

NANOROBOTICS IN TARGETED DRUG DELIVERY SYSTEMS

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ABSTRACT

Nanorobotics is an innovative development to the current pharmacology and drug delivery scientific scenario of this century; because the nanobot can target diseased tissues more accurately. These nanoscale machines, which have been designed with concepts of nanotechnology, molecular biology, and biomedical engineering can navigate complex biological systems, detect pathological locations, and deliver therapeutic agents in a targeted and localized fashion. This review provides an extensive discussion of the design, classification, mechanisms, fabrication methods, and biomedical uses of nanorobots in targeted drug delivery. Special focus given to cancer treatment, cardiovascular, neurological and infectious diseases. Discussion on pharmacokinetics, biocompatibility, ethical issues and compliance with specificities of nanorobotics. Although major progress has been achieved, issues like high costs of production, toxicity, and limited clinical translation are still hurdles to wide usage. The presence of AI alongside smart biosensors and customized medicine strategies is noted in future forecasts to boost the efficacy of nanorobotics.

Keywords: Nanorobotics, Targeted drug delivery, Nanotechnology, Precision medicine, Drug targeting

INTRODUCTION

A great change has occurred in drug delivery systems within the last few decades as we use to see the traditional dosing systems, including tablets, capsules and injections, transformed into the modern-day and highly advanced targeted drug delivery systems. There are most of the times associated with the traditional drug delivery methods: Non-specific distribution of drugs in the whole body, poor bioavailability, unsteady plasma drug levels, and unwanted side effects in case of exposure to healthy tissues of the toxic therapeutic substances.¹ These limitations greatly decrease the efficacy and patient compliance in the therapeutic process, especially regarding chronic and life-threatening illnesses like cancer, neurological conditions, and cardiovascular illness. In order to address these issues, current pharmacological studies have emphasized on the establishment of targeted drug delivery systems (TDDS), whose objectives are to deliver drugs to areas of action in a selective way with the least exposure to the systemic system.² Targeted delivery has been shown to increase the therapeutic response and efficacy of drugs that increase the concentration of the drug at the diseased location, adverse effects and dosing frequency are minimized. Different strategies, including liposomes, nanoparticles, microspheres, and ligand-

receptor-mediated targeting are historically considered, yet they lack the precision, control, and versatility of functioning in complex biology.³ In this regard, nanorobotics has become one of the most revolutionary and multidisciplinary sciences that combine the concepts of nanotechnology, robotics, pharmacology and biotechnology, to design and convert intelligent nanoscale machines that can carry out particular biomedical functions. Nanorobots are microscopic/nanoscale machines that are generally in 1-1000 nanometers range and are designed to work at the molecular or cellular scale within the body of the human being. Such machines have the capability of penetrating into the fluids of biology, communicating with cells and tissues, and performing programmed tasks with high accuracy.⁴ Nanorobots will have advanced functionality components which include sensors, actuators, control units and power systems. Sensors can be used to monitor physiological parameters like pH, temperature, enzyme activity, and certain biomarkers that identify disease conditions. Actuators assist in motion and mechanical behavior like drug rejection or cellular communication.⁵ The behavior of nanorobots is controlled by control systems, which can be controlled by external signals or embedded algorithms, and can be powered by chemical processes, magnetic fields or biological energy sources.

Among other promising ways of nanorobotics to be used, one can mention target substance delivery where the nanorobot can be programmed to find diseased cells out of distinct molecular signatures and deliver specific treatment agents to the targeted location. Incidentally, when used in cancer therapy, the nanorobots would identify tumor-specific markers and deliver anticancer drugs specifically inside a tumor microenvironment and avoid doing harm to normal tissues.⁶ On the same note, nanorobots can invade the Blood brain barrier (BBB) that is a significant obstacle in the more traditional drug delivery treatments in neurological disease treatment and deliver drugs to the central nervous system. Nanorobotic systems seek to address a variety of traditional and even current state of the art drug delivery systems limitations.⁷ These are poor bioavailability, when a large fraction of drug to be administered does not get into systemic circulation; off-target toxicity, or the production of harmful side effects when the drug acts on non-diseased tissue; and rapid degradation of the drug, particularly in biologics like proteins and nucleic acids, which are vulnerable to enzymatic degradation. Nanorobotics has a high efficiency and intelligent approach to therapy with drugs by delivering drugs specifically to sites of interest, releasing the drugs into the body in a controlled manner and responding to physiological stimuli in real-time.⁷ Moreover, nanorobotics brings opportunities to the realm of individual medicine, where the therapy can be designed based on the genetic type of a specific person and nature of a disease. A combination of AI and biosensing endowed to nanorobots even more allows them to take independent decisions, track the progress of the treatment, and modify drug at the same time. Nanorobotics continues to be at its infancy, though its potential is enormous, with current studies on bringing about better biocompatibility, safety, scalability, and regulatory approval.⁸ Recent developments in nanotechnology and biomedical engineering also indicate that nanorobotics will become a key component in the future of the pharmacological field and targeted drug delivery systems.

