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THE FUTURE SCOPE OF NANOROBOTS IN CANCER THERAPY

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Abstract : *Cancer remains one of the leading causes of death worldwide due to challenges in early detection and limitations of conventional treatment methods. Traditional therapies such as chemotherapy, radiotherapy, and surgery, although effective in certain cases, are often associated with severe systemic toxicity, poor specificity, and drug resistance. Therefore, there is a growing need for advanced and precise therapeutic approaches that can enhance treatment efficacy while minimizing side effects. Recent advancements in nanotechnology have led to the emergence of nanobots and nanocarriers as highly promising tools for cancer diagnosis and therapy. These nanoscale devices, typically ranging from 1 to 100 nanometers, demonstrate excellent biocompatibility and are capable of delivering drugs directly to targeted tumor cells. By ensuring controlled and localized drug release, nanobots significantly reduce damage to healthy tissues and improve therapeutic outcomes compared to conventional methods. In brain cancer, where treatment is often hindered by the presence of the blood–brain barrier, nanobots offer a unique advantage. Their ability to encapsulate, transport, and release drugs precisely at the lesion site allows for effective treatment of tumors located in hard-to-reach areas. Moreover, nanobots can be designed for real-time monitoring and imaging, aiding in both diagnosis and therapy .This review discuss the current progress, mechanisms of action, and clinical potential of nanobot-assisted cancer therapy. It summarizes key findings from recent studies published in reputed journals such as Springer, Elsevier, and Nature, focusing on the transition of nanobot technology from research laboratories to clinical applications. The integration of nanobots and nanocarriers into cancer treatment represents a revolutionary advancement toward precision medicine, offering enhanced drug delivery, improved patient safety, and better therapeutic outcomes.*

INTRODUCTION

Cancer is currently one of the leading causes of mortality worldwide and represents a major public health challenge. The term “cancer” originates from the Greek word karkinos, meaning crab, which was historically used to describe the claw-like invasion of malignant tumors into surrounding tissues. At the cellular level, cancer arises due to the failure of regulatory mechanisms that control cell growth, differentiation, and programmed cell death. These protective processes, collectively referred to as tumor suppression mechanisms, are essential for maintaining tissue homeostasis. Disruption of these mechanisms leads to uncontrolled cellular proliferation and tumor development [1].

The global incidence of cancer continues to increase as a result of environmental pollution, sedentary lifestyles, dietary changes, exposure to carcinogens, and genetic susceptibility. Although conventional treatment strategies such as chemotherapy, radiotherapy, and surgery remain the mainstay of cancer management, their effectiveness is often limited by non-specific drug distribution, systemic toxicity, poor penetration into tumor tissues, and the development of multidrug resistance. Consequently, there is an increasing demand for innovative therapeutic approaches that can selectively target cancer cells while minimizing damage to healthy tissues [2].

Advances in nanotechnology have enabled the development of nanoscale systems capable of interacting with biological structures at the molecular and cellular levels. Among these innovations, medical nanorobots represent a highly advanced class of nanosystems designed to perform specific biomedical functions. Medical nanorobots can be described as nanoscale devices capable of converting chemical, magnetic, acoustic, or optical energy into mechanical motion to execute predefined medical tasks. Due to their extremely small size, nanorobots can interact directly with cells and intracellular components, allowing precise intervention at the site of disease [3].

Nanorobots are an interdisciplinary technology integrating principles from nanotechnology, molecular biology, medicine, robotics, and materials science. In oncology, they are being explored for applications in cancer diagnosis, targeted drug delivery, tumor imaging, and minimally invasive therapeutic procedures. Unlike conventional nanocarriers that rely primarily on passive accumulation mechanisms, nanorobots possess the ability to actively navigate biological environments, recognize disease-specific markers, and release therapeutic agents in a controlled manner [4].

One of the most challenging aspects of cancer therapy is drug delivery to brain tumors due to the presence of the blood–brain barrier (BBB), which restricts the passage of most therapeutic agents. Drug transport across the BBB can occur through passive diffusion, carrier-mediated transport, receptor-mediated transcytosis, or adsorption-mediated pathways. Nanorobots offer a promising solution for overcoming these barriers by enabling active targeting and controlled drug release within the complex microenvironment of the brain. Intelligent nanorobotic systems can be programmed to navigate autonomously or be externally guided to reach lesion sites with high precision .

Once localized at the target site, nanorobots can identify disease-specific biomarkers expressed on cancer cells or pathogens, ensuring selective binding and therapeutic action. This highly precise approach, often referred to as nanorobotic therapy, minimizes off-target effects and enhances treatment efficacy. The ability of nanorobots to combine sensing, navigation, and therapeutic functions within a single platform positions them as a transformative technology in future cancer management strategies [5].

