WORLD JOURNAL OF PHARMACEUTICAL RESEARCH
Coden USA: WJPRAP Impact Factor 8.453
Volume 15, Issue 1, 493-510. Review Article ISSN 2277–7105

NANOROBOTS - THE FUTURE OF TARGETED THERAPEUTICS

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Article Received on 04 Dec. 2025,
Article Revised on 24 Dec. 2025,
Article Published on 01 Jan. 2026,
https://doi.org/10.5281/zenodo.18093931

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How to cite this Article: *[1]Neelima Devi, [2]Kasala Sindhuja, [3]Kavvampalli Shirisha, [4]Kemidi Srikanth, [5]Kokkonda Rajashekar Reddy, [6]Kolakani Shivani. (2026) NANOROBOTS - THE FUTURE OF TARGETED THERAPEUTICS. "World Journal of Pharmaceutical Research, 15(1), 493–510.

ABSTRACT

Nanorobots, nanoscale devices (<100 nm), are poised to revolutionize medicine by enabling ultra-targeted therapeutics. These engineered systems are designed to overcome the critical limitations of conventional treatments—such as systemic toxicity and non-specific distribution—especially in diseases like cancer. Composed of integrated sensors, propulsion systems, and encapsulated payloads, nanorobots can autonomously navigate the body, identify pathological biomarkers (e.g., tumor antigens), and precisely deliver therapeutic agents (drugs, genes) directly to the disease site. This targeted delivery significantly increases local drug concentration while minimizing damage to healthy tissues, thus boosting efficacy and reducing debilitating side effects. While challenges remain in biocompatibility, mass production, and in-vivo navigation control, rapid progress in nanotechnology and bioengineering suggests a near future where nanorobots are central to precision medicine. They represent a paradigm shift towards highly effective, safer, and personalized healthcare solutions.

KEYWORDS: Targeted Delivery, Therapeutic payloads, Chemotherapy, Surgery, Precise, Personalized, Cancer, Genetic conditions.

I. INTRODUCTION

Nanorobots (also called nanobots or nanomachines) are incredibly tiny robotic devices, usually 1 to 100 nanometers in size, representing a cutting-edge medical application of nanotechnology. The core idea is to create machines that can travel inside the human body to precisely diagnose, monitor, and treat illnesses at the molecular or cellular level.

The primary purpose of these medical nanorobots is to accomplish tasks that current methods struggle with. For instance, they can deliver drugs directly to specific targets, like cancer cells, which both reduces side effects and boosts the treatment's efficiency. They also show promise for detecting harmful agents, mending damaged cells, conducting targeted surgical procedures, and tracking biological signals within the body.

Typically constructed from biocompatible materials (such as gold, silica, or biodegradable polymers) to prevent harm or immune responses, nanorobots can be moved and controlled via magnetic fields, chemical energy, or outside triggers like light or ultrasound.

The development of nanorobots signals a major shift toward personalized and precision medicine. While the technology is currently in the research and testing phase, it has immense potential to radically change how diseases are diagnosed, treated, and prevented, eventually providing healthcare systems with safer, quicker, and more effective medical solutions.[1]

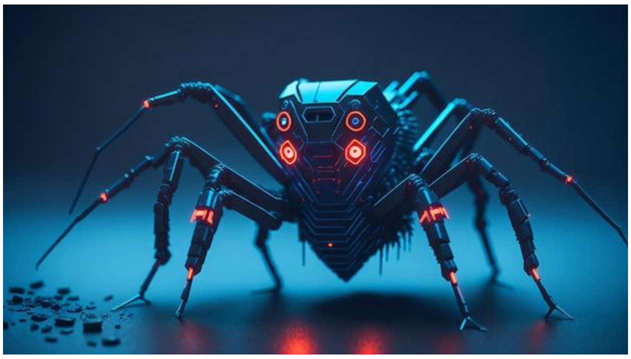

Figure 1: Conceptual model of a medical nanorobots.

II. Classification of NanoRobotics

Nanorobots used in medicine are grouped based on four main characteristics that define how they function and operate within the body:

1. Structure (What they're made of)

Bio-nanorobots are made from biological materials like DNA and proteins. These materials are valued for their compatibility with the body and their ability to self-assemble.

