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Nanorobotics in Medicine: A Systematic Review of Advances, Challenges, and Future Prospects with a Focus on Cell Therapy, Invasive Surgery, and Drug Delivery

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Abstract

Nanorobotics offers an emerging frontier in biomedicine, potentially revolutionizing diagnostic and therapeutic applications through its unique capabilities in manipulating biological systems at the nanoscale. Following PRISMA guidelines, a comprehensive literature search was conducted using IEEE Xplore and PubMed databases, identifying and analyzing 414 papers. The studies were filtered to include only those that addressed nanorobotics and direct medical applications. Our analysis traces the technology's evolution, highlighting its growing prominence in medicine as evidenced by the increasing number of publications. Applications ranged from targeted drug delivery and single-cell manipulation to minimally invasive surgery and biosensing. Despite the promise, limitations such as biocompatibility, precise control, and ethical concerns were also identified. This review aims to offer a thorough overview of nanorobotics in medicine, specifically on niches such as laparoscopic surgery, drug delivery, and cell manipulation, drawing attention to current challenges and opportunities and providing directions for future research in this rapidly advancing field.

Keywords: nanorobotics, precision medicine, surgery, swarm robotic, multi-robot systems, cancer, orthopedics

Introduction

Nanorobotics, a field merging nanotechnology with teleoperated and autonomous robotics, presents groundbreaking solutions unattainable with conventional robotics. A nanorobot, also known as a nanomachine, is a miniature mechanical or electromechanical device designed to perform specific tasks at the nanoscale level [1]. Unlike nanorobotics, nanoparticles are tiny particles with unique properties used for applications like drug delivery. Nanorobotics involves designing molecular-scale robots for tasks such as targeted medical procedures. The former is about passive materials, while the latter introduces active, controllable machines at the nanoscale. These miniature robots, due to their size, offer unique opportunities for operations at molecular and cellular levels.

The trend toward miniaturization in medical robotics has been gathering considerable momentum, and the potential impacts of this trend on biomedicine are profound. Beyond macroscale medical robotics, the exploration of small-scale medical robotics, ranging from several millimeters to a few nanometers in all dimensions, has intensified. These micro and nanoscale robots have been investigated for diverse biomedical and healthcare applications, including single-cell manipulation and biosensing, targeted drug delivery, minimally invasive surgery, medical diagnosis, tumor therapy, detoxification, and more [2].

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By providing innovative ways to interact with biological systems at the cellular level, nanorobots promise to revolutionize various sectors of medicine, from diagnostics to treatment. The unique capabilities of nanorobots have opened up a new paradigm for problem-solving in biomedicine, enabling innovative approaches to challenges that were previously insurmountable. The potential to precisely manipulate biological materials at a cellular level has expanded the horizons of diagnostic and therapeutic procedures, bringing forth more targeted, efficient, and minimally invasive solutions.

Purpose, Rationale, and Limitations

This paper conducts a systematic review of the use of nanorobots in the medical field, with a specific focus on their applications and limitations in cancer treatment, invasive surgery, and cell therapy. We recognize that the field is continually evolving, and while our focus is on these three areas, the scope of this review could be adjusted to encompass emerging trends and breakthroughs. Through this exploration, we aim to provide a comprehensive overview of the current state of nanorobotics in medicine, trace the trajectory of this transformative technology, and highlight key challenges and potential solutions, providing direction for future research in this exciting and rapidly developing field.

This review is also limited by focusing on nanorobotics papers explicitly stating a clinical or healthcare, which may introduce a selection bias, as relevant research that does not explicitly emphasize clinical applications and these papers may not be found. However, we acknowledge the limited integration of nanorobotics into clinical applications. This lack of integration poses a challenge in providing a comprehensive overview of the practical impact of nanorobotics in medical settings, as the field may still be in its early stages of clinical adoption. The review also acknowledges that the term “nanorobotics” is used loosely in the clinical field, as researchers may apply the term to describe a range of technologies. This loose definition may introduce ambiguity and challenges in categorizing and analyzing diverse technologies under a unified framework.

