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Engineering Nanobots for Targeted Drug Delivery

Bwanbale Geoffrey David

Faculty of Pharmacy Kampala International University Uganda

ABSTRACT

The advent of nanotechnology has revolutionized targeted drug delivery through the development of nanobots, autonomous nanoscale devices engineered to navigate biological environments and deliver therapeutics with spatial and temporal precision. These nanobots leverage advanced propulsion mechanisms, including magnetic fields, enzymatic reactions, and temperature gradients, to overcome pharmacokinetic barriers and reach difficult-to-access disease sites such as tumors. Modular in design, nanobots often incorporate biosensors, pH-responsive gates, and biocompatible shells for controlled release and targeting. This paper provides an interdisciplinary overview of nanobot architecture, from historical foundations in nanomedicine to the latest advances in materials, navigation systems, and targeting strategies. Key mechanisms of drug release, such as ligand-receptor binding and stimulus-responsive actuation, are discussed in depth, along with the safety, stability, and efficacy of nanobot-mediated drug delivery. The study also evaluates challenges, including scale constraints, propulsion efficiency, and regulatory hurdles, and proposes future directions for clinical integration. With demonstrated potential in cancer treatment and other complex diseases, nanobots represent a transformative frontier in personalized medicine.

Keywords: Nanobots, Targeted Drug Delivery, Nanomedicine, Magnetic Propulsion, pH-Responsive Release, Biocompatible Nanocarriers, Tumor Targeting.

INTRODUCTION

Principal investigators in AI and Robotics are developing highly functional nanoscale robotic vehicles, or nanobots, that could transform therapeutic drug delivery. The bio-nano-micro-terra-meter regime is suited for creating "code" that incorporates modular components (like nanoscale biosensors) into a digital programming language for bio-manufacturing. These bio-nano-bots require a navigation system to determine their position, speed, and motion in relation to their environment. They utilize stochastic strategies such as Brownian random walks or muscle contractions to propel themselves, generating a four-byte space-time hydrocarbon actuation "code." With the implementation of self-propelling aquatic molecular refrigerators and nanocompressors, targeted drug delivery can be programmed and executed autonomously. These magnetic nanorobots, which navigate through biological fluids and improve pharmacokinetics, represent a promising strategy for cancer therapy. A specific multi-component magnetic nanobot is designed using magnetic nanoparticles, antibodies, and carbon nanotubes loaded with an anticancer drug. These nanobots can attain high velocities in complex biological fluids and release drugs directly into the intracellular lysosomal compartment of cancer cells. They have shown to reduce tumor spheroids more effectively than free drugs. Designing miniaturized robots within a few micrometers offers significant potential for biomedical applications, particularly in drug delivery. Miniature robotic systems offer advantages over conventional therapies, addressing pharmacokinetic limitations of existing delivery systems that are passive and lack navigation capabilities. Desired traits for nanocarriers include self-propelling force, navigational functions, precise targeting, and effective tissue penetration. Micro/nanomotors that efficiently tow cargo and penetrate tissues make them ideal for targeted therapeutic delivery [1, 2].

Historical Background of Nanotechnology

Nanotechnology as a building block for nanomedicine, a natural application, has been researched since 1999 and the term itself was coined in 1990. It refers to the application of science and technology at the nanometer scale, such as the engineer of nanoparticles with diameters smaller than 100 nm, which is kind

of a radical engineering approach to achieve material properties not accessible by conventional means. Recently, nanotechnology has become a popular term representing the main efforts of the current science and technology. Though a popular word, its definition is not strongly fixed. Recently a broad definition is purposed that nanotechnology usually means research at the scale of 100 nm or less. Beyond strictly scientific quantities, simply nanotechnology means technology directed towards all scientific and technological pursuit at acceptably accurate length scales. Successfully, some things seem to be known from 'the small world'. Formal definitions of nanotechnology and nanometer and lists of nano-sized things are available. The questions of whether a nanoparticle is global and what of the various nano-sized things that are not of interest appear to be more difficult. Understanding and manipulating the behavior of objects at the nano-scale is popular. One of the important areas of nanotechnology is 'nanomedicine,' which means the science and technology for highly specific medical intervention at the molecular scale for diagnosis, prevention, and treatment of diseases. Nanotechnology and specifically the Nanoparticles are important elements in novel drug delivery systems called Nanomedicine. From their inception around 1980, with the development of first polymer conjugated agents for cancer therapy, this development of nanoparticles had brought a revolutionary change in the field of drug delivery systems. Generally, there are currently four categories of NP-based DDS, and decades of extensive studies on them have focused on the evaluation of these carriers' feasibility to act as new DDS. However, in drug delivery, nano is still not. In fact, nanodrugs and nanomedicine do not mean hard Capsules assemblies but rather a more sophisticated and scientific solid-state drug delivery system or 'engineering' nanobots. On a different note, Cancer is one of the most challenging diseases today, which accounts for almost 25% of total deaths worldwide, ranks above heart diseases as the No. 1 killer globally, and is termed by WHO as one of the top 5 threats to humanity in the 21st century. Brain cancer such as glioblastoma is one of the most difficult malignancies to detect and treat mainly because of the difficulty in getting imaging and therapeutic agents across the blood-brain barrier and into the brain [3, 4].

