

Nanotechnology-Based Pharmacological Treatment for Brain Tumors

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Abstract. One of the most aggressive forms of cancer, brain tumors, especially glioblastoma multiforme (GBM), have a short survival period and a high death rate. It is estimated that 94,390 new cases of primary brain and other central nervous system (CNS) tumors would occur in the United States alone in 2023. The blood-brain barrier's (BBB) protective role and the aggressive nature of GBM provide significant therapeutic challenges. The inability to accurately target tumor cells without harming nearby healthy tissue, poor drug penetration through the blood-brain barrier, and resistance to conventional therapies are some of the drawbacks of current treatments like radiation, chemotherapy, and surgery. A potential solution to these issues is drug delivery systems based on nanotechnology. Nanoparticles, such as carbon-based nanomaterials, liposomes, and polymeric nanoparticles, enhance drug solubility, target certain cells, and enable controlled release. Because of this, therapeutic medications can more easily cross the blood-brain barrier and build up at the tumor site, reducing systemic toxicity. With an emphasis on the advantages of various nanoparticle systems, such as liposomes, polymeric nanoparticles, stimulus-responsive nanoparticles, and carbon nanotubes, this study explores the application of nanotechnology in the treatment of brain tumors. The study examines the shortcomings of existing treatments for brain cancer and how nanodelivery systems can address these issues, ultimately providing a response to the following research question: How can drug delivery systems based on nanotechnology enhance the effectiveness of treatments for brain tumors?.

Keywords: Brain Tumors; Nanotechnology-Based; Treatment.

1. Introduction

About 15% of all primary brain tumors identified each year are brain tumors, with glioblastoma multiforme (GBM) being one of the most aggressive and deadly forms of malignancy. Due to the tumor's aggressive growth and ability to penetrate nearby brain tissue, complete surgical excision is nearly impossible for GBM patients, who nonetheless have a very poor prognosis with a five-year survival rate of less than 5% [1, 2]. GBM is particularly challenging to treat because it can evade conventional therapies such chemotherapy, radiation therapy, and surgery [3]. About 3 out of 100,000 persons in the US alone are affected by this aggressive cancer each year, and the incidence rate is significantly greater in high-income nations than in low-income ones [1, 2]. Due primarily to the restrictions imposed by the blood-brain barrier (BBB), the prognosis for people with GBM is still dismal despite advancements in medical technology and therapeutic approaches [3].

There are significant drawbacks to conventional GBM treatments, including as radiation, chemotherapy, and surgical resection. Despite being the first line of treatment in many cases, surgery is rarely curative because the tumor is infiltrative, making complete excision impossible [3]. The majority of GBM patients reported tumor recurrence after six months, even after maximal surgical resection, according to Montemurro et al., highlighting the significance of adjunct therapy to enhance results. Although radiation therapy is useful for destroying remaining tumor cells, it frequently seriously damages healthy brain tissue [4, 5]. During chemotherapy, especially when temozolomide is used, the BBB restricts the amount of medication that can reach the tumor location. Additionally, resistance to these medications is frequently developed by GBM cells, which eventually decreases the effectiveness of treatment [4, 5].

In particular, drug delivery systems based on nanoparticles that can get beyond the BBB's restrictions present a viable alternative to conventional treatment modalities. Liposomes, polymeric

nanoparticles, and carbon nanotubes (CNTs) are examples of nanoparticles that have been created to more efficiently deliver therapeutic medicines to brain tumors. Chemotherapeutic medicines' solubility, targeting, and sustained release are improved by these nanodelivery systems, which also reduce systemic toxicity and boost therapeutic efficacy [3]. In order to improve medication accumulation and tumor regression, Kong et al. created transferrin-conjugated PEGylated liposomes that bind to transferrin receptors that are overexpressed on the BBB and glioma cells, hence increasing the targeting of GBM cells. Likewise, Ko et al. examined the application of liposomes containing paclitaxel and anti-angiogenic medications in GBM to target the blood supply as well as tumor formation, and they discovered notable enhancements in anti-tumor efficacy .