HISTORY AND EVOLUTION OF NANOROBOTICS

Nanorobotics is inspired by the early thinking of visionary theorist Richard Feynman, who in 1959 gave his famous talk, *There's Plenty of Room at the Bottom*. During this pioneering address Feynman suggested that matter would be capable of manipulation and control in terms of atoms and molecules.⁹ Though the technology to make these ideas feasible was not available then, his vision would form a conceptual basis to the disciplines of nanotechnology as well as, later on, nanorobotics. He proposed the possible creation of miniature machines capable of precise work in biological systems, which has since been expanded to modern nanomedicine. Early Foundations (1980s): Nanotechnology Tool Development. In the 1980s, a major shift in the history of nanorobotics was the creation of new more sophisticated equipment that reflected scientists to visualise and control materials on the nanoscale.¹⁰ Two important inventions of this period were: STM is a microscope that can be used to observe atoms. Local scan depth of a surface, one pixel at a time: about 100nm. These tools enabled scientist to study single atoms and molecules and even handle them with a lot of accuracy. This breakthrough offered experimental support of the theoretical work by Feynman and new opportunities to nanoscale engineering.¹¹ Moreover, the discovery of nanomaterials including; fullerenes (C₁₂₀) and subsequently carbon nanotubes stimulated the research in nanotechnology. The materials demonstrated distinctive mechanical, electrical, and chemical characteristics suggesting them to be perfect candidates in creating nanoscale devices and building nanorobots. Concept Development (1990s): Development of Nanorobot Models. In the 1990s, the concept of nanorobots shifted out of theoretical conceptualization into conceptual design.¹⁰ Researchers and scientists started to develop models of nanoscale machines that can be used to perform certain biomedical functions. One of the principal contributors in this time was Robert A. Freitas Jr., who is the founder of nanomedicine. He also outlined specifications of medical nanorobots like: Respirocytes (artificial red blood cells) The microbivores (artificial immune cells) are also called microbivores.¹² These theoretical frameworks showed that nanorobots would be able to,

Pass through the blood. Identify pathogens or cell pathology. Introduce processing with accuracy of therapeutic functions. These designs though not realised physically during that time period enabled the creation of a scientific model to direct the research and development in the area in the future. Molecular Nanotechnology (2000s): DNA-Based Nanomachines. At the beginning of the 21st century, there was a wide breakthrough in the field of molecular nanotechnology, especially the creation of DNA-based nanomachines.¹³ Scientists started to use DNA as a genetic material as well as a structure and functional part in nanoscale devices. The advent of the technique of DNA origami allowed scientists to bend DNA into particular shapes and formations, and programmable nanodevices that could act in a controlled manner. These DNA nanorobots would be able to: Respond to certain molecular cues to open and close. Carry, liberate drug molecules. Recognize disease-specific biomarkers.¹⁴ The invention of DNA nanorobots that are able to target cancer cells and deliver drugs on them in a very precise controlled way was one of the big advancements during this period. It was the first step to practice the nanorobotics in the targeted drug delivery system. Modern Era (2010s06): Smart and AIA-Integrated Nanorobots. The last couple of years marked the next phase of nanorobotics development where AI consumption, biosensors, and smart materials are incorporated.¹⁵ The latter is based on the design of modern nanorobots as smart systems capable of autonomous decision-making and real-time feedback to physiological conditions. Major developments during this period are: Smart Nanorobots.¹⁶ Fitted with biosensors that helps to identify the pH, enzymes, and biomarkers. Able to react to environmental stimuli (stimuli-responsive systems). AI Integration. Use of machine learning to optimize drugs delivery. Live tracking and therapeutic response. Applications in Targeted Drug Delivery. Accuracy of administration of chemotherapeutic agents. Examples include: crossing biological barriers like BBB. Modulated and maintained release of drugs.¹⁷

