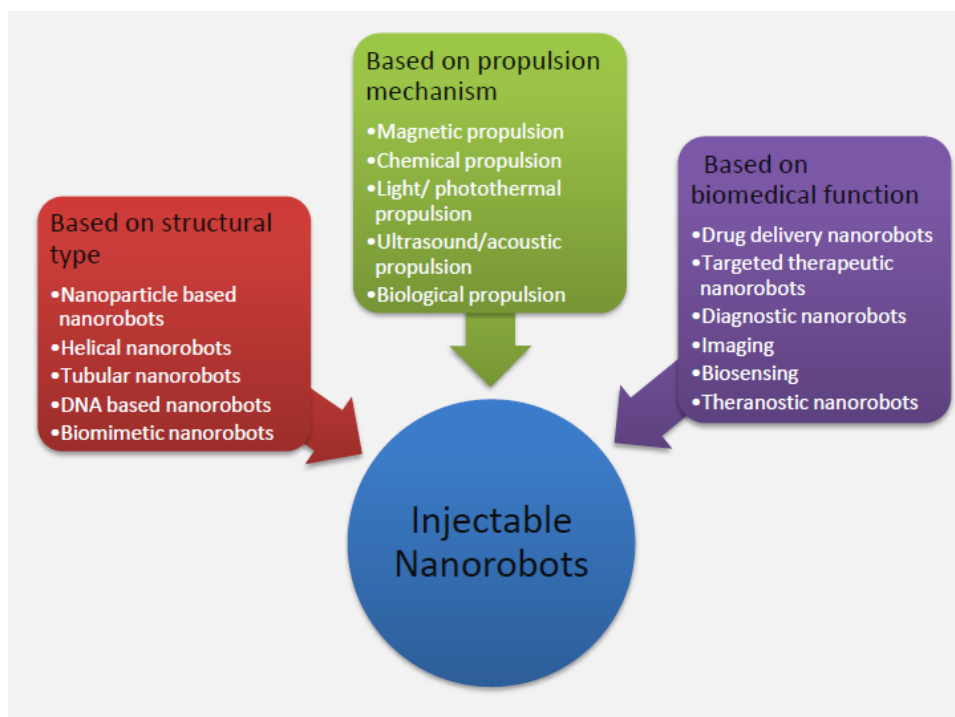


Figure 1.

STRUCTURAL COMPONENTS

The performance of injectable nanorobots depends on the integration of multiple structural components that function together as a single therapeutic platform.^[1] Unlike conventional nanoparticles, nanorobots are engineered with specialized architectures that enable locomotion, target recognition, drug transport, controlled release, and external guidance.^[25]

The design of an ideal injectable nanorobot incorporates multiple functional elements, such as a structural scaffold, propulsion mechanism, targeting unit, therapeutic payload carrier, biosensor, protective surface layer, and communication or imaging system.^[22]

The effective coordination of these components plays an important role in determining the nanorobot's overall performance, stability, and potential for clinical use.^[22] Recent research suggests that multifunctional nanorobots may offer greater advantages over conventional passive drug delivery systems by combining targeted therapy, controlled navigation, and diagnostic capabilities within a single nanoscale platform.^[5]

Structural Framework

The structural framework serves as the main supporting component of an injectable nanorobot, maintaining its mechanical integrity while moving through blood and other biological fluids.^[6] To enable movement through narrow capillaries and complex tissue environments, the framework must possess adequate strength while retaining sufficient flexibility.^[24] Depending on the specific therapeutic purpose, various materials can be used to construct the framework, including biodegradable polymers, silica, metallic nanoparticles,

hydrogels, lipid-based materials, and DNA-based nanostructures.^[22] Recent developments have increasingly focused on biodegradable framework materials, as they can help reduce the possibility of prolonged accumulation in tissues once the therapeutic process is completed.^[6]

Drug Payload Chamber

The therapeutic payload chamber is designed to carry various therapeutic and diagnostic substances, including drugs, nucleic acids, proteins, enzymes, antibodies, and imaging agents.^[9] The method used for loading these substances depends largely on their physicochemical characteristics and the intended drug-release pattern.^[25] Advanced payload chambers are engineered to maintain the stability of the therapeutic cargo during systemic circulation and release it selectively in response to specific biological or external triggers. These triggers may include acidic pH, enzymes, reactive oxygen species (ROS), magnetic fields, ultrasound, or near-infrared (NIR) light.^[1] Such controlled and targeted release can minimize unwanted systemic exposure while improving the therapeutic effectiveness of the treatment.^[5]