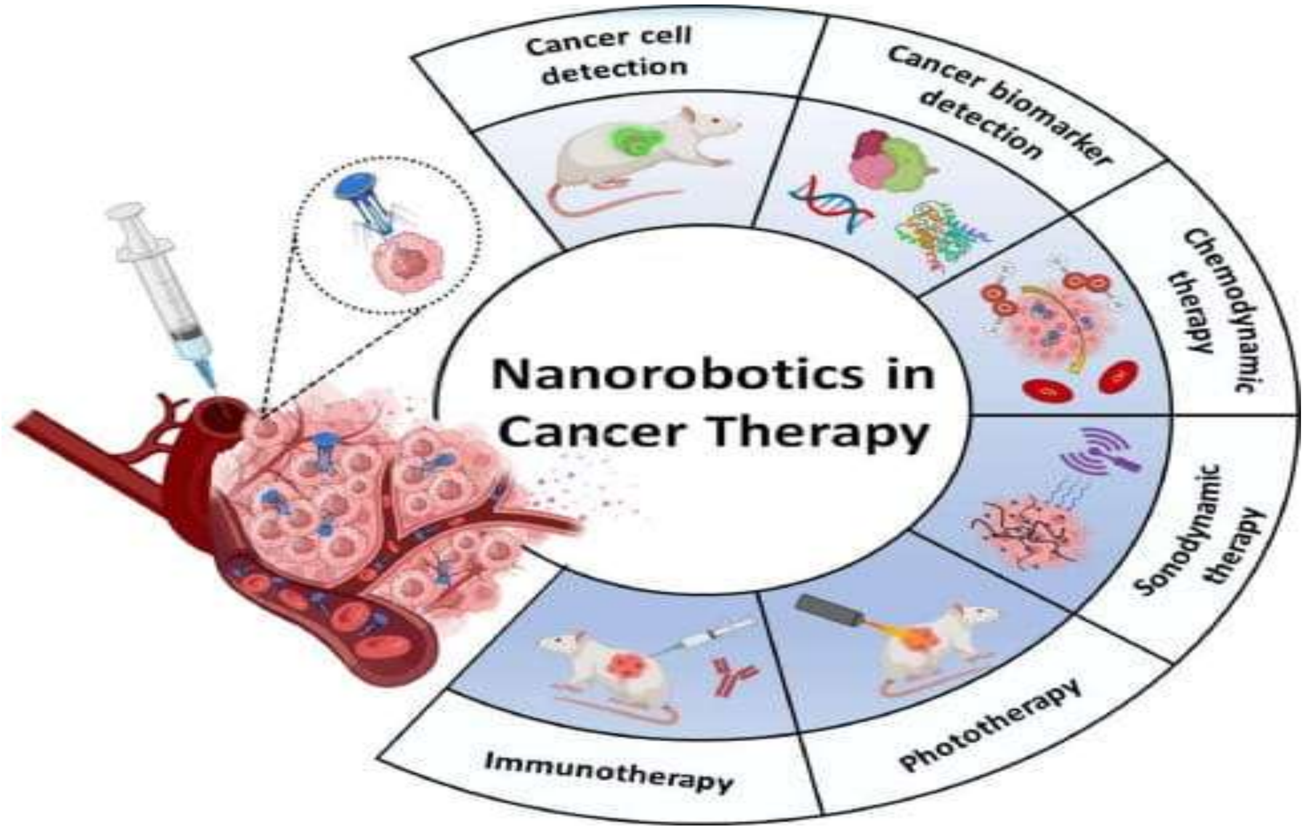


Figure 1. Nanorobotics In Cancer Therapy

Fundamentals of Nanorobots:-

Definition of Nanorobots:-

Nanorobots are nanoscale engineered devices designed to perform specific functions within biological systems by operating at the molecular or cellular level. These devices typically range in size from a few nanometers to several hundred nanometers and are constructed using biocompatible materials such as polymers, metals, ceramics, or nucleic acid-based frameworks. Nanorobots are capable of sensing their surrounding environment, responding to biological signals, and executing programmed actions such as targeted drug delivery, diagnostics, or therapeutic intervention. Their ability to interact directly with cells and intracellular components distinguishes them from conventional drug delivery systems and positions them as a key technology in advanced nanomedicine [6,7].

Components of Nanorobots:-

Nanorobots are composed of multiple integrated functional units that enable their operation in complex biological environments. The major components include sensors, actuators, power sources, control systems, and payload modules.

1. Sensors:-

Sensors are responsible for detecting specific biochemical and physiological signals within the body. These signals may include variations in pH, temperature, enzyme activity, oxygen concentration, or the presence of tumor-specific biomarkers. By continuously monitoring the local microenvironment, sensors allow nanorobots to differentiate between healthy and diseased tissues. This selective recognition capability is critical for achieving precise targeting and minimizing off-target effects in cancer therapy [8].

2. Actuators:-

Actuators enable mechanical motion and functional responses in nanorobots. They are responsible for propulsion, navigation, tissue penetration, and controlled release of therapeutic agents. Actuation mechanisms may rely on chemical reactions, magnetic fields, acoustic waves, or light stimulation. Through these mechanisms, nanorobots can actively move toward target sites and perform localized therapeutic actions, unlike passive nanoparticles that depend solely on diffusion or blood circulation [9].

3. Power Supply:-

Power generation is one of the most challenging aspects of nanorobot design. Nanorobots may obtain energy from endogenous biological sources such as glucose, ATP, or ionic gradients. Alternatively, external energy sources including magnetic fields, ultrasound, or electromagnetic radiation can be used to activate and control nanorobot function. Efficient energy utilization is essential for sustained operation and safe in vivo performance [10].

4. Control Systems:-

Control systems regulate the behavior, navigation, and task execution of nanorobots. These systems may operate autonomously based on pre-programmed responses to environmental stimuli or be externally guided using magnetic or optical control methods. Advanced control systems enable real-time decision-making, adaptive behavior, and coordinated actions among multiple nanorobots, enhancing therapeutic precision and reliability [11].

5. Payload and Functional Modules:-

The payload module carries therapeutic or diagnostic agents such as anticancer drugs, genes, RNA molecules, or imaging contrast agents. The release of these payloads can be triggered by internal biological cues or external stimuli, ensuring spatially and temporally controlled therapy. In multifunctional nanorobots, diagnostic and therapeutic modules may be combined within a single platform, enabling simultaneous disease detection and treatment [12].

