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Advancement and Future of Nanorobotics in Medicine: A Narrative Review

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Abstract: Nanorobots are nanoscale devices engineered to perform precise diagnostic or therapeutic tasks in the body. This narrative review synthesizes advances in nanorobot design (materials, propulsion, navigation, and communication) and highlights applications in drug delivery, imaging/diagnostics, surgery, and immune system modulation. We searched PubMed and Google Scholar using keywords "nanorobots," "nanorobotics," "drug delivery," "diagnostics," and "theranostics," including peer-reviewed English original research and review articles and excluding non-peer-reviewed. In drug delivery, targeted nanocarriers have enabled precise chemotherapy delivery; a stimulus-responsive DNA-origami nanobot delivered ligands to cluster death receptors on breast cancer cells, yielding ~70% tumor reduction in a mouse model. Other designs use magnetic or chemical propulsion to traverse barriers (e.g., blood–brain barrier) and release drugs via triggers (pH, temperature, enzymes). In imaging/diagnostics, magnetically actuated nanorobots carrying radiopaque materials (barium sulfate/magnetite) have been navigated for micro-Computed Tomography tracking of gastrointestinal targets, and sensor-equipped nanobots can detect tumor biomarkers and relay signals for early disease detection. In microsurgery, remotely controlled microdrills and soft robots enable minimally invasive procedures such as plaque removal and targeted thrombectomy. Nanorobots can also modulate immunity: polymeric nanocarriers deliver immunosuppressants to inflamed tissue, and artificial antigen-presenting nanobots expand regulatory T cell populations in vivo. These advances demonstrate high-precision capabilities, but findings remain largely preclinical, and we have tempered language about "imminent" translation. Clinical readiness requires overcoming biocompatibility, powering, manufacturability, and safety hurdles; regulatory classification is unclear, and many may be high-risk (Class III) devices requiring full premarket approval. Ethical and societal issues (patient autonomy, data privacy, long-term persistence, equitable access) also demand attention, while bio-hybrid designs (cell-membrane coatings, living cell robots) seek to mitigate immune clearance. Conclusion: nanorobots hold transformative potential for personalized medicine, but cautious optimism is warranted.

Keywords: nanorobotics, nanomedicine, targeted drug delivery, diagnostics, theranostics, microsurgery, immune modulation

1. Introduction

Advances in nanotechnology have enabled nanorobotics; the design and deployment of nanoscale robots (1–100 nm) that can operate in biological environments to deliver drugs, sense biomarkers, and perform microsurgery. First envisioned by Feynman in 1959 ("There's plenty of room at the bottom" [1]), these tiny machines promise to revolutionize medicine by enabling precision treatment at the cellular level. Unlike conventional drugs, nanorobots can specifically target diseased cells (e.g., tumor cells) and release therapy locally, thereby protecting healthy tissue and reducing systemic side effects. For example, experimental cancer nanotherapies have significantly reduced chemotherapy-related toxicity [2].

However, nanorobotic medicine also faces significant challenges. These include ensuring biocompatibility and minimizing toxicity, penetrating biological barriers (e.g., the blood–brain barrier (BBB)), powering and controlling robots in vivo, and navigating complex regulatory and ethical landscapes [3, 4]. Most published studies to date focus on specific proofs of concept in cell cultures or animal models [5]. A comprehensive review that integrates engineering design, biomedical applications, and translational challenges is needed to assess the field's clinical readiness. This review aims to fill that gap by summarizing recent nanorobotic developments, critically analyzing their translational hurdles, and discussing future directions.

