

Nanorobot-Mediated Targeted Therapy in Neuro-Oncology

Choudari Tarun*¹, Sasubilli Akshaya², Dr. P. Shailaja³, R. Sandhya Jyothi⁴

^{1,2} Student, AU College of Pharmaceutical Sciences, Andhra University, Visakhapatnam, Andhra Pradesh, India.

³ Associate Professor, AU College of Pharmaceutical Sciences, Andhra University, Visakhapatnam, Andhra Pradesh, India.

⁴ Research Scholar, AU College of Pharmaceutical Sciences, Andhra University, Visakhapatnam, Andhra Pradesh, India.

*Corresponding Author, Email: tarunlucky225@gmail.com

Abstract - Brain tumors are considered some of the most critical and difficult cancers to treat because of their rapid growth, intricate location within vital brain structures, and the presence of the blood-brain barrier (BBB), which limits the entry of many therapeutic agents. Even with improvements in diagnostic imaging, neurosurgical techniques, radiation therapy, and chemotherapy, outcomes, especially in aggressive conditions like glioblastoma, remain unsatisfactory. Traditional treatments often struggle with limited drug accumulation at the tumor site, unwanted systemic side effects, and poor penetration across the BBB. Recent progress in nanotechnology has introduced nanorobotics as a novel strategy in neuro-oncology. Nanorobots are engineered microscopic devices designed to move within biological systems, deliver drugs directly to diseased tissues, and assist in diagnostic monitoring. They can be constructed from a range of materials, including biodegradable polymers, metallic components, and DNA-based structures, and may integrate intelligent control systems for guided navigation. By employing both passive accumulation and active targeting mechanisms, these systems improve precision in tumor localization, increase therapeutic payload delivery, and allow controlled drug release triggered by specific biological signals. Some advanced models, such as enzyme-driven or cell-mediated platforms, have shown encouraging ability to traverse the BBB and penetrate deeply into tumor tissue. Beyond brain tumors, nanorobotic technologies are being explored for applications in infectious diseases, cardiovascular conditions, kidney disorders, and inherited illnesses. Although issues related to safety, large-scale production, regulatory approval, and ethical considerations must be carefully addressed, nanorobotics holds considerable promise as a future tool for highly targeted and personalized treatment in brain tumor management.

Key Words: Nanorobots, Blood-Brain Barrier, Glioblastoma, Targeted Drug Delivery, Nanomedicine.

1. INTRODUCTION

Cancer remains one of the leading causes of mortality worldwide, accounting for approximately one in every six deaths globally. Current projections estimate that by 2030 the global burden of cancer may reach nearly 26 million newly diagnosed cases, with close to 17 million deaths occurring annually [1]. Extensive research in genetic and molecular architecture indicates that changes in lifestyle patterns, dietary habits, and environmental exposures have collectively contributed to the steady rise in cancer incidence [1]. Among the various malignancies, tumors that originate within or metastasize to the nervous system represent some of the most serious contributors to cancer-related mortality and long-term neurological disability [2]. According to the GLOBOCAN 2020 database, tumors of the brain and central nervous system (CNS) rank 19th in global incidence and 12th among causes of cancer-related death, contributing nearly 2.5% of total oncology mortality worldwide [1]. Over the past two decades, the incidence of brain tumors in adults has increased by more than 40%, with the highest reported rates occurring in Northern Europe and comparatively lower rates observed in several African regions, largely due to differences in diagnostic access, genetic background, and healthcare infrastructure [1]. Overall mortality associated with brain tumors remains considerable at approximately 3.4 deaths per 100,000 population, and the growing disease burden is increasingly associated with population aging, urbanization, and evolving lifestyle factors [3]. In general, brain tumor incidence is higher in Western populations and developed countries such as Australia, North

America, and Northern Europe, whereas lower rates are reported in many African regions [4].