Targeting Module; First Aid Kit

Target recognition in injectable nanorobots can be achieved by modifying their surface with specific ligands that interact preferentially with biomarkers associated with diseased tissues.^[17] Common targeting agents include antibodies, peptides, aptamers, folic acid, transferrin, hyaluronic acid, and cell-membrane-based coatings.^[2] Through active targeting, nanorobots can more effectively differentiate between healthy and pathological tissues, promoting greater accumulation of the therapeutic payload at the desired site and potentially

reducing unwanted off-target effects.^[6] Recent dual-targeting approaches combine passive accumulation with active molecular recognition to enhance targeting precision and improve delivery efficiency.^[17]

Biosensors and Imaging components

The more advanced injectable nanorobots contain miniaturized biosensors that sense molecular biomarkers, inflammatory mediators, metabolic products or

alterations in the tumor microenvironment.^[40] Imaging agents like iron oxide nanoparticles, fluorescent probes, quantum dots, and contrast materials allow real-time visualization using magnetic resonance imaging (MRI), fluorescence imaging, photoacoustic imaging, or computed tomography.^[5] These multifunctional systems allow simultaneous diagnosis and treatment, an operation commonly referred to as theranostics.^[22]

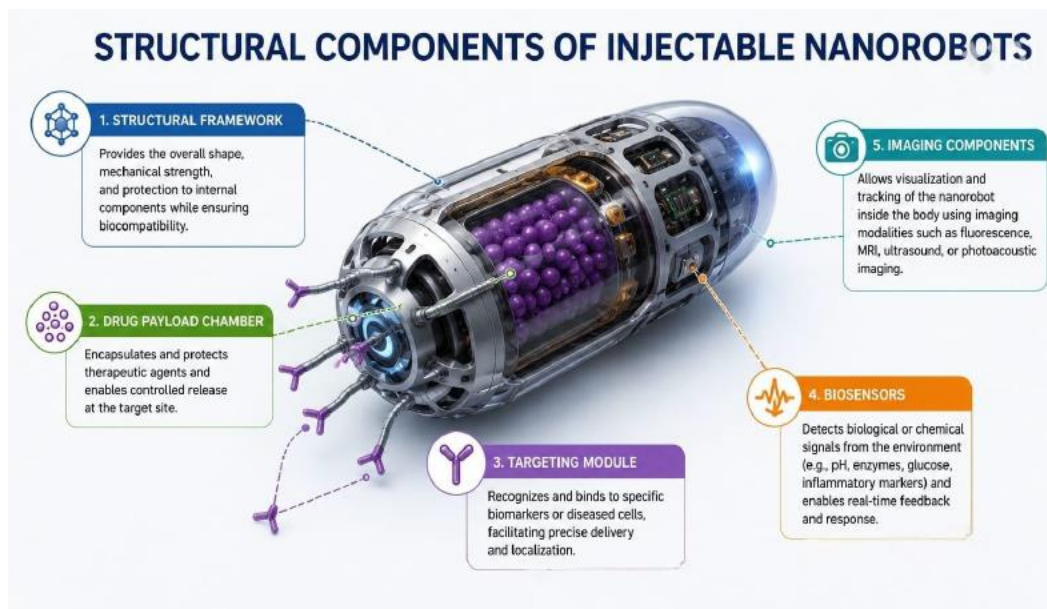


Figure 2.