Additionally, regulated drug release has been created for polymeric nanoparticles made of poly(lactic-co-glycolic acid) (PLGA), which extends the period that therapeutic agents remain in the tumor environment. Veronesi et al. discovered that in animal models of GBM, temozolomide-loaded PLGA nanoparticles enhanced drug transport across the blood-brain barrier and markedly decreased tumor size. Similar to this, research is being done to enhance targeted medication delivery using stimulus-responsive nanoparticles, which release their payload in response to changes in the pH or temperature of the tumor microenvironment [4, 5].

The creation of pH-sensitive nanoparticles for the treatment of GBM that release drug cargo in response to the acidic tumor microenvironment was detailed by Zhou et al. Lower systemic adverse effects and more tumor cell death resulted from this. Additionally, gold nanoparticles producing localized heat in response to near-infrared light have been used in photothermal therapy, where temperature-sensitive nanoparticles have been used to improve therapeutic efficacy and increase medication release accuracy.

The application of carbon-based nanomaterials, including carbon nanotubes (CNTs), in the treatment of brain tumors is also being researched. Chemotherapeutic medications can be encapsulated in CNTs for controlled drug release due to their large surface area and hollow shape. Transferrin-functionalized CNTs were developed by Liu et al. to deliver paclitaxel to glioma cells, improving drug accumulation and therapeutic outcomes. Additionally, CNTs have been investigated as biosensors for glioblastoma biomarker detection, providing a non-invasive approach for treatment monitoring and early identification [3]. An intriguing prospect for tailored treatment strategies in brain cancer therapy is presented by CNTs' dual function in drug transport and diagnostics [3].

In summary, nanotechnology-based drug delivery devices offer a promising alternative to traditional GBM treatment methods, which are limited in their effectiveness by tumor resistance mechanisms and BBB barriers. By enhancing drug transport across the blood-brain barrier and enabling the targeted, controlled release of therapeutic drugs, these devices have the potential to revolutionize the treatment of brain tumors. This study will examine several nanodelivery systems, including as carbon-based materials, liposomes, and polymeric nanoparticles, and how they can enhance the effectiveness of GBM treatment [1-3].

2. Background on brain tumors: current status, epidemiology and pathogenesis

Brain tumors continue to pose significant challenges within the realm of oncology, primarily due to their aggressive characteristics and the complexities associated with their treatment, which are exacerbated by the presence of the blood-brain barrier (BBB). In the year 2023, it is anticipated that approximately 94,390 new cases of primary brain tumors and other central nervous system (CNS) tumors will be diagnosed in the United States, with malignant tumors, particularly glioblastoma multiforme (GBM), contributing to the highest mortality rates [1, 2]. GBM is notably aggressive, with a five-year survival rate of merely 5%, a statistic that can be attributed in part to its ability to infiltrate adjacent tissues and exhibit resistance to standard therapeutic interventions [3]. There is notable regional heterogeneity in the incidence of brain tumors, with lower rates in low-income regions (1.8 occurrences per 100,000 people) and greater rates reported in high-income countries (7.4 cases per 100,000 population) [1, 2].

Brain tumors have a complex etiology that includes genetic abnormalities, particularly those affecting the p53 tumor suppressor gene and the epidermal growth factor receptor (EGFR) gene, which lead to unchecked cell division [4, 5]. Moreover, the heterogeneity and progression of these neoplasms are exacerbated by epigenetic changes, such as DNA methylation and histone modifications [3]. The development of successful therapeutic strategies is still limited, despite significant progress in our understanding of the molecular biology underlying brain tumors. A large percentage of patients have poor prognoses because of the blood-brain barrier's impermeability, which severely restricts the ability of many systemic pharmacological medicines to reach the tumor site [4].

3. Therapeutic approaches: nanotechnology-based drug delivery systems

By tackling the problems caused by tumor heterogeneity and the blood-brain barrier, nanotechnology has completely changed the way drugs are delivered to brain tumors. Because they improve targeting, increase medication solubility, and enable controlled release, nanoparticles are a desirable alternative for treating brain cancers. Numerous nanoparticle systems have been created, and each has unique benefits for delivering and encapsulating chemotherapeutic drugs.