Methods and Materials

To understand the applications and limitations of nanorobots in the medical field, we systematically reviewed the literature following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. Two independent reviewers conducted our review, each thoroughly examining the available literature. The objective of this process was to identify research that provides information on how nanorobots are aiding advancements in the medical field, specifically through methods such as nano-cell manipulation robots, micro-laparoscopic surgery, and drug delivery, as well as other areas of importance.

We did not set a date range for our literature search, from the earliest relevant papers to the most recent ones, aiming to capture the entire development arc of nanorobotics in medicine. The selection criteria necessitated the literature to include both nanorobotics and medicine. Therefore, articles solely focusing on nanorobots without any direct medical applications or articles strictly on the medical field without reference to nanorobots were excluded from our review. To achieve this, we employed a structured keyword search strategy, outlined in the next section, which guided the literature selection process, ensuring a balanced representation of the two intersecting domains under review: nanorobotics and medicine.

The literature search was conducted on two comprehensive and well-regarded databases: IEEE Xplore and PubMed. These databases were chosen based on their accessibility and the high merit of the works they contain, particularly in the intersecting domains of technology and medicine. In analyzing the data, we noticed a recent increase in the number of papers published on this topic, indicating a growing interest in the intersection of nanorobotics and medicine. This trend is visually represented in Figure 2, underscoring the escalating attention given to this research area. Our search was broad, without any date range filters, to capture the field’s evolution and growth since its inception. The keyword search was constructed to pull relevant literature that overlapped the areas of nanorobotics and biomedicine. Our general keyword search strategy was as follows: (“swarm robotics” OR “swarm intelligence”

OR "swarm behavior" OR "Multi-robot systems" OR "microbots" OR "nanorobots") AND ("biomedicine" OR "medical applications" OR "healthcare" OR "medicine" OR "surgery"). The same keywords were used for the IEEE Xplore database. For the PubMed search, these terms were additionally constrained to the Title/Abstract fields of the papers. From our initial search, we retrieved 110 results from PubMed and 304 results from IEEE Xplore. These results underwent further screening and filtration based on the relevance and quality of the content, as detailed in the next section.

Following the initial extraction of papers, the literature was further refined through a second filtration stage based on their relevance to nanorobotics and medical applications. This involved a detailed review of each paper to ensure they intersected these two topics. Papers that focused exclusively on either nanorobots (without direct medical application) or medical topics (without the use of nanorobots) were excluded at this stage. During filtration, we also noticed many papers that focused on 'nano intelligence' rather than 'nano robotics' or 'nano technology.' While related, the domain of 'nano intelligence' largely covers algorithmic development and computational models, which falls outside nanorobotics' mechanical or electromechanical focus. Considering the scope and purpose of our review, we decided to exclude these papers to maintain a clear focus on nanorobotics in the context of medical applications. That said, we have included some broader literature on nanorobotics, which provided essential context and historical development of the field. This allows us to present a comprehensive picture of the journey of nanorobots from a conceptual stage to the sophisticated tools they represent today in the realm of medicine. A full pipeline of our methodology can be found in Supplemental Figure 1.

Summary of Relevant Literature

The stringent filtration process resulted in a final selection of 45 papers that fit our criteria. An analysis of these papers revealed their focus on diverse subfields within the scope of nanorobotics in medicine. Specifically, 15 papers were dedicated to cancer-related research, 7 papers targeted cell, tissue, or organ treatment, 10 discussed surgical applications, 8 covered nanorobotic applications in drug delivery, and 5 covered other miscellaneous topics relevant to nanorobotics. Refer to Figure 1. The remaining papers consisted of general reviews on nanorobotics or tackled miscellaneous topics that could not be neatly categorized into any of the aforementioned areas.