Inorganic nanorobots are constructed from strong synthetic materials, such as metals and carbon. This makes them more durable and easier to control from the outside.

Hybrid nanorobots combine both types. They have inorganic cores for control and biological coatings for better targeting.

2. Mode of Operation (How they move)

Externally controlled nanorobots are guided by outside forces, such as magnets or ultrasound.

Autonomous nanorobots move on their own, using internal programs or sensing chemical signals to navigate and perform tasks without external help.

3. Power Source (What drives them)

They can get their power from chemical reactions (catalytic nanomotors), external magnetic fields, biological motors (like flagella), or energy from light or ultrasound.

4. Function (What they do)

Diagnostic nanorobots work as nanosensors to detect diseases and monitor the body.

Therapeutic nanorobots deliver drugs or other treatments directly to a specific area, such as a tumor.

Surgical nanorobots carry out tiny physical tasks, like removing blockages.

Cellular repair nanorobots aim to fix or replace damaged cells and organelles.[2]

III. Outline

Nanorobots are minuscule devices, between 1 and 100 nanometers in size, revolutionizing cancer care by offering early, precise, and minimally invasive detection at the molecular level.

Core Function and Mechanism

Engineered for oncology, these nanorobots navigate the body to find specific cancer biomarkers (like abnormal proteins or genetic changes). Their tiny size lets them reach areas conventional tools cannot access.

They work by being functionalized with components like antibodies or biosensors that stick specifically to cancer cells or tumor markers. Once they detect the target, they can:

Emit a detectable signal (e.g., fluorescent or magnetic).

Collect diagnostic information.

Deliver contrast agents to enhance imaging techniques (MRI, PET, CT).
Variety and Utility

Several types of nanorobots are being developed

Magnetic nanorobots are steered externally to the tumor site.
DNA-based nanorobots are built from programmable DNA that reacts to specific cancer signatures.
Chemical nanorobots respond to variations in the tumor's environment, such as changes in pH or enzyme levels.
Photoresponsive nanorobots are activated by light to identify or tag cancer cells.

These capabilities translate into powerful applications, including detecting cancer at its earliest molecular stage, monitoring tumor status in real-time, improving the accuracy of medical imaging, and functioning as a sophisticated liquid biopsy tool.[3]

IV. Impact and Roadblocks

Nanorobots offer significant advantages: they provide extremely high sensitivity, are minimally invasive, and hold potential for theranostics (combining diagnosis and treatment).

However, significant hurdles remain, including concerns over biocompatibility and toxicity, the high cost and complexity of manufacturing, and navigating regulatory and ethical issues. Looking ahead, the fusion of nanotechnology, AI, and bioengineering is expected to produce smart nanorobots capable of autonomous function, paving the way for truly personalized and adaptive cancer diagnosis.[4]

Overall mechanism of Nanorobots

Nanorobots are miniature, programmable medical devices (1–100 nanometers) designed to operate at the cellular and molecular level within the body. Their overall medical function is a precisely controlled process involving six key steps

Targeted Navigation: They enter the body and use mechanisms like magnetic control, chemical gradients, or biological homing to find the exact disease site (e.g., a tumor).

Sensing and Recognition: Once there, integrated biosensors identify specific markers of illness, such as cancer antigens or pathogens.

Therapeutic Action: The nanorobot then performs its programmed task, which could be releasing medication directly to the diseased cells (targeted drug delivery), performing nanoscale surgery, or repairing tissue.

Communication and Monitoring: They transmit real-time diagnostic data to external monitors using signals (like fluorescence or MRI), allowing doctors to track their effectiveness.

Safe Clearance: After completing their job, the devices are designed to either safely biodegrade into harmless components or be naturally excreted from the body.

In short, nanorobots offer high-precision, minimally invasive diagnosis and treatment by performing intelligent actions directly where they are needed, promising a revolution in personalized medicine.[5]

V. Nanorobots in Cancer Treatment

Nanorobots are ultra-small structures, typically ranging from 1–100 nanometers, designed to recognize, reach, and treat cancer cells with exceptional accuracy. They function at the molecular scale and are capable of transporting drugs, sensing abnormal signals, and even directly destroying malignant cells.