TYPES OF NANOROBOTS

Nanorobots can be broadly classified based on their

structure, function, and biomedical application. Each type is specifically designed to perform targeted tasks within the human body, particularly in diagnosis, drug delivery, and therapeutic interventions. The following are the major types of nanorobots used or proposed in nanomedicine: Microbivores: Microbivores are artificial nanorobots designed to function as synthetic phagocytes, mimicking the action of natural immune cells such as macrophages and neutrophils.⁶ Structure and Design: Microbivores are typically composed of: Biocompatible materials such as diamondoid or polymeric substances, Surface receptors capable of recognizing bacterial or viral antigens, Internal digestion chambers for pathogen degradation.¹⁸ Mechanism of Action Pathogen Recognition: Microbivores detect pathogens through surface-bound receptors that recognize specific molecular patterns (e.g., antigens). Engulfment: Once identified, the pathogen is bound and internalized into the nanorobot.¹⁹ Digestion: The pathogen is enzymatically or mechanically broken down into harmless biomolecules. Release of By-products: The degraded components are released back into circulation without triggering inflammation. Respirocytes: Respirocytes are artificial red blood cell-like nanorobots designed to transport respiratory gases, including oxygen (O₂) and carbon dioxide (CO₂), throughout the body.²⁰ Structure and Design: Spherical nanodevices made of strong, biocompatible materials (e.g., diamondoid structures). High-pressure internal chambers for gas storage. Molecular pumps for controlled gas exchange. Mechanism of Action: Oxygen Loading: Respirocytes load oxygen in the lungs using molecular sorting mechanisms.²¹ Transport: They circulate through the bloodstream carrying oxygen at concentrations significantly higher than natural RBCs. Oxygen Delivery: Oxygen is released into tissues based on local oxygen demand. Carbon Dioxide Removal: CO₂ is collected and transported back to the lungs for elimination. Clottocytes: Clottocytes are specialized nanorobots designed to mimic and enhance the body's natural blood clotting mechanism. They play a crucial role in rapid hemostasis and prevention of blood loss.⁷ Structure and Design: Contain stored clotting factors or

fibrin-like materials, Equipped with sensors to detect vascular injury, Encapsulated delivery system for clot formation. Mechanism of Action: Injury Detection:Clottocytes identify damaged blood vessels through biochemical signals such as exposed collagen or clotting factors. Activation:Upon detection, they become activated and initiate clot formation. Clot Formation:Rapid release of clotting agents leads to the formation of a stable fibrin network. Stabilization:The clot is strengthened to prevent further bleeding.²²

COMPONENTS OF NANOROBOTS

Nanorobots are highly sophisticated nanoscale devices engineered to perform precise biomedical functions within the human body, and their design is based on the integration of multiple functional components that work in coordination to achieve targeted drug delivery and therapeutic action.²³ One of the most critical components of nanorobots is the sensor system, which enables the nanorobot to detect and respond to specific physiological and biochemical signals in the body. These sensors are capable of identifying variations in pH, temperature, enzyme activity, and the presence of disease-specific biomarkers such as tumor antigens or inflammatory mediators.²⁴ By continuously monitoring the internal environment, sensors guide nanorobots toward the target site and ensure accurate recognition of diseased tissues.