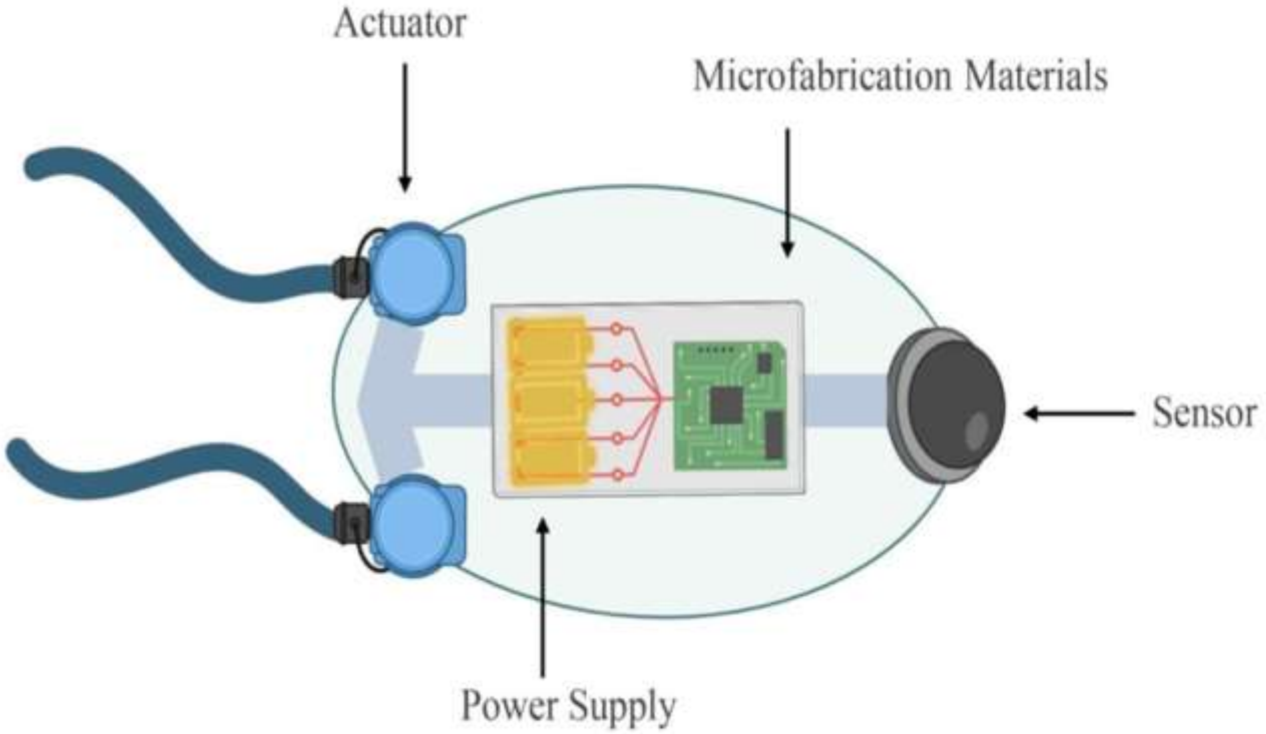


Figure No 2. Nanorobots

Materials needed for the synthesis of nanobots:-

Nanobots are made using a multidisciplinary method that combines material science, engineering, and nanotechnology. The design and functionality of nanobots, including performance, biocompatibility, and application, will undoubtedly be impacted by the choice of materials. Depending on the needs of the application, thousands of different types of materials are used. Among the most often utilised metals are silver and gold. The other particle is specifically gold nanoparticles, which are added to chemical ones because of their superior optical, electrical, and physical characteristics. The effectiveness of their developers and the potential for their application in areas like medication fitting, biosensing, and most importantly, imaging services, are the reasons for their good biocompatibility. Iron oxide ($Fe3O4$) and other magnetic nanoparticles, which are the second most well recognised type of nanoparticles, have the ability to change the magnetic field, which could have an impact on target-specific medication delivery and potential illness diagnostics. The following are a few of the materials used in the creation of nanobots**:**

a) Polymeric materials:- These offer still another adaptable choice. In order to improve biocompatibility and provide regulated medication release, biodegradable polymers like polylactic acid (PLA), poly(lactic-co-glycolic acid) (PLGA), and polyethylene glycol (PEG) are commonly chosen for the production of nanobot coatings or structures. The ability of stimuli-responsive polymers to alter their characteristics, like solubility or shape, in response to environmental changes, such pH or temperature, adds a creative element. As a result, they can function as adaptable nanobots.

b) Carbon-based materials:- Carbon-based materials have been identified as a crucial element in the creation of nanobots. Because of its high surface area-to-mass ratio and excellent conductivity, graphene is a good material for biosensing.

Additionally, functionalised graphene oxide has demonstrated favourable outcomes in active targeting. Additionally, carbon nanotubes are used in medication administration and intracellular sensing because of their exceptional mechanical strength, electrical conductivity, and ease of penetration of biological membranes.

c) Materials based on silicon:- These materials have the same stability and porosity control as silicon and silicon oxide nanoparticles. As a result, the materials are excellent since they may be utilised for controlled medication administration in addition to being biosensors.

d) Biological material:- One such challenge in drug targeting and molecular recognition is the creation of nano-robots using biological materials like DNA and RNA. Because of their inherent biocompatibility and functional adaptability, proteins and lipids are already recognised as the most popular configuration for the creation of biohybrid nanorobots.

e) Hybrid and other organic materials:- The focus is on hybrid materials that fall within a category of materials like metal-organic frameworks (MOFs), which are made up of organic ligands and metal ions. They are employed in certain applications like drug administration and diagnosis because of their huge surface areas and the ability to modify their capabilities depending on the target. Products like titanium dioxide (TiO_2) are used because they have photocatalytic properties that allow nanobots to interact with light for applications in medicine and water purification.

The introduction of precisely selected materials to carry out specific tasks, such as medicine delivery, biosensing, or environmental cleanup, is necessary for the realisation of nanobots. In addition to being essential for their use in practical applications, the combination of biocompatible and multipurpose materials ensures their success[13].

Types of Nanobots:-

1. DNA-Based Nanobots:-

DNA-based nanobots are nanoscale robotic systems constructed using programmable DNA molecules. These systems are commonly fabricated using DNA origami, a technique in which a long single-stranded DNA scaffold is folded into predefined two- or three-dimensional shapes with the help of short staple strands. Due to their molecular precision, DNA nanobots can be engineered to perform highly specific biomedical tasks within the human body.

One of the most promising applications of DNA nanobots is targeted cancer therapy. These nanobots function as intelligent drug carriers that remain closed during circulation, thereby protecting the therapeutic cargo from premature .release. Upon recognizing disease-specific molecular signals, such as tumor biomarkers, the nanobot undergoes a structural transformation and releases its payload at the target site. This stimulus-responsive behavior significantly minimizes systemic toxicity and improves therapeutic efficiency.

A well-known example is a DNA origami nanorobot designed to deliver thrombin specifically to tumor vasculature. The nanorobot remains in a closed tubular conformation while circulating in the bloodstream. Targeting aptamers on its surface recognize nucleolin, a protein overexpressed on tumor endothelial cells. Binding to nucleolin triggers the nanobot to open, releasing thrombin and inducing localized blood clotting, which blocks the tumor's blood supply and leads to tumor starvation. Structural transitions of such nanobots have been experimentally confirmed using atomic force microscopy, demonstrating their controlled activation and functional reliability. Overall, DNA-based nanobots represent a highly biocompatible and programmable platform for precision oncology [14,15].