Principles of Nanobot Design

The integration of miniaturized robotics and nanotechnology holds great potential in the biomedical field, especially in targeted drug delivery. Designing robots just a few micrometers in size could enhance conventional therapies. Current anticancer drug delivery systems have pharmacokinetic restrictions and are limited by their passive nature and lack of propulsion. These systems struggle with prolonged circulation, targeting, localized delivery, and tissue penetration, issues exacerbated when anticancer agents are used with liposomes. Even with surface modifications for improved targeting, nanocarriers cannot effectively navigate to their targets, necessitating an external motion source for optimal drug delivery. To combat cancer, targeted nanobots are created using a streamlined one-pot process featuring pH-responsive release and magnetic ejection for precise drug delivery. These nanobots include a magnetically-driven motor, a mesoporous silica shell for doxorubicin storage, and selective targeting molecules that inhibit drug release under normal conditions. The nanobot operates autonomously, aiding deep tissue penetration through a combination of magneto- and pH-responsive mechanisms. This innovative design meets crucial requirements for navigation, targeting, and drug delivery, potentially revolutionizing targeted therapeutic delivery. A novel propulsion system enables tumor-targeted navigation via external magnetic direction and pH-triggered drug release, demonstrating effective doxorubicin internalization and cancer cell growth inhibition while remaining biocompatible and non-toxic to healthy cells [5, 6].

Types of Nanobots

There are a variety of nanobots designed for specific functions with capabilities varying from propulsion mechanisms, target specificity, and distribution pattern. A diphtheria toxin nanobot smaller than a virus hijacked the cellular endosomal-lysosomal system by exploiting RNase activity to induce protein degradation and promote point single-nucleotide change to silence gene expression. A two-dimensional hairpin assembly sequence of six to forty-nine bases showed a strong target resolution and turn-on response that could differentiate single base mismatch. Some smart guest-host based drug delivery platforms utilized physical/chemical interactions for recognition and detection processes. However, pH-responsive nanocarriers lacking biological inhibition, toxicity with cargo leakage upon aggregation in the biological environment are ineffective in precisely controlling drug delivery. Wavy belt-shaped Janus-Fe_3O_4/Silica/Gold autonomous micromotors were propelled by triggering a temperature difference producing a continuous convective flow transferring the heat to the surrounding medium. The micromotors retained 18-37% temperature increase during swim, were magnetic-field retrievable and either circulate within HCT116 cells reducing spheroids or inhibited cell growth. Cationic magnetic

nanocomposites were synthesized through polymerization of cationic monomers on the surface of super paramagnetic iron oxide nanocrystals and showed size dependent strong magnetic responses. Silica crosslinking improved the chemical stability at high temperature and diluted acid, biocompatibility, and resulted in shape evolution from spheres to ovals, dumbbell, and yolk-shell particles [7, 8].