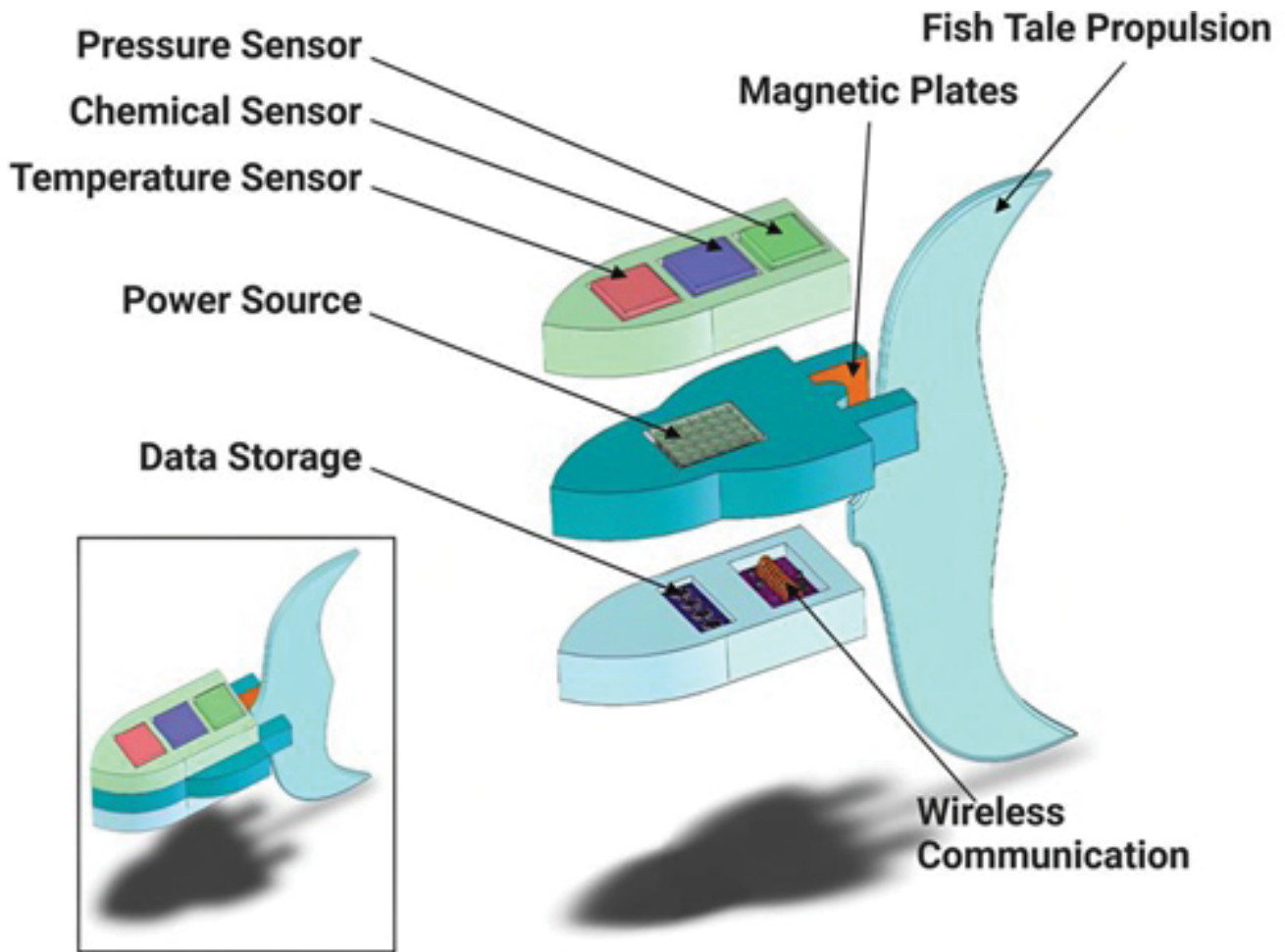


Figure 1: Structure of a Nanorobot

The actuator system is another important part and that provides movement and mechanical operation. Actuators enable nanorobots to move through biological fluids like blood, interstitial, and they do so in many cases by means of chemical reactions, magnetic fields, acoustic waves, or flagella-like propulsion systems. Besides locomotion, actuators are used to achieve drug release by inducing structural alterations in the nanorobot, which can be used to direct and suggestive delivery of therapeutic reagents.²⁵ Power source is an important aspect that offers energy needed to make nanorobots work. Nanorobots can be powered either by internal biochemical processes like glucose oxidation or by external sources, like magnetic fields, ultrasound, or light, depending on the design. Other more advanced nanorobots will be able to extract energy directly out of the biological environment and thus will be more efficient and long lasting in the body.²⁶ Accurate performance of nanorobots regarding the identification of target site, deactivation of drug release, and shutting down after achieving their purpose is provided through these systems. Another essential part is the drug storage and delivery module but this particular component is actually set to transport therapeutic agents that include drugs, genes, or proteins.²⁷ The module is designed to preserve the drug at once but not to be degraded in the circulation and it also releases controlled amount of the drug when they are at the target location. Specific stimuli, like the change of pH, temperature, enzyme presence or external factors, like light or magnetic fields, can trigger the drug release, thus providing the necessary accuracy and reducing the side effects. Moreover, advanced nanorobots also have communication systems to allow them to communicate with other nanorobots or external devices.²⁸ These systems can be either chemically signaled, electromagnetically wave guided or optically guided by sending information regarding the internal environment, the progress of treatment or the status of the systems to enable real time monitoring and control.²⁹ Lastly, the outer coating or surface layer which is biocompatible is vital in the safety and stability of the nanorobots in the biological system. Such a layer is usually composed of non-toxic and inert material like

polymers, lipids or biomimetic compounds that cause the immune system not to recognize the surface and mitigate the possibilities of being toxic. The surface functionalization with ligands or antibodies can also be used to promote the targeting capacity of nanorobots i.e. it allows targeted diseased cells to be bound.³⁰