Brain cancer is characterized by uncontrolled and abnormal cellular proliferation within the brain or its surrounding tissues, resulting in tumor masses capable of disrupting normal neurological function [3]. Brain tumors are broadly classified as primary tumors, which originate within the brain parenchyma or supporting structures such as glial cells and vasculature, and metastatic tumors that arise from malignancies located elsewhere in the body and spread to the brain through hematogenous dissemination, most commonly from lung or breast cancer [3]. The World Health Organization (WHO) grading system categorizes brain tumors into four histopathological grades, where Grades I and II are considered low-grade tumors and Grades III and IV represent highly aggressive malignancies [3]. Neurological manifestations associated with brain tumors arise through multiple mechanisms, including tissue infiltration, compression of normal brain structures, and disruption of essential neural pathways [5]. Because the brain is enclosed within the rigid cranial vault, progressive tumor growth and associated edema frequently result in elevated intracranial pressure, while lesions near the ventricular system may obstruct cerebrospinal fluid circulation and lead to obstructive hydrocephalus [5]. Several factors have been associated with an increased risk of brain cancer, including radiation exposure, genetic predisposition, hormonal influences, nutritional patterns, alcohol consumption, smoking, immune system status, and possible exposure to mobile radiation [4].

Despite considerable advances in diagnostic techniques such as imaging, molecular detection methods, and immunohistochemistry, several limitations remain in accurately detecting and characterizing brain tumors in certain clinical settings [1]. Glioblastoma multiforme, for instance, remains one of the most lethal malignancies with a median survival of only 12–15 months even with intensive treatment approaches [6]. Conventional imaging modalities including MRI and CT scans often face challenges in identifying very small lesions and in accurately evaluating therapeutic response [7]. Furthermore, many aggressive brain tumors continue to exhibit poor prognosis despite multimodal treatment strategies. One of the most significant barriers in the treatment of brain tumors is the presence of the blood–brain barrier (BBB), which severely restricts the delivery of therapeutic agents from systemic circulation into brain tissue. It is estimated that more than 98% of small-molecule drugs and nearly all macromolecular therapeutics fail to effectively cross the BBB, significantly limiting treatment efficacy [8]. In addition, systemic drug administration often results in off-target distribution and significant systemic toxicity [8]. An ideal brain-targeted drug delivery system should therefore possess high targeting specificity, efficient BBB penetration, strong drug-loading capacity, controlled drug release, and excellent biocompatibility [8]. Although conventional delivery systems and nanocarriers have attempted to address these challenges through passive targeting and surface modification strategies, substantial limitations still persist in achieving precise and efficient drug delivery to brain tissues [8].

Recent advances in nanotechnology have opened new possibilities for improving the diagnosis and treatment of neurological disorders and cancers. Nanotechnology focuses on the manipulation and engineering of materials at the nanoscale and has emerged as a rapidly expanding field in biomedical research [5]. Over the past few decades, it has also become a major technological driver in multiple areas including electronics, environmental monitoring, and nanomedicine [9]. The field has evolved beyond conventional drug delivery platforms toward the development of advanced "smart" nanodevices capable of sensing, actuation, and controlled therapeutic response [7]. Among these emerging technologies, medical micro- and nanorobots (MNRs) have attracted significant attention due to their ability to navigate complex biological environments and deliver therapeutic agents directly to diseased tissues. These miniaturized systems operate at micro- and nanoscale dimensions and are engineered to access anatomically challenging locations such as cerebral vasculature, where they can perform specialized biomedical tasks including targeted drug delivery, microsurgical intervention, and diagnostic monitoring either autonomously or through external control using magnetic fields, ultrasound, light, thermal energy, or electrical stimuli [8].

Therefore, the article aims to review the design principles, technological advancements, and therapeutic potential of nanorobots in improving targeted drug delivery and treatment outcomes in brain cancer.