By successfully overcoming the challenges posed by the blood-brain barrier and tumor heterogeneity, nanotechnology has fundamentally changed the way pharmaceutical drugs are delivered for the treatment of brain tumors. The application of nanoparticles makes them a viable substitute for brain tumor treatment since it increases drug solubility, improves targeting, and permits controlled release. Numerous nanoparticle systems have been created, and each offers special benefits for the delivery and encapsulation of chemotherapeutic drugs.

3.1. Liposomes

Particularly for brain cancers, liposomes—spherical vesicles composed of one or more phospholipid bilayers—offer a variety of medication delivery options. They are perfect for a range of chemotherapeutics because of their ability to encapsulate lipophilic drugs in their lipid bilayer and hydrophilic drugs in their aqueous core. Liposomes' biocompatibility and capacity to enhance drug penetration across the blood-brain barrier (BBB) make them highly valuable in the treatment of brain tumors. Nevertheless, normal liposomes are quickly cleared by the mononuclear phagocyte system (MPS), which shortens their half-life [6].

PEGylated liposomes have been developed as a solution to this problem by modifying the liposome surface using polyethylene glycol. This alteration not only lengthens the time in circulation but also reduces immune system recognition, which makes it possible for the medication to more efficiently collect at the site of the tumor. Chemotherapeutic medications have been successfully administered to gliomas via PEGylated liposomes, such as Doxil, a doxorubicin-based liposomal formulation [7, 8]. The capacity of these liposomes to carry a variety of drugs, such as immunotherapeutics and RNA-based therapies, is also being investigated. This could result in combination treatments that attack the tumor from several angles.

In order to enhance targeted distribution, current research has also concentrated on functionalizing liposomes with specific ligands. Ligand-targeted liposomes have the ability to attach to tumor cells' overexpressed receptors, including transferrin receptors, which are prevalent in the blood-brain barrier [3]. By improving drug transport to the brain, this receptor-targeting technique increases therapeutic efficacy while lowering off-target effects. Temperature-sensitive liposomes, which release their cargo when exposed to high temperatures (for instance, during localized tumor heating), represent another innovation. Systemic toxicity is decreased by this technique, which permits controlled medication delivery at the tumor site [9].

Lai et al., for instance, developed transferrin-conjugated liposomes to treat brain tumors. Liposome transport and drug accumulation in brain tumors are facilitated by transferrin, a protein that binds to overexpressed transferrin receptors on the blood-brain barrier and tumor cells. Immordino et al.

discovered that by increasing drug circulation and decreasing immune clearance, PEGylated liposomal formulations of doxorubicin (Doxil) enhanced the outcomes of glioma treatment [10].

Additionally, combined therapy has been used with liposomal formulations. Liposomes containing paclitaxel and an anti-angiogenic medication for brain tumors were investigated by Ko et al. Targeting the growth of the tumor as well as its blood supply, the combination of these drugs improved the anti-tumor effect [11]. Temperature-sensitive liposomes, which react to hyperthermia by releasing their therapeutic payload, are another recent development. In order to improve drug delivery to gliomas, Pradhan et al. developed heat-sensitive liposomes that release chemotherapeutics when mild hyperthermia (about 42°C) occurs. The versatility of liposomes in addressing BBB challenges and tumor heterogeneity in brain cancers is demonstrated by these examples [12].

3.2. Polymeric Nanoparticles

Because polymeric nanoparticles are composed of biodegradable and biocompatible polymers, they provide a perfect platform for controlled drug delivery in brain tumors. The FDA has approved poly(lactic-co-glycolic acid) (PLGA) for a number of drug delivery applications, making it one of the most studied materials for this purpose. PLGA nanoparticles improve the pharmacokinetics of drugs that would otherwise be quickly eliminated from the body by providing sustained and controlled drug release. Moreover, PLGA nanoparticles have the potential to encapsulate a variety of medications, ranging from large macromolecules like proteins and nucleic acids to smaller ones like temozolomide [6, 7].