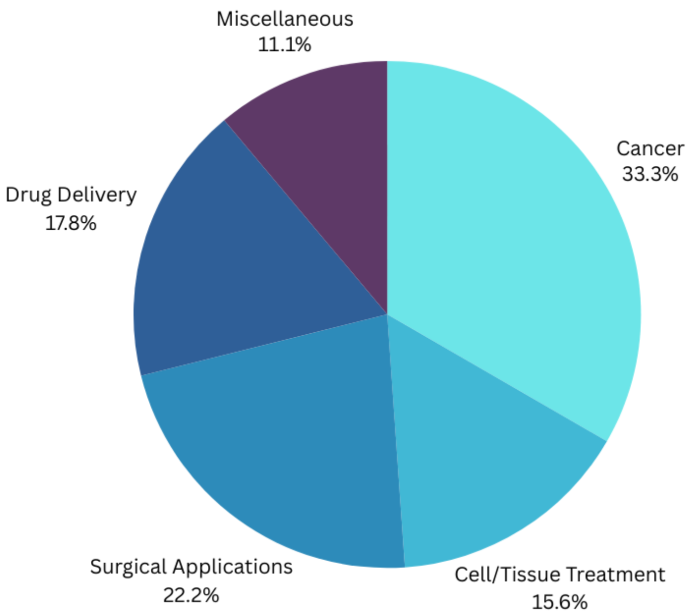

Figure 1. Pie chart of applications of nanorobotics in medicine.

A temporal analysis of these selected papers indicated a notable trend: out of the 45 papers, 33 were published after the year 2017, and the majority of these appeared after 2021. This pattern signals a burgeoning interest in the field and points to the rapid evolution of nanorobotics in medical applications in recent years. This trend is depicted graphically in Figure 2, which shows the growing scholarly attention to this field over time.

Interestingly, the selected papers showcased a high degree of international authorship, pointing to the global interest and collaborative effort in exploring nanorobotic applications in medicine. We provide a graphical representation of this international engagement in Figure 3 below, further underscoring the widespread academic pursuit of solutions and advancements in nanorobotics.

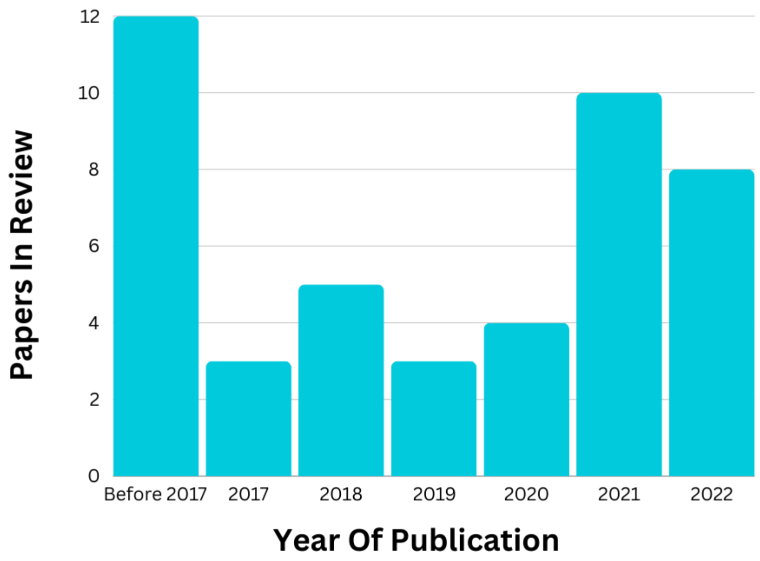

Figure 2. Number of papers in the field by year. The Y-axis shows the number of papers published, and the x-axis is the publication year(s).

Figure 3. Number of papers in biomedical nanorobotics by region. The number inside each red circle represents the number of papers from each region.

Discussion

Cancer

Cancer remains one of the most formidable health challenges worldwide. Its complexity and heterogeneity necessitate treatments targeting aberrant cells specifically while sparing healthy ones. Over the years, traditional treatments like radiation and chemotherapy have seen widespread use; however, their systemic administration often leads to significant adverse effects due to a lack of selectivity. Herein, the field of nanorobotics offers an innovative paradigm for cancer therapeutics.