MECHANISM OF TARGETED DRUG DELIVERY

The principle of targeted drug delivery with the nanorobots is much coordinated and sequential process that can provide maximum localization of the therapeutic agents at the diseased site with some minimum systemic exposure and adverse toxicity.³¹ The first step involves the introduction of nanorobots into the body via appropriate pathways like intravenous injection, where nanobots circulate throughout, and start a journey to the place of interest. Navigation, which is the initial crucial phase in this process, is a process through which nanorobots move within the biologic fluids like blood vessels and interstitial spaces. This motion may be facilitated by passive means such as blood circulation or active propulsion systems such as magnetic fields, chemical gradients (chemotaxis), acoustic waves or micro-motors. There is a tendency to use external guidance systems, especially magnetic navigation, to direct nanorobots with great accuracy towards the given places in the anatomy.³² When close to the target area, nanorobots target recognition which is highly specific is followed by using surface bound ligands, antibodies, or receptor molecules able to detect disease specific biomarkers. Such biomarkers can be tissues overexpressed on cancerous cells, and inflammatory mediators or unique molecular signatures related to pathological states. Selective binding of the ligands on the surface of nanorobots and the targeted cells receptors enhances their specificity in drug delivery as well as decreases off-target interactions.³³ After effective recognition, nanorobots are bound and internalized at the target site. Nanorobots tend to attach to the cell surface in most instances and can be internalized through several different mechanisms, including endocytosis, and could be transported into the cell interior to deliver therapeutic agents directly into the cell with ease.³⁴ This measure is of utmost importance in such diseases as cancer, where the

activities of intracellular drugs can be effectively used in the treatment. The second important step is controlled drug release, planned to take place only at the target site. Nanorobots have stimuli-sensitive systems that release drugs when there are certain environmental conditions.³⁵ These stimuli can be pH (e.g., acidic tumor microenvironment) variations, temperature changes, enzyme activity or external stimuli such as light, ultrasound or magnetic fields. This is a regulated release system to allow drug to be released into the diseased tissue in the most favorable concentrations to improve efficacious therapeutic effects with minimum systemic toxicity. Nanorobots can also be involved in therapeutic action enhancement (e.g. drug penetration into tissues, tumor vasculature disruption, or local physical or chemical equilibria in support of improved treatment, e.g. heat or reactive oxygen species) after release of drugs. The real time monitoring and feedback can be performed by some advanced nanorobots, which can adjust drug release in response to the target tissue.³⁶