Why Use Nanorobots Against Cancer?

High Precision: They can selectively target tumor cells while leaving normal tissues unharmed.

Lower Toxicity: Their targeted action reduces the side effects seen with conventional chemotherapy.

Early Detection: Nanorobots can detect cancer markers at very early stages.

Controlled Release: They deliver therapeutic agents precisely at the tumor site, improving treatment effectiveness.[6]

VI. Types of Nanorobots

1. DNA-Based Nanorobots

Constructed from folded DNA structures (DNA origami), these nanorobots can open up like a capsule and release anti-cancer drugs only when they reach cancerous tissues.

2. Magnetic Nanorobots

These are steered using external magnetic fields and are used for targeted drug delivery or heating tumor cells through hyperthermia.

3. Biological/Bacterial Nanorobots

Genetically modified bacteria function as microscopic machines. They naturally move toward low-oxygen regions, a characteristic feature of tumor environments.

4. Enzyme or Chemical-Powered Nanorobots

They utilize chemical reactions inside the body—such as with glucose or urea—to move and reach cancer cells efficiently.[7]

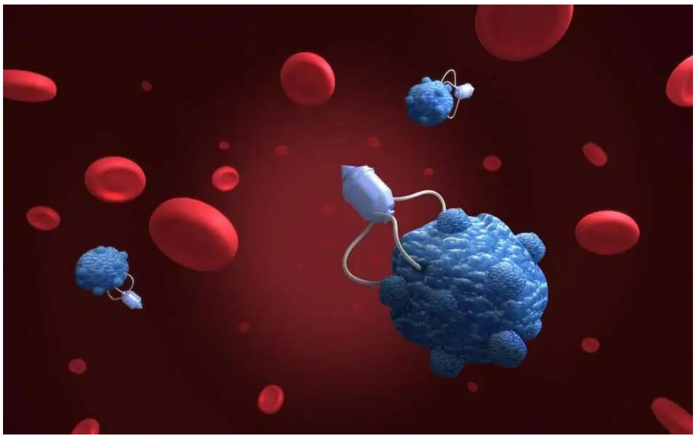

Figure 2: Targeted Delivery and Cellular Interaction.

VII. How Nanorobots Work

1. Targeted Drug Delivery

Nanorobots carry chemotherapy drugs and release them specifically into cancer cells, enhancing drug efficiency and minimizing harm to healthy tissue.

2. Tumor Detection

They detect abnormal biological signals such as tumor-specific markers, acidic pH, overexpressed proteins, and blood vessel growth associated with cancers.

3. Cancer Cell Destruction

Nanorobots can eliminate tumor cells through heat (hyperthermia), physical disruption of cell membranes, or by delivering gene-silencing molecules like siRNA.

4. Cutting Off Blood Supply

Certain nanorobots can block the blood vessels feeding tumors, causing the cancer cells to die due to lack of nutrients.

Areas Where They Are Being Used

- Breast cancer
- Lung cancer
- Brain tumors
- Prostate cancer
- Melanoma[8]

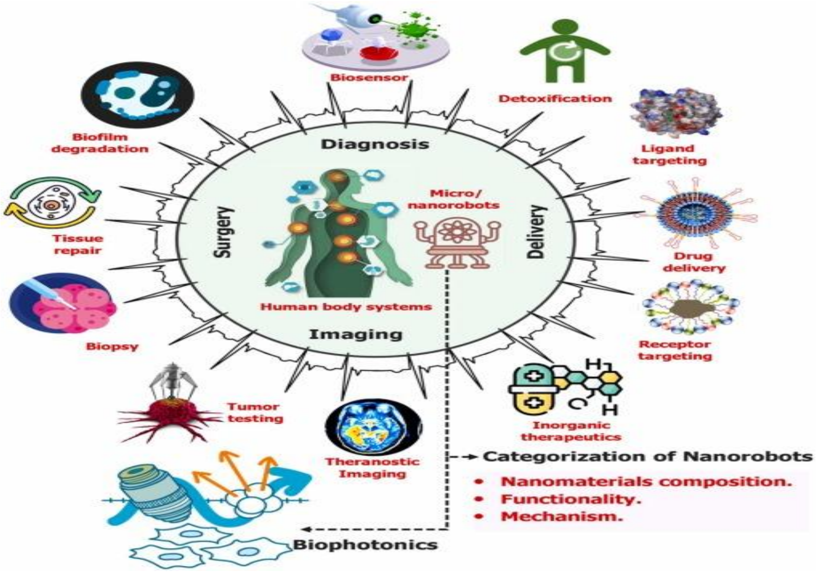

Figure 3: Integrated medical applications of nanorobots.

