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A Review on Nanorobots in Cancer Treatment

Sushil G. Gadekar[1], Shubham G. Doifode[2], Dr. Sunil S. Jaybhaye[3], Komal B. Jaiswal[4], Varad D. Wagh[1]

1.Student of Bachelor in Pharmacy, Dr.Babasaheb Ambedkar Technological University, Raigad, Lonere. India.
2. Department of Pharmaceutics, Dr. Babasaheb Ambedkar Technological University, Raigad, Lonere. India.
3.Department of Pharmaceutical Analysis, Dr. Babasaheb Ambedkar Technological University, Raigad, Lonere. India.
4. Department of Pharmaceutical Chemistry, Dr. Babasaheb Ambedkar Technological University, Raigad, Lonere. India.

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ABSTRACT

Nanorobots are tiny machines designed to treat cancer by targeting cancer cells while leaving healthy cells unharmed. They deliver medicine directly to tumors, making treatment more effective and reducing the side effects of traditional therapies like chemotherapy. These robots are programmed to release drugs only at cancer sites, ensuring precise treatment without harming healthy tissues. Beyond cancer, nanorobots could potentially treat other diseases such as Alzheimer's. Recent technological advances are bringing nanorobots closer to reality. In the future, cancer treatment may involve injecting nanorobots to eliminate tumors without the painful side effects of chemotherapy or radiation, offering quicker recovery and greater comfort for patients.

Keywords: Nanorobots, Cancer Treatment

INTRODUCTION

In the past few decades, researchers have highlighted nanotechnology as an exceptional technological trend. It is distinguished by the rapid spread of electronics for use in environmental monitoring, nanomedicine, and communication. Scientific bottlenecks that impact the lifespan of living things, especially humans, are currently the subject of research. Illnesses with few or no options for treatment and recovery are one of these limitations. An alternative diagnosis and/or treatment that has been demonstrated in the medical community is referred to as a drug delivery system (DDS) [1,2]. Similar to microelectromechanical systems (MEMS), which is already a multibillion-dollar industry, nanorobots are nanoelectromechanical systems (NEMS), a relatively new chapter in miniaturisation. Nanorobotics and NEMS research include the design, architecture, production, programming, and implementation of such biomedical nanotechnology. Calculations, commands, actuation and propulsion, power, data sharing, interface, programming, and coordination are all included in robotics at any scale. Actuation, a crucial requirement for robotics, is heavily stressed [1]. Nanorobots' size resemblance to organic human cells and organelles raises a wide range of potential applications in the fields of healthcare and microorganism monitoring in the environment. In the future, nanorobots may be able to help heal damaged cells if they are made small enough to reach them. Tiny sensors and actuators will play an important role in creating smarter and more connected technology systems. Scientists imagine artificial cell-like nanorobots that could travel through the bloodstream, constantly monitoring the body and quickly detecting and destroying infections before they become serious, opening exciting possibilities for advanced medical treatments. This technology could become a programmable medical system with powerful effects, bringing a revolutionary change in the way diseases are treated. In current cancer treatment, chemotherapy drugs spread throughout the entire body instead of targeting only cancer cells. As a result, these drugs affect both cancerous and healthy cells, which limits how much medicine can safely be given and often causes severe side effects due to the high toxicity of chemotherapy on normal body tissues. It is now widely accepted that modern, molecule-focused medical treatment has developed as a better way to overcome the lack of accuracy seen in traditional cancer therapies. With the help of nanotechnology, drugs can be guided to collect more effectively inside cancer cells while reducing damage to healthy cells. This is achieved using different targeting techniques that help improve treatment effectiveness and minimize harmful side effects.

NANOROBOTS AND THEIR TYPES

Nanorobots are extremely small machines that can perform tasks similar to today’s advanced machines. They have many useful applications in medicine, industry, and energy conservation, such as the development of tiny motors that help save energy. In the medical field, nanorobots have also shown promise in helping reduce infertility by attaching to sperm cells and improving their movement, which can increase the chances of successful fertilization.[2] Both organic and inorganic nanorobots are widely studied by researchers. Organic nanorobots, also called bio-nanorobots, are made by combining genetic material from viruses and bacteria, allowing them to interact more naturally with living cells and perform medical functions in a safer and more efficient way.