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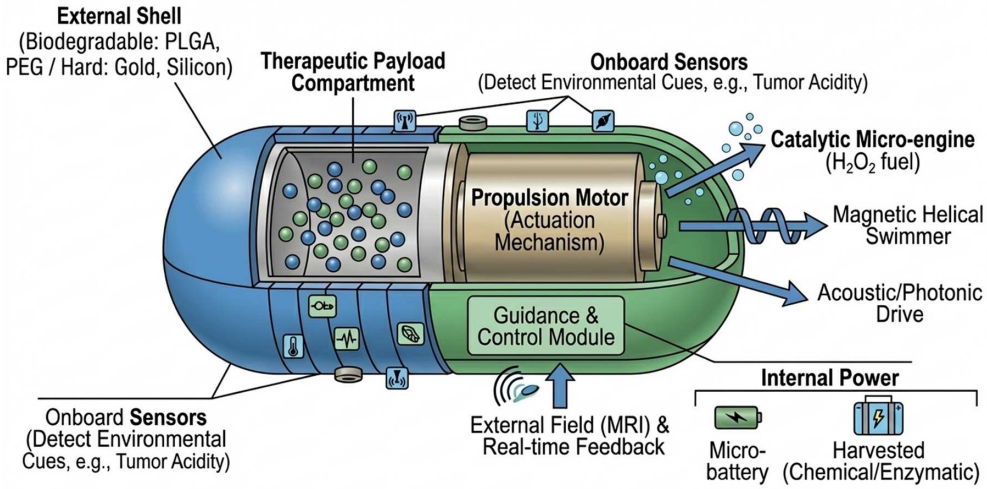
Figure 1
Schematic of a medical nanorobot (illustrative)



Note: The diagram shows an external casing (shell), internal propulsion motor, guidance/control module, onboard sensors, and therapeutic payload compartment.

2. Methodology

This narrative review was conducted through a literature search by using PubMed and Google Scholar. We used keywords including "nanorobot," "nanorobotics," "targeted drug delivery," "micro/nano surgery," "nano theranostics," and "nanomedical ethics." Inclusion criteria were peer-reviewed original research and review articles on medical nanorobot design, fabrication, and biomedical application and articles published in the English language. We excluded non-peer-reviewed sources, patents, and conference abstracts. Although not a systematic review, we aimed to cover a broad range of topics; we identified >200 relevant articles and selected those most representative of each domain. No formal meta-analysis was performed; this narrative approach allows for interpretive synthesis but does not quantitatively compare studies. We acknowledge that this method may miss some literature and is subject to selection bias, which is an inherent limitation of narrative reviews.

3. Fundamentals of Nanorobotics

Nanorobots consist of multiple functional elements and subsystems. Fundamental components typically include a biocompatible shell or casing (e.g., made of silicon, carbon-based materials, or polymers) to protect the interior, an internal power source (such as a micro-battery, enzyme fuel, or external field-driven energy), sensors for chemical or physical signals (pH, temperature, enzymes, biomarkers), therapeutic payload compartments (e.g., drug reservoirs or gene delivery vectors), actuators (mechanical appendages or mechanisms to release drugs, exert force, or drill), and communication interfaces (for receiving control signals or transmitting data) [6]. Figure 1(see below) conceptually illustrates a nanorobot design with labeled components such as the external casing, propulsion unit, guidance system, sensor suite, and payload chamber.

4. Fundamentals of Nanorobotics

4.1. Design and architecture

Nanorobots must balance miniaturization with functionality [6]. Common shell materials include biodegradable polymers (PLGA, PEG) that safely degrade after use or hard materials (gold, silicon, diamond-like carbon) for structural rigidity. Internal power can be stored (micro-batteries) or harvested (e.g., chemical reactions, enzymatic fuels). Sensors embedded on the robot surface can detect local environmental cues (e.g., tumor acidity) to trigger actions. Actuation mechanisms may be magnetic (rotating or oscillating fields acting on magnetic components), acoustic (ultrasound-driven microjets), or photonic (light-driven motion) (6, 7). For example, catalytic micro-engines use local chemical fuel (like H_2O_2) to propel nanomotors, while magnetic helical swimmers convert external magnetic fields into corkscrew motion. Guidance and control are often provided by external fields (e.g., MRI gradient steering) combined with real-time imaging feedback.

4.2. Materials

Biocompatibility is paramount. Polymers (e.g., hydrogels, PLA, PLGA) yield soft, degradable bodies; metals (iron oxide, gold, platinum) add strength and catalytic functions [8]; carbon nanomaterials (nanotubes, graphene) offer extreme strength and conductivity but often require surface functionalization to avoid toxicity [9]. Biomolecular components (e.g., DNA-origami structures) are also used to achieve precise folding and drug loading. Hybrid structures combine these materials for optimal properties: for example, polymer-coated magnetic cores that dissolve after mission completion.