Surface modification to enhance tumor targeting and BBB penetration is one of the latest developments in polymeric nanoparticles. For instance, like PEGylated liposomes, PEGylation of PLGA nanoparticles might increase circulation while lowering immune clearance [7]. Additional methods include binding antibodies or directing ligands to the surface of the nanoparticle, which enables receptor-mediated endocytosis. Because specific receptors, such transferrin and integrins, are overexpressed on glioma cells and BBB endothelial cells, this approach is particularly effective for targeting brain cancers [3]. On-demand drug release in the tumor microenvironment is also made possible by the ability to control polymeric nanoparticles to react to particular environmental stimuli, such as pH or temperature changes [7].

Another kind of polymeric nanoparticle produced by amphiphilic block copolymers self-assembling is called a polymeric micelle. Because of their hydrophobic core, these micelles can encapsulate poorly water soluble medications, improving their stability and solubility [6]. Because of their enhanced permeability and retention (EPR), polymeric micelles have demonstrated promise in the delivery of drugs like paclitaxel to brain tumors [3]. Because of their versatility and diversity, polymeric nanoparticles hold great promise as a platform for the upcoming generation of treatments for brain tumors.

3.3. Biomimetic Nanoparticles

By utilizing the body's natural mechanisms, biomimetic nanoparticles offer a novel strategy to drug administration that improves biocompatibility, targeting effectiveness, and therapeutic results. One example of this technique is cell membrane-coated nanoparticles, which are nanoparticles covered with membranes that are taken from natural cells like cancer cells, leukocytes, or red blood cells. These coatings offer a number of benefits, such as extended circulation time and immune recognition avoidance. Research has shown that these biomimetic nanoparticles may replicate the biological characteristics of the cells they originate from, allowing for better tumor cell targeting by utilizing the tumor microenvironment [3, 7]. Drug delivery across the blood-brain barrier (BBB), one of the major obstacles in the treatment of brain malignancies, has been accomplished with the use of this kind of nanoparticle.

Virus-mimetic nanoparticles have gained interest in addition to cell membrane coatings. Since viruses are naturally highly good at locating cells and overcoming biological barriers, these nanoparticles are made to mimic their form and function [2]. By utilizing the targeting capabilities of

viruses, these nanoparticles can selectively deliver therapeutic medications to tumor cells while minimizing off-target effects. For instance, preclinical studies of virus-like particles (VLPs), which have been developed to deliver gene therapies and chemotherapeutic medications to glioma cells, reveal encouraging outcomes [3]. In order to improve the results of brain tumor therapy, these particles are particularly good at piercing the blood-brain barrier and focusing on the intricate environment of the brain.

Examples of biomimetic techniques that significantly increase the efficacy of drug administration are virus-mimetic and cell membrane-coated nanoparticles. By facilitating precise targeting and reducing systemic toxicity, they hold potential for tailored therapeutic applications. Additionally, further investigation into modifying these particles to incorporate ligands, antibodies, or small molecules can enhance their specificity of targeting, hence boosting the effectiveness of treatments for brain malignancies [3, 7].

3.4. Vesicular Systems

Vesicular systems, including exosomes, niosomes, and liposomes, offer a versatile platform for administering medicinal substances to brain tumors. Because liposomes are composed of phospholipid bilayers, they can encapsulate medications that are hydrophilic or hydrophobic, protecting them from enzymatic degradation and boosting their bioavailability. The ability of liposomes to alter their surface characteristics, which enables them to evade the immune system and lengthen their circulation time, is one of their most noteworthy benefits. Polyethylene glycol (PEG)-modified liposomes, or PEGylated liposomes, have demonstrated exceptional efficacy in increasing medication concentration at tumor sites and drug transport across the blood-brain barrier [6].