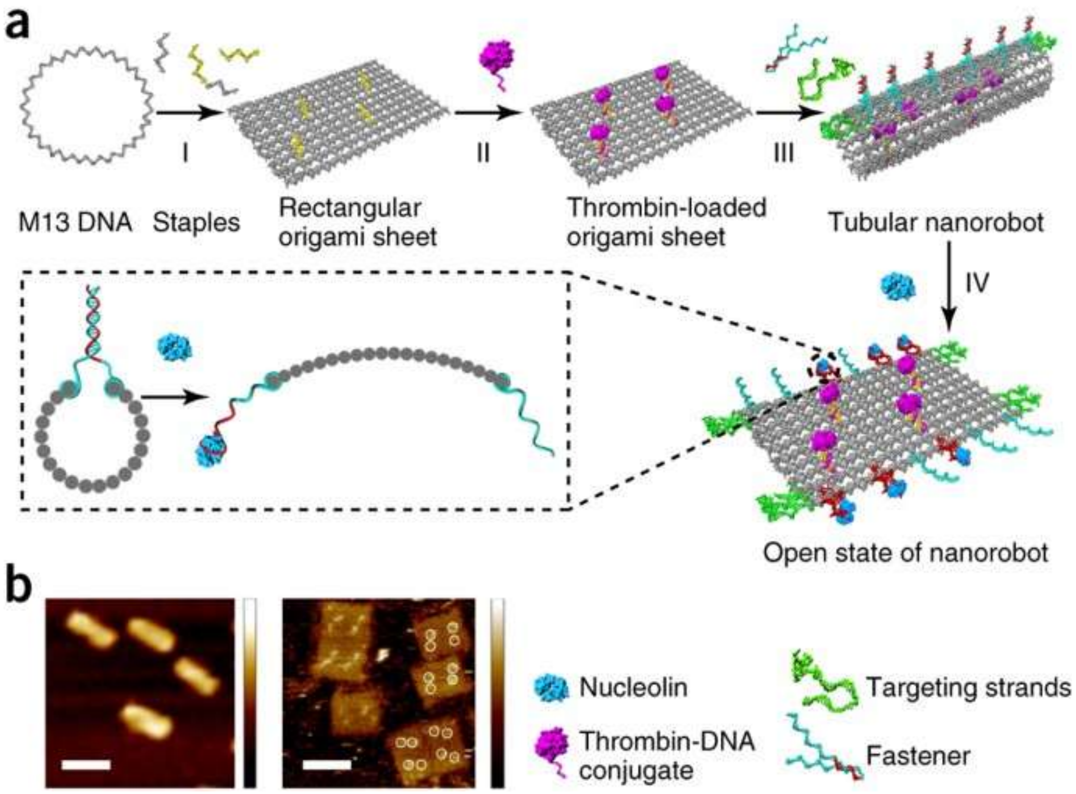


Figure No 3. DNA-Based Nanobots

2. Magnetic Micro / Nanorobots:-

Magnetic micro- and nanorobots are miniature robotic systems fabricated from magnetic materials such as iron, nickel, or cobalt. Their movement and positioning are remotely controlled using externally applied magnetic fields, allowing non-invasive navigation within the human body. This remote actuation eliminates the need for onboard power sources, making magnetic nanorobots particularly attractive for biomedical applications.

These robots have been explored for targeted drug delivery, cancer therapy, and minimally invasive procedures, including the removal of vascular blockages. Locomotion is achieved by manipulating magnetic field gradients, enabling controlled translation, rotation, and walking-like movements. For example, microrobots fabricated from nickel and elastomeric polymers such as PDMS have demonstrated bipedal walking behavior through sequential pitch and yaw motions induced by electromagnetic coils.

Beyond direct therapeutic action, magnetic microrobots can also perform indirect manipulation, such as pushing or transporting micro-objects in confined environments. Their ability to be precisely guided to specific anatomical locations while minimizing damage to healthy tissues highlights their potential as safe and effective tools for future nanomedical interventions [16,17].

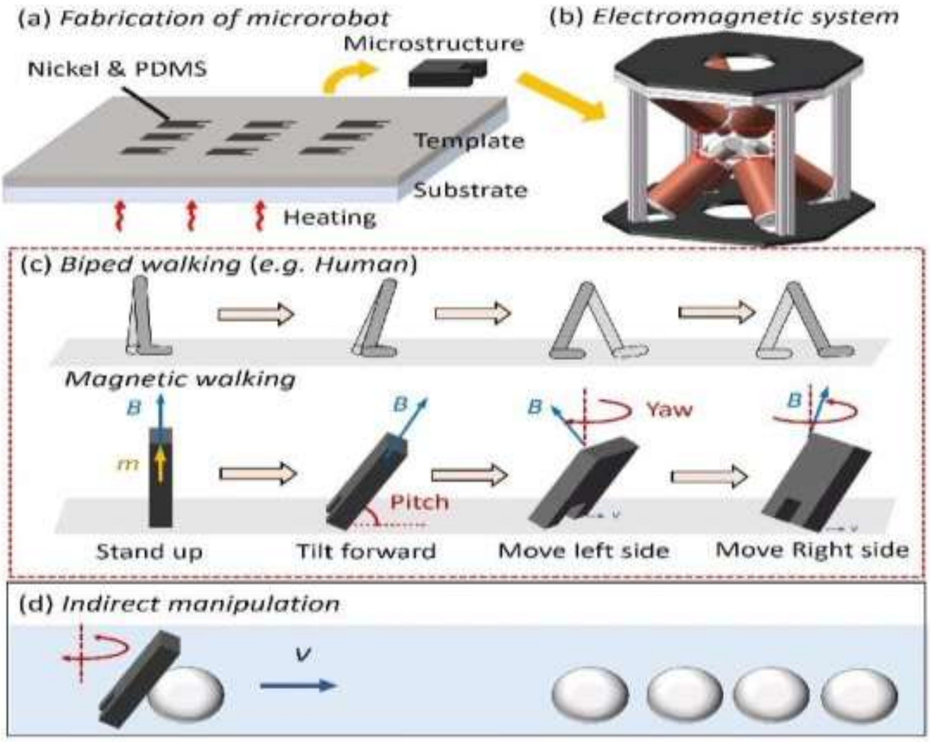


Figure No 4 . Magnetic Micro / Nanorobots

3. Biomimetic Nanobots:-

Biomimetic nanobots are engineered systems that imitate the structural and functional characteristics of natural biological entities, including cells, vesicles, and viruses. A widely adopted strategy involves coating synthetic nanoparticles with natural cell membranes derived from red blood cells, platelets, or cancer cells. This membrane camouflage allows the nanobots to evade immune recognition, prolong systemic circulation, and enhance biocompatibility.

The retained membrane proteins and receptors enable homotypic targeting and selective interaction with diseased tissues. For instance, red-blood-cell-membrane-coated nanobots have shown remarkable stability in circulation while efficiently delivering therapeutic agents. Advanced biomimetic designs include gold nanostar-based nanobots encapsulated within silica shells and loaded with chemotherapeutic drugs such as doxorubicin.

Upon administration, these nanobots accumulate at tumor sites and can be externally activated using near-infrared (NIR) light. NIR stimulation triggers drug release and local tumor microenvironment remodeling, resulting in enhanced cancer cell destruction. By seamlessly integrating synthetic nanotechnology with biological functionality, biomimetic nanobots offer a stealthy and highly effective approach for next-generation cancer therapy [18,19].

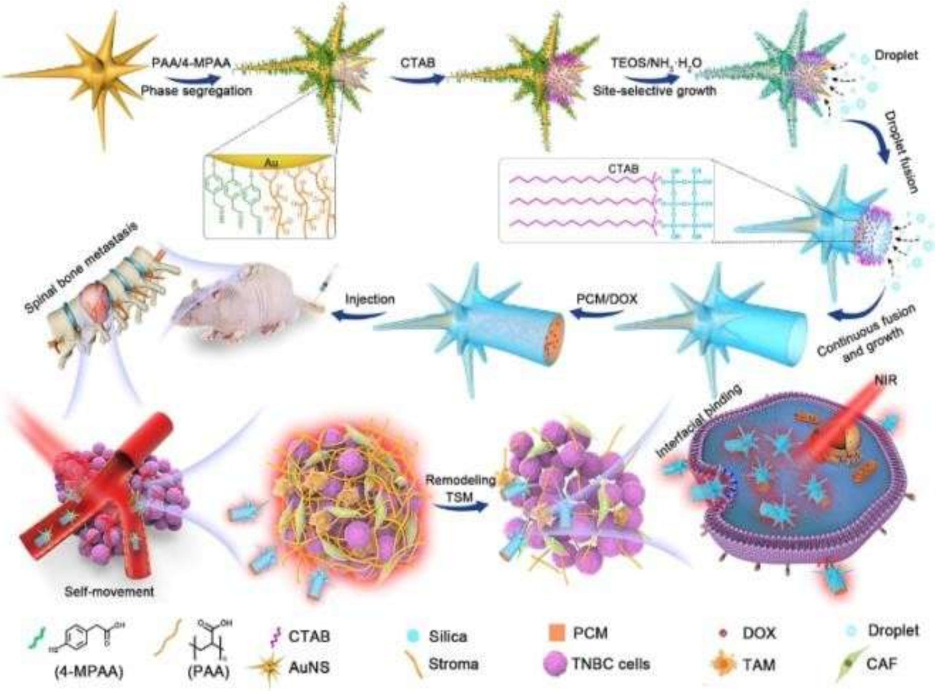


Figure No 5. Biomimetic Nanobots

4. Biohybrid Nanobots:-

Biohybrid nanobots combine living cells or microorganisms with synthetic nanostructures to harness natural biological motility and sensing capabilities. Common biological components include bacteria, macrophages, neutrophils, and sperm cells, all of which possess intrinsic propulsion and navigation mechanisms such as chemotaxis or magnetotaxis.