4.3. Powering and control mechanisms

Nanorobots are propelled either by external fields (exogenous methods) or onboard chemical/biological reactions (endogenous methods). Exogenous propulsion includes magnetic fields (rotating or gradient fields acting on magnetic components) and ultrasound vibrations driving motion [10]. Light (photothermal) can locally heat or push robots with lasers. Enzymatic or catalytic reactions (e.g., decomposition of hydrogen peroxide) can provide chemical propulsion. Some designs harness living organisms or cells as engines: for example, sperm-driven micro-tubes or flagellated bacterial carriers. Communication often occurs via long-range external signaling: for example, the robot updates its status by responding to

changing magnetic fields or radiofrequency (RF) tags [11]. Short-range wireless communication (optical or acoustic) is also being explored, but current robots mainly rely on external control signals to coordinate actions [12].

4.4. Navigation and localization

In vivo, nanorobots use external guidance (steerable magnetic gradients, directed ultrasound beams) combined with real-time imaging (fluorescence, MRI, ultrasound) for localization [13]. For instance, magnetic or fluorescent labeling allows tracking by MRI or optical microscopes [14]. Some advanced proposals use onboard chemotactic sensors to autonomously follow biological signals (e.g., inflammatory cytokines) toward target sites [15]. In practice, hybrid approaches dominate: researchers often use external fields for gross steering (e.g., via MRI magnetic coils) while monitoring robot positions via ultrasound or fluoroscopy. The goal is closed-loop control: for example, adjusting field parameters in real time based on imaging feedback to keep nanorobots on course.

4.5. Communication methods

Direct wireless communication at the nanoscale remains limited. Short-range signaling (RF, optical, or acoustic) is under study. Many designs rely instead on a "centralized" scheme: a clinician's computer or external controller sends commands (magnetic field changes) and infers robot state from imaging or readouts. Some lab-on-robot experiments embed nanoelectronics to transmit data (e.g., a sensor reading) when near a detector [16]. Swarms of nanorobots can be programmed to release drugs in a synchronized manner by timed external triggers.

4.6. Integration of engineering and biological constraints

Effective design must bridge engineering functionality with physiological realities. For example, magnetic actuation is strong at the surface but attenuates in deep tissue; field strengths safe for patients may be insufficient to power tiny robots at depth. Onboard chemical fuels (like H_2O_2) can be toxic at useful concentrations. Crucially, uncoated nanorobots are quickly recognized as foreign and cleared by the immune system. To address this, researchers are developing bio-hybrid and biomimetic robots. Recent examples include microrobots cloaked in neutrophil or red blood cell membranes, which inherit biological stealth features to evade clearance and prolong circulation. Others use bacterial or cell-derived components for self-propulsion. These bio-integrated designs demonstrate how engineering principles must adapt to biological constraints: successful nanorobot design often requires incorporating life-inspired solutions (flagellar motility, membrane camouflages, etc.) [17, 18].

5. Applications of Nanorobotics in Medicine

Nanorobots have been explored in multiple biomedical domains. Below, we describe key application areas and summarize their state of the art. (Five summary tables are provided to synthesize mechanisms, examples, benefits, challenges, and clinical readiness in each domain.)

5.1. Drug delivery

Nanorobots can deliver therapeutic agents with unprecedented precision. Common mechanisms include ligand-targeted binding to diseased cells, stimuli-responsive release (pH, temperature, enzymes), and penetration of biological barriers (e.g., via receptor-mediated transcytosis across the BBB) [19]. For instance, one DNA-origami nanorobot was engineered to remain inert at physiological pH (7.4) but to unfold in acidic tumor microenvironments (pH ~6.5), clustering cell-death ligands on cancer-cell membranes and inducing apoptosis. In animal studies, this approach achieved ~70% tumor reduction with minimal harm to healthy tissue [20]. Other examples include magnetically propelled nanocarriers that traverse the bloodstream, tethered to ligands for cancer-specific receptors (e.g., Prostate-Specific Membrane Antigen (PSMA)-targeted nanoparticles delivering chemotherapeutics) [21].

Challenges: Tumors are heterogeneous, so targeting ligands may be variably expressed. The BBB limits Central Nervous System (CNS) drug delivery; while some nanorobots show promise in animal models, precise BBB penetration in patients remains challenging [19]. Powering and control deep inside the body are engineering hurdles. Biocompatibility and immune clearance remain concerns; payloads must be released before robots are sequestered by immune cells. Large-scale manufacturing of complex nanorobots is also nontrivial [22].