MATERIALS USED

One of the most important elements affecting nanorobot performance is material selection.^[24] The ideal material should have good biocompatibility, biodegradability, mechanical strength, chemical stability, low immunogenicity and high drug-loading capacity.^[5] The material should also be amenable to facile surface modification and respond appropriately to internal or external stimuli.^[22] Recent advances in biomaterials have enabled the development of multifunctional nanorobots capable of performing complex therapeutic tasks while minimizing toxicity.^[5]

1. Polymer Materials
2. Metallic Nanomaterials
3. Lipid-Based System
4. Biohybrid Materials

Polymeric Materials

Biodegradable polymers such as PLGA, PEG, chitosan, alginate, gelatin, polycaprolactone, and hyaluronic acid are widely used because of their excellent safety profiles and controlled degradation characteristics.^[24] Both hydrophilic and hydrophobic medications can be encapsulated by polymeric nanorobots, enabling sustained release over extended durations.^[8] Their surfaces are readily modified with targeting ligands to improve specificity toward diseased tissues.^[5]

Metallic Nanomaterials

Because they may be remotely led by external magnetic fields, magnetic iron oxide nanoparticles continue to be the most researched materials for injectable nanorobots.^[4] Gold nanoparticles contribute excellent biocompatibility, photothermal properties, and facile surface chemistry, whereas titanium and nickel alloys provide mechanical strength in specialized microrobotics systems.^[32] However, long-term accumulation of non-biodegradable metals remains a significant concern for clinical translation.^[6]

Lipid-Based Systems

Lipid nanoparticles and liposomes offer outstanding biocompatibility and have already demonstrated clinical success in drug delivery.^[5] Their ability to encapsulate sensitive biological molecules such as mRNA, siRNA, and proteins makes them attractive components of injectable nanorobotic systems.^[10] Researchers are currently integrating lipid nanoparticles with active propulsion systems to combine the advantages of conventional nanomedicine and intelligent nanorobotics.^[10]

Biohybrid Materials

Biohybrid nanorobots combine synthetic materials with living biological components including bacteria, red blood cells, stem cells, immune cells, sperm cells,

extracellular vesicles, and exosomes.^[4] These hybrid systems exploit natural cellular motility and immune evasion mechanisms while providing enhanced biocompatibility and prolonged circulation.^[8] Biohybrid platforms represent one of the fastest-growing research areas in injectable nanorobotics.^[3]

FABRICATION TECHNIQUES

The fabrication of injectable nanorobots requires highly controlled manufacturing methods capable of producing uniform structures with reproducible size, morphology, and functional properties.^[22] Fabrication techniques influence propulsion efficiency, drug-loading capacity, targeting ability, and biodegradation.^[1] Continuous advances in nanofabrication have enabled increasingly sophisticated multifunctional nanorobotic platforms.^[5]

Self-Assembly

Self-assembly is among the most widely employed fabrication methods because it allows spontaneous organization of molecules into ordered nanostructures

through intermolecular interactions.^[6] DNA origami, peptide self-assembly, lipid self-assembly, and polymeric self-assembly provide excellent control over nanoscale architecture while reducing manufacturing complexity.^[6]

Microfluidic Fabrication

Microfluidic technology enables precise control of particle size distribution, encapsulation efficiency, and surface functionalization.^[5] Continuous-flow synthesis improves reproducibility and scalability compared with conventional batch preparation methods.^[22]

Three-Dimensional Nanoprinting

Recent advances in nanoscale 3D printing permit fabrication of highly complex micro- and nanorobotic geometries, including helical swimmers, tubular motors, and biomimetic architectures.^[24] Although currently limited by production cost and throughput, additive manufacturing is expected to play an increasingly important role in personalized nanomedicine.^[22]

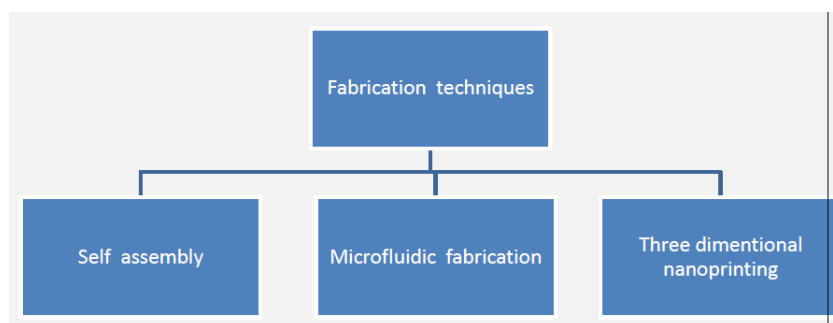


Figure 3.