Synthetic elements, including magnetic nanoparticles or polymeric drug carriers, are integrated with the biological component to enable cargo loading and external control. This hybrid design allows biohybrid nanobots to autonomously navigate complex physiological environments and penetrate dense biological barriers that are otherwise difficult to access.

In cancer therapy, macrophage-based microrobots have been used to exploit the natural tumor-homing ability of immune cells for targeted drug delivery. Similarly, neutrophil-based nanobots have demonstrated the ability to cross the blood–brain tumor barrier, delivering therapeutic payloads to malignant gliomas. These systems represent a transformative approach to intelligent,self-powered, and adaptive drug delivery within complex disease microenvironments [20,21].

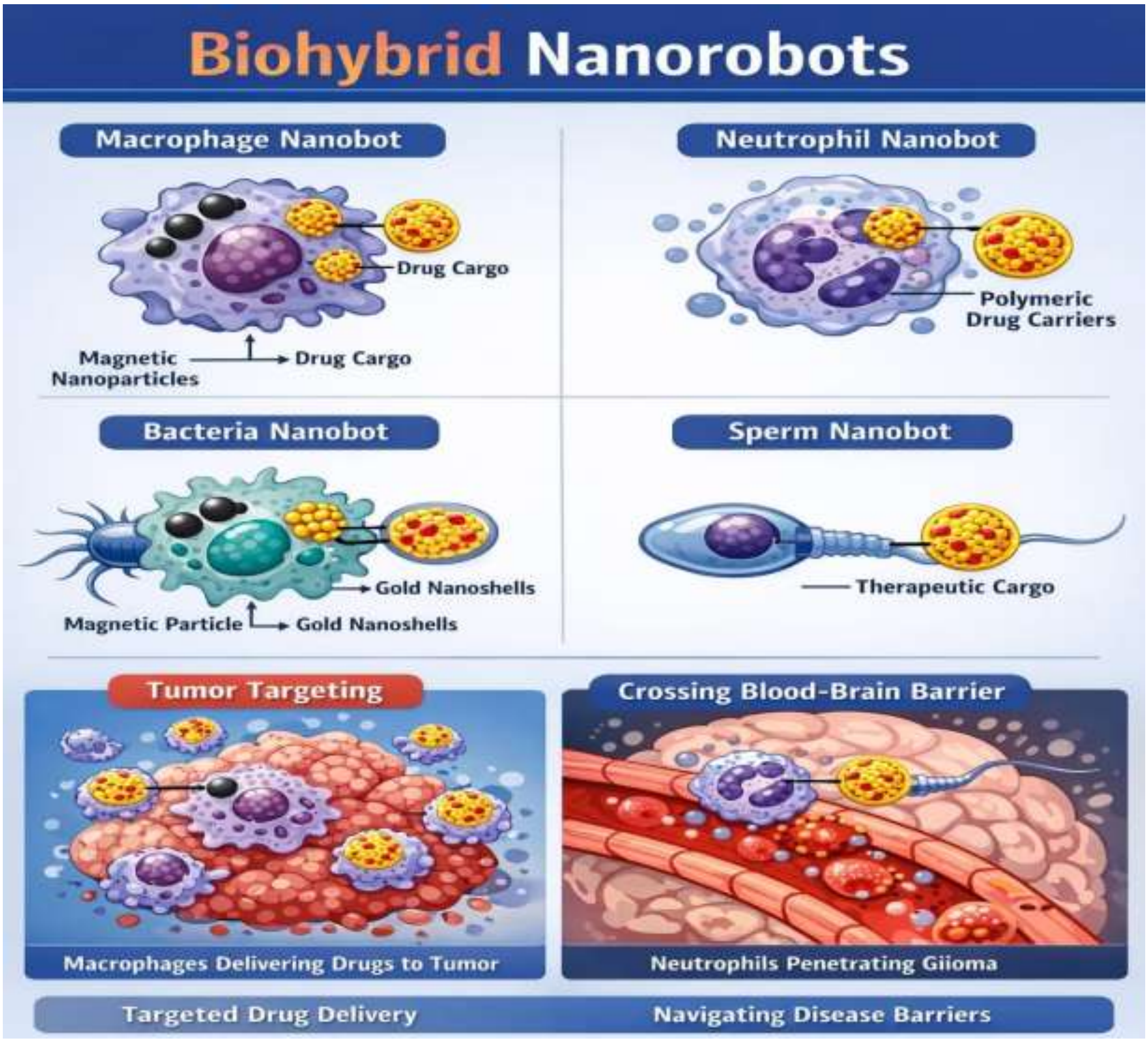


Figure No 6. Biohybrid Nanobots

5. Injectable Nanorobots:-

Injectable nanorobots are conceptual nanoscale devices designed to be administered into the body via conventional injection methods. Due to their extremely small size, often smaller than human cells, these nanobots can freely circulate through the bloodstream and reach otherwise inaccessible regions of the body.

The primary objective of injectable nanorobots is precision medicine, where therapeutic actions are confined strictly to diseased sites. Once they reach their programmed target, such as a tumor, infected tissue, or clogged artery, they can release drugs, mechanically disrupt pathological structures, or assist in tissue repair. This targeted approach significantly reduces adverse side effects, enhances treatment efficacy, and accelerates recovery.

Although many injectable nanorobots remain in the experimental or conceptual stage, ongoing advances in nanofabrication, materials science, and artificial intelligence continue to bring this vision closer to clinical reality. Injectable nanorobots symbolize the future of medicine as an internal, autonomous, and highly precise therapeutic system operating at the cellular level [22,23].

