REVIEW ARTICLE

Nanorobots: The Tiny Heros Fighting Cancer

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Abstract

Introduction: Cancer is one of the most challenging diseases globally. Early cancer detection is pivotal for improving patient outcomes and survival rates; however, it remains a significant challenge owing to the asymptomatic nature of earlystage malignancies and the limitations of existing diagnostic tools. Traditional therapeutic strategies, including chemotherapy, radiation, and surgery. Nanorobots are emerging as a groundbreaking approach for cancer detection and treatment.

Objective: This review aims to provide a comprehensive overview of the design principles, working mechanism, biomedical applications of nanorobots in cancer diagnosis and treatment, highlighting their advantages, challenges and future prospects.

Methods: An extensive literature survey was conducted using databases such as PubMed, Scopus, and ScienceDirect. Studies published between 2000 and 2025 that focused on nanorobot fabrication, targeting mechanism, therapeutic delivery and imaging studies were critically reviewed and summarized.

Results: These nanoscale devices are designed to navigate biological environments with precision, enabling the identification of cancerous cells at the molecular level, targeted drug delivery, and real-time monitoring. Magnetic, chemical and biohybrid nanorobots have shown improved drug localization, reduced systemic toxicity, and enhanced therapeutic outcomes compared to traditional therapies. Despite these advantages, technical complexities, immune clearance and regulatory hurdles remain major barriers to clinical translation.

Conclusion: Nanorobots represent a transformative innovation in precision oncology integrating diagnostics and therapeutics into a single platform. On going regulatory frameworks will be crucial to bring nanorobot-based cancer therapy from concept to clinical reality.

Keywords: Nanorobots, Cancer therapy, Targeted drug delivery, Tumour microenvironment, Nanomedicine, precision oncology.

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Introduction

Cancer encompasses a wide range of conditions that can originate in almost any organ or tissue of the body. These days, Cancer is one of the most common causes for mortality.[1]

Chemotherapy, Immunotherapy, Phototherapy, and radio therapy have all found to be successful for cancer treatments. The methods which are using for treating cancer have a number of issues such as, Targeted drug delivery, biological barriers, intricate tumour micro environment (TME) and also lack of real time tracking have undermined their therapeutic efficacy. Furthermore, passive diffusion powered by blood circulation is the mainstay of conventional drug delivery methods for in vivo research, which severely restricts the drug's ability to penetrate into the tumour cells and along with that it limits the cellular internalization of the drug [2]. Nano technology has made it possible to develop materials with an astonishingly broad variety of complex properties. This rapidly expanding field holds great promise for number of sectors such as healthcare, construction, and electronics. Its progress has driven remarkable innovations in medical science, particularly in oncology. The emergence of nano oncology – a field focused on the use of nanotechnology in cancer treatment has revolutionized the drug delivery landscape. Nanoparticle-based drug carriers are capable of selectively targeting cancer cells while safeguarding healthy tissues. Owing to their nanoscale size, these particles can also traverse the body's physiological barriers with ease. Beyond targeted drug delivery, nanotechnology finds application in minimally invasive surgeries, biomedical imaging, biosensing, and various other medical interventions. Additionally, nanotechnology plays a vital role in the development of advanced diagnostic tools, with nanomedicine focusing on the diagnosis and treatment of diseases using these nanoscale innovation.[3] Nanorobots