PROPULSION MECHANISMS

One of the key features that distinguishes injectable nanorobots from conventional nanoparticle-based systems for drug delivery is their efficient propulsion.^[22] Conversely, injectable nanorobots can move actively or be externally controlled and hence can penetrate complex

biological environments and target diseased tissues with higher accuracy, compared to passive nanoparticles that rely on blood circulation and diffusion.^[4] The propulsion mechanism^[22] governs the nanorobot's speed, directionality, targeting efficiency, energy consumption, and overall therapeutic efficacy.^[6]

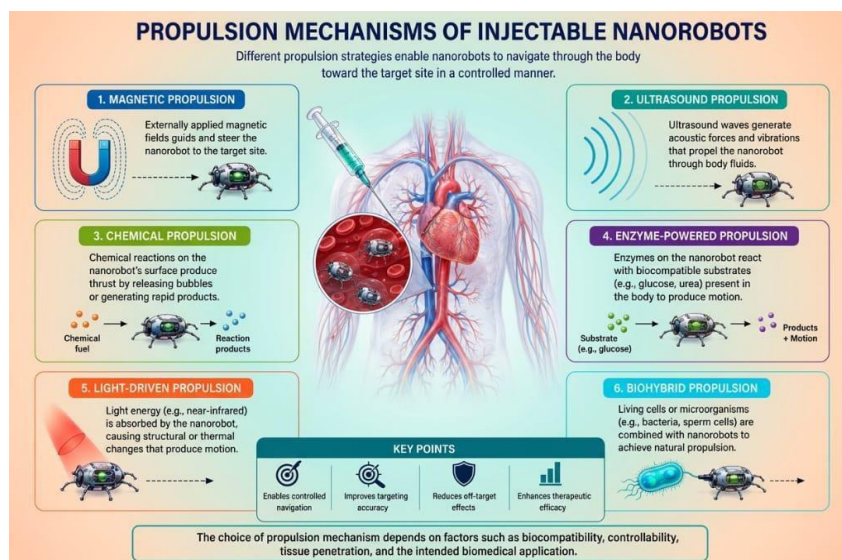


Figure 4.

Magnetic Propulsion

Magnetic propulsion is one of the most investigated strategies for injectable nanorobots, enabling deep penetration into biological tissues without ionizing radiation.^[32] Nanorobots, loaded with magnetic materials (e.g., iron oxide nanoparticles), respond to the externally applied magnetic field, thus enabling clinicians to direct their movement to the desired anatomical locations.^[1] This procedure allows accurate localization while minimizing the damage to adjacent healthy tissues.^[6] Magnetic propulsion has shown promising results in targeted drug delivery, thrombus removal, localized hyperthermia and minimally invasive interventions.^[6] However, precise navigation inside extremely complex vascular networks is still a major engineering challenge.^[24]

Ultrasound Propulsion

Ultrasound-driven nanorobots convert the acoustic energy to mechanical motion via acoustic streaming, cavitation, or oscillatory forces.^[40] Magnetic propulsion is one of the most investigated strategies for injectable nanorobots, enabling deep penetration into biological tissues without ionizing radiation.^[22] Nanorobots, loaded with magnetic materials (e.g., iron oxide nanoparticles), respond to the externally applied magnetic field, thus enabling clinicians to direct their movement to the desired anatomical locations.^[1] This procedure allows accurate localization while minimizing the damage to adjacent healthy tissues.^[6] Magnetic propulsion has shown promising results in targeted drug delivery, thrombus removal, localized hyperthermia and minimally invasive interventions.^[1] However, precise navigation inside extremely complex vascular networks is still a major engineering challenge.^[32]

Enzyme-Driven Propulsion

Enzyme-powered nanorobots use naturally available substrates in the body to catalyze biochemical reactions producing motion.^[4] Enzymes such as urease, catalase and glucose oxidase, convert chemical energies to mechanical motion, so that the nanorobots can work without external power sources.^[31] It is that these systems are more biocompatible than chemically powered systems since they use endogenous biological molecules.^[4] As they are self-driven, they are attractive for long-term therapeutic applications, but their propulsion speed and directional control are still limited compared to externally guided systems.^[22]

Chemical Propulsion

The motion of nanomachines driven by chemical reactions is controlled by chemical fuels and catalytic materials.^[24] Hydrogen peroxide has been a common fuel source in early experimental designs due to its decomposition generating oxygen bubbles that can drive the motion of micro-and nanorobots.^[33] This method exhibited promising locomotion in the lab, but hydrogen peroxide is not a suitable fuel for clinical application due to the concerns of toxicity and tissue damage.^[5]