This type of nanorobot is considered safer and less harmful to the human body. In contrast, inorganic nanorobots are made using materials such as diamond-like structures, synthetic proteins, and other artificial materials, which can be more risky and potentially harmful compared to organic nanorobots. To reduce the problem of toxicity, researchers have developed a method of coating or encapsulating the nanorobot. This protective layer helps prevent the body's natural defence system from destroying it, allowing the nanorobot to work more safely and effectively inside the body. [5,6]. By understanding how natural biological motors work inside living cells, scientists can learn how to power tiny micro- and nano-sized devices using similar natural reaction processes.[7] Scientists at the Chemistry Institute of the Federal Fluminense University developed a tiny "nano-valve." It works like a microscopic storage tank with a small lid. Inside it, dye molecules are stored, and when the lid opens, the molecules are released in a controlled and uniform way. This device is made from natural and compatible materials such as silica (SiO_2), beta-cyclodextrins, and organo-metallic molecules. Because of its safe material composition, it is expected to be used in medical and therapeutic applications. Some research studies use proteins as a source of energy to power nanomotors, allowing them to move objects much larger than themselves. In addition, DNA hybridization and antibody–protein systems are used in the development of nanorobots to improve their movement, recognition ability, and targeting of specific cells. DNA hybridization is the natural process in which two matching single-stranded DNA or RNA molecules join together to form a double-stranded structure. Using this principle, nanorobots can be modified and enhanced with different chemical compounds, allowing them to perform specific tasks such as targeting certain cells or delivering drugs more effectively[8]. In nanomedicine, nanorobots have been studied for use in drug delivery systems (DDS) that work directly on targeted cells in the human body. Scientists are developing devices that can deliver medicines to specific areas while carefully controlling the dose and the speed of drug release. These nanorobot-based drug delivery systems have the potential to treat a wide range of conditions, including joint disorders, dental diseases, diabetes, cancer, hepatitis, and many other illnesses. [2,9]. One of the main advantages of this technology is that it can diagnose and treat diseases in a very precise way, causing minimal harm to healthy tissues. This reduces the chances of side effects and helps guide healing and tissue repair directly at the cellular and even subcellular levels. [12].

CANCER TREATMENT

Drug Delivery Systems for Anticancer Drugs

Paclitaxel is administered intravenously and is used to treat breast cancer. Bone marrow concealment and combined neurotoxicity are two of the negative effects that some people actually experience.

Because camptothecin inhibits sort I topoisomerases, an essential enzyme for cell replication of genetic material, it is used to treat neoplasias. Clinical trials are essential for the introduction of new therapeutic options into the market because they allow people to assess the security and sufficiency of new medications [14]. In any event, only a few DDS—such as those primarily consisting of doxorubicin, paclitaxel, camptothecin, and platinum edifices—achieved more advanced stages of clinical evaluation. Doxorubicin was piled on top of the exterior of SWNTs (single-walled carbon nanotubes). The main focus of nanotechnology is always the search for biocompatible materials that can serve as a drug delivery system. Paclitaxel (Tax), an antineoplastic specialist, was administered using nanoparticle HA (Hydroxyapatite), a notable component of bone and teeth. The results indicate great desire with treatment starting from hydrophobic drugs.[12]