are autonomous or semi-autonomous nanoscale devices designed for active targeting and therapeutic interventions.[1] Nanorobots equipped with self-propelling abilities, it can overcome the above- mentioned limitations in traditional therapies and nanorobots have the unique advantages in the field of tumour diagnosis and treatment. [2]. Because of their small size Nanorobots can directly get into contact with the cells and even penetrate into them, providing direct access to the cellular machinaries.[4] Conventional cancer therapies like chemotherapy, radiation, surgery and hormonal treatments have greatly improved patient outcomes but they have lot of drawbacks. According to research 99% of medicines delivered during chemotherapy are unable to reach the tumour cells, causing systemic toxicity and harmful side effects on healthy tissues. Chemotherapy usually faces low drug efficiency. Surgery and radiation therapies are useful for removing and destroying tumours, but they are not precise enough to completely eliminate the heterogenous cancer cells in difficult to reach places without endangering nearby healthy tissues. Hormonal therapy may induce resistance and effect patient quality of life adversely. These drawbacks show how urgently new focused and effective and minimally invasive treatment strategies are needed.[5] These problems can be solved by nanorobots, which are incredibly tiny programmable devices that function at the nanoscale. By precisely navigating biological surroundings and focusing on cancer cells, nanorobots can maximize therapeutic payloads and minimize off-target consequences. They may be able to penetrate physiological barriers like the blood-brain barrier, making it possible to treat malignancies that would otherwise be unreachable by traditional means. Additionally, multifunctional nanorobots can be designed to combine adaptive therapeutic responses that are sensitive to tumour microenvironments, real-time tumour monitoring, and targeted drug delivery. The problems that traditional medicines face, such as drug resistance, non-specific distribution, and restricted tumour accessibility, should be resolved by this multifunctional capability.[1,4] Nanorobotics in cancer diagnosis and treatment is still mostly in the conceptual or preclinical stage, despite these encouraging possibilities. There are still unanswered questions about biocompatibility, long-term safety, real-time control, effective propulsion in vivo, and scalable nanorobot manufacture. Their applicability to clinical practice is further limited by a lack of comprehensive clinical trials confirming their safety and effectiveness. The objective of this review is to compile recent developments in nanorobot design principles, operation, and biomedical applications while critically analyzing their benefits and drawbacks. By doing this, it hopes to direct future investigations to get over the current technical and legal obstacles, accelerating the clinical implementation of nanorobotic cancer treatments.[1,4]

Design principles of Nanorobots

Nanorobots are also called nanobots or micro/nanorobots (MNRs) are tiny devices these are usually made up of micro or nanoscale components and range in size from 0.1 to 10μm,[3]

these robots are capable of performing particular tasks like operations at the cellular level or molecular assembly and repair.[6] Their design is guided by several key principles that integrate nanotechnology, material science, bioengineering and robotics.

Core components and structure:

Shell

The exterior casing must be biocompatible, typically made from materials like silicon, carbon or diamond .Its design influences performance and safety with shapes ranging from spherical to irregular forms to optimize interaction with target tissues and minimize tissue damage.[4]

Power source

In order to operate, medical nanorobots require an energy source. This could be energy produced by the body's metabolism, a battery, or a hydrogen fuel cell. An important factor in determining the nanorobot's performance, stability, and safety is how the power source is incorporated into its design. The power supply may be integrated into the shell or affixed to the exterior as an external part. For the power source to operate at its best, its size and location must be taken into account.[4]

Playload

This is meant to perform specific functions that a nanorobot was created to carry out, including tissue repair, imaging, or targeted drug delivery. Medical nanorobots can have their payload integrated into their shell or affixed to their surface as an external component. Efficacy and safety standards as well as the intended use will determine the kind and quantity of payloads needed. A nanorobot intended for drug delivery, for example, might carry medications or therapeutic agents, whereas a nanorobot intended for imaging might carry contrast agents or imaging agents.[4]

Sensors (Detection Unit)

Nanorobots are often integrated with highly sensitive molecular or chemical sensors that provide the ability to detect disease-associated biomarkers and guide navigation. These sensors can recognize specific stimuli such as pH changes, oxygen gradients, glucose concentrations, or inflammatory cytokines, which frequently mark pathological environments like tumours or infected tissues. Molecular recognition elements, including aptamers, antibodies, and peptide ligands, are increasingly incorporated to achieve selective binding to target cells. Coupling biosensors with actuation systems allows the nanorobot to respond autonomously to environmental cues and enhances precision in diagnostic and therapeutic functions.[7]

Actuators (Effector Unit)

Actuators serve as the active components that execute therapeutic or mechanical tasks in response to sensor input or external control. Depending on the intended application, actuators may deliver localized physical effects—such as generating heat under laser or magnetic stimulation for tumour ablation—or exert mechanical forces to disrupt biofilms or penetrate cellular membranes. In drug-delivery systems, actuators can trigger controlled release of encapsulated agents upon exposure to specific stimuli (pH, enzymes, or temperature shifts). These capabilities make actuators essential for converting detection into meaningful therapeutic action.[8]

Communication system

Enabling nanorobots to communicate with each other and external devices through wireless signals, electromagnetic waves, or physical connections, facilitating coordinated actions and real-time data transmission.[4]

Materials of nanorobots

The biocompatibilities of materials were the main factor taken into account when designing nanorobots, which operate at nanoscale scales inside tumour tissues and cells. Since a microrobot's functionality is primarily dependent on the characteristics of its surface and materials, materials science or surface science presents a problem when creating a nanorobot to perform medical duties. The motion control of a nanorobot in a biological environment is significantly impacted by the molecular interactions between biological species and the nanorobot's surfaces. The majority of materials used to make nanorobots are biocompatible or biodegradable. When their functions are complete, these biodegradable compounds can dissolve or vanish.[4]

The materials should offer flexibility, deformability and the capacity to respond to physical or chemical stimuli like temperature, pH or enzymatic activity which are critical for targeted drug release and task adaptability.[4]

Propulsion of nanorobots

Nanorobots' power sources are creatively separated into two categories: endogenous dynamics and exogenous dynamics. Typically, exogenous dynamics comprise light-driven, magnetic, and ultrasonic propulsion, whereas endogenous dynamics are typically accomplished through chemical or biological reactions (Figure 1).