2. NANOROBOTS: CONCEPT, CLASSIFICATION, AND DESIGN

2.1. Overview and Historical Background

- The term "nano" was popularized by Nobel Prize-winning physicist Richard Feynman in his landmark lecture, *There's Plenty of Room at the Bottom*, where he emphasized the vast potential of engineering at extremely small scales and predicted its inevitable development. Since that time, nanotechnology has expanded into diverse domains, including diagnostics, advanced materials, and therapeutic systems. The word nanotechnology itself was formally introduced by a student at a Tokyo science university in 1974. [10,11]
- Nanomedicine is now regarded as a transformative branch of healthcare that applies nanoscale science and engineering principles to develop advanced diagnostic and therapeutic platforms. [12]
- Over the last several decades, rapid progress in nanomedicine has demonstrated major potential in oncology, with nanorobots emerging as a particularly innovative approach for precision targeting and minimally invasive therapeutic intervention. [1]
- The concept of nanorobots combines "nano," referring to dimensions at the nanometer scale, and "robot," denoting a programmable machine capable of executing defined functions. [12]
- Nanorobotics—also referred to as nanobotics—is an evolving discipline focused on the design and fabrication of machines at approximately 10^{-9} meter scale. These devices, typically ranging from 0.1 to 10 micrometers in size, are assembled from nanoscale or molecular components and are also described as nanobots, nanites, or nanomachines. [12]
- Nanorobots are generally defined as autonomous nanoscale constructs capable of navigating biological environments, and they represent one of the most promising practical extensions of nanomedicine. Their ability to access anatomically restricted regions enables highly selective and localized medical intervention. [12]
- Bionanorobots are nanoscale devices developed using biological materials such as peptides and DNA frameworks. These biologically derived systems are intended to address complex biomedical challenges through programmable and adaptive behavior. [13]
- These nanoscale systems, commonly measuring between 0.1 and 10 micrometers, can circulate through the bloodstream, identify malignant cells, and deliver therapeutic payloads with high spatial precision. Importantly, their capacity to traverse biological barriers—including the BBB—allows them to reach sites that are otherwise difficult to access using conventional delivery systems. [14]
- Nanorobots are therefore being actively explored for targeted drug delivery and for the management of neurological disorders, particularly in applications that require BBB penetration. [14]
- Current nanorobot designs for neuro-diagnostics and neurochemotherapy are often engineered within a 10–100

nm size range to facilitate BBB passage and effective cellular interaction. Frequently used platforms include DNA origami architectures, biocompatible polymer systems, and functionalized carbon nanotubes. Propulsion strategies vary and may involve externally applied magnetic fields, chemical gradients, or biologically derived motor mechanisms. [7]

- Conventional diagnostic technologies typically detect tumors only when they exceed about 5 mm in diameter, whereas nanorobot-assisted techniques have the potential to identify lesions as small as approximately 1 mm. [7]
- Such nanocarrier and nanorobot systems enhance drug solubility, physicochemical stability, and tumor-site localization. The incorporation of stimuli-responsive materials further improves therapeutic precision and release control. Nanobots play a significant role in modern cancer strategies by detecting malignant growths, penetrating protective biological barriers, and delivering therapeutic agents with high accuracy. [15]
- Integration of artificial intelligence and machine learning is further expanding nanorobot capability in navigation control, target recognition, and payload delivery across the BBB, while simultaneously reducing the risk of unintended toxicity. [14]

2.2. Types of Nanorobots

- **Organic Nanobots:** Also called bio-nanorobots, these are produced using biological entities such as viral or bacterial DNA systems and are generally associated with lower toxicity to living organisms.
- **Inorganic Nanorobots:** These are fabricated using non-biological materials and protein-based synthesis approaches, often forming rigid, diamond-like structural frameworks.
- **Respirocytes:** Respirocytes are artificial red-blood-cell-like nanorobots about 1.4 μm in diameter, designed to store and transport up to billions of oxygen and carbon dioxide molecules, potentially exceeding the gas-carrying capacity of natural RBCs.
- **Microbivores:** Also termed nanorobotic phagocytes, these function as artificial white blood cells and are typically constructed from durable materials such as diamond and sapphire.
- **Clottocytes:** Clottocytes act as artificial hemostatic agents and may function 100–1000 times faster than the natural clotting system. They release biodegradable mesh at injury sites after detecting pressure changes.
- **DNA Nanorobots:** These are created using layered DNA strand folding techniques (DNA origami) to produce flexible, programmable nanostructures.
- **Biohybrid Nanorobots:** These consist of biological components integrated with electronically generated wave systems that support rapid and directed movement.
- **Diamondoid Mechanosynthesized Nanorobots:** As described by Robert A. Freitas, these nanorobots are built with atomically precise, diamondoid structures with positionally controlled assembly from start to finish.