With the aid of nanorobotics and current stages of restorative advancements and treatment devices, cancer can be successfully treated. Determine the final factor that determines a cancer patient's chances of survival: how it was previously examined, another crucial aspect to achieve the development of effective, targeted medication delivery to lessen chemotherapy symptoms is a successful treatment for patients. The number of people affected by cancer each year continues to rise, and it can be defined as a collection of illnesses characterized by the unchecked growth and spread of abnormal cells in the body. At present, the nanorobots are customized to perceive 12 kinds of cancer cells. Also, the sub-atomic engines of these gadgets can change their compliance under outside boosts of bright light and drill through cell bilayers to initiate rot of undesirable cells or to acquaint adjusted species and drugs with specifically target sites. A few techniques created by researchers planned to combine drug-stacked nanoparticles where the helpful agents will cling to the cancer cell and will discharge the drug locally. The connection of nanoparticles to cancer cells can be acknowledged by the RNA strands situated to the outside of nanoparticles.[13]

CHEMOTHERAPY DRUG DELIVERY USING NANOROBOTS IN CANCER TREATMENT

New advances in drug delivery have made treatments more precise and effective. These systems use nanosensors to identify specific cells and control the release of medicines through smart, responsive drug systems [1]. Traditional chemotherapy drugs work by killing cells that divide very quickly, which is a key feature of cancer cells. However, these drugs are not very selective and often damage healthy, fast-growing cells as well. This includes cells in the bone marrow, immune system (macrophages), digestive tract, and hair follicles. As a result, patients may experience serious side effects such as myelosuppression (reduced white blood cell production leading to weak immunity), mucositis (inflammation of the digestive tract lining), hair loss (alopecia), organ damage, low platelet count (thrombocytopenia), anemia, and other blood-related problems. Doxorubicin is a widely used chemotherapy drug for many cancers, including Hodgkin's disease, and it is often combined with other anticancer drugs to help reduce its toxic effects while improving treatment effectiveness. [15,16]. Paclitaxel is a cancer drug given through an intravenous (IV) injection and is commonly used to treat breast cancer. However, it can cause serious side effects, including suppression of bone marrow activity and long-term nerve damage (neurotoxicity). Cisplatin is another chemotherapy drug that works by binding inside the DNA of cancer cells and stopping their growth. Its major side effects include dizziness, severe nausea and vomiting, and damage to the kidneys (nephrotoxicity) [1]. Camptothecin is used in cancer treatment because it blocks an important enzyme called topoisomerase I, which cancer cells need to copy their genetic material and multiply. Many research efforts are now focused on using nanotechnology to develop drug delivery systems (DDS) that can reduce the harmful side effects of traditional cancer treatments. In one such approach, the anticancer drug doxorubicin has been coated onto the surface of single-walled carbon nanotubes (SWNTs) to improve targeted delivery [17]. Doxorubicin has been used to treat metastatic tumor cells by combining it with a polymer prodrug and collagen to form a hybrid system. This approach represents a new and innovative advancement in cancer treatment, where polymer-based nanotechnology is used to more effectively target rapidly dividing abnormal cells while reducing damage to healthy tissues [18]. Nanotechnology is constantly searching for biocompatible materials that can be safely used in drug delivery systems (DDS). Hydroxyapatite (HA) nanoparticles, which are a natural and important component of bones and teeth, have been used to deliver the anticancer drug paclitaxel. The results suggest that this method may be especially effective for delivering hydrophobic (water-insoluble) medicines [19]. Many research efforts are focused on using nanotechnology to develop advanced drug delivery systems (DDS) that can reduce the harmful side effects of traditional chemotherapy. One major limitation of conventional chemotherapy is that it cannot selectively target only cancer cells, so healthy cells are also damaged. These unwanted side effects often lead to delays in treatment, lower doses of medicine, or even temporary stopping of therapy [20]. Because nanorobots can travel through the bloodstream, they have the potential to help in important medical procedures such as early disease detection and the intelligent, targeted delivery of medicines [21]. A nanorobot can support smart chemotherapy by delivering medicines directly to cancer cells. It works by identifying and targeting only cancer-specific cells and tissues, while protecting the surrounding healthy cells from the toxic effects of chemotherapy drugs. When used as drug