VIII. NANOROBOT APPLICATIONS

Table 1: Primary applications of Nanorobots in medicine.

Field	Application Area	Description and examples tasks
Medicine(Nanomedicine)	Targeted Drug Delivery	Delivery The primary goal. Nanobots deliver therapeutic agents (e.g., chemotherapy) directly to diseased cells (like tumors), minimizing side effects on healthy tissues.
	Minimally Invasive Procedures	Performing micro-scale tasks, such as clearing arterial plaque (thrombus removal), breaking up kidney stones, or repairing cell-level damage.
	Diagnostics & Monitoring	Functioning as advanced biosensors to detect disease biomarkers (e.g., cancer cells, pathogens) and continuously monitor

		physiological parameters in real-time within the body.
	Regenerative Medicine	Stimulating tissue repair, supporting cell regeneration, and potentially aiding in precise gene therapy by editing molecular structures.
Environmental	Pollution Remediation	Neutralizing or breaking down toxins and pollutants in soil, air, or water with high specificity and efficiency (e.g., cleaning up oil spills).
	Environmental Monitoring	Deploying swarms of nanobots to continuously monitor chemical or biological contaminants in remote or hazardous areas.
	Positional Nanoassembly	Precisely manipulating individual molecules or atoms to build complex nanostructures and devices from the bottom up (nanofactories).
	Quality Control	Inspecting microelectronic circuits or surfaces for defects with nanometer-scale resolution, improving product quality and consistency
	Biohazard Defense	Rapidly detecting and neutralizing biological and chemical weapons or hazardous agents in the field.
	Micro-surveillance	Creating extremely small, stealthy sensors for advanced monitoring and intelligence gathering

The mechanism of the nanorobot in cancer detection, detailing the coordinated steps right from navigation up to signal generation and eventual elimination from the body.

- **Mechanism of Nanorobots in Cancer Detection**

Cancer detection by nanorobots is a multi-stepped process that leverages the power of molecular specificity and advanced sensing into the precise location and signaling of malignant cells.

1. Targeting and Navigation

First of all, nanorobots have to efficiently travel through the body to reach the tumor site. This navigation is achieved through engineered guidance systems:

Chemical Gradients: moving based on local chemical cues such as higher acidity or enzyme concentrations near tumors.

Magnetic Guidance: being controlled remotely by an external magnetic field for very precise steering.

Biological Directives: Coating with targeting molecules such as antibodies, peptides, or aptamers that can only bind to the overexpressed receptors present on the surface of cancer cells, for example, HER2, EGFR.

2. Recognition of Cancer Cells

Upon reaching the target site, nanorobots recognize cancer cells through specific biomarkers. This is mediated via biosensors or molecular probes on the surface of the nanorobot:

Molecular Markers: Abnormal proteins, antigens (e.g., PSA, CEA), and DNA/RNA sequences are detected.

Receptor Overexpression: binding to overexpressed cell surface receptors.

Microenvironment indicators: detect changes in the tumor's surroundings, such as aberrant pH, oxygen levels, or activity of certain enzymes.

Binding of the probe to the target generates a detectable response.

3. Signal Generation and Detection

Once cancer has been identified, a signal detectable by external medical apparatus is produced by the nanorobot. This allows the clinicians to accurately visualize and locate the cancerous tissue:

Optically/fluorescently active: Utilized in high-resolution imaging and microscopy.

Magnetic Signals: These are detected by MRI scanners to visualize deep tissues.

Radioactive Tracers Used in PET or SPECT scans.

Electrochemical Signals: Applicable for either localized or implantable diagnostic devices.

4. Data Transmission and Clearance

Data Reporting: Advanced nanorobots can wirelessly transmit data or alter their detectable properties to relay diagnostic information in real time, often communicating with AI algorithms for monitoring.