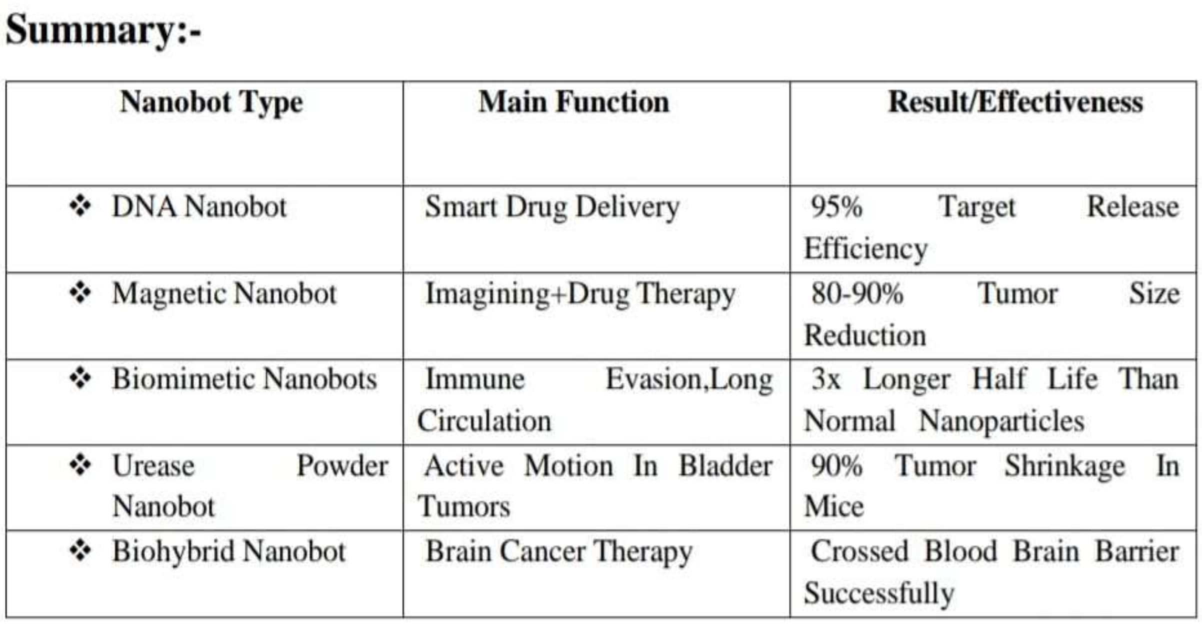
Figure No 7. Injectable Nanorobots

Mechanism of action :-

Nanobots rely on a complex network of mechanisms to improve the accuracy, effectiveness, and safety of therapeutic interventions. These nanoscale technologies were created to move in the human body with extreme accuracy and target the desired cells—that is, the cancer cells—in order to bring about the far more precise and effective administration of medications compared to the traditional ones. In the instance of cancer therapy, the nanobots can be used to deliver the required medications to the precise targets. One of the fundamentals is the avoidance of undesirable effects by converting the external surfaces of nanobots into selection mechanisms for medication administration.

The covalent attachment of target ligands (such as antibodies, peptides, or tiny molecules) that are highly specific to the markers or receptors expressed by cancer cells on the surface of the nanobots may clog them or otherwise functionalise them. For example, the therapeutic payload is administered by nanoparticles that have anti-cancer antibodies attached to them, causing them to bind to the cancer cells precisely. The approach lowers systemic toxicity by increasing medication concentration in the tumour site while decreasing off-target effects through ligand-receptor interaction. Controlled, triggered drug release is another method that nanobots employ to distribute specific medications. Stimuli-sensitive nanobots are designed to respond to requests based on the state of a specific location. Their use as therapeutic release agents may result in the formation of circumstances like low pH, hypoxia, or increased enzyme activity in the microenvironments of tumours. pH-sensitive nanobots could be chosen for transportation in the acidic environment of the solid tumour in contact. Furthermore, thermal triggers can be used in conjunction with photothermal therapy when the nanobots help kill cancer cells by producing heat and administering medication[13].

Nanobot applications in cancer treatment:-



Summary:-

Nanobot Type	Main Function	Result/Effectiveness
❖ DNA Nanobot	Smart Drug Delivery	95% Target Release Efficiency
❖ Magnetic Nanobot	Imagining+Drug Therapy	80-90% Tumor Size Reduction
❖ Biomimetic Nanobots	Immune Evasion,Long Circulation	3x Longer Half Life Than Normal Nanoparticles
❖ Urease Powder Nanobot	Active Motion In Bladder Tumors	90% Tumor Shrinkage In Mice
❖ Biohybrid Nanobot	Brain Cancer Therapy	Crossed Blood Brain Barrier Successfully

One of the most notable features of nanobots is their ability to improve the precision and adaptability of traditional cancer treatments, which makes them an essential component of the cancer treatment plan. By targeting and reducing the side effects of radiation and chemotherapy, these nanoscale devices can improve cancer therapy by causing certain chemical molecules to strike cancer cells directly. The study areas of targeted medication delivery, immunotherapy enhancement, gene therapy, and diagnostics are the primary focus of the classification of nanobot applications in cancer therapy.

a) Targeted drug delivery:- Nanobots have been employed in cancer treatment for a number of years in a variety of ways. One of the most common uses of nanobots is the targeted delivery of pharmaceuticals. Because medications typically disperse non-specifically throughout the body, systemic toxicity is a common adverse effect of traditional chemotherapy. In order to lessen the negative effects on healthy cells, therapeutic drugs can be encapsulated in nanobots and then transferred to the cancer locations. Because the cancer locations are overloaded with the drugs, this delivery method yields the best treatment outcomes.

According to the latest research, nanobots have the unique ability to combat some pathogenic bacteria that have their stronghold in the brain, such as aggressive cancer types like glioblastomas. To the best of researchers' knowledge, it is unknown how doxorubicin-loaded nanobots cause tumours to accumulate through their pH-sensitive mechanisms. These microscopic devices can also be designed to deal with the unique environment of tumours. For instance, they will deliver their payloads precisely on the designated regions because to the high acidity or low oxygen levels.

b) Immunotherapy enhancement:- Nanobots have the potential to improve cancer immunotherapy as well. They can increase the efficacy of therapies. intended to assist the immune system in identifying and target cancer cells by administering immune cytokines, altered T cells, or checkpoint inhibitors to tumours. This strategy is particularly beneficial for tumours that avoid detection by the immune system. Nanobots may also carry adjuvants or vaccinations to encourage the immune system, resulting in a stronger assault on tumour cells.

c) Gene therapy:- Gene therapy is an intriguing use of nanobots. They can introduce molecules of DNA or RNA into cancer cells to change their genetic composition. This might entail making genetic flaws, inhibiting genes that promote tumour growth, or increasing the output of cancer-fighting proteins Nanobots are especially helpful in overcoming obstacles such as safeguarding genetic stuff from deteriorating before it gets to its intended destination. They clear the path by resolving these delivery problems. for gene-based cancer treatments that are more successful. The delivery of CRISPR-Cas9 gene-editing instruments by Nanobots to specifically modify cancer cells' DNA One recent advancement is cells.