Mechanisms of Drug Delivery

The performance of drug delivery nanovectors is evaluated based on four aspects: safety, efficacy, stability, and targeting capability. Intuitively, the safety of drug delivery nanovectors relates to their inherent biocompatibility, including toxicity and biodistribution. Various natural nanoparticles (NPs) with high biocompatibility are described to minimize toxicity. The efficacy of drug delivery nanovectors mainly refers to their drug loading and release capability to provide the right drugs at the targeted sites within the effective concentration and therapeutic period. Delivery failure can significantly limit the efficacy of drugs, especially for macromolecular drugs. To enhance the efficacy of delivery nanovectors, different strategies are discussed, including 4D printing techniques to enhance stability, covalent bonding, and polymer coating. The capacity for establishing a suitable nanocarrier platform is also discussed. The targeting capability of drug delivery nanovectors is one of the most stimulating areas in nanomedicines and drug delivery, mainly falling into passive targeting and active targeting mechanisms. Passive targeting strategies are achieved by physical effects, while the targeting capability of active-based strategies relies on the interaction of ligands with corresponding receptors on target sites. Upon intravenous injection, drug carriers encounter a series of biological barriers, leading to the invasion of the extravascular space surrounding blood vessels and subsequent cellular uptake. Along with these events, drug carriers are anticipated to release their drug cargoes at the targeted sites. For successful biological intervention, it is crucial that the drug motivates, migrates, and transforms at the targeted sites within the time frame needed. Furthermore, the drugs need to access the targeted compartment for exact therapeutic effects. Nevertheless, the dynamics of complex systems in vivo differ significantly from the in vitro environment. The understanding of the mechanisms of drug release, drug migration, and cellular uptake remains quite limited, making the prediction of drug release at targeted sites enigmatic and strenuous. Hence, to select a viable drug delivery strategy, credible understanding should be established on how to achieve the desired spatiotemporal conditions through an optimized design of drugs, drug carriers, and their assembly via soft and/or smart structures [9, 10].

Targeting Mechanisms

Different kinds of targeting mechanisms have been employed for targeted delivery of drugs using nanobots. Drug nanocarriers can evade the biological barriers present in the body and reach their target site by employing these strategies. Furthermore, after reaching the target site, these nanobots can also be triggered by the mechanism which helps them to release their drug payloads only at the desired site. Active targeting strategy is a strategy that can be used to enhance the tissue-selective accumulation of nanocarriers. Passive targeting is a simple approach that can enhance drug delivery to the diseased site by simply having a large tumor burden that can block the circulation of the nanocarriers biological barrier system. However, passive targeting does not guarantee delivery to the specific disease site. Therefore, the specific targeting of a drug-delivering nanocarrier is considered highly desirable. The efficacy of cancer chemotherapy regimens can be improved by the use of specific peptide ligands that have high binding affinity and specificity toward cancer cells. Targeting moieties have been widely employed to tailor the surface properties of drug loaded nanocarriers to achieve enhanced tumor targeting. The surface of drug-loaded nanoparticles can be tuned with a specific peptide, which has been used for targeted delivery of nanomedicine. Further, these surface changes can also be coupled with the drug delivery of nanoparticles. Self-propelling magnetic nanobots with light/catalytic/magnetic functionality have been designed, which enable deep penetration into the tumor by addressing the critical issue of intrinsic-guided navigation in the tumor microenvironment without external eld guidance. Moreover, due to the acidic tumor microenvironment and the photothermal effect by the inward switchable pH/temperature-responsive gate, the nanobots can provide personalized therapy with an on-demand drug release. This delegation assumes particular importance in the intelligent design of high performance multifunctional nanocarriers to achieve accurate, time-controlled and spatio-resolved delivery of therapeutic agents. Localized stimulation by infrared light prompts the nanobots to release cytotoxic agents only in the vicinity of the tumor. More specifically, mechanochemical or physicochemical nanoscale switching domains reveal the intricate 'on-off' response mechanisms of nanocarriers to stimuli [11, 12].

Materials Used in Nanobot Fabrication

Robotics auisition and nanotechnology has made tremendous advancement and is hence being cross utilized in fields such as drug delivery, tissue engineering and analyte analysis. Lagging behind are the active and versatile micro/nano robots. Design of handle, actuators and power source of such robots were plausible but lacking materials properties in small scale limited their broad application. Based on the natural self-targeting ability of salmon DNA and the acid-induced dissociation property of Fe3O4@SiO2, the developed nanobots were able to differentiate malignant cells from normal. The biocompatibility and biodegradability of DNA nanobots were theoretically and experimentally established, establishing a promising method for tumor-targeted drug delivery. Mathematical modeling of DNA nanobots was conducted, revealing the impact of different parameters on the tracking efficiency and the best operation parameters. To realize the automated, controlled and effective tracking of tumor-targeted DNA nanobots, an optimal dual magnetic field was designed, and the tracking efficiency of it was demonstrated to be around 4 times that of the single magnetic field. The study opens up new avenues for the application of a DNA nanobot in drug delivery and for the development of an integrated micro/nano robot systems in biomedical applications. To integrate controllable transporting, targeted delivery, and imaging functions in one nanosystem, a novel multifaceted starch/AuNP @CF3-Ig G antibody structured carrier was fabricated for capturing, imaging and monitoring EGFR targeted drug delivery of PASS-MSN-NIR797 SSD. The EA-SS-NIR797 drug had a clearly time-dependent releases manner with 686 times of DOX increase after 3 h free drug release, proving the feasibility of design and packaging of the nanocarrier. The engineered system is expected to have a promising potential in multifaceted drug delivery to better treat diseases at raised levels [13, 14].