Thus, current research focuses on the development of propulsion systems based on safer endogenous molecules or biodegradable catalysts.^[22]

Light-Responsive Propulsion

Light-responsive nanorobots move by generating local thermal gradients using laser irradiation or near-infrared light.^[22] Near-infrared light is especially attractive due to its relatively deep penetration in biological tissues and lower phototoxicity compared to ultraviolet light.^[24] Photothermal activation can improve drug delivery and propulsion, as well as selectively destroy tumor cells.^[31] However, the limited light penetration in deep tissues restricts its use to superficial or image-guided therapeutic procedures.^[24]

Biohybrid Propulsion

Biohybrid propulsion is one of the most recent advances in injectable nanorobotics.^[36] These systems integrate synthetic nanomaterials with naturally motile biological entities such as bacteria, sperm cells, immune cells, algae or other living cells.^[8] The biological part offers intrinsic motility and better compatibility with the physiological environment, and the synthetic part is loaded with therapeutic agents or imaging probes.^[22] Experimental models have demonstrated promising results for tissue-specific transport and targeted drug delivery using biohybrid nanorobots.^[20] However, these advances have not yet overcome the major challenges remaining before clinical implementation, including biosafety and immune response concerns, as well as large-scale manufacturing.^[39]

COMPARISON OF PROPULSION STRATEGIES

Different propulsion strategies offer distinct benefits as well as specific limitations.^[35] Magnetic propulsion provides precise external control over nanorobot movement; however, its operation generally depends on specialized magnetic equipment.^[1] Ultrasound-based propulsion is advantageous because it allows non-invasive guidance and can be integrated with technologies already used in clinical settings.^[40] Enzyme-powered nanorobots are considered relatively biocompatible, although their movement is generally slower compared with other propulsion systems.^[4] Chemical propulsion can produce efficient locomotion under laboratory conditions, but its clinical application may be restricted by concerns regarding fuel toxicity.^[33] Biohybrid nanorobots combine the natural movement capabilities of biological components with the functional advantages of synthetic materials, although further development is required to overcome challenges associated with clinical translation. Light-activated propulsion systems provide accurate spatial and temporal control, but their effectiveness can be reduced by limited light penetration through biological tissues.^[36] Future injectable nanorobots are therefore expected to incorporate complementary propulsion strategies within a single platform, potentially enabling more precise navigation and improved therapeutic performance.^[1]

Navigation and Targeting Strategies

Precise navigation and selective targeting are essential for achieving effective performance from injectable nanorobots.^[22] Following administration into the bloodstream or directly into a specific tissue, these nanosystems must move through complex biological environments, avoid premature removal by physiological defense mechanisms, identify the intended diseased site, and deliver their therapeutic cargo accurately.^[25] Effective navigation and targeting can minimize unintended drug distribution to healthy tissues, thereby reducing systemic toxicity and improving overall therapeutic outcomes.^[6]

Passive Targeting

Passive targeting is based on physiological characteristics of diseased tissues rather than on specific recognition molecules.^[17] In solid tumors, abnormal and highly permeable blood vessels allow nanoscale particles to accumulate more readily than in normal tissues, while impaired lymphatic drainage prolongs their retention.^[10] To enhance medication accumulation in tumors, this phenomenon has been extensively employed.^[25] However, passive targeting alone is often insufficient because the extent of vascular permeability varies among patients and disease types.^[17]

Active Targeting

Active targeting is achieved by modifying the nanorobot surface with molecules that recognize and bind to specific receptors or biomarkers expressed on diseased cells.^[22] Targeted ligands such as monoclonal antibodies, peptides, aptamers, folic acid, transferrin, and hyaluronic acid are often used.^[7] These ligands decrease exposure to healthy tissues while enhancing cellular absorption and raising drug concentration at the intended site.^[7] Active targeting is particularly valuable in cancer therapy, where overexpressed receptors can serve as molecular targets.^[17]

Magnetic Navigation

Magnetic navigation uses externally generated magnetic fields to guide nanorobots containing magnetic materials such as iron oxide nanoparticles. By adjusting the direction and strength of the magnetic field, researchers can influence the movement of nanorobots toward specific anatomical regions.^[1] This approach offers precise spatial control and has been investigated for targeted drug delivery, vascular interventions, and localized treatment of tumors.^[22]