- **Assembler:** Assemblers are basic, cell-like nanobots capable of arranging atoms or molecules in defined configurations under specialized programmed control.

- **Self-Replicator:** These are advanced assembler-type nanobots capable of producing copies of themselves rapidly and at large scale. [13]

2.3. Ideal Characteristics of Nanorobots

- Nanorobots should typically measure between 0.5 and 3 microns, with internal components in the 1–100 nm range.
- Devices larger than this may obstruct capillary circulation.
- They should avoid immune attack by using passive, diamond-like outer surfaces.
- They should be able to communicate with clinicians by encoding information into acoustic signals within 1–100 MHz carrier frequencies.
- They may have the capability to generate replacement units through self-replication when components wear out. [10]

2.4. Design Principles of Nanorobots

- The medical design of nanobots requires collaboration across multiple disciplines. Choice of material is crucial for ensuring biocompatibility, structural strength, and stimulus responsiveness. Common options include DNA frameworks, polymer systems, carbon nanotubes, and metallic nanoparticles, each selected based on features such as flexibility, ease of functionalization, or responsiveness to magnetic or acoustic control.
- Propulsion strategy is another key factor. Nanobots must move through viscous biological environments where microscale fluid forces dominate. Movement can be achieved through chemical reactions, magnetic steering, acoustic waves, or light-driven systems.
- Targeting design is equally important. Surface functionalization with ligands, antibodies, or aptamers allows nanobots to recognize specific receptors or disease markers, ensuring selective payload delivery and minimizing injury to healthy tissues. [16]

2.5. Materials and Components

- The structural body of a nanorobot is generally built from biocompatible materials that do not trigger immune rejection. Frequently used materials include gold, silver, and platinum because of their compatibility and ease of surface modification.
- Biodegradable polymers such as PEG and PLGA are also widely used due to their flexibility and safe degradation profiles.
- Liposomes are another commonly used structural platform in nanorobotic systems.
- Because of their extremely small size, nanorobots cannot rely on conventional batteries; instead, many are powered through wireless electromagnetic energy transfer.
- Sensors are essential components that allow nanorobots to detect environmental signals such as chemical levels, pH, temperature, and bioelectric activity.

- Sensor data are processed using AI/ML algorithms to guide behavioral responses.
- Movement control is achieved using micromotors and micro-vibration systems. [17]

3. ADVANTAGES AND DISADVANTAGES OF NANOROBOTS

3.1. Advantages

- Useful for detecting very small or diffuse tumors at early stages.
- Helps lower false-positive findings and unnecessary biopsies.
- Supports personalized therapy selection. [7]
- Favorable cost–benefit potential.
- Environmentally friendly.
- Rapid task execution.
- Minimally invasive operation.
- Precise targeted drug delivery.
- Reduced harmful side effects. [12]
- High durability.
- Faster performance compared with larger robotic systems.
- Programmable self-replication capability. [1]

3.2. Disadvantages

- High development and production costs.
- Design and manufacturing complexity.
- Customization challenges.
- Privacy and data concerns. [12]
- Electrical components may generate stray fields that interfere with biological molecular recognition systems.
- Electrical nanorobots may be affected by outside electromagnetic interference.
- Potential misuse risk in terrorism contexts. [1]