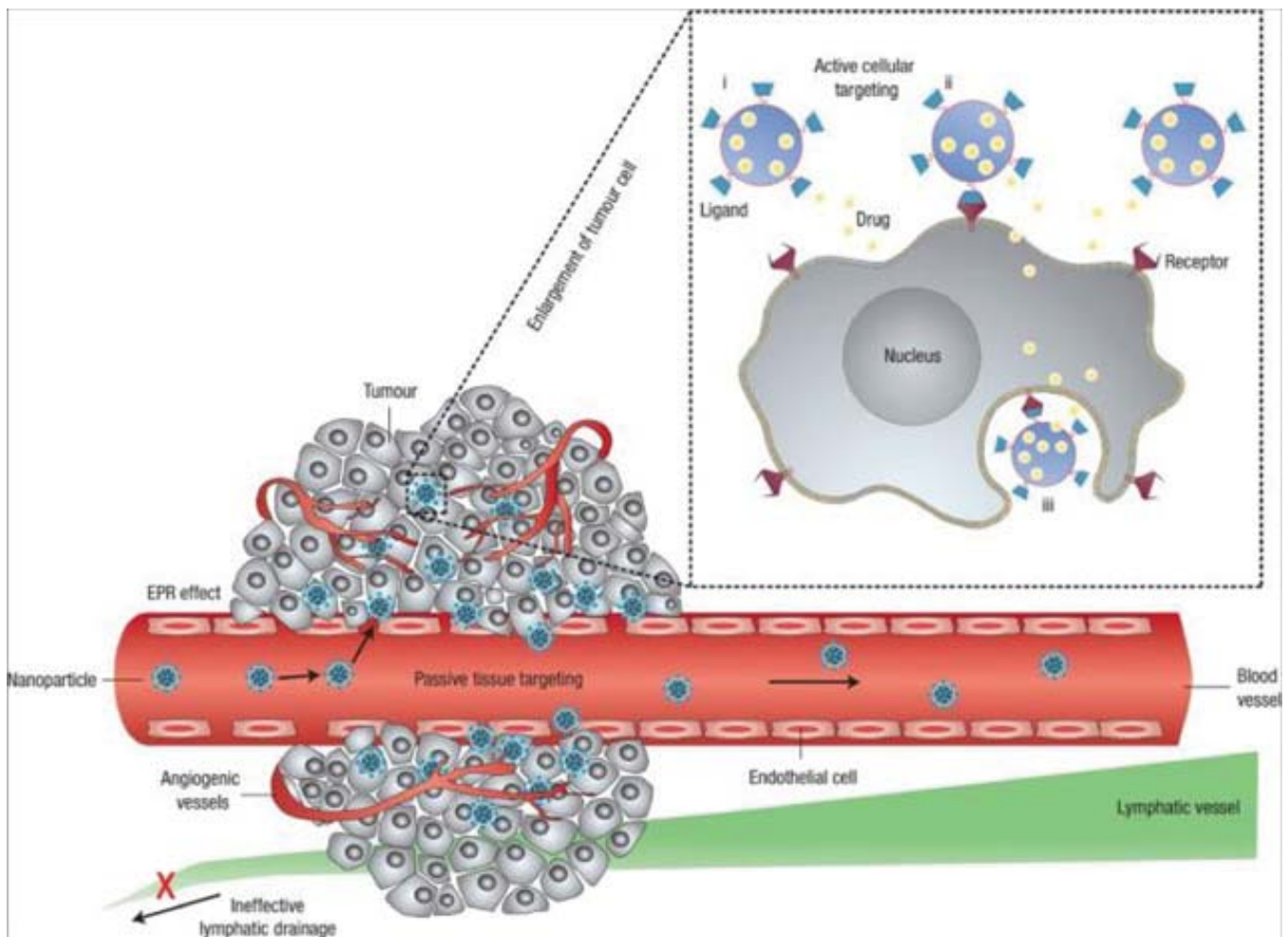


Figure 2: Mechanism of Targeted Drug Delivery by Nanorobots (Nanorobots navigate through the bloodstream, recognize specific disease biomarkers, and bind selectively to target cells. They then release therapeutic agents in a controlled manner at the diseased site, ensuring maximum efficacy with minimal side effects).

Finally, once their function is completed, nanorobots undergo clearance or degradation. They are designed to be biodegradable or small enough to be eliminated from the body through physiological pathways such as renal or hepatic excretion. This ensures minimal long-term accumulation and reduces the risk of toxicity.

Overall, the mechanism of targeted drug delivery by nanorobots integrates navigation, recognition, binding, controlled drug release, and elimination into a single, highly efficient system. This precise and intelligent approach represents a significant advancement over conventional drug delivery methods, offering improved therapeutic outcomes, reduced side effects, and the potential for personalized treatment strategies in modern medicine.

APPLICATIONS IN DRUG DELIVERY

Nanorobotics has become a very promising system in targeted drug delivery and can find extensive applications to various areas of treatment since it can apply drugs to specific locations in the body. Among the greatest is in cancer treatment where nanorobots are capable of selecting the tumor cells based on their biomarkers or receptors that are over expressed on the cancerous tissues.³⁷ These nanorobots are then localized at the tumor site where they release chemotherapeutic agents in a regulated fashion, often in response to the acidic tumor microenvironment or certain enzymes, and with deep decreases of systemic toxicity and damage to normal cells. This focused delivery method, besides improving the activity of anticancer therapies, has been useful in overcoming the problem of multidrug resistance, and low penetration of drug into solid tumors.³⁸ Nanorobots are also useful in the provision of thrombolytic agents to clots of blood promptly, which, in the case of myocardial infarction and stroke, is diagnosed as cardiovascular diseases. They also can be designed to eliminate atherosclerotic plaques, or provide drugs beneficial in stabilizing arterial walls to enhance overall cardiovascular health. They are more precise, and the presence of this feature minimizes the risk of hemorrhage and other adverse outcomes of traditional systemic therapy. Nanorobotics can also be used to deliver drugs to the treatment of neurological disease where the blocking of drugs is commonly caused