Nanorobots, characterized by their operation at the molecular level, are well-suited for cancer treatment applications. Their miniature size, comparable to biological macromolecules, allows them to navigate the intricate biological landscape with a degree of precision unattainable by traditional therapeutic modalities. This high level of precision helps reduce harm to non-target cells, a notable downside of standard radiation and chemotherapy treatments. One of the critical utilities of nanorobots in oncology is providing high-resolution information to surgeons. Through their ability to map out cancerous cells in site, nanorobots can aid surgeons in planning and executing intricate surgical procedures, thereby enhancing surgical outcomes and patient prognosis. For instance, nanorobots could offer real-time mapping of the areas requiring dissection during laparoscopic cancer surgery, thereby guiding the surgeon's actions to maximize tumor removal and minimize damage to healthy tissues. Moreover, beyond their navigational prowess, nanorobots can potentially intervene directly in the tumor microenvironment. They can carry therapeutic payloads, specifically deliver these to cancer cells, and even execute programmable actions upon reaching the target site. This feature helps to increase the treatment's specificity significantly, subsequently reducing systemic toxicity [3], [4].

The temporal aspect of cancer treatment is a critical consideration, often linked to patient survival rates. Traditional treatment methods like chemotherapy, while effective, are often protracted, requiring multiple cycles spread over months. In contrast, nanorobots' precise delivery and operation can expedite the treatment process, potentially resulting in quicker therapeutic responses. The versatility of nanorobotics in cancer therapy is further exemplified by their potential synergy with conventional treatment modalities. Nanorobots can also serve as reservoirs of therapeutic agents in the bloodstream [5]. By continuously releasing agents, such as doxorubicin and paclitaxel (used for chemotherapy), over an extended period, they can enhance the efficacy of chemotherapy and potentially other systemic treatments. This ability of nanorobots to act as delivery platforms can significantly extend the functional half-life of the therapeutic agents and maintain optimal drug concentration levels in the systemic circulation. Nanorobots can augment the overall therapeutic outcomes while potentially mitigating side effects through targeted delivery by operating in tandem with traditional therapies such as chemotherapy or radiation.

An integral feature of nanorobots that considerably enhances their functionality in cancer treatment is their sensor-based ability to detect and surgically excise tumors. Innovative frameworks such as Tumor Sensitization and Targeting have been proposed to aid surgeons in detecting and operating on tumors located within difficult-to-reach tissues and body cavities, a task currently beyond the capabilities of existing surgical technologies [6], [7]. What makes these nanorobotics-based strategies unique is their reliance on swarm intelligence. Many nanorobots can work collectively, like a swarm, to achieve a common goal [8]. This approach leverages the power of cooperation, enabling nanorobots to cover large areas or perform complex tasks that would be impossible for a single nanorobot.

Moreover, the design and fabrication of nanorobots have also been inspired by naturally occurring biological substances. These biomimetic nanorobots incorporate natural components to circumvent potential immune responses and minimize side effects during treatment. By aligning with the body's innate biological systems, these nanorobots can function more efficiently, reducing the potential for adverse reactions while maintaining therapeutic effectiveness. These approaches encompass emulating red blood cell attributes within the bloodstream to mitigate immune reactions and applying specialized coatings to evade immune system recognition.

An essential characteristic of nanorobots that significantly contributes to their effectiveness in cancer management is their ability to traverse freely within the body without causing disruptions or adverse effects [9]. Their small size, comparable to that of cellular organelles, permits them to operate at the cellular level, providing therapeutic benefits directly to the cells [10]. Their nanometric scale allows these machines to infiltrate cellular structures, perform tasks, and navigate the intricate pathways within the human body that are inaccessible to conventional medical tools. This capability has the potential to revolutionize treatment methods by providing highly localized treatments, which can lead to more efficient therapies with fewer side effects. Furthermore, due to their small size, nanorobots can be utilized in higher numbers to maximize their collective impact, bringing us back to the concept of swarm intelligence. By combining their efforts, nanorobots can collectively execute complex tasks more efficiently than a single entity, making them a useful tool in the medical field.

Surgical Applications

Using nanorobots in surgical applications has demonstrated a substantial potential for enhancing the precision and efficiency of medical procedures.[12],[13] Nanorobots uniquely integrate with materials such as colloidal gold and quantum dots. These materials exhibit distinct structural and chemical properties that are not accessible to larger-scale entities [14],[15]. This unique feature enhances the versatility of nanorobots, enabling them to perform tasks that would be challenging or even impossible for larger robots, thus making surgical procedures more efficient and manageable. For instance, nanorobots equipped with such materials can target and treat tumors and malignant cells with high precision. When used with nanorobots, these materials can facilitate the targeted delivery of therapeutic agents in high-specificity and affinity-type environments [16]. This ability to accurately target pathological cells while sparing healthy ones not only improves the efficacy of the treatment but also minimizes potential side effects, thereby showcasing the vast potential of nanorobots in advancing surgical applications.