Clinical readiness: So far, nanorobotic drug delivery is at the preclinical stage. Some targeted nanoparticles (e.g., polymeric carriers) have entered clinical trials (e.g., BIND-014, a prostate-specific antigen-targeted docetaxel nanoparticle [21]), but no true autonomous nanorobot therapy has yet reached human trials. Cautious optimism is warranted, as experimental results are encouraging but early.

A comparative overview of nanorobotic drug delivery mechanisms, representative studies, benefits, challenges, and clinical readiness is provided in Table **1**.

Table 1
Summary of nanorobotics in drug delivery

Mechanism	Key studies/examples	Benefits	Challenges	Clinical status
Stimuli-responsive, targeted release (ligand-receptor targeting; triggered by pH, enzymes, temperature)[1]; magnetic or ultrasound propulsion for directed delivery	DNA-origami nanobot (acid-activated, clustered death ligands; ~70% tumor shrinkage in mice [20]); polymeric microcarriers (PSMA-targeted docetaxel nanoparticle, BIND-014, in Phase I/II trials [21])	High delivery precision; reduces systemic toxicity and side effects [20]; can cross barriers (e.g., BBB) via specialized mechanisms [19]	Tumor microenvironment variability (heterogeneous pH, receptor expression); immune clearance of foreign payloads; complex manufacturing; ensuring controlled release timing	Preclinical. Several nanoparticle-based drug delivery systems have entered clinical trials (e.g., Phase I/II targeted chemo-carriers [21]), but fully autonomous nanorobot therapies remain experimental

Table 2
Summary of nanorobotics in diagnostics and imaging

Mechanism	Key studies/examples	Benefits	Challenges	Clinical status
Magnetic/optical tracers; molecular biosensors; lab-on-robot platforms	Radiopaque magnetic nanobots (barium sulfate/magnetite) for GI tract imaging [23]; fluorescent/magnetic nano-swimmers with antibody sensors for virus detection (COVID-19 spike protein in vitro [25].	Enables targeted real-time imaging; high sensitivity; can reach deep or hidden tissues	Sensor reliability and calibration in vivo; limited penetration depth for optical methods; unknown human safety (animal data only [23]); potential interference from complex body milieu	Experimental. Demonstrated in animals or in vitro. No nanorobot diagnostic product yet in clinical use

5.2. Diagnostics and imaging

Nanorobots can enhance in vivo imaging and sensing. For imaging, magnetically navigable nanodevices have been created. In one study, spherical robots of barium sulfate and magnetite were injected into the gastrointestinal (GI) tract of pigs and steered by external magnets; their barium content made them radiopaque on Computed Tomography, enabling real-time tracking of digestive flow. Such approaches demonstrate the potential of nanorobots as traceable agents for targeted imaging [23]. For diagnostics, sensor-equipped nanorobots can detect biomarkers at the molecular level. Some designs incorporate nanoscale cameras or binding elements that latch onto cancer-specific molecules and emit signals. For example, prototype nanobots have been tested in animal models for early tumor detection by carrying Positron Emission Tomography (PET) tracers or biosensors to tumor sites [24].

Benefits: Nanorobotic tracers can reach deep or hidden tissues and yield high-resolution images or signals. Sensor nanorobots offer continuous, real-time monitoring of biochemical parameters inside the body. This could enable earlier diagnosis or monitoring of diseases at the point of need.

Challenges: Reliability and accuracy in complex human environments remain issues. Individual biological variability (e.g., differing biomarker profiles) may lead to false negatives or positives. Ensuring patient safety is critical: most reported nanorobotic imaging results are from animal studies, and human biocompatibility/safety is unproven [23]. Data interpretation from in vivo nano-sensors is also technically challenging.

Clinical readiness: Still at the experimental stage. Radiopaque nanobots and nano-sensors have demonstrated feasibility in preclinical models [23], but no nanorobot-based diagnostic device is yet approved. Ongoing work focuses on improving targeting, sensor specificity, and demonstrating safety in larger animal studies. The principal diagnostic and imaging applications of nanorobotics, including mechanisms, key examples, advantages, limitations, and current clinical status, are summarized in Table 2.