carriers, nanorobots can release the correct dose at the right time and help keep the drug in the bloodstream for the required duration. This improves drug effectiveness and produces better pharmacokinetic behavior in anticancer treatments. as shown in Figure 1 [22-25]. Nanorobots can be used clinically for diagnosis, treatment, and even surgical applications by injecting them into the bloodstream through an intravenous (IV) route. Once in the body, they can assist in delivering chemotherapy more precisely. Chemotherapy involves how the drug is absorbed, metabolized, and eliminated, along with rest periods that allow the body to recover before the next treatment. For small tumors, patients are often treated in two-week cycles to balance effectiveness with safety [26]. Nanorobots can be used for rapid medical assessment and diagnosis by detecting tumors within a short period using proteomic-based sensors. Additionally, studying how small molecular-weight contrast agents are absorbed in magnetic resonance imaging (MRI) can help predict how protein-based drugs will be delivered to solid tumors [27]. Testing and diagnostics are essential aspects of nanorobotics research. Nanorobots can provide rapid diagnostic results during the initial visit, eliminating the need for follow-up appointments and enabling earlier detection of diseases. However, one limitation of using nanorobots in the body is their energy requirement for movement. Due to their small size, they experience low inertia and high viscous forces, which reduces their efficiency and requires higher amounts of energy to move effectively [28]. The effectiveness of a drug delivered by nanorobots depends on how long it stays within the tumor after crossing cellular membranes for targeted delivery. The way the drug moves from the bloodstream to the tissue—determined by its structure and transport pathways—also affects how well chemotherapy works, helping achieve more effective treatment of tumors [27]. Recent research shows that nanotechnology, including DNA-based construction of molecular-scale devices with precise control over their shape and function, offers exciting opportunities in advancing nanomedicine. However, challenges remain, such as the unpredictability of the biological environment and activation of the body's immune system, which limit their use inside the body. The main advantage of nanorobots in cancer treatment is their ability to reduce the side effects of chemotherapy. Modern designs often combine carbon nanotubes and DNA, making them promising candidates for the latest nanoelectronic applications and targeted medical therapies [29]. A complementary metal-oxide-semiconductor (CMOS) can be used to build circuits with features as small as a few tens of nanometres. When combined with single-chain antigen-binding proteins, it acts as a compound biosensor capable of detecting specific biological molecules with high precision [30]. In this approach, drug release is controlled by signals from proteomics and bioelectronics. When the nanorobot detects specific changes in protein levels, nanoactuators are activated to adjust the delivery of the medicine, ensuring precise and timely treatment [1,31]. Changes in thermal and chemical signals play an important role in identifying medical targets in the body. For example, proteins such as nitric oxide synthase (NOS), E-cadherin, and B cell lymphoma-2 (Bcl-2) can show altered levels near diseased tissues. In addition, tissues affected by inflammation often experience changes in temperature, which can serve as another signal for targeting treatment [32]. The system combines chemical and thermal properties as key criteria for designing and evaluating nanorobot frameworks for medical and therapeutic purposes. Simulations in a three-dimensional, real-time environment aim to create a realistic model of how nanorobots navigate and operate inside the body. One notable advancement is the development of a hardware structure based on nano-bioelectronics, which enables the use of nanorobots in cancer treatment [33,34]. Ongoing research in medical micro-robotics has led to the first conceptual studies of a complete medical nanorobot. One notable example, published in a peer-reviewed article, is the “Respirocyte”—a theoretical artificial mechanical red blood cell. Designed with 18 billion precisely arranged atoms, a Respirocyte could deliver up to 236 times more oxygen to the body’s tissues and cells per unit volume than natural red blood cells [35]. Microbivores, also called artificial phagocytes, are designed to patrol the bloodstream and detect harmful pathogens like bacteria, viruses, or fungi. They can operate continuously using very little power (around 200 pW) and break down trapped germs efficiently. These nanobots function much like natural immune cells but can work up to 1,000 times faster. Even severe septic infections could be cleared quickly. Unlike the natural immune response, microbivores fully digest pathogens into harmless sugars and amino acids—their only output—eliminating the risk of sepsis or septic shock [36,37].