Elimination: Nanorobots are designed for biological exit, whereby they biodegrade into non-toxic components or are excreted through the body's natural clearance pathways after a completed mission, for example, via the kidneys or the liver.

Summary Flow of Mechanism

Injection: Nanorobots enter the bloodstream.

Navigation: They are guided to the tumor site, magnetically or chemically.

Recognition: They bind to cancer biomarkers.

Activation Signal: They emit a detectable signal, such as fluorescent and magnetic.

Detection: Imaging systems capture the signal for diagnosis.

Elimination: They are cleared from the body.[9]

IX. CRYONICS

Cryonics is an innovative preservation technique that stores biological tissues or whole organisms at extremely low temperatures to completely stop metabolic and biochemical functions. Its primary purpose is to keep life suspended until future scientific progress enables the restoration and healing of the preserved structures. The integration of nanorobots into cryonic procedures marks a groundbreaking development in biomedical science. These nanoscale machines are capable of performing highly precise actions at cellular or molecular levels, enabling them to repair damage caused by freezing and thawing, maintain tissue integrity, and prevent the formation of harmful ice crystals that typically damage cells during cryopreservation. The combination of cryonics with nanotechnology opens possibilities such as long-term organ storage, revival of terminally ill patients, and potentially extending human lifespan. This emerging interdisciplinary field offers great potential for advancements in regenerative medicine, organ transplantation, and life-extension technologies.[10]

HISTORY OF CRYONICS

Cryonics involves preserving humans or animals at extremely low temperatures after legal death, with the belief that future scientific advancements may eventually make revival possible. Its scientific roots trace back to the late 1800s and early 1900s, when researchers explored how freezing affects living tissues and identified cryoprotective agents that help prevent cellular damage from ice formation. The modern idea of cryonics gained attention in the 1960s after Robert Ettinger published “The Prospect of Immortality” (1962), proposing that people could be frozen and later brought back to life. The first cryonically preserved person was Dr. James Bedford in 1967. Soon after, organizations like the Alcor Life Extension Foundation (established in 1972) and the Cryonics Institute (started in 1976) began supporting cryonic storage and research. Major progress came in the 1990s with the development of vitrification, which improved preservation techniques. Today, several hundred people worldwide remain in cryonic suspension, and ongoing innovations in nanotechnology and regenerative medicine continue to advance the field.[11]

Figure 4: Future frontiers in life extension and Cryopreservation.

X. Future of Cryonics

Cryonics refers to the preservation of individuals at ultra-low temperatures after legal death, with the hope that future technology may enable revival. Although still experimental, advancements in biotechnology, nanoscience, and computing are helping define a more realistic scientific pathway. The progress of cryonics largely depends on overcoming two major barriers: preventing biological damage during freezing and ensuring a revival that preserves personality, cognition, and memory.

1. Progress in Cryopreservation Methods

1.1 Next-Generation Vitrification Techniques

Future developments are likely to include:

Novel cryoprotective agents (CPAs) with lower toxicity.

Nanoparticles that inhibit internal ice formation.

Smart CPAs capable of regulating their distribution or activity based on temperature.

Such improvements could make it possible to safely preserve entire organs or even whole bodies.

1.2 Advancements in Organ and Brain Storage

Growing success in cryopreserving organs like kidneys, reproductive tissues, and other biological samples suggests that:

Long-term organ storage may become standard in medical practice.

Techniques effective for whole organs may eventually be applied to the brain, strengthening the scientific basis of cryonics.

This could greatly improve the credibility of cryonics as a medical field.[12]

2. Nanotechnology and Molecular-Level Repair

Nanotechnology is anticipated to play a key role in enabling future cryonics applications.

2.1 Nanorobotic Repair Systems

Potential future functions of molecular nanorobots include:

Repairing membrane damage caused during freezing.

Removing or neutralizing CPA-related toxicity.

Correcting DNA breaks from ice or stress.

Restoring synaptic structures and tissue organization.

2.2 Rebuilding the Neural Connectome

Maintaining the brain’s structural and functional map, which encodes memory and identity, is essential. Future innovations may involve:

High-resolution mapping of neural circuits.

AI-based reconstruction of damaged synapses or networks.

Regeneration of neurons using biological or synthetic methods.