Techniques such as the PANDA ring resonator utilize these distinct materials to transport nanorobots and enable their deployment for surgical treatment.[16]

In addition to material advancements, novel nanorobot propulsion methods are being explored. Some of these techniques include the use of light-driven nanomotors. The strength of the motors can be adjusted by varying the intensity of light [17], [18]. This allows for fine-tuning nanorobot movement and control, which is critical for navigating intricate biological structures.

These innovations in nanorobotics open the door to unique applications in biomedicine. It becomes conceivable that complex surgical procedures could be conducted at single-cell precision without requiring invasive surgical incisions. Nanorobots allow for medical interventions to be less invasive, more precise, and personalized, reinforcing the value of nanorobotic research and development.

Drug Delivery

Nanorobots can revolutionize drug delivery methods, improving the speed, efficiency, and specificity of treating diseases and infections. By utilizing built-in sensors, nanorobots can precisely locate diseased or infected regions within the body where the administration of therapeutic drugs is necessary. These nanorobots can autonomously or via remote controls administer the appropriate drugs at the target site, effectively bypassing the need for invasive surgical procedures [19], [20], [21].

The advent of nanorobotics in drug delivery can lead to significantly enhanced therapeutic outcomes while minimizing potential side effects commonly associated with systemic drug delivery. By delivering drugs directly to the pathologic site, nanorobots can ensure that the therapeutic agents exert their maximal effect at the desired location while minimizing systemic exposure, thus reducing the likelihood of adverse effects. This concept, often called targeted drug delivery, is one of the most promising benefits of integrating nanorobotics into modern medicine.

Janus micro/nanorobots, named for their dualistic nature, represent a promising frontier in drug delivery applications. A Janus micro/nanorobot is a mobile micro/nanomachine with a dual structure that can efficiently transform various energy sources, including local and external power, into mechanical force, encompassing motors, swimmers, and actuators, among others [22]. The advantageous structure of Janus robots enables them to leverage fuel-effective materials, which, coupled with their exceptional maneuverability, allows them to navigate within the human body with remarkable precision. Their dualistic nature, often with one side being passive and the other active, facilitates differential responses to the environment or stimuli, providing them with a controlled and directed motion capability. This precise control over their movement, when paired with appropriate drug-carrying materials, opens up new possibilities for drug delivery. They can transport therapeutics directly to the required site, thereby minimizing systemic side effects and maximizing drug efficacy. The efficient energy translation capabilities and precision navigation of Janus robots substantially enhance the efficacy of drug delivery. These nanoscale robots offer a new therapeutic approach, with potential applications extending beyond medicine into broader fields of biotechnology and nanotechnology.

Nanorobots present an encompassing solution for drug delivery, demonstrating capabilities in sensing, initiating, and administering treatment in targeted areas. Due to their intricate design and multifaceted functionality, these miniature machines can serve various roles in the biomedical field [12]. One key advantage of nanorobots is their ability to navigate through biological fluids, a task previously unachievable by larger-scale medical devices.[23] Recent research has proposed fluid-traveling nanorobots, which use flagellar motion patterns—akin to the propulsion method used by certain bacteria—to travel within the human body. These nanorobots, essentially microscale swimmers, can traverse the viscous environment of bodily fluids, delivering therapeutics directly to the targeted site [24], [25].

By mimicking the biological propulsion mechanisms found in nature, these nanorobots can overcome the physical challenges presented by the human body's environment. Therefore, the ability of nanorobots to perform an array of tasks within a single unit—coupled with their unique propulsion mechanisms—promotes innovation in drug delivery and, more broadly, in the field of nanomedicine.