Image-Guided Navigation

Medical imaging technologies can support the localization and monitoring of injectable nanorobots during therapy.^[5] Contrast agents incorporated into nanorobots enable visualization using techniques such as magnetic resonance imaging, fluorescence imaging, photoacoustic imaging, or computed tomography.^[22] Image-guided navigation allows clinicians to monitor

biodistribution, verify target localization, and evaluate treatment response in real time.^[5]

Challenges in Navigation

Despite significant advances, navigation within the human body remains challenging.^[22] Targeting efficiency can be decreased by tissue barriers, immune clearance, blood flow dynamics, and changes in the disease microenvironment.^[4] Multifunctional nanorobots that incorporate sensitive materials, sophisticated imaging, and intelligent control systems while preserving biocompatibility and safety are the goal of future research to increase navigation accuracy.^[4]

Controlled Drug Release and Drug Loading

The capacity of injectable nanorobots to deliver therapeutic chemicals directly to sick tissues and release them under regulated conditions is one of its main benefits.^[25] Drugs may be encapsulated within internal compartments, adsorbed onto the nanorobot surface, or chemically linked through cleavable bonds.^[9] The loading strategy is chosen based on the therapeutic use, the material selected for the nanorobot, and the physicochemical properties of the drug.^[1]

Internal stimuli, such as acidic pH, elevated enzyme activity, reactive oxygen species, or changes in the tumor microenvironment, can trigger controlled drug release.^[1] External triggers—including magnetic fields, ultrasound, or near-infrared light—provide additional control over the timing and location of drug release.^[22] Stimuli-responsive systems are designed to reduce premature drug leakage during circulation while maximizing drug availability at the target site.^[25]

Drug loading efficiency, release kinetics, stability during circulation, and preservation of drug activity are important factors influencing therapeutic success.^[5,22] Researchers continue to optimize nanorobot designs to increase payload capacity while maintaining structural integrity and minimizing unintended drug release before reaching the target tissue.^[24]

Cellular Uptake and Intercellular Transport of Injectable Nanorobots

Injectable nanorobots are designed to effectively penetrate cells by membrane fusion, receptor-mediated internalization, and endocytosis, allowing for precise intracellular drug administration and therapeutic activity.^[3] Their surface functionalization and nanoscale dimensions facilitate penetration into complicated biological tissues and increase cellular absorption.^[33] Biohybrid and stimuli-responsive nanorobots can navigate intracellular environments and transport therapeutic cargo between cells through controlled release and cell-to-cell interactions.^[36] Advanced propulsion systems further facilitate movement across biological barriers and improve intercellular communication and targeted therapy.^[30] These capabilities make injectable nanorobots promising

platforms for cancer treatment, regenerative medicine, and precision intracellular diagnostics.^[7]

Biodistribution and pharmacokinetics

Injectable nanorobots exhibit unique biodistribution and pharmacokinetic profiles that significantly influence their therapeutic efficacy and safety.^[25] After administration, these nanorobots circulate through the bloodstream and distribute to target tissues based on their size, shape, surface characteristics, and propulsion mechanisms.^[33] Active guidance strategies such as magnetic, acoustic, and chemical navigation improve accumulation at diseased sites while reducing off-target distribution.^[39] Surface modifications using polyethylene glycol and biomimetic coatings enhance circulation time and minimize rapid clearance by the reticulo-endothelial system.^[36] Pharmacokinetic studies assessing distribution, metabolism, and elimination are essential for optimizing therapeutic outcomes.^[27] Furthermore, advanced imaging techniques enable real-time tracking of nanorobot localization and clearance pathways in vivo.^[40] Understanding these parameters is crucial for dose optimization and successful clinical translation of injectable nanorobots.^[25]