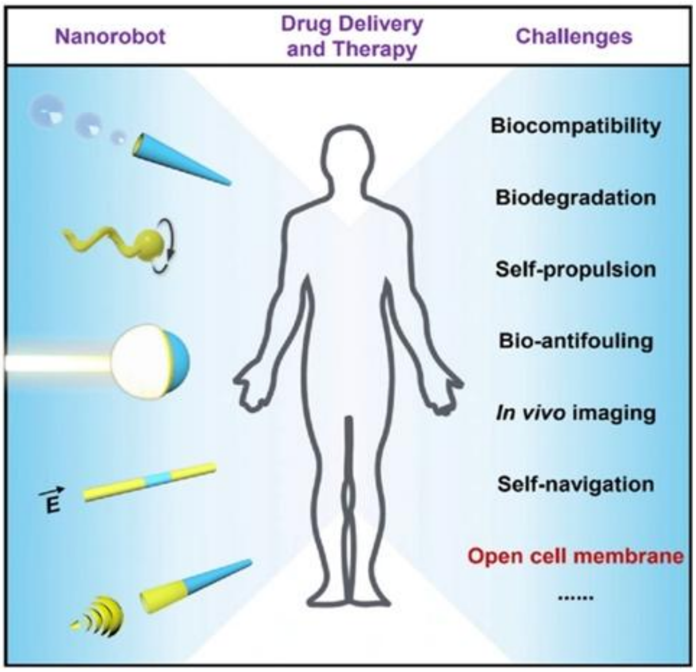

FIGURE 1: CHALLENGES OF NANOROBOTS IN DRUG DELIVERY

FUTURE OF NANOTECHNOLOGY IN THE AREA OF MEDICINE

Developing these advanced technologies requires combining expertise from many traditional scientific fields, including medicine, chemistry, physics, materials science, and biology. Together, they form the rapidly growing field of nanotechnology, which has a wide range of potential applications (Figure 2) [39]—from improving existing methods to creating entirely new tools and capabilities. In recent years, interest in nanotechnology has grown exponentially, leading to the discovery of novel medical applications and the emergence of a specialized branch called nanomedicine. Nanomedicine involves using nanoscale materials, biotechnology, and genetic engineering to diagnose, treat, and prevent diseases, manage injuries, alleviate pain, and enhance overall human health. It also includes the development of complex nanoscale machines and nanorobots for advanced medical interventions (Figure 3) [40,41].

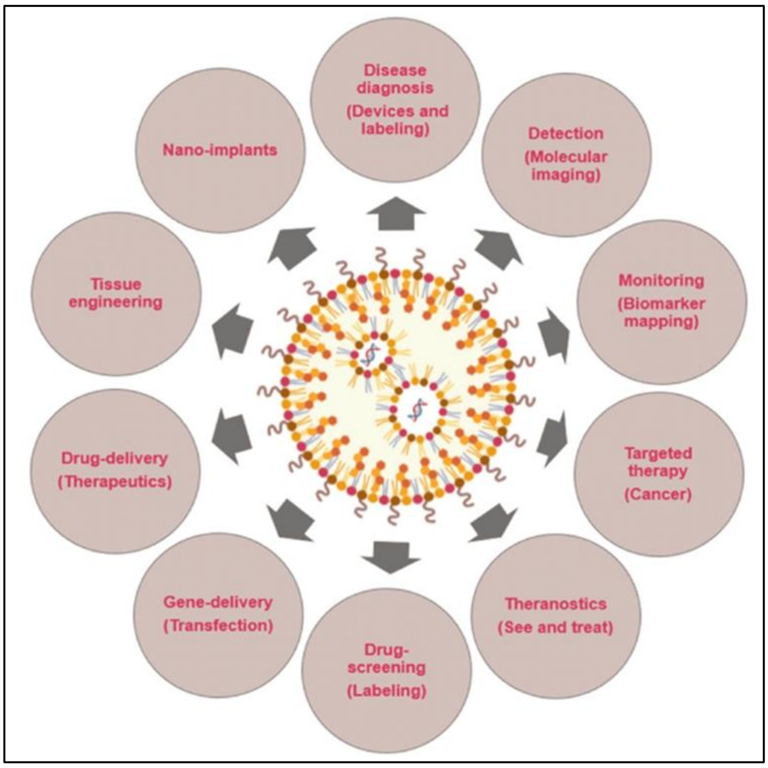

FIGURE 2: ILLUSTRATION SHOWING VARIOUS OTHER APPLICATIONS OF NANOTECHNOLOGY IN MEDICINE.