This could address the current challenge of preserving memory during cryopreservation.[13]

3. Future Revival Technologies

3.1 Regenerative and Reconstructive Approaches

Multiple fields may contribute to eventual revival:

Stem cell–based tissue engineering

Organ and tissue regeneration

Xenobiology for repairing cellular architecture

Biofabricated tissues and organ replacements

People revived from cryonic preservation may require extensive regenerative treatments.

3.2 Whole-Body Rewarming Systems

Nanoparticle-enabled volumetric heating is emerging as a method to:

Achieve uniform rewarming

Prevent cracking or thermal stress

Make cryopreservation reversible

Such techniques have already shown positive results in small.[14]

XI. Nanorobots for Cryonics Revival

The idea of using nanorobots in cryonics is a futuristic concept. It suggests that tiny, atomic-level repair machines, developed through future Molecular Nanotechnology (MNT), could revive patients who have been cryopreserved by fixing all types of damage.

Nanorobots would act as small repair teams with two main goals:

1. Reversing Cryopreservation Damage

The nanobots would address cellular and structural damage caused by current freezing methods:

* Cellular Repair: Known as "Cell Repair Robots," these nanobots would fix broken cell membranes, organelles, and repair molecular damage from the freezing process or the cryoprotective chemicals (CPAs). They are crucial for restoring delicate tissues, especially the brain.

* Nanowarming: A more immediate idea involves using nanoparticles (or basic nanobots) activated by an external radiofrequency (RF) field for quick, even warming. This step is essential to avoid the serious formation of ice crystals (devitrification) that happens during slow, traditional thawing.

2. Eliminating the Cause of Death

Since patients are legally dead when preserved, the nanobots also need to reverse the original issue:

* Pathology Elimination: They would be designed to find and eliminate all traces of the terminal illness, such as cancer cells, or fix localized damage from events like strokes.

* Restoring Vital Systems: They would repair the damage from lack of oxygen (ischemia) that occurred before preservation and restore essential systems like the circulatory system (theoretical "Vasculoid" nanobots) to ensure organ function.[15]

XII. How Nanorobots Operate in Cryonics

Cryonics is the preservation of a human body at extremely low temperatures (around −196°C) after legal death, with the hope that future technological advances will allow revival. Nanorobots, microscopic machines capable of operating at the molecular level, are expected to play a critical role in repairing and restoring the body and brain after thawing.

Although still theoretical in the context of cryonics, scientists have proposed how nanorobots might function during the revival process.[16]

XIII. Process of Nanorobot Action in Cryonics

1. Scanning and Mapping

Once the body is warmed, nanorobots would travel through the blood vessels and tissues. They would scan cells and biological structures at the molecular level, creating a comprehensive map to identify areas of damage.

2. Repairing Freezing Damage

Ice crystals formed during freezing can rupture cell membranes. Nanorobots would remove these ice crystals, repair damaged membranes and organelles, and restore cells to their normal structure and function.

3. Eliminating Toxic Cryoprotectants

Cryoprotectants prevent ice formation but can be toxic in high amounts. Nanorobots would detect and safely remove these chemicals, replacing them with natural body fluids.

4. Repairing DNA and Molecular Damage

Nanorobots could correct DNA breaks and mutations, restore damaged proteins and enzymes, and fix biochemical imbalances to return cells to a healthy state.

5. Restoring Neural Networks

Because memory and identity are stored in neural connections, nanorobots would scan and repair synapses, reconnect damaged neural pathways, and help preserve cognitive functions and memories.

6. Reactivating Biological Functions

After completing repairs, nanorobots would assist in restarting blood circulation, restoring cellular energy production, and supporting the functioning of vital organs, enabling the body to return to life similarly to advanced resuscitation.[17]

XIV. Importance

Cryonics is an advancing scientific method that aims to preserve human tissues, organs, or the whole body at extremely low temperatures immediately after legal death, with the hope that future medical technologies will be capable of restoring life and normal biological function. Its importance increases considerably when viewed alongside nanorobots, as nanotechnology offers innovative ways to address many of the current obstacles in long-term biological preservation. Together, cryonics and nanorobots present a highly advanced concept for life extension, tissue regeneration, and next-generation medical treatment.