Working mechanism of nanorobots

The functional efficiency of nanorobots in cancer therapy relies on their ability to autonomously sense, navigate, and deliver therapeutic agents within the complex biological environment of the human body. A nanorobot's working mechanism integrates multiple subsystems-including control, sensing, locomotion and energy modules-that operates synergistically to achieve precise tumor targeting and localized drug release.

Initial activation and navigation

Micro/nanorobots provide significant benefits for high-precision, minimally invasive surgery because of their dimensions, which correlate with those of the tiny biological entities they must treat. Micro/nanorobots with nanoscale surgical components, powered by various energy sources, can access biological tissues for precise surgery. These tiny robots are capable of performing procedures down to the cellular level and navigating via the body's thinnest capillaries, unlike their larger robotic counterparts.[9] After entering into the body they activate through exposure to physiological conditions or external stimuli such as magnetic or optical fields. Once active, nanorobots begin exploring their environment, guided by physical or biochemical gradients (e.g., pH, temperature or oxygen concentration) that differentiate tumour tissue from healthy cells.[9]

Control unit

Acts as the command centre, coordination motion and function through decision making algorithm and motor control mechanisms. It processes sensory data, plans navigation paths, and adapts to dynamic biological environments, enabling precise maneuvering toward tumour sites.[4]

Sensing module

It is equipped with a variety of sensors-including temperature, pressure, chemical, and optical sensors -that help in detection of parameters and bio chemical signals in the tumour microenvironment(TME).These sensors allow the nanorobot to recognize specific cancer markers, monitor environmental changes, and provide real time feedback for adaptive responses.[10]

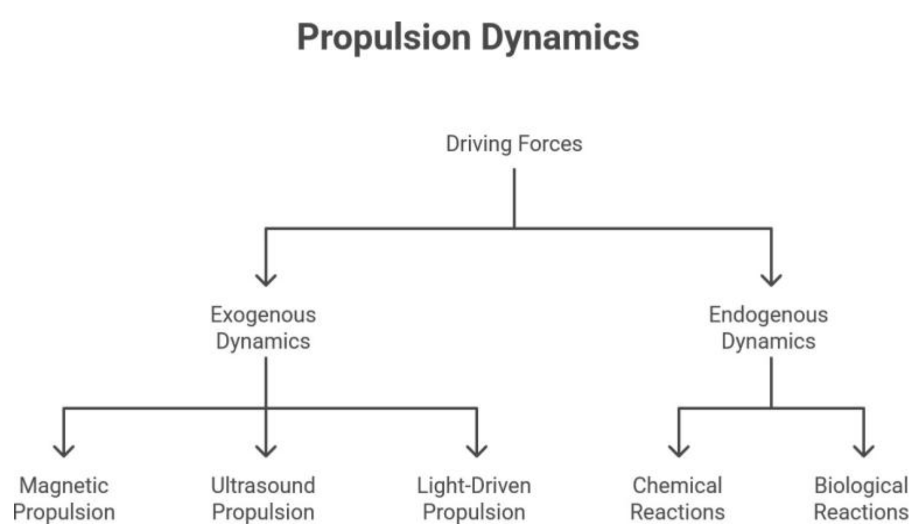

Figure 1: Schematic illustration of propulsion dynamics in nanorobots, depicting various mechanisms such as chemical, magnetic, acoustic, and light-driven motion for targeted navigation in biological environments

Locomotion

The primary obstacle to robot downsizing at the micro and nanoscales is locomotion. Brownian motion and the low Reynolds number environment present a significant obstacle to the machine's ability to move when its dimensions are reduced.