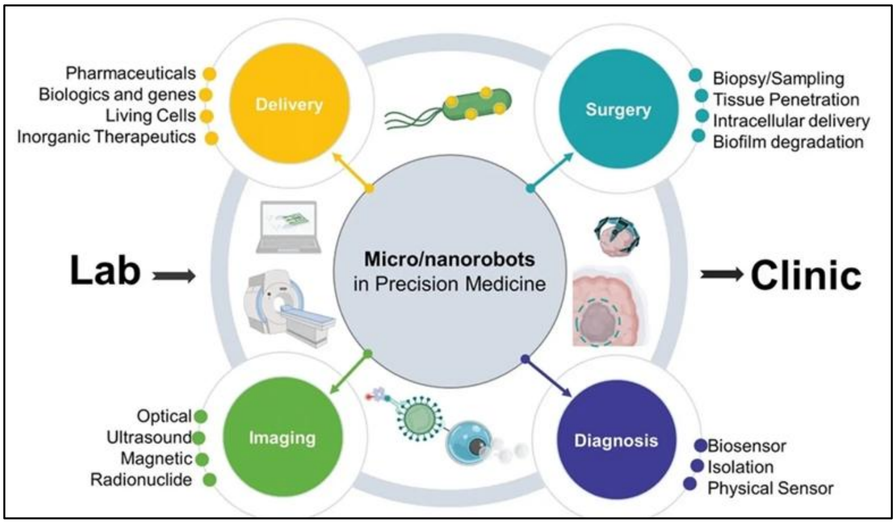

FIGURE 3: SCHEMATIC DIAGRAM OF THE CURRENT TRENDS OF MICRO/NANOROBOTICS IN PRECISION MEDICINE.

In vivo diagnostics with nanomedicine could lead to technologies capable of acting inside the human body to detect diseases earlier, as well as identify and measure toxic substances and tumor cells. In surgery, nanorobots introduced into the body via intravenous routes or body cavities could function as semi-autonomous miniature surgeons, guided or supervised by a human surgeon. An onboard computer could control the nanorobot's tasks, such as detecting disease or repairing tissue through precise nanomanipulation, while staying in communication with the surgeon via coded ultrasonic signals [37].

Researchers have also developed self-powered medical devices, sensors, and portable gadgets by converting mechanical energy from body movements, muscle stretching, or fluid flow into electricity [39]. Nanogenerators create electricity by bending and releasing piezoelectric and semiconducting zinc oxide nanowires, which can be fabricated on polymer-based films. Using flexible polymer substrates, future portable devices might be powered entirely by the user's movements. [39]

Applications of nanomedicine include fluorescent biological labeling, targeted drug and gene delivery, pathogen detection, protein sensing, DNA structure analysis, tissue engineering, tumor identification, separation and purification of biological molecules and cells, MRI contrast enhancement, and phagokinetic studies. Long-term, nanomedicine aims to develop and manipulate nanoscale molecular machinery within cells. Precise control of these nanomachines can provide deeper insights into cellular processes and open the door to advanced medical interventions.