5.3. Surgery and tissue repair

Nanorobotic systems can perform minimally invasive microsurgeries and assist tissue regeneration. Because of their small size, nanorobots can navigate through capillaries and thin vasculature. For example, magnetically guided microdrills and soft robots have been demonstrated to excise microscale arterial plaques under image guidance. In cardiovascular models, swarms of magnetic micro-bots have mechanically disrupted thrombi and delivered clot-busting agents (t-PA) directly to occlusions, achieving recanalization faster than conventional methods [26]. Spiral-shaped microrobots controlled by external fields have been tested for targeted thrombectomy in small vessels [27]. Other designs include self-folding microdevices for targeted biopsies and continuum robots (soft, deformable catheters) for tissue repair. These devices promise surgeries at the cellular scale, reducing the need for large incisions and speeding recovery [26, 27].

Benefits: Nanorobotic surgery offers unparalleled precision: robots can approach tumors or lesions that are inaccessible to macro- or endoscopic tools. They minimize collateral damage and patient trauma, potentially improving outcomes in stroke, cardiovascular disease, and oncology [26, 27].

Challenges: Controlling robots in flowing blood and complex anatomy is difficult. Removing debris (e.g., disrupted plaque material) must be managed to avoid downstream emboli [28]. Real-time imaging is required to guide microrobots safely. Regulatory approval for implantable or intraoperative nanodevices is also complex. Current prototypes require large external magnets or guides, which may be impractical in a clinical setting.

Clinical readiness: Largely preclinical. Several studies report successful thrombectomy or microscale surgery in animal models [27]. No nanorobot has yet been used in human surgery; clinical translation will require robust safety data and medical device trials. Representative nanorobotic approaches for microsurgery and tissue repair, along with their mechanisms, benefits, challenges, and developmental status, are summarized in Table **3**.

5.4. Theranostics and personalized therapy

Theranostic nanorobots integrate diagnostics and therapy. One approach is to combine payload delivery with real-time sensing. For example, a nanorobot might carry a drug and an imaging reporter, releasing therapy only after confirming target engagement via fluorescence or another signal [30]. Another vision is patient-specific nanorobots designed via organ-on-chip testing: using tumor biopsies, researchers can screen multiple nanotherapies on microfluidic chips before selecting the optimal one [31]. This "preclinical personalization" could refine cancer treatment plans.

Benefits: Theranostic robots can tailor treatment to individual patients and monitor response dynamically. They can adapt dosing or delivery based on immediate feedback. This suits precision medicine paradigms in oncology and beyond.

Challenges: These systems are highly complex. They must carry multiple functional modules (sensors, logic, drug carriers) in a single device. Each added function increases regulatory and manufacturing hurdles. Also, combining drug (biologic/pharmacologic) and device functions may trigger dual regulatory pathways (as noted below).

Table 3
Summary of nanorobotics in diagnostics and imaging

Mechanism	Key studies/examples	Benefits	Challenges	Clinical status
Magnetic/ultrasound-actuated microrobots; microdrills, cutters, and continuum manipulators	Magnetically guided microdrills for arterial plaque removal (in vitro) [26]; magnetic micro-bot swarm delivering thrombolytics for clot clearance [26]; soft continuum microrobot for vessel thrombectomy [29]	Precise targeting of lesions; minimal invasiveness; reduced incision size and faster healing; can reach deep microvascular targets	Navigating complex vasculature; ensuring stable steering and retrieval; debris management after cutting; safety of long-term implants; manufacturing reliability	Prototype stage. Successful demonstrations in animal studies [27]. No human trials yet for surgical nanorobots

Table 4
Summary of theranostics (diagnostic + therapeutic) nanorobots

Mechanism	Key studies/examples	Benefits	Challenges	Clinical status
Integrated sensing and actuation; feedback-controlled release based on in vivo signals	Conceptual: nanoparticle-drug conjugates with PET tracers; organ-on-chip screening for personalized nanotherapy [31].	Enables real-time treatment monitoring and adaptive therapy; supports personalized medicine	High complexity: multifunction integration; device + drug dual regulation; difficult to manufacture; potential interference between diagnostic and therapeutic components	Theoretical/preclinical. No clinical devices yet; research ongoing in multifunctional nanoparticle platforms

Clinical readiness: Pure theranostic robots remain conceptual. Some multifunctional nanoparticles (like those combining imaging agents with drugs) have entered trials, but fully autonomous theranostic nanorobots have not yet. *Examples of theranostic nanorobotic platforms integrating diagnostic and therapeutic functions, together with their advantages, limitations, and translational status, are summarized in Table 4.*

5.5. Immune system modulation

Nanorobots also interact with the immune system. Targeted immunotherapy: Nanocarriers can deliver immunosuppressive or immunostimulatory drugs to specific immune cells. For example, PLGA nanoparticles bearing IL-2 and TGF-β were used as artificial antigen-presenting cells (aAPCs) in mice, expanding regulatory T-cells and reducing autoimmune symptoms [32]. Liposomal nanodrugs for transplantation immunosuppression (e.g., nano-formulated cyclosporine) have shown improved targeting of graft sites. Such platforms promise to modulate immunity with fewer off-target effects [33].