Therefore, a swimming strategy that functions under these low Reynolds number limits and a navigation approach to overcome the Brownian motion are necessary for the construction of an effective nano/microscale machine. To address the demanding powering and locomotion requirements, unique bioinspired design principles are needed because conventional power supply components and batteries are not feasible at these small dimensions. These small devices usually use either externally powered motors that primarily use magnetic and ultrasonic energies (and occasionally optical, thermal, and electrical energies) to generate their motion or chemically driven motors that transform locally provided fuels into force and movement.[9]

Energy sources

The micro/nanorobots get the engery from various sources such as exogenous and endogenous sources.[4] Exogenous sources are external energy sources such as light, magenetic field, optical field and endogenous sources are internal energy sources such as chemical reactions and biological dynamics.[4] These sources help in propulsion of nanorobot.

Final outcome

It involves performing targeted therapeutic function s like drug delivery or microsurgery with high precision and minimal collateral damage. By integrating signal recognition with decision making and motor control, nanorobots achieve effective localization, controlled therapeutic agent release, and safe interaction with biological tissues[4] (Figure 2).

Application Of Nanorobot In Cancer Therapy

Modern oncology has undergone a revolution because to the combination of nanotechnology and robotics, which has made nanorobots precise, intelligent machines that can identify, target, and cure cancerous cells at the molecular level. A significant improvement over conventional chemotherapy and radiation therapy, nanorobots can carry out site-specific actions while reducing systemic toxicity. Numerous therapeutic uses, such as targeted drug delivery, photothermal treatment, gene silencing, and immunological modulation, are made possible by their multifunctionality.

Targeted drug delivery

It is the most extensively studied application of nanorobots in oncology. Systemic circulation is the main component of the conventional drug delivery route, although it has drawbacks such low tissue permeability and local drug delivery capacity, which lead to ineffective drug delivery. These difficulties can be addressed, though, as microrobot technology advances. When medications are transported by microrobots, deep tissues can be precisely targeted for drug administration, increasing delivery efficiency and lowering dosages.[6]

Photothermal and Photodynamic therapy

Near-infrared (NIR) light is a highly spatiotemporal selective photothermal therapy that can be absorbed by nanorobots and transformed into local thermal heat to trigger the death process of cancer cells. In vitro tests revealed that

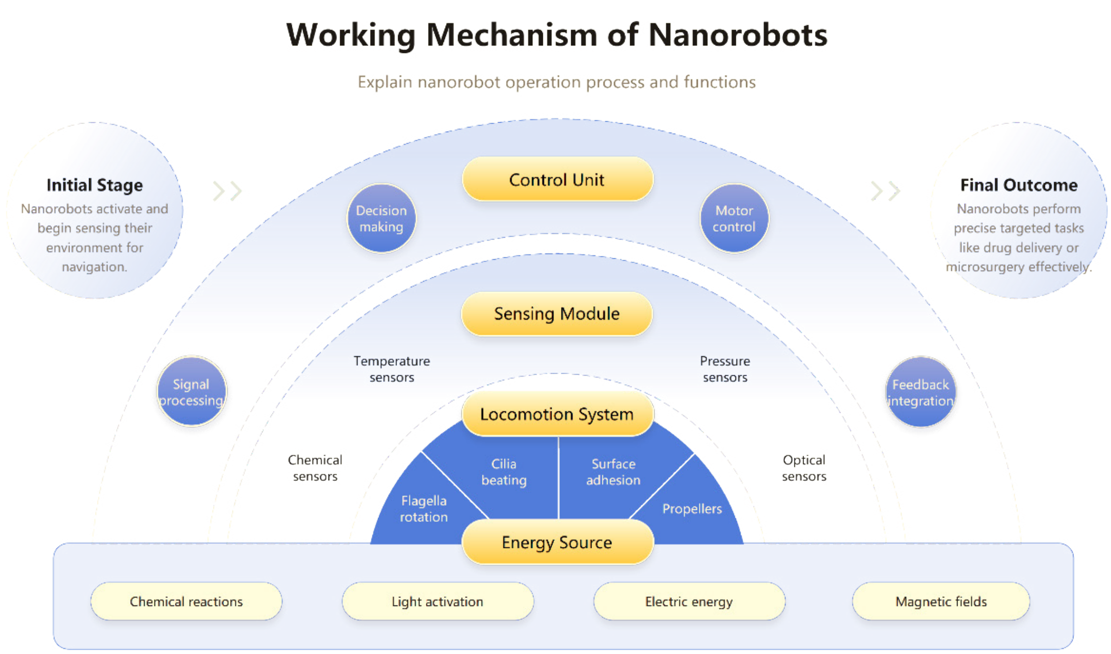

Figure 2: Schematic illustration of the operational mechanism of nanorobots, from activation and sensing to navigation, energy source utilization, and final therapeutic outcome

the microrobots have quick NIR-responsive photothermal properties. When the local temperature hit 50 °C, microrobots were set off to release the medications they were carrying. The successful application of targeted chemotherapy-photothermal therapy to lung cancer cells in vitro showed the viability of using nanorobotic targeted chemotherapy-photothermal therapy in cancer treatment. The microrobots inside the microchannel could target tumour cells.[6]