Nanobot Navigation Techniques

Nanobots are engineered devices designed to navigate the body and deliver therapeutics precisely to disease sites. Their travel distances depend on various propulsion modes and guiding techniques that extend beyond traditional Brownian diffusion. This includes self-propulsion through enzymatic or chemical reactions on their surfaces, remote actuation via magnetic fields, ultrasound, and optical traps, as well as diffusion-driven propulsion. The application of these techniques is discussed in fluids like blood and tissues. Although promising, nanobots face challenges in practical clinical use, particularly in complex biological environments. New methods for actuation and navigation are needed, taking into account the scale of nanobots and the characteristics of biological fluids. Current drug delivery methods typically involve using bioconjugated polymers or lipids to guide drugs passively through blood flow into diseased areas. However, this approach struggles with solid tumors, which complicates anticancer treatment efficacy. Additionally, chemical modifications for drug conjugation can limit the types of medications that nanobots can deliver effectively. On the other hand, nanobots are highly adaptable and can be designed to load and deliver various drugs. Enhanced navigation resulting from chemotactic stimuli allows for improved delivery to solid tumors, the primary cause of cancer mortality. Thus, nanobots have significant potential for cancer diagnosis and treatment, capable of entering blood circulation similarly to blood cells and specifically targeting solid tumors to inhibit their growth [15, 16].

Challenges in Nanobot Development

Engineering drug delivery nanobots faces challenges due to size and propulsion limitations. Medical microrobots show promise but are not suitable for FDA approval with sizes between 1-3-20 μm. Biological applications target from 20 μm at the macroscale to a few nm at the molecular scale. Larger microrobots can explore various propulsion strategies, but options decrease with size due to fluid mechanics and surface interactions. Nanobots must resist Brownian motion, complicating designs that prevent particle accumulation. For 10-30 nm dimensions, propulsion mechanisms can utilize diffusion of reactive particles and surface interactions. Special design considerations ensure safety and compliance with regulations from authorities such as the European Food Safety Authority. Proposed strategies for reliability and safety include assembling with silica rods and using bio-compatible coatings like polyethylene glycolylation and surface-modified silica. Verification strategies involve biocompatible materials, toxicity tests, and in vivo imaging. Current biomedical nanobots aid in food protection, drug delivery, and bioimaging of tumors and viruses. Miniaturized nanobots hold promise for efficient drug delivery, with designs enabling specific targeting and effective release through methods like hydrogel disintegration or pH-induced inflation. They navigate by tumbling and swimming, but developing a cost-effective and user-friendly control system with both high-level and low-level motion controls remains a challenge [17, 18].

Applications in Medicine

Nanorobots with both motility and targeting abilities were developed for biomedical applications in drug delivery. By employing a combined bottom-up and top-down approach, a versatile drug carrier system has been developed by assembling several nanocomposite parts on a heterogeneous silicon wafer. The resulting nanorobots are composed of self-propelling MgO, hollow silica nanoparticles, and magnetic sapphire nanoparticles. In vitro experiments demonstrate that the nanorobots can autonomously transport drug-laden silica microparticles toward the tumor cells and effectively deliver them. Fluorescent signals from the doxorubicin drug reveal a more than two-fold increase in the uptake of the nanorobots with drugs in the target tumors, which, in combination with an external rotating magnetic field, show great promise for targeted drug delivery in cancer therapy. Packing motility and functionalities into a single nanomotor is an attractive strategy to engineer more efficient drug delivery systems. After being well biofunctionalized, the nanodroplet-carrying dual-functional anisotropic nanomotors are able to provide pH-responsive propulsion and tumor microenvironment-targeting accumulation. Upon exposure to acidic microenvironment, the trigger dissolution of layer-structured nanomotors enables continuous propelling motion and enhanced cytotoxic intracellular drug delivery. This work opens avenues for the design of multifunctional self-propelled nanomotors for biomedical applications in the future [19, 20].