Cellular Nanorobotics

The compact size of nanorobots enables them to penetrate cells, opening up new possibilities for cellular treatments. These microscopic machines can be pre-programmed with specific functions, which reduces the likelihood of errors and broadens the scope of possible treatments.

One noteworthy type of nanorobot is the DNA nanorobot, which has been gaining significant attention in recent years. These nanorobots are engineered with many unique attributes, such as tissue penetration, site-targeting, stimuli responsiveness, and cargo-loading capabilities. This makes them highly suited for precision medicine applications, as they can deliver targeted interventions at a cellular or even molecular level. Nanorobots can be designed with sophisticated logic gates, enabling them to perform a series of actions in response to various stimuli [26], [27], [28]. This level of functional complexity enhances their versatility in biomedical applications and promises to pave the way for more personalized, efficient, and accurate treatments.

One of the significant advantages of nanorobots is their ability to be engineered using various functional nanomaterials, giving them diverse functionality. Integrating these nanomaterials can modulate a nanorobot's performance, allowing it to adapt to a range of biomedical tasks. [29], [30], [31]. The flexibility of nanorobots' design and functionality is highlighted by the development of 'Respirocytes,' artificial red blood cells capable of carrying oxygen and carbon dioxide. These respirocytes can serve as temporary substitutes for natural blood cells during emergencies, thereby revolutionizing the treatment of heart diseases and the field of hematology in general [32], [33], [34].

Further, nanorobots have been demonstrated to be capable of promoting desirable cell behavior and growth. This means they can potentially regulate cell function thanks to their versatility [35], [36]. These developments underscore the potential of nanorobots to serve as powerful tools for precision medicine, capable of operating at a cellular or even molecular level to diagnose, monitor, and treat diseases.

Miscellaneous

The collective operation of nanorobots, or swarm robotics, presents a transformative approach to various other medical applications. Nanorobots functioning in a swarm can be coordinated to execute complex tasks collectively and cooperatively, significantly enhancing their efficacy. Swarms of nanorobots can be maneuvered collectively via the same fuel source, such as light or magnetic fields [37], [38].

This ability for swarm control means that all the nanorobots can be simultaneously subjected to the same stimuli, streamlining the execution of medical procedures. Moreover, applying swarm intelligence models can potentially simplify the control over these nanorobot swarms, making them more manageable [43]. The application of swarm intelligence extends to medical imaging, where it has been deployed to identify metastasis, micro-calcifications, and brain image segmentation [40], [41], [42]. These findings underscore the potential for nanorobot swarms to revolutionize areas of medicine ranging from targeted therapeutics to sophisticated imaging techniques.

Nanorobots also offer promising advances in medical instrumentation, owing to their versatility and adaptability. The construction of nanorobots can be adjusted by manipulating their constituent materials, enabling them to serve diverse functionalities, an invaluable feature for medical instrumentation [43].

Neurology can also benefit from nanorobots, particularly in precisely delivering neuroprotective drugs and monitoring neurological disorders. For instance, nanorobots could be engineered to transport drugs across the blood-brain barrier, a challenge that conventional methods often struggle with. This could facilitate the treatment of conditions like Parkinson's disease by delivering therapeutic agents directly to affected brain regions, thereby enhancing drug efficacy and minimizing side effects. Furthermore, nanorobots offer a promising avenue for monitoring and managing neurological disorders. By integrating sensors or imaging components into their design, nanorobots could provide real-time data on brain activity or the presence of specific biomarkers associated with disorders such as epilepsy. This would enable more accurate diagnoses and personalized treatment strategies [44].

Challenges

Introducing nanorobots into medical treatment confronts many intricate challenges and limitations, each requiring careful examination. A primary concern centers on the biocompatibility of nanorobots, especially when inorganic materials are integrated into their construction. Inadequate biocompatibility can trigger unwarranted immune responses, such as the recruitment of white blood cells, potentially compromising nanorobot functionality and posing health risks to the patient. Therefore, meticulous examination, testing, and optimization of nanorobot materials are essential to ensure their seamless integration with the human body. For instance, nanorobots employing biocompatible polymers or surface modifications, such as PEGylation, can enhance their biocompatibility [45].