Imaging and Biosensing of Injectable Nanorobots

Injectable nanorobots integrate advanced imaging and biosensing capabilities to enable real-time monitoring, precise navigation, and targeted therapeutic interventions within the human body.^[3] These nanorobots employ magnetic, ultrasound, fluorescence, and X-ray imaging techniques for accurate localization and tracking in vivo.^[31] Embedded nanosensors can detect biomarkers such as pH, enzymes, and cancer-specific molecules, facilitating early disease diagnosis and responsive drug release.^[21] Biohybrid and stimuli-responsive nanorobots further enhance sensing accuracy and biocompatibility in complex biological environments.^[5] Recent studies demonstrate that imaging-guided nanorobots can simultaneously diagnose and treat diseases, paving the way for minimally invasive precision medicine and personalized healthcare applications.^[11]

Biomedical Applications of Injectable Nanorobots

- In cancer therapy
- In cardiovascular disease
- In neurological disorder
- In infectious disorder
- In diabetes
- In regenerative medicine

In Cancer and Cardiovascular Disorders of Injectable Nanorobots:

Injectable nanorobots have emerged as a promising tool for cancer therapy by enabling targeted drug delivery to tumor tissues, enhancing therapeutic efficacy and minimizing systemic toxicity.^[33] Additionally, their imaging and biosensing capabilities help with tumor localization, early cancer diagnosis, and controlled drug release in response to particular biomarkers.^[3]

Nanorobots can precisely navigate blood vessels in cardiovascular illnesses to remove arterial plaques, provide thrombolytic medicines, and encourage tissue regeneration.^[4] Magnetic and biohybrid nanorobots are useful for minimally invasive treatments in vascular disorders and personalized medicine because they enhance biocompatibility and navigation.^[38]

Neurological Disorders, Infectious Disorders, Diabetes, and Regenerative Medicine of Injectable Nanorobots

Injectable nanorobots have become promising approaches for the treatment of neurological disorders owing to their capabilities of providing precision therapy for neurodegenerative diseases and targeted drug delivery across the blood-brain barrier.^[17] Additionally, their biosensing and antibacterial properties help identify and eliminate infectious microorganisms, which enhances infection control and lowers systemic toxicity.^[31] Nanorobots can provide responsive treatments for improved glycemic control, monitor glucose levels, and administer insulin in a regulated way.^[15] Furthermore, biohybrid and regenerative nanorobots support tissue engineering, stem-cell delivery, and tissue repair, offering innovative strategies for regenerative medicine and personalized healthcare applications.^[5]

Injectable nanorobots with AI

Injectable nanorobots are improved by artificial intelligence (AI), which allows for precision targeting and therapy by accurately identifying diseased tissues and cancer cells.^[35] AI-driven machine learning algorithms optimize the navigation and propulsion of nanorobots through complex biological environments such as blood vessels and tumor tissues.^[19] Advanced AI systems regulate drug release patterns and dosage according to the body's improved through AI-assisted sensing technologies.^[39] Furthermore, AI supports autonomous decision-making for intracellular diagnosis and treatment applications.^[31] Personalized medicine and precision therapies are anticipated to develop with the integration of AI with injectable nanorobots.^[5]

Toxicity and biosafety

Injectable nanorobots must possess excellent biocompatibility to prevent adverse immune responses, inflammation, and tissue damage following administration.^[30] Surface modifications using polymers, cell membranes, or other biomimetic coatings help reduce immune recognition and prolong circulation time within the body.^[5] However, metallic elements, degradation byproducts, or long-term buildup of nanorobots in organs such as the liver, spleen, and kidneys may raise toxicity concerns.^[33] As a result, materials that are biodegradable and bioresorbable are becoming more and more popular for creating nanorobots.^[40] Cytotoxicity, hemocompatibility, biodistribution, and clearance mechanisms need to be evaluated by extensive in vitro and in vivo studies.^[38] Advanced imaging and tracking technologies further

support safety evaluation and real-time monitoring of nanorobot fate in the body.^[40] For injectable nanorobots to be successfully translated into clinical settings, long-term toxicity and biosafety must ultimately be guaranteed.^[21]

Clinical Translation and Current Clinical Trials of Injectable Nanorobots

The clinical translation of injectable nanorobots is progressing from preclinical animal studies toward early human applications, driven by advances in biocompatibility, controllable propulsion, and targeted drug delivery systems.^[38] Current research focuses on overcoming challenges related to safety, biodegradability, immune responses, and large-scale manufacturing before widespread clinical adoption.^[30] Magnetically guided and biohybrid microrobots have demonstrated encouraging outcomes in localized medication delivery and targeted cancer therapy, bringing them closer to clinical use.^[34] For accurate navigation and real-time monitoring in vivo, imaging-guided and stimuli-responsive nanorobots are also being developed.^[40] Although fully autonomous injectable nanorobots have not yet entered routine clinical trials, ongoing translational research holds great promise for minimally invasive treatments and precision medicine in the future.^[18]