4. DRUG LOADING AND TARGETING MECHANISMS

- Nanorobots (including micro/nanorobots, DNA nanostructures, and hybrid bio-systems) employ multiple payload loading approaches to transport therapeutic agents.
- Common loading methods include covalent linkage to the nanorobot framework, encapsulation or intercalation within structural cavities, adsorption onto chemically modified surfaces, and entrapment inside polymer coatings or liposomal shells integrated with the robot.
- DNA-based nanorobots enable highly precise loading of proteins, nucleic acids, small drug molecules, and even nanoparticles through programmable cavities and sequence-specific binding regions.
- For solid nanorobot systems made of metal, silica, or polymers, drugs and prodrugs are often attached through surface functional groups such as thiol, silane, or carboxyl chemistries for controlled later release.

- Targeting strategies are broadly divided into two categories: (1) passive targeting, which depends on physiological conditions such as the enhanced permeability and retention (EPR) effect that allows accumulation in tumor tissue; and (2) active targeting, where nanorobots are decorated with ligands like antibodies, peptides, or aptamers to recognize specific cellular markers, or are externally guided using magnetic, acoustic, or optical fields.

- Motile nanorobots add further precision by actively navigating toward difficult microenvironments, such as hypoxic tumor cores or biofilm interiors, through autonomous or externally triggered movement. [18]

5. CROSSING THE BLOOD–BRAIN BARRIER

5.1. The Blood–Brain Barrier: A Major Limitation and Nanorobot Strategies to Overcome It

- The blood–brain barrier (BBB) is a highly selective interface formed by cerebral capillary endothelial cells, basement membrane, astrocyte end-feet, and pericytes. It maintains brain homeostasis by allowing only limited passage of small lipophilic molecules, thereby greatly restricting drug delivery to brain tissue.
- As a result, developing delivery strategies that can cross or bypass the BBB remains a major challenge.
- Current BBB-crossing approaches include: (i) carrier-mediated transport systems such as glucose transporter-1 (GLUT1) and L-type amino acid transporter-1 (LAT1); (ii) receptor-mediated transport pathways such as transferrin and insulin receptors; (iii) chemical modification strategies including liposomal systems and prodrug design; (iv) nanocarrier-based platforms; and (v) externally assisted disruption techniques such as focused ultrasound and near-infrared radiation, which enhance drug penetration into brain tissue.
- Since the brain consumes nearly 20% of the body's oxygen and glucose, the BBB tightly regulates nutrient transport channels, especially for glucose entry into neural tissue.
- Nanorobots have shown strong potential for precise navigation, deep tissue penetration, and stable drug carriage within cerebral blood vessels and cerebrospinal fluid, making them promising candidates for BBB traversal.
- Crossing the BBB remains one of the most critical research challenges in micro/nanorobot-based therapy. For example, Guan's group developed magnetic liquid metal microrobots by embedding iron nanoparticles into gallium–indium liquid metal matrices. This design merges shape adaptability with magnetic responsiveness, enabling successful BBB penetration. [8]

5.2. Mechanism of Action

- Nanorobots can recognize and analyze neuro-chemotherapy targets using multiple coordinated strategies.
- Active targeting is achieved through surface ligands that bind specific tumor markers—for example, antibodies directed against EGFR receptors on glioblastoma cells.

- Passive targeting occurs through the EPR effect, where leaky tumor vasculature allows nanorobots to accumulate preferentially at tumor locations.
- After reaching the target, sensing and therapeutic actions can be triggered on demand using external stimuli such as near-infrared light or focused ultrasound. [7]

5.3. Steps Involved in Diagnosis

Nanorobot-assisted diagnosis generally follows a structured sequence of steps:

- Nanorobot administration and biodistribution tracking, typically monitored through real-time imaging techniques.
- Navigation and localization at the tumor site through either active targeting or passive accumulation.
- Target recognition and attachment via surface derivatives present on nanorobots.
- Signal generation, such as fluorescence output or magnetic resonance signal alteration.
- Data collection and computational processing using specialized imaging systems and analytical software.
- Image reconstruction and interpretation, often supported by machine learning-based classification methods. [7]