New technologies for disease detection and medication. The advantage of this research is the formation of a platform technology that will affect nanoscale imaging methodologies aimed to investigate molecular pathways in organic cells. [40,42]

REGULATORY AND ETHICAL CONSIDERATIONS

The use of nanorobots in medicine, especially for treating cancer, raises important ethical and regulatory questions. It's essential to prioritize patient safety, ensure that patients fully understand the treatment through informed consent, and carefully consider any potential long-term effects before these technologies are used in clinics. Regulatory bodies like the FDA and EMA are still working on detailed guidelines for nanomedicine, so following these emerging standards is crucial to guarantee that nanorobots are used safely and responsibly in healthcare.[43]

CLINICAL TRIALS AND CURRENT STATUS

Although much of the research on nanorobots is still at the preclinical or experimental level, several clinical studies have begun to explore their safety and effectiveness in humans. These trials are primarily focused on nanorobot-assisted drug delivery systems for targeted chemotherapy and precision medicine. Early findings suggest that nanorobots can improve the delivery of drugs directly to cancer cells while minimizing damage to healthy tissues, resulting in fewer side effects compared to conventional chemotherapy.[44]

LIMITATIONS AND CHALLENGES

Despite the tremendous potential of nanorobots, several challenges remain before they can be widely used in clinical settings. The human immune system may recognize and eliminate nanorobots before they reach their target, reducing their effectiveness. Precisely controlling their movement within the complex environment of the bloodstream, ensuring adequate energy for autonomous operation, and scaling up production for large-scale clinical use are additional significant hurdles that researchers must overcome.[45]

COMPARATIVE ADVANTAGE OVER CONVENTIONAL METHODS

Nanorobot-assisted chemotherapy offers a significant improvement over traditional cancer treatments by selectively targeting cancer cells while minimizing harm to healthy tissues. This precision reduces common side effects such as organ toxicity, hair loss, and suppression of the immune system. By concentrating the therapeutic effect on the tumor, nanorobots enable higher drug doses, better pharmacokinetic behavior, and improved overall patient outcomes. Including a table or diagram comparing conventional chemotherapy with nanorobot-assisted therapy can effectively illustrate these benefits.[46]

FUTURE PERSPECTIVES AND EMERGING TRENDS

The future of nanomedicine is poised to be transformative, with smart nanorobots capable of performing multiple functions, including disease detection, targeted drug delivery, and continuous patient monitoring. The integration of artificial intelligence could allow these nanorobots to make autonomous decisions, optimizing treatment in real time. Furthermore, hybrid nanorobots that combine organic and inorganic components may enhance both safety and functionality, paving the way for next-generation, personalized medical therapies that are more precise and effective than current approaches.[47]

SAFETY AND TOXICITY STUDIES

Toxicity remains a key concern in the use of nanorobots for medical therapies. Inorganic nanorobots have the potential to trigger immune responses or accumulate in organs, which may lead to adverse effects. In contrast, organic nanorobots are generally safer and more biocompatible. Strategies such as coating nanorobots with protective layers, using biodegradable materials, and precisely targeting tumor cells help minimize toxicity while enhancing therapeutic effectiveness. These approaches are critical for ensuring safe and efficient clinical application of nanorobot-based treatments.[48]

APPLICATIONS BEYOND CANCER

• Targeted chemotherapy

• Cancer diagnostics

• Gene therapy

• Photothermal & photodynamic therapy

• Real-time tumor imaging

CONCLUSION

Nanorobots are opening an exciting new chapter in cancer treatment. Their ability to move through the body at a microscopic level, find cancer cells with remarkable accuracy, and deliver treatment directly where it's needed gives them the potential to solve problems that traditional therapies often struggle with, such as harmful side effects and resistance to drugs. While many of these technologies are still in early development, steady progress in fields like materials science, bioengineering, and advanced imaging is bringing them closer to real-world medical use.

Even with their promise, important challenges remain. Questions about safety, how the body reacts to these tiny machines, how they can be produced on a large scale, and how they will be regulated all need to be addressed before nanorobots can become part of everyday cancer care. Still, the direction of current research is encouraging. With continued collaboration across scientific and medical fields, nanorobots could become powerful tools in personalized cancer treatment—making therapies more precise, more effective, and easier on patients. What once seemed futuristic may soon become a meaningful reality in the fight against cancer.

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