Regulatory and Manufacturing Challenges of Injectable Nanorobots

The clinical translation of injectable nanorobots is hindered by significant regulatory and manufacturing challenges.^[8] Regulatory agencies require comprehensive evaluations of biocompatibility, toxicity, biodegradation, and long-term safety before human application.^[24] The absence of standardized guidelines for nanorobot design, performance assessment, and quality control further delays approval processes.^[22] Manufacturing challenges include scalable production, reproducibility of nanoscale structures, and maintaining precise functional properties during fabrication.^[30] Integrating propulsion systems, biosensors, and drug payloads into a single platform also increases production complexity and costs.^[37] For injectable nanorobots to be successfully commercialized in precision medicine, these problems must be resolved by uniform rules and cutting-edge production techniques.^[4]

Ethical Considerations of Injectable Nanorobots

Regarding patient safety, privacy, and long-term biocompatibility, the clinical use of injectable nanorobots presents serious ethical issues.^[8] Potential risks include unintended tissue interactions, immune responses, and difficulties in controlling or retrieving nanorobots after administration.^[19] Concerns about the gathering, storing, and security of sensitive biological data are also raised by the application of biosensing nanorobots.^[7] Regulatory challenges include establishing standardized safety protocols, informed consent procedures, and rigorous preclinical testing before human applications.^[28]

Furthermore, equitable access to these advanced technologies and prevention of misuse for non-therapeutic purposes remain important societal considerations.^[11] These ethical concerns need to be addressed for the safe and responsible integration of injectable nanorobots into clinical practice.^[25]

Advantages of Injectable Nanorobots

Injectable nanorobots provide highly targeted drug delivery, which allows therapeutic agents to reach diseased tissues with minimal damage to healthy cells and improved treatment efficacy.^[33] When compared to traditional medicines, their capacity to negotiate intricate biological contexts improves precision medicine and lowers systemic side effects.^[30] Therapeutic results are improved by regulated, site-specific drug release made possible by advanced propulsion and stimuli-responsive systems.^[31] Injectable nanorobots also support real-time imaging, biosensing, and disease monitoring, facilitating early diagnosis and personalized treatment strategies.^[7] Additionally, biohybrid and magnetic nanorobots are attractive instruments for future clinical applications in regenerative medicine and cancer therapy because of their outstanding biocompatibility and minimally invasive operation.^[20]

Limitations of Injectable Nanorobots

Injectable nanorobots have a lot of potential, but they also have a number of drawbacks that prevent their use in clinical settings.^[8] Fluid dynamics, physiological obstacles, and low propulsion efficiency make precise navigation and control in complicated biological contexts difficult.^[32] For in vivo applications, safety concerns are further raised by problems with long-term biocompatibility, toxicity, biodegradation, and immunological responses.^[5] Their practical application is further limited by manufacturing complexity, high production costs, and challenges in large-scale fabrication.^[21] Clinical use of these technologies is further delayed by ongoing development of real-time imaging, localization, and regulatory approval procedures.^[40] The successful integration of injectable nanorobots into future precision medicine depends on overcoming these obstacles.^[25]

Future Perspectives of Injectable Nanorobots

The future of injectable nanorobots depends on the development of fully autonomous and intelligent systems capable of accurate diagnosis, targeted therapy, and real-time monitoring inside the human body.^[25] Advances in artificial intelligence, biohybrid designs, and stimuli-responsive materials are expected to improve navigation, adaptability, and therapeutic efficiency.^[2] Integration of multifunctional imaging and biosensing platforms will enable personalized medicine and early disease detection.^[40] Future research is also focused on enhancing biocompatibility, biodegradability, and large-scale clinical translation of nanorobots.^[38] Further advancements in propulsion technology and targeted drug delivery systems could lead to the development of

injectable nanorobots that have the potential to revolutionize cancer therapy, regenerative medicine, and minimally invasive healthcare applications.^[17]

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