6. CASE STUDY: TROJANBOT ENZYMATIC NANOBOT SYSTEM FOR GLIOBLASTOMA THERAPY

- A recent investigation introduced a multi-stage targeted delivery platform known as a Trojanbot to overcome BBB restriction and poor tumor penetration in glioblastoma.
- Scientists engineered doxorubicin-loaded gelatin nanoparticles coated with bacterial membrane vesicles and catalase to form enzyme-powered nanobots, which were then engulfed by neutrophils.
- Neutrophils acted as biological carriers, migrating across the BBB toward inflammatory tumor signals.
- After reaching the tumor environment, inflammatory triggers caused neutrophils to release the catalase nanobots, which used local hydrogen peroxide to generate oxygen and propel themselves deeper into tumor tissue.
- These particles demonstrated suitable nanoscale size (~200–330 nm), stable surface charge, strong drug loading, preserved enzyme activity, and pH-responsive drug release with faster release under acidic tumor-like conditions.
- In vitro BBB models showed substantially greater penetration for Trojanbots (about 30–50%) compared with free nanoparticles (<10%).
- In 3D tumor spheroids, the nanobots achieved deep penetration, induced strong tumor cell apoptosis, and caused spheroid breakdown while also lowering intracellular hydrogen peroxide and improving oxygenation.
- In glioblastoma animal models, Trojanbots achieved the highest tumor accumulation—around five times greater

than non-cellular nanobots—along with prolonged circulation and superior therapeutic outcomes.

- Overall, this study confirms that neutrophil-carried, enzyme-driven nanobot systems can achieve staged BBB crossing, deep tumor delivery, controlled release, and enhanced therapeutic benefit in aggressive brain tumors. [19]

7. THERAPEUTIC APPLICATIONS OF NANOROBOTS

- **Cancer treatment – targeted delivery and reduced side effects:** Nanorobots and programmable nano-systems provide active, site-specific cancer therapy by overcoming the limits of passive nanoparticles, such as low tumor accumulation and off-target toxicity. Two main approaches are used: (a) targeted payload delivery through molecular recognition and stimulus-responsive release; and (b) physical or mechanical tumor disruption, including localized energy release or vascular blockage.
- **Infectious diseases – pathogen detection and targeted antibiotic delivery:** Nanorobotic and smart nano-carrier systems improve antimicrobial treatment by binding pathogens selectively, breaking down biofilms, and releasing drugs locally. Motile micro/nanorobots can penetrate resistant biofilm layers and deliver high local antibiotic concentrations while reducing systemic exposure and resistance risk.
- **Neurological disorders – crossing the blood–brain barrier (BBB):** BBB penetration remains a major hurdle in CNS therapy. Ligand-functionalized nanoparticles, peptide-decorated carriers, and motile nanorobot-like systems have shown promise in transporting drugs and genetic cargo across the BBB via receptor-mediated transport, temporary tight-junction modulation, or region-specific delivery.
- **Cardiovascular diseases – plaque removal and clot dissolution:** Intravascular microrobots are under development for plaque clearance, localized thrombolytic delivery, and mechanical clot fragmentation with high positional accuracy. Untethered microrobots can be directed by magnetic or acoustic control toward blocked vessels.
- **Gene and cell therapy – precision at the cellular level:** Nanorobotic delivery improves gene and cell therapy by enhancing targeting accuracy, transfection efficiency, and release control. Functionalized nanoparticles and biohybrid microrobots can transport nucleic acids or CRISPR systems to selected cell populations while protecting cargo during transit.
- **Nanorobots in kidney diseases:**
 - i. Diagnosis and targeted therapy – Kidney disorders such as CKD and AKI are often detected late due to lack of sensitive biomarkers. Nanorobots equipped with biosensing units can detect renal markers like creatinine, urea, and cystatin-C in blood, enabling earlier diagnosis.
 - ii. Regenerative and detoxification functions – Nanorobots can also support renal tissue regeneration by controlled release of growth-promoting cytokines

such as VEGF and FGF to accelerate nephron repair. [18]