Gene silencing

Gene silencing via nanorobots involves delivering small interfering RNA (siRNA) or antisense oligonucleotides specifically to cancer cells to inhibit the expression of oncogenes responsible for tumor growth and metastasis. Nanorobots provide a protective vehicle that enhances the stability and intracellular delivery of these nucleic acids, shielding them from enzymatic degradation in the bloodstream and improving cellular uptake through targeted recognition of tumor markers.[10]

Immunomodulation

Nanorobots have shown promising potential in modulating the immune system to enhance anti-cancer responses. By delivering immunomodulatory agents directly into the tumor microenvironment, nanorobots can stimulate immune cell activation, overcome tumor-induced immunosuppression, and promote tumour cell recognition and destruction. Targeted delivery improves the efficacy of immunotherapy and reduces systemic side effects commonly associated with conventional treatments.[11] Advanced nanorobotic systems can also be engineered to release immune checkpoint inhibitors or cytokines in a controlled manner, facilitating personalized and adaptive immunotherapy strategies.[4]

Tumour Ablation

Nanorobots offer innovative approaches for tumour ablation through localized delivery of therapeutic modalities such as photothermal therapy, magnetic hyperthermia, or chemical cytotoxins. Through precise navigation and accumulation in tumour tissues, nanorobots minimize damage to surrounding healthy cells. Photothermal nanorobots convert light energy into heat, selectively killing cancer cells upon activation. Similarly, magnetically controlled nanorobots generate localized heat in response to alternating magnetic fields, leading to effective tumour eradication.[1] These approaches show high potential for minimally invasive surgeries and treatment of hard-to-reach tumours.

Cancer Theranostics

One of the most exciting features of nanorobots is their capability for theranostics, combining diagnostic and therapeutic functions within a single platform. Nanorobots can carry imaging agents to provide real-time tumour visualization while simultaneously delivering treatment. This dual capability enables early detection, monitoring of therapeutic response, and adaptive treatment adjustments. Integration of sensors allows detection of biomarkers and tumour microenvironment characteristics, enhancing precision medicine approaches. Multifunctional nanorobots thus streamline cancer management, offering personalized, timely, and effective interventions with minimal patient burden.[10,4]

Challenges And Future Directions

Although nanorobots show immense potential in cancer therapy, multiple challenges still need to be addressed:

Biocompatibility

Ensuring that nanorobots are compatible with the human body and do not elicit adverse immune responses is crucial.[4]

Controlled Activation

Developing mechanisms that allow nanorobots to release their therapeutic payloads exclusively in the presence of cancer cells is essential to prevent unintended effects.[4]

Scalability and Manufacturing

- Producing nanorobots on a scale sufficient for widespread clinical use, while maintaining precision and functionality, presents a significant challenge.[4]
- Ongoing research is focused on addressing these challenges, with studies exploring various nanocarriers and compounds for selective tumour targeting. The development of nanorobots continues to evolve, with the aim of improving the diagnosis and treatment of malignant tumours.

Conclusion

Nanorobots hold great promise as a breakthrough technology in cancer diagnosis and therapy, offering targeted precision, therapeutic efficiency, and reduced invasiveness compared to conventional modalities. Nanorobots herald a new era in cancer treatment by seamlessly integrating control, sensing, locomotion, and energy systems into compact, smart devices capable of precise navigation and selective therapeutic delivery. Their ability to interpret complex biological signals, adjust their behaviour accordingly, and execute targeted actions such as drug delivery, gene silencing, and tumour ablation highlights their transformative potential. By harnessing multiple energy sources and advanced locomotion strategies, nanorobots can overcome physiological barriers and achieve deep tumour penetration with minimal invasiveness. Furthermore, their multifunctional capabilities support combined therapeutic and diagnostic ("theranostic") roles, enabling real-time monitoring of treatment efficacy and personalized interventions. While substantial challenges remain, including optimizing control mechanisms, ensuring biosafety, and achieving clinical translation, continued research promises to refine these nanoscale systems further. Ultimately, nanorobots stand poised to revolutionize oncology by offering highly targeted, adaptive, and effective cancer therapies with fewer side effects, marking a pivotal shift toward precision medicine.

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