High costs associated with nanorobot development constitute a multifaceted challenge. The precision and intricacy of manufacturing demand substantial resources, including state-of-the-art fabrication facilities and specialized expertise. Additionally, the programming of nanorobots to execute intricate tasks and their deployment in clinical settings contribute significantly to their expense. The cost-benefit analysis of nanorobot utilization must address these financial constraints, especially in healthcare systems with limited resources.

Integrating nanorobots with complementary medical techniques, such as medical imaging systems, is paramount. This integration enables precise navigation and real-time monitoring of nanorobots within the body. The complexity arises from the need for seamless coordination between nanorobot functions and imaging modalities. Additionally, the integration necessitates substantial resources in terms of equipment and expertise to ensure seamless cooperation between these technologies [47], [52].

Intravenously administering nanorobots poses intricate challenges. As these diminutive agents traverse the bloodstream, they confront various barriers. These encompass the possibility of provoking immune responses, the potential for adverse side effects arising from interactions with diverse cell types, and heightened concerns about causing obstructions or damage to blood vessels during intricate navigation [5].

The financial implications of intravenous administration are notable, as precise manufacturing, the orchestration of sophisticated control mechanisms, and ongoing maintenance are necessary. Thus, scalability in resource-limited healthcare contexts is hampered by financial constraints. The endurance of nanorobots under physiological conditions is a substantial concern. Questions loom over their ability to function optimally over extended durations. This uncertainty could necessitate repeated dosing regimens, further increasing the financial burdens associated with nanorobot deployment. Strategies like incorporating resilient materials and developing self-repair mechanisms are under investigation to address these concerns.

The quest for safe and efficient propulsion methods within the human body is a complex challenge. Propulsion mechanisms must meet stringent criteria to ensure safety and efficacy, including non-toxicity, non-immunogenicity, and nanoscale efficiency. Promising methods include using biological motors, such as flagella, to propel nanorobots, but extensive research is ongoing to optimize these systems for clinical use. Additionally, regulatory frameworks for nanorobots in medical contexts are still in their infancy. A comprehensive and stringent regulatory framework is indispensable to ensure the safety and efficacy of nanorobotic devices. This framework necessitates exhaustive pre-clinical testing, validation, and risk assessment, adding a layer of complexity and cost to the deployment process. International standards are also under development to harmonize regulations across borders. These multifaceted and highly nuanced challenges underscore the necessity for interdisciplinary collaboration spanning engineering, biology, ethics, and regulatory oversight to navigate the intricacies and address the limitations associated with nanorobots, ultimately allowing for their effective and responsible integration into medical practice.

Conclusions

Nanorobotics is a rapidly advancing field with the potential to change medicine in many ways. As a promising tool, nanorobots hold the potential to enhance drug delivery, enable precise surgical interventions, and even promote desired cellular behavior. While it's true that there are still obstacles to overcome, including bio incompatibility, high costs, and the challenges of independent functionality, the advancements in nanotechnology and robotics are paving the way for potential solutions. As our understanding of nanoscale materials, propulsion mechanisms, and cellular interactions deepens, these challenges will likely become less formidable. Moreover, as resources become increasingly available and as the designs for various nanorobots with different functionalities continue to evolve, these tiny medical marvels are expected to find wider applications in the medical field. Growing interest in this field will likely spur further research and development, leading to more innovative designs and applications. Future work should focus on making nanorobots more biocompatible, cost-effective, and autonomous and developing safe and efficient propulsion methods.

In the future, integrating nanorobots with medical imaging systems should be explored in greater depth. Collaboration across disciplines, such as materials science, biology, robotics, and medicine, will be essential to realize the full potential of nanorobots. With more research, regulatory advancement, and clinical trials, we can anticipate a future where nanorobots are a standard part of medical treatments, improving patient outcomes and quality of life.

Conflict of interest

The authors declare no conflict of interest. For a signed statement, please contact the journal office at editor@precisionnanomedicine.com.

Author Contributions

Sh. R and Su.R. conceived the idea. Sh. R and Su. R conducted the literature survey. Sh. R wrote the manuscript. Sh. R, Su. R, A.S., and P.S. edited and approved the manuscript.

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