Benefits: Precision immune modulation may improve treatments for autoimmune diseases, graft rejection, and immuno-oncology. By delivering payloads only to relevant immune niches, systemic toxicity is reduced.

Challenges: The immune system is complex and varies between individuals. Ensuring that synthetic nanorobots interact safely (without over-suppressing or over-activating immunity) is nontrivial. Long-term effects (e.g., unintended tolerance) are unknown. Manufacturing bio-hybrid immune robots (e.g., cell-coated) is also a challenge.

Clinical readiness: Early-stage/preclinical. The aAPC nanorobot mentioned above improved survival in a humanized mouse model [34], but human trials for such therapies have not yet occurred. *Key nanorobotic strategies for immune modulation, including targeted cytokine delivery and artificial antigen-presenting systems, are summarized in* Table 5.

6. Current Status of Nanorobotics in Medicine

6.1. Research and development efforts

Nanorobotics research is rapidly expanding. Various types are under study: molecular machines (DNA or protein-based), synthetic nano-swimmers (magnetic helices, microjets), and cell-based hybrid robots (e.g., immune cells or sperm acting as carriers) [35, 36]. Researchers are improving propulsion (self-propulsion, bio-hybrid, or external fields), navigation (advanced imaging and tracking), and intelligence (e.g., swarming algorithms). Patent analyses show increasing innovation aimed at scalable manufacturing and robot autonomy [37]. Major focus areas are biocompatibility, precise control, and integration with diagnostics [18, 35].

6.2. Prototype performance

Most existing nanorobots remain lab prototypes. In vitro and animal studies show promising functions (targeting, movement, sensing) [35]. However, performance in vivo can differ: complex bodily fluids and immune clearance often degrade effectiveness. Reproducibility and batch consistency are notable problems. Current robots often rely on specialized conditions (e.g., high field strengths or chemical fuels) that are not straightforward in clinical settings. Improved imaging (MRI/ultrasound) and biocompatible actuation methods are being developed to bridge this gap. Notably, a few devices have reached early clinical testing: for example, gold

Table 5
Summary of nanorobotics in immune modulation

Mechanism	Key studies/examples	Benefits	Challenges	Clinical status
Nanocarriers or nanorobots delivering cytokines/antigens to immune cells (e.g., aAPCs); bio-hybrid immune cell robots	PLGA nanoparticles with IL-2/TGF-β acting as artificial APCs to induce T-regs (mouse model) [32]; liposomal nano-formulated immunosuppressants (e.g., tacrolimus) targeting inflamed tissue [33]	Site-specific immune modulation; enhanced efficacy and reduced systemic side effects [33]	Immune system variability; risk of broad immunosuppression or unintended immunotolerance; ensuring safety of persistent nanodevices; reproducibility of bio-hybrids	Preclinical. Demonstrated efficacy in animal models [32]. Human clinical studies of immune-modulating nanobots are not yet available

nanoparticles (not autonomous robots) are approved for photothermal cancer therapy, illustrating the potential to adapt nanorobot-like principles clinically. But true nanorobots are still far from human use.

6.3. Preclinical and clinical studies

Several nanotechnology-based systems related to robotics are in early trials. For targeted drug delivery, numerous nanoparticle therapies (liposomes, polymeric particles) have FDA approval or are in late-stage trials (e.g., nanoparticle-carried chemotherapy [21]). However, none of these are self-propelled or autonomous in the robotic sense. A few micro/nanorobotic devices have entered small clinical feasibility studies (for instance, magnetically guided capsule endoscopes, which are macro-scale micro-swimmers). In oncology, nanoparticle contrast agents (e.g., iron oxide) are FDA-approved for MRI imaging, akin to passive nanorobots for diagnostics. Active nanorobot trials are very limited; most are registered as exploratory first-in-human studies focusing on the safety of specific designs.

7. Future Directions and Challenges

Nanorobotics promises to transform medicine (personalized therapy, continuous monitoring, minimally invasive surgery). However, critical hurdles remain.