8. ETHICAL CONSIDERATIONS

- Clinical translation of nanorobot technology for brain disease treatment raises multiple ethical, regulatory, and technical concerns that must be carefully managed. Ethical frameworks should ensure that nanorobot deployment follows strict safety and responsibility standards.
- Regulatory authorities play an essential role in establishing approval pathways specific to nanorobot systems, including preclinical evaluation, risk assessment, and post-marketing surveillance to balance innovation with patient safety. [20]

Key ethical issues include:

- **Informed consent:** Because nanorobot technology is highly novel, explaining risks and benefits clearly to patients can be challenging.
- **Data security:** Molecular-level data collected by nanorobots must be strongly protected against misuse or breaches.
- **Equitable access:** Advanced nanorobot diagnostics and therapies should be accessible to all population groups, not only privileged sectors.
- **Incidental findings:** Highly detailed nanorobot diagnostics may reveal unexpected conditions, raising questions about disclosure and follow-up procedures. [7]

9. FUTURE PROSPECTS

- The future of nanocarriers and nanobots in cancer therapy appears highly promising. Continued advances in nanotechnology, materials science, and biomedical engineering are expected to substantially improve safety and effectiveness. Research is focusing on better targeting accuracy through biomarker integration and stimulus-responsive release systems. [15]
- Optimization of physicochemical parameters—such as size, shape, propulsion, surface chemistry, and drug functionalization—is crucial for improving BBB traversal in brain disorder therapy. [20]
- Future work should enhance imaging sensitivity and spatial-temporal resolution while improving compatibility between propulsion systems and imaging platforms to maintain precision and safety. [20]
- Close collaboration between materials scientists, AI specialists, and medical researchers is necessary to fully realize nanorobot capabilities in drug delivery, tumor detection, minimally invasive surgery, and early diagnosis. [21]
- Researchers should align nanorobot design with clinical oncology needs to accelerate translation from laboratory models to real-world applications. [21]
- Nanorobots are expected to evolve into integrated multi-purpose anticancer platforms in the near future. [21]
- Beyond oncology and surgery, medical nanobots are expanding into infectious disease management, tissue regeneration, and anti-aging interventions. As regulatory

pathways mature, nanobots are likely to reshape modern medicine through minimally invasive and highly targeted solutions. [22]

10. CONCLUSION

Brain tumors remain difficult to manage because early detection is often limited, drug delivery across the blood–brain barrier is restricted, and recurrence is common. Although surgery, radiotherapy, and chemotherapy are fundamental components of care, survival rates—particularly in highly aggressive tumors such as glioblastoma—are still unsatisfactory.

Nanorobot-based technologies present a promising alternative by integrating targeted movement, precise drug release, sensing capabilities, and minimally invasive action within a single system. Their capacity to cross the blood–brain barrier, concentrate within tumor tissue, and deliver therapy accurately helps overcome key weaknesses of conventional treatments. Preclinical studies, including enzyme-powered and biohybrid designs, show improved tumor targeting, deeper penetration, and greater therapeutic impact compared to standard nanocarriers.

Despite this potential, clinical application requires careful assessment of long-term safety, compatibility with biological systems, large-scale manufacturing feasibility, and appropriate regulatory and ethical frameworks. Continued collaboration across engineering, medical, and computational fields—along with advancements in intelligent control and targeting—will be essential. With these developments, nanorobotic systems could significantly advance early detection and personalized treatment in brain tumor care.

Author Contributions: Conceptualization, Ch. Tarun. and S.Akshaya.; literature review and writing – original draft Ch. Tarun.. and S.Akshaya.; writing – review and editing, Dr P.Shailaja. and R.SandhyaJyothi.; supervision, Dr P.Shailaja. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Informed Consent Statement: Not applicable. This article is a literature review and did not involve human participants.

Conflicts of Interest: The authors declare no conflict of interest.

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