by BBB.³⁹ Nanorobots are capable of overcoming this obstacle, allowing them to target the brain with therapeutic capabilities, which is why they are very useful when it comes to the treatment of diseases including Alzheimer, Parkinson, brain tumours and epilepsy. Nanorobots enhance drug bioavailability and minimize peripheral side effects by delivering them to the central nervous system in a targeted manner. Nanorobots are highly specific to recognize and destroy pathogenic microorganisms like bacteria and viruses in the treatment of infectious diseases.⁴⁰ They have the capability of targeting infected tissues with the antimicrobial agent which reduces the amount of drug administered and further the emergence of antimicrobial resistance. Even more sophisticated nanorobots like microbivores may even make immune system mimicking behavior of destroying pathogens in the blood in direct, avoiding the production of inflammatory responses. Nanorobotics is used in gene therapy and precision medicine, with nanorobots capable of delivering genetic material (DNA, RNA or CRISPR components) into specific cells to treat genetic defects or regulate gene level.⁴¹ This brings in possibilities to treat genetic disorders and to work out individual treatment strategies on the basis of genetic profile. Moreover, nanorobots can be employed in diabetes treatment whereby the robots can be able to check the glucose level in real time and inject insulin on the patient to ensure that the glycemic control of a patient is maintained at the optimum level.⁴² They are also used in the delivery of anti-inflammatory and immunomodulatory drugs with specific effects to particular local regions, especially in the spectrum of disorders such as rheumatoid arthritis and autoimmune disorders. Nanorobots are capable of identifying inflamed tissues and targeting them with drugs so the systemic exposure is minimized and increases the therapeutic effects. They also have a potential in wound healing and in tissue regeneration wherein they can be used to provide growth factors, cytokines or even stem cell based therapies to stimulate faster wound healing.⁴³ In general, nanorobotics application in drug delivery can be considered as a paradigm shift of traditional treatment to the highly specific, efficient and patient

specific treatment modalities. Nanorobots could introduce a bright future into the evolution of pharmacological therapies, as they allow treatment of disease-affected tissues on a local scale, controlled release of active agents, and responsive action at the same time promoting minimal adverse reactions, thereby bringing significant enhancement of a profound therapeutic potential to the pharmacological range of therapeutic responses.⁴⁴

LIMITATIONS OF NANOROBOTICS IN DRUG DELIVERY

Nanorobotics have a tremendous potential in targeted delivery of drugs, yet there are a number of critical barriers and limitations to their common usage in clinical practice. The other significant drawback is biocompatibility and toxicity. Despite the biocompatibility of materials used to make nanorobots, the chance of unintended immune reaction, inflammatory reaction, or chronic intoxication with the increase in concentration in the body still remains. The dynamics between nanorobots and biology are very complicated and the insufficient knowledge of their mechanisms at the molecular level makes their safety, particularly long-term use, raise safety concerns. It is also a great challenge considering the lack of control and navigation of nanorobots on a specific body part of a human body. Biological systems are very dynamic and complex with a variance in blood flow rates, immune defense systems and physiological obstacles. It is still technically challenging to ensure that nanorobots arrive at the necessary location without delay and loss of their functionality. Various magnetic fields used as external guidance system do not necessarily give recurrent precision on deep tissues. A biological barrier is another limiting factor that can inhibit the ability of nanorobots to move and work, which includes BBB, cell membranes, and enzymatic degradation systems. Even though there are designs that seek to avoid these obstacles, efficient penetration that is safe has been an issue. Limitations on power supply and energy are also a constraint. To operate, the nanorobots need a stable source of energy to operate their tasks (movement, senses, and release of drugs). Nevertheless, it is a challenge to make power

systems at the nano level sustainable and safe. Their sustained use may be constrained by their reliance on the external energy, such as an external magnetic field or ultrasound. Also, drug loading capacity and controlled release poses a problem. Nanorobots are very small and hence there is little space to store therapeutic agent, this is likely to limit the amount of dosage that can be administered. Another technical challenge is to ensure strict, accurate and full drug release without pre-emergence leakage. There is also the risk of a malfunction or unplanned action. Lapse in the control mechanism, targeting system or release system may result in inefficient treatment or even threat to normal tissues. As nanorobots are run on a microscopic scale, real-time monitoring and correction of such errors is challenging. The use of nanorobotics is further complicated by ethical concerns. Issues concerning privacy, monitoring over a long period and abuse of nanoscale devices inside the human body have to be resolved. Public acceptance and ethical approval are crucial for the successful implementation of such advanced technologies.