One of the primary challenges in cryonics is damage to cells caused by freezing and thawing processes, including ice crystal formation, loss of cellular water, and chemical imbalance. Nanorobots could potentially reduce or reverse this damage by operating directly at the molecular and cellular levels. These microscopic devices may be engineered to repair broken cell membranes, restore damaged organelles, and normalize chemical gradients after rewarming. Their precise action could significantly improve both the survival and functionality of preserved tissues.

Another critical concern in cryonics is the protection of neural tissues, particularly the brain, which stores memory, consciousness, and personal identity. Even very small disruptions at the molecular level can permanently erase neural information. Nanorobots may help safeguard neural architecture by stabilizing synapses and preserving neural connections during or after cryopreservation. In future applications, they might also assist in repairing injured neurons or reestablishing disrupted neural communication, thereby increasing the potential for meaningful recovery.

Cryonics also involves the use of cryoprotective agents to prevent ice formation, but these substances can be toxic and difficult to control over long periods. Nanorobots could precisely regulate the delivery and concentration of these agents within tissues, reducing harmful effects while improving protective efficiency. Additionally, they may help remove toxic byproducts that accumulate during preservation, maintaining cellular balance and integrity. Such fine control is not possible with current conventional techniques, highlighting the revolutionary role nanorobots could play.

The role of cryonics combined with nanorobots extends beyond preservation alone and into future medical treatment. People suffering from diseases that are currently incurable or terminal could be preserved until advanced nanorobotic therapies are developed. These future treatments may repair genetic damage, eliminate malignant cells, or regenerate tissues at the molecular scale. In this way, cryonics serves as a bridge between today's medical limitations and tomorrow's technological possibilities.[18]

XV. Significance of Nanorobots in Cryonics

1. Repairing Damage at the Cellular and Molecular Level

Freezing and thawing can cause serious harm to cells, such as membrane breakdown, protein deterioration, and structural damage.

Nanorobots could

Mend DNA and cell membranes

Repair or replace damaged organelles

Restore disrupted neural pathways

2. Eliminating Ice Crystals

Despite using cryoprotective agents, tiny ice crystals can still form and damage tissues.

Nanorobots may:

Detect and break down internal ice

Safely substitute crystallized water with biological fluids

3. Rebuilding Brain Architecture

The preservation of neural networks is essential for maintaining personality, memories, and identity.

Nanorobots could

Map neurons at an atomic scale

Rebuild synaptic and neural structures

4. Reducing Cryoprotectant Toxicity

Cryoprotectants used during vitrification may become toxic.

Nanorobots might

Remove harmful chemicals gradually

Introduce safer biological substances

5. Regenerating Organs and Tissues

Nanorobots may serve as microscopic repair systems capable of:

Assisting in tissue regeneration

Healing organs damaged prior to death, such as the heart or brain

6. Controlled Revival and Real-Time Monitoring

During the rewarming process, nanorobots could:

Monitor biochemical conditions continuously

Manage temperature, oxygen levels, and healing responses precisely.[19]

XVI. ACKNOWLEDGMENT

I sincerely thank everyone who played a role in the successful completion of this work on Nanorobots in Targeted Drug Delivery. I am deeply grateful to my guide and faculty members for their consistent support, constructive feedback, and encouragement throughout the study. I also appreciate my institution for providing the required facilities and a conducive learning environment. I extend my thanks to the researchers and authors whose scholarly work offered valuable knowledge and references. Lastly, I acknowledge my family and friends for their unwavering motivation and support during this academic journey.

CONCLUSION

Nanorobots have emerged as a highly promising advancement in modern healthcare, providing exceptional precision at both cellular and molecular scales. Their diverse potential—from targeted drug delivery and real-time diagnostics to tissue repair and biosensing—positions them as powerful tools capable of improving the accuracy, efficacy, and safety of medical treatments. While most nanorobotic systems are still in the developmental stage, ongoing innovations in nanofabrication techniques, smart biomaterials, artificial intelligence, and biocompatibility are steadily accelerating their path toward clinical application. As these technologies mature, nanorobots are expected to become integral components of personalized medicine, offering minimally invasive, highly specific, and efficient therapeutic solutions for a wide range of disease.

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