d) Diagnostic and imaging applications:- Nanobots are also employed as diagnostic agents for cancer detection and therapy progress tracking. By adding particles that can sense fluorescent lights, X-rays, and fields, nanobots are intelligent enough to improve magnetic procedures. Consequently, magnetic resonance imaging will enable early tumour detection and therapeutic efficacy monitoring. Additionally, they may have receptors for specific biomarkers linked to cancer, which could result in more precise and timely cancer diagnosis and therapy tracking. By adding particles that can sense fluorescent lights, X-rays, and fields, nanobots are intelligent enough to improve magnetic procedures.

e) Minimally invasive surgery:- Nanobots are a non-invasive substitute for conventional surgical techniques. They shorten the healing period and eliminate the necessity for extensive cellular-level incisions by using precision targeting. This is very helpful for treating brain tumours and other sections of the body that are inaccessible, like brain surgery. They shorten the healing period and eliminate the necessity for extensive cellular-level incisions by using precision targeting. This is very helpful for treating brain tumours and other body areas that are inaccessible

f) Overcoming multidrug resistance:- Another use of nanobots in the field of cancer treatment is overcoming multidrug resistance (MDR). Nanobots reach the deeper parts of the malignant process by drug transport to cancer cells or by interfering with the action of such efflux pumps, which are the main cause of MDR. One of the main obstacles to very effective chemotherapy is multidrug resistance in cancer cells. Certain treatments are less effective because of efflux pumps, such P-glycoprotein, which actively remove medications from cancer cells. By delivering the medications straight to the cancer cells or interfering with the pumps, nanobots have been created to combat this resistance.

g) Synergistic (combination) therapies:- A novel technology that integrates many treatments on a single platform is based on nanobots. They can be used in place of immune-modulatory medications, chemotherapeutic medicines, or other combinations that are specific to each tumour. Resistance is the biggest issue with cancer medications, although it can be addressed with a variety of strategies[13].

Advantages of Nanorobots in Cancer Therapy :-

1.Targeted drug delivery:- Nanorobots can selectively recognize cancer cells and deliver anticancer drugs directly to tumor sites, which improves therapeutic efficiency and minimizes damage to healthy tissues [24].

2.Reduced side effects:- By limiting systemic distribution of chemotherapeutic agents, nanorobots significantly reduce common side effects such as toxicity to normal cells and immune suppression [25].

3.Improved tumor penetration:- Due to their nanoscale size and active movement, nanorobots can penetrate dense tumor microenvironments more effectively than conventional drug carrier[26].

4.Controlled and sustained drug release:- Nanorobots enable controlled release of drugs at the target site, ensuring optimal dosage over time and reducing drug wastage [24].

5.Real-time monitoring:- Nanorobots can be designed with biosensing capabilities to monitor tumor response during treatment, allowing timely adjustments in therapy [26].

Challenges and limitations in the use of nanobots in Cancer Therapy:-

a) Toxicity and biocompatibility:- One of the biggest challenges of employing nanobots for cancer treatment is ensuring that they are biocompatible. Even though nanobots can be specifically designed to target cancer cells, the materials used to construct them may still be dangerous to healthy tissues. Because some nanomaterials are linked to symptoms that are often associated with inflammation or oxidative stress in organ tissue, their long-term toxicity is a worry.

b) Immunogenbots:- The immune system may be activated by immunogenbots and their component parts, which could result in immunogenicity issues. By identifying the nanobots as foreign material, the immune system can launch an attack on them. The nanobots might be eliminated from the body too soon, which would make them less beneficial.Additionally, inflammation could result from an activated immune system.

c) Delivery and distribution issues:- It is still very difficult to deliver nanobots that successfully target the location of tumours. Even though nanobots are tiny, there is no guarantee that enough of them will reach the tumour site. The ability of nanobots to find and enter tumours may be impacted by tumour heterogeneity, or the variations in the size, shape, and blood supply of different cancer types.1 Tumour heterogeneity, which results from variations in the size, shape, and blood supply of the various cancer kinds, can also slow down the racing of the nanobots to the tumour zone.

d) Ethical and legal concerns:- Obtaining regulatory approval for nanobots is another significant obstacle. Regulatory agencies like the Food and Drug Administration (FDA) have little experience assessing the safety and effectiveness of nanomedicines because they are still in their infancy. Creating standardised procedures for nanobot approval is crucial and difficult, in addition to comprehensive preclinical and clinical testing. The employment of nanobots in the human body is still regarded as a long-term intervention with ethical issues, particularly when considering the possible unintended consequences of genetic modification or nanobot particles migrating to unintended sections of the body.

e) Scalability and manufacturing costs:- The cost of producing nanobots in large quantities at competitive rates is another drawback. Nanobot construction necessitates carefully regulated materials and procedures, which are typically costly and time-consuming. Furthermore, production consistency and repeatability are critical to the safety and effectiveness of nanobots. Despite the development of nanofabrication techniques, there are still some financial and technological obstacles to large-scale production.

f)Limitations in Production, Costs, and Toxicology:- One of the main obstacles to ensuring the success of nanopharmaceuticals is the economy. Their products are particularly costly due to the high price of the production process and raw ingredients. For instance, the cost of producing medications like AbraxaneTM and DoxilTM is significantly higher than that of its free-drug equivalents, paclitaxel and doxorubicin. It is projected that the complete process of commercialising a revolutionary nanodrug will cost over $1 billion and take over 10 to 15 years. Therefore, the clinical advantages of nanomedicines should be evident to support their greater cost as compared to traditional treatments[13].

Current Clinical Research and Progress of Nanorobots in Cancer Therapy:-

1. Preclinical Studies:-

Most progress in nanorobot-based cancer therapy has been achieved at the preclinical level. Laboratory and animal studies demonstrate that nanorobots can be engineered to actively navigate biological environments, selectively target tumor tissues, and release therapeutic agents in a controlled manner. These studies report improved tumor accumulation, enhanced drug penetration, and reduced systemic toxicity compared with conventional chemotherapy, highlighting the strong therapeutic potential of nanorobots before human application[24].

2. Experimental Models of Nanorobots in Cancer:-

Experimental cancer models, including cell cultures and tumor-bearing animal models, are widely used to evaluate nanorobot performance. Magnetically guided nanorobots, enzyme-powered nanomotors, and biohybrid nanorobots have shown the ability to penetrate dense tumour microenvironments, disrupt cancer cell membranes, and enhance intracellular drug uptake. These experimental models confirm that active nanorobot movement provides superior targeting efficiency compared to passive nanocarriers [27].

3. Ongoing Clinical Trials:-

At present, fully autonomous nanorobots have not yet entered large-scale human clinical trials. However, several nanorobot-inspired technologies, such as targeted nanoparticles and biohybrid nanocarriers (e.g., exosome-based systems), have progressed into early-phase clinical trials. These trials primarily assess safety, biodistribution, and preliminary therapeutic efficacy in cancer patients. The absence of direct nanorobot trials reflects ongoing challenges related to biosafety, control, and regulatory approval [24,28].