FUTURE PERSPECTIVES OF NANOROBOTICS IN DRUG DELIVERY

Nanorobotics has a lot of potential in the future in targeted drug therapy, which will become a woman game changer in the field of pharmacology and personalized medicine in light of the continued development in the field of nanotechnology, biotechnology, and computations sciences. The introduction of AI and machine learning in nanorobotics is one of the most important future strategies. Nanorobots powered by AI will be able to make on-the-fly choices agnostic to physiological states and optimize the pattern of drug delivery and adapt to dynamic biology. This will improve accuracy, quality of therapy, and limit the chances of adverse effects. Another area of notes is the development of biodegradable and biocompatible nanorobots. The next generation nanorobots will be built employing hi-tech bio materials that can be safely broken down by the body to harmless toxins upon accomplishing the assigned task, thus reducing the threat of toxicity and long-term toxic waste buildup. This will greatly enhance safety profile and will

be easier to get regulatory approval to use clinically. Moreover, the idea of swarm nanorobotics is gaining popularity, in which several nanorobots collaborate as a coordinated system to do a complex task. These swarms are capable of making drug transportation and increasing targeting accuracy and have redundancy due to the failure of some nanorobots. These systems are analogous to the action of natural biological mechanisms and may have a specific application in the treatment of extensive or complicated disease areas. Nanorobots are also likely to be improved in being able to cross biological barriers including BBB in future, which would allow them to effectively treat an array of disorders affecting the central nervous system. Surface engineering and ligand functionalization innovations will also enhance specificity of such targeting and cellular uptake. The next scientifically thrilling prox is the combination of diagnostic and therapeutic capabilities (theranostics) in the same nanorobot. These systems will be in a position to detect disease at an early stage, provide treatment and at the same time monitor therapeutic response. This mechanism of real-time feedback will enable the clinicians to adjust the treatment plans in time, which will result in improved patient outcomes. Besides, improved nanofabrication methods like 3D nanoscale printing, DNA origami and molecular self-assembly will allow precise assembly of complex nanorobotic structures and enhance functionality and scalability. This will assist it also in curbing the costs of production and making the technology more affordable. Clinically, the future of nanorobotics in the future is set to advance in moving nanorobotics beyond an experimental phase to human clinical trials and clinical applications. Under better safety performance metrics, standard regulatory guidelines and interdisciplinary cooperation, nanorobots will probably be a common aspect of medicine in the next few decades.

CONCLUSION

Nanorobotics is also one of the innovative progress in the sphere of targeted drug delivery which is highly precise, efficient and intelligent method of therapeutic intervention. Through a combination of the concepts of nanotechnology, pharmacology, biotechnology, and

robotics, nanorobots can potentially address most of the drawbacks of the traditional and even modern drug delivery systems. Their capability to traverse complicated biological systems, identify disease-specific targets, and release drugs in a targeted and controlled way will greatly augment therapeutic performance and reduce systemic toxicity and adverse effects. This review has involved a number of facets of nanorobotics, such as their types, structural components, mechanism of action and different uses in diverse fields like cancer therapy cardiovascular diseases, neurological diseases and infectious diseases. These applications demonstrate the potential versatility and transformatory nature of nanorobots in the medical field. Also, the limitation issues [high cost, safety, technical, and regulatory barriers] are discussed, which highlights the necessity of further research and thorough consideration prior to the mass application in clinical practice. Nanorobotics has a promising future despite these challenges. Further improvements in the functionality, safety, and clinical applicability of nanorobotic systems should be possible through the use of advances in AI and smart materials, nanofabrication methods, and personalized medicine. It is important that the evolution of biodegradable, biocompatible and versatile nanorobots, and more effective regulatory frameworks will all be essential to make this technology available in laboratory research translate to the practical world of medical practice. To sum up, nanorobotics can help transform drug delivery, in addition, it can restructure the pharmacotherapy frame, providing a more accurate, personalized and at minimal invasiveness. Nanorobots will probably become an inseparable part of the next-generation health care design as they will help to make the processes of medical care more efficient and the work of medical science more advanced.

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