Translational challenges: Manufacturing complexity and cost are major barriers. Fabricating uniform nanorobots at scale with high yield is nontrivial. Quality control for such complex devices (ensuring each robot has functional sensors, fuel, and payload) is difficult. Regulatory pathways are unclear: nanorobots blur the line between drugs and devices (3, 35). In the USA, nanorobots may be treated as Class III medical devices requiring full premarket approval [3]. In Europe, nanomedicines are often regulated case-by-case basis without a dedicated pathway [35]. This uncertainty complicates development and clinical planning.

Regulatory and safety: There is a growing recognition that existing frameworks may not fully address nanorobot risks [35]. For example, what constitutes adequate animal testing for a microscopic robot that degrades in the body? How to define safety endpoints for devices that function in vivo? We have expanded our discussion of regulatory issues, emphasizing that most nanorobots will require rigorous evaluation under medical device regulations, potentially combined with drug regulations if they carry drugs. Standards for toxicity, immune response, and long-term fate must be developed.

Ethical, social, and societal implications: We now devote greater attention to ethics. Key concerns include patient autonomy and informed consent for autonomous devices (who is responsible if a nanorobot malfunctions?). Privacy and data security are critical, since nanorobots may generate detailed physiological data. Maintaining trust requires transparent communication of risks [38]. Equity is also a concern: like other cutting-edge therapies, nanorobotics could widen health disparities if only available to the wealthy [39]. We have added paragraphs discussing these issues and the need for guidelines on responsible use.

Engineering-biology integration: As noted above, engineering solutions must respect biology. Deep-tissue actuation requires novel physics (strong but safe fields) and bio-hybrid approaches. Immune evasion will remain a key focus: recent studies show that biomimetic strategies (cell membrane cloaks) can meaningfully reduce clearance [17, 18]. We have strengthened the text to highlight how engineering designs are being adapted to physiological constraints (and vice versa) to facilitate translation.

Future outlook: Continued interdisciplinary collaboration is essential. We highlight that training of "nano-engineers" and medical professionals together will be important. Advances in Artificial Intelligent (AI) and machine learning may optimize robot control and decision-making in real time. Regulatory bodies should develop clear guidelines for nanomedical products. Clinicians and ethicists should engage early on to shape responsible translation. With these efforts, the "nano-submarine" vision (autonomous robots diagnosing, repairing, and monitoring tissue in vivo) could become a reality in the future.

8. Conclusion

Nanorobotics in medicine has advanced rapidly in the lab. Prototype nanorobots demonstrate precise drug delivery, real-time sensing, and microscale surgical tasks (as shown by examples above) [20, 26]. These milestones suggest a transformative potential for personalized and precision healthcare. However, clinical success requires rigorous validation. The current literature largely reports proof-of-concept results in controlled settings [35]. Translation to human therapy will demand addressing biocompatibility, immune safety, reliable control, and cost-effectiveness – challenges that we have emphasized throughout this review.

We have also integrated engineering and biomedical perspectives more tightly, noting that every design choice impacts biological deployment. For example, flagellar drives and membrane coatings are being actively studied to marry microrobotics with living systems [17, 18]. Regulatory and ethical considerations are no longer peripheral; they must be part of each development pathway. Nanorobot development will progress hand in hand with new standards and ethical frameworks.

In summary, nanorobotics holds promise but also faces formidable barriers. Overcoming these will require sustained interdisciplinary research, transparent regulatory efforts, and proactive engagement with societal implications. If successful, the next generation of medical nanorobots could truly herald a new era of medicine, where miniature machines perform on-demand diagnostics, deliver therapy precisely where needed, and even orchestrate tissue regeneration from within.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data are available from the corresponding author upon reasonable request.

Author Contribution Statement

Sai Han Htun: Conceptualization, Methodology, Validation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Iqra Mumtaz:** Conceptualization, Validation, Resources, Data curation, Writing – original draft. **Umaira Abbasi:** Methodology, Resources, Writing – original draft. **Marriyum Rashid Khan:** Conceptualization, Resources, Writing – original draft. **Saptarshi Mukherjee:** Resources, Writing – original draft, Visualization, Supervision. **Arun Kumar Maloth:** Conceptualization, Resources, Writing – original draft. **Fadila shuaibu Bello:** Resources, Writing – original draft.

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