4. Comparison with Other Nanomedicine Approaches:-

Compared to conventional nanomedicine approaches such as liposomes and polymeric nanoparticles, nanorobots offer active motion and navigation, enabling deeper tumor penetration and more precise drug delivery. Traditional nanomedicines rely mainly on passive diffusion and the enhanced permeability and retention (EPR) effect, which can be inconsistent across tumor types. In contrast, nanorobots can be externally guided or self-propelled, potentially achieving higher targeting accuracy and therapeutic efficiency. Despite these advantages, nanorobots remain less clinically mature than established nanomedicine platforms, which already have several FDA-approved formulations [28].

Future directions:-

a) Integration with new technologies:- A growing number of nanobots are made to work in tandem with cutting-edge technologies like artificial intelligence, machine learning, and organ-on-a-chip models. By evaluating massive amounts of biological data, AI systems can improve the design and optimisation of nanobots, enabling more accurate targeting of mutations specific to cancers and individualised treatment.Furthermore, before clinical trials are conducted, nanobots with organ-on-a-chip models can produce realistic preclinical testing environments that can aid in predicting the behaviour of nanobots in human tissues [108].109. These could improve the therapeutic efficacy of nanobots in cancer treatment, speed up research, and streamline design procedures.

b) Intelligent nanobots and accurate targeting:- The foundation of nanobots' potential in cancer treatment is their capacity to deliver medications or therapeutic agents with a high degree of precision.Researchers are working on creating "smart" nanobots that react to particular stimuli in the tumour microenvironment, such as pH, temperature, or specific enzymes that cancer cells overexpress. By using responsive material, these nanobots would be able to make decisions and then release drugs to the tumour spot without harming healthy cells. This would reduce the side effects of traditional chemotherapy. Additionally, the accuracy of nanobot-based treatments will be improved by the development of selective targeting of tumour markers, such as those found on cancer stem cells or circulating tumour cells.

c) Personalised medicine:- Nanobots have a lot of potential in precision medicine, especially when it comes to treating cancer. These nanobots can be used in conjunction with genetic and proteomic data to enable highly customised treatments. AI is essential for improving the nanobots' ability to accurately target tumor-specific mutations. Recent developments have demonstrated that AI can direct nanobots to target cancer and deliver the necessary treatment for more potent cancer treatments by taking into account both genetic and proteomic data.

d) Treatment combinations:- Using nanobots for combination treatments is another exciting path. By co-delivering a variety of therapeutic chemicals, such as immune checkpoint inhibitors, chemotherapeutic drugs, or even genetic material like siRNA or CRISPR-Cas9 components, nanobots could concurrently target cancer cells from many angles. Such a strategy might be the only way to address the most serious issue with traditional anti-cancer treatments: drug resistance. For example, nanorobots can be employed as delivery systems for immune system repair by administering targeted pharmaceuticals to combat tumour cells and administering chemotherapy treatments. This alternative, which consists of many components, may be the most effective cancer medication and the state-of-the-art in study for those who encounter this illness once more.

e) Real-time monitoring and feedback:- Future developments in nanobots are likely to include real-time monitoring capabilities. Nanobots with sensors could track changes in the tumour microenvironment, cancer markers, and the effectiveness of medicine administration.

f) Nanobot-mediated immunotherapy:- Immunotherapy has transformed cancer treatment, and nanobots may improve it even further. Nanobots can deliver immuno-checkpoint inhibitors, cytokines, or altered T cells directly to the tumour location. By specifically controlling the production of those immune-modulating substances, nanobots may be better able to convince the body to defend itself by eliminating the immune detection resistance mechanisms of cancer cells. Additionally, employing nanobots in conjunction with CAR-T (chimeric antigen receptor T-cell) therapy will result in more effective and focused immune responses. When it comes to cancer immunotherapy, nanobots can be quite beneficial.

g) Overcoming drug resistance:- A nanobot is one of the most effective ways to manage the issue of cancer cells' resistance to drugs. Tumour cells that become accustomed to chemotherapy medications are created under the presence of changing how pharmaceuticals function in the human body or allowing drugs to be released before they start to take effect. The nanobots' gene expression can be altered or they can be programmed to co-deliver many medications in order to get around these processes. An excellent illustration of this would be the use of nanobots in conjunction with chemotherapeutic medications to deliver small interfering RNAs (siRNAs), which quiet the genes responsible for drug resistance and boost treatment effectiveness.

h) Developments in ethics and regulations:- Nanotechnology for cancer treatment requires the development of juridical and ethical frameworks in tandem with the science. Future advancements will require extensive processes for clinical testing, safety evaluations, and long-term monitoring of nanobot-based therapeutics[13].

Ethical, Legal and Social Implications of Nanorobots in Cancer Therapy:-

1. Patient Safety and Long-Term Effects:-

Patient safety is a primary ethical concern in the development of nanorobots for cancer therapy. Since nanorobots are designed to operate inside the human body, uncertainties remain regarding their long-term biocompatibility, potential toxicity, immune system activation, and accumulation in organs. Current preclinical studies focus mainly on short-term outcomes, while long-term effects such as chronic inflammation, genetic damage, or unforeseen interactions with biological systems are not yet fully understood. Ensuring patient safety therefore requires extensive long-term studies before widespread clinical use [24,28].

2. Regulatory Framework:-

The regulation of nanorobots presents significant legal challenges because these systems combine features of medical devices, pharmaceuticals, and advanced robotics. Existing regulatory frameworks, such as those of the U.S. Food and Drug Administration (FDA) and the European Medicines Agency (EMA), are not fully tailored to autonomous or semi-autonomous nanorobotic systems. Regulatory agencies must establish clear guidelines for safety testing, manufacturing standards, clinical evaluation, and post-market surveillance. The lack of specific regulations currently slows clinical translation and raises concerns about accountability and liability in case of adverse events [29].

3. Public Acceptance and Cost Issues:-

Public acceptance plays a crucial role in the successful adoption of nanorobot-based cancer therapies. Concerns related to safety, ethical use, and loss of control over autonomous technologies may affect patient trust. Additionally, the high cost of research, development, and large-scale manufacturing of nanorobots could limit accessibility, especially in low- and middle-income countries. Without equitable pricing strategies and transparent communication, nanorobot therapies risk increasing existing healthcare disparities [28,30].

CONCLUSION

Nanorobots represent a revolutionary leap in precision medicine, offering a targeted alternative to traditional cancer treatments by delivering therapeutic agents directly to tumor cells while sparing healthy tissue. These nanoscale devices can actively navigate complex biological environments and overcome formidable barriers like the blood-brain barrier, making them particularly effective for hard-to-reach malignancies. While currently most successful in preclinical stages, the integration of nanorobots with Artificial Intelligence (AI) and personalized medicine promises highly customized treatments tailored to an individual’s genetic profile. However, widespread clinical adoption still faces significant hurdles, including concerns over long-term biocompatibility, high manufacturing costs, and the need for standardized regulatory frameworks to ensure patient safety.

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