Ethical Considerations

Desktop applications of nanomedicine give rise to ethical considerations. The term ethical issues will be taken to mean practical ethical issues stemming from the use of nanotechnology in human medicine. Only currently available desktop applications will be considered. Attempts will also be made to broaden the discussion to include possible impacts of medical nanotechnology on other domains. Recent advances in nanomedicine, nanostructures, and engineered nanosystems to actively seek and identify targets at the cellular and molecular levels could provide a promising basis for their future use. Would prefer to consider making a distinction between drug delivery systems that could be assembled in a desktop fashion and those that would require a facility such as an automated cell factory or lab? The first class of systems would include DNA nanostructures, liposomes such as lipoplexes, or dendrimers, which could be assembled in any lab by a grad student. Would also be externally visible and measurable, and provide an understanding of the principles of metabolic targeting and drug delivery. Probes that could pair with the delivery vehicles and report on their function non-invasively may also be developed – an ideal undergraduate thesis project that a group of expansionist grad students could perform in a few months and which would make a good presentation for an international meeting. It would be more difficult to emulate and probably more costly to manufacture DNA origami nanostructures, SNDs, and other polynanosystems that could autonomously perform complex actions and thus far become the focus of more fundamental research questions, such as control or how to study complex, out-of-equilibrium systems. Diagnostics based on nanosensors may be less of a concern given their invisibility and current lack of usefulness, but might become an issue as they improve. It would likely be quite invisible to those being interrogated. Would encroach on new grounds of surveillance and regulation, and thus require new regulatory agencies. Would filter discussions and advance legal protections [21, 22].

Future Perspectives

Concerns in nanobot medicine development include engineering design options, drug delivery and release mechanisms, how to clear excess vehicles from the patient, and how to ensure biological safety. Social concerns include how the policy of nanobiotech medicine will affect the larger context of the health care business and how safety will be ensured on the market. Providing devices, procedures, and standards for the design, evaluation, and application of such devices is outlined. It is important to demonstrate the safety and reliability of these products to secure public trust and acceptance, as well as widespread, beneficial applications. In addition to technological and societal concerns, ethical concerns must also be addressed, e.g., how nanobot medicine would affect the relationship between physician and patient. Products of DIYbio movements and labs should either fall within pre-prescribed frameworks or otherwise have to be considered the same way as those obtained in any other amateur lab. This does not mean that oversight can take months or years, which would stall innovation, nor can it be based only on principles that are worded vaguely and incomprehensibly. Better knowledge transfer and understanding from the scientific institutions to the civic society, and also vice versa, is highly requested. A broad combination of methods would undoubtedly be most effective and especially educational measures for youth, which are of importance in the next couple of decades. An overview of possible nano-pollutants in life cycles for various health care innovations was given. Expected effects of nano-pollution on microbes, humans, and

other organisms were articulated, and modeling for eco/toxo-logical risk predictions was proposed. Therefore, special safeguards, such as countermeasures, double-check systems, warranties, risk assessments, early warning systems, failure prediction systems, and breakdown safety guidelines, should be in place to contain or minimize the damage from mishaps. This would also yield highly needed knowledge to design safer nanotechnology [23, 24].

Case Studies

A major focus of nanotechnology over the past thirty years has been engineering nanoscale materials for applications in biology and medicine. Potential applications in biology and medicine are vast, but one of the more exciting and widely studied themes is nanometer-scale vehicles for drug delivery. Nano-carriers offer the promise of "Magic Bullet" therapy: targeting a specific organ or tissue with an effective therapeutic agent while minimizing toxicity to normal tissues. Much attention has been directed at making nano-formulations made of polymeric micelles and liposomes, and conjugates of antibody-nanoparticle, antibody-polymer-drug, etc., for highly variable applications. Along with this work, the polymer-based formulations have become quite successful in research laboratories. The understanding of the size-dependent biophysics of injection-mode mammalian systems is still early in its evolution, and strategies for nano-discovery explorations have not yet matured beyond the already decade-old works of E. H. K. A. E. de Mello. On the one side, although much progress has been made in achieving selective targeting of drug delivery vehicles to disease sites, designer vehicles typically don't release active agents once they arrive. Mechanisms of vendor discovery, development, and evaluation of biointegrity and biocompatibility of nano-drugs for targeted delivery are as un-geldy as those for their macro-drug-mates: the rich and famous nanoparticle vendors don't yet exist. On the other side, miniaturized mechanical robots have revolutionized micro-manipulation at the micrometer-scale (for hardware) and enhanced the motility of biocompatible carriers at the nanoscale (for applications). Encapsulation of active hydrogel particles within a mesoporous membrane achieves encapsulation of nanocapsules within nanorobots. Here, a mesoporous silica-encoded nanorobots that pump micro-thermal transport solution into encapsulated silica nanocapsules with cracks on the areal side are proposed as an alternative study to the augmentation of the motility of nanorobots [25, 26].

Regulatory Framework

Regulatory oversight of nanomaterials in drug products faces unique challenges due to the complexity of small molecular assemblies formed by various molecular interactions. These assemblies can range in size and form, complicating their characterization, quality control, and regulatory evaluation compared to traditional drug substances. In contrast, nanocarrier polymers' therapeutic components, which resemble traditional active pharmaceutical ingredients (APIs), provide a basis for developing a regulatory framework for targeted nano-drug products. Although scientists and engineers have made strides in engineering nanocarriers for targeted therapy, regulatory bodies are still in the early stages of assessing these new products. Key challenges include defining identity, subclassification, and characterization of products that overlap with conventional drugs but don't fit established categories. FDA guidelines offer some direction for identifying critical quality attributes (CQAs) vital for developing tests and evaluating nanoscale products akin to traditional pharmaceuticals. Questions regarding products' regulatory evaluation include prioritization of CQA characterization, assessment of similarity to non-nano models, and establishing a mode of action framework for assessing complex nanocarrier products. Addressing these questions may form a new analytical foundation for evaluating targeted therapeutics, equipping regulatory agencies to keep pace with rapid advancements in research and commercialization. The FDA notes that nanotechnology in biopharmaceuticals is a frontier science, with ongoing research needed to properly characterize nanopharmaceuticals. The FDA recognizes that understanding these products' functions, potential toxicological effects, and testing methods is still developing. Foundational work is underway, complemented by regulatory input and collaborative dialogues through consortia, workshops, and discussions with stakeholders on nanomedicines [27, 28].

Public Perception of Nanobots

The pursuit of bio-nano robots is fueled by the need to enhance human health care, with diverse nano-devices being developed for diagnostics, targeted drug delivery, surgical interventions, and tissue repair. After years of limited efficacy, recent reports have renewed public interest, though issues of bio-compatibility and safety remain. The demand for targeted drug delivery has surged due to unmet medical needs in chronic diseases. The initial promise of anti-cancer therapies has fallen short, fostering renewed focus on nanoparticle-based delivery, contingent on safe integration with drug carriers. Despite this optimism, skepticism remains prevalent. Advanced tools for molecular imaging and monitoring

therapeutic activities exist, but anatomical barriers still obstruct drug access to solid tumors. Current agents are often slow to diffuse within tumors, impacting efficacy and safety. Adjustments to the physicochemical properties of drug carriers can improve tumor localization via the enhanced permeability and retention effect, yet vascularization varies significantly among tumor types. Additionally, carriers face issues like non-specific aggregation in circulation, leading to inconsistent discharge rates in contemporary targeted drug delivery nanomedicines. The addition of targeting ligands can either enhance diffusional passivity or promote rapid internalization, but often, the detectable fraction remains minimal, inhibiting effective drug transit and resulting in substantial washout signaling [30-34].

CONCLUSION

Nanobots stand at the intersection of engineering, robotics, and molecular medicine, offering a paradigm shift in how drugs are delivered within the human body. Their ability to autonomously navigate complex biological environments, respond to localized stimuli, and deliver therapeutic agents with precision makes them ideal candidates for overcoming the limitations of traditional drug delivery systems. While the design and fabrication of functional nanobots present considerable technical and regulatory challenges particularly concerning size, propulsion, and biocompatibility, ongoing innovations in smart materials, DNA nanotechnology, and magnetic control systems continue to close the gap between theoretical potential and clinical application. As research advances and interdisciplinary collaboration grows, nanobots are poised to play a central role in future medical therapies, especially in treating diseases like cancer, where precision and efficacy are paramount. The continued refinement of these nanoscale machines could herald a new era of minimally invasive, highly effective, and patient-specific healthcare.

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