Compared to liposomes, niosomes—vesicles made of nonionic surfactants instead of phospholipids—are more stable and economical. Because of their ability to cross the blood-brain barrier and transport drugs straight to tumor cells, niosomes have shown promise in the treatment of brain tumors and may encapsulate a variety of therapeutic compounds [6]. Preclinical research has demonstrated that niosomal formulations of chemotherapeutic medications, including paclitaxel and temozolomide, have improved pharmacological efficacy and reduced systemic toxicity [3].

The usage of exosomes, which are tiny extracellular vesicles produced by cells, is another fascinating development in vesicular systems. Exosomes are ideal vehicles for delivering therapeutic agents like proteins, RNA, or small molecule medications because of their innate capacity to move materials across cells. Because exosomes can naturally penetrate the blood-brain barrier and target different cells depending on where they originate, exosome-based drug delivery systems are especially intriguing for treating brain malignancies [3]. Although research on exosomes for brain cancer treatment is still in its infancy, they have a lot of promise for providing precision medicine tailored to the molecular and genetic features of specific tumors [7].

3.5. Targeted Nanoparticles

By delivering therapeutic medications straight to the tumor location while minimizing harm to healthy tissue, targeted nanoparticles mark a substantial advancement in precision medicine. Ligands, such as peptides, antibodies, or small molecules, that specifically bind to overexpressed receptors on tumor cell surfaces are known as ligand-modified nanoparticles. By increasing the targeting efficiency of nanoparticles, this technique guarantees that drugs build up at the tumor site while lowering off-target effects. Utilizing transferrin-modified nanoparticles, which capitalize on the overexpression of the transferrin receptor on brain capillary endothelial cells, is a noteworthy usage of ligand-modified nanoparticles. It has been demonstrated that these nanoparticles may cross the blood-brain barrier and transport therapeutic medications to gliomas, leading to much better treatment results [3, 7].

Iron oxide nanoparticles and other magnetic nanoparticles serve two purposes in therapy and imaging. An external magnetic field can be used to guide magnetic nanoparticles to tumor locations, enabling more accurate targeting of drug delivery systems. Iron oxide nanoparticles are also

commonly used as contrast agents in magnetic resonance imaging (MRI), which enables real-time therapy process monitoring [3]. Theranostics, a combination of diagnostic and therapeutic capabilities, has the potential to revolutionize the treatment of brain tumors by providing individualized treatment plans that are continuously assessed and modified in response to the tumor's reaction [3].

Additionally, targeted nanoparticles that react to particular stimuli in the tumor microenvironment have been developed. In reaction to environmental cues, stimuli-responsive nanoparticles—such as pH- or temperature-sensitive nanoparticles—release therapeutic payloads. For instance, temperature-sensitive nanoparticles can release pharmaceuticals in response to localized hyperthermia, while pH-sensitive nanoparticles can release therapeutics in an acidic tumor microenvironment [6, 7]. By ensuring that therapeutic chemicals are delivered exactly when and where they are needed, this degree of control over pharmaceutical release improves treatment efficacy and reduces adverse effects.

3.6. Stimulus-Responsive Nanoparticles

When certain environmental stimuli, like changes in pH or temperature, occur, stimulus-responsive nanoparticles are made to release their pharmacological payloads. In order to improve therapeutic targeting and reduce systemic toxicity, pH-sensitive nanoparticles are designed to release their contents in the acidic microenvironments typical of tumors [6]. In a similar vein, localized heating—which can be achieved by inducing hyperthermia—can cause temperature-sensitive nanoparticles to release medications [7].

The ability of stimulus-responsive nanoparticles to release therapeutic chemicals in response to particular environmental signals—like pH, temperature, or enzymes—that are regularly changed in the tumor microenvironment has drawn interest. pH-sensitive nanoparticles were created by Wang et al. to treat glioblastoma [13]. The method released encapsulated doxorubicin directly into the site by using a pH-sensitive polymer that breaks down in the tumor's acidic environment. This approach improves therapeutic efficacy while decreasing off-target effects.

Liu et al. reported a gold nanoparticle-based nanocarrier system for photothermal treatment (PTT) of brain cancers in the context of temperature-sensitive nanoparticles. Gold nanoparticles cause tumor hyperthermia and the release of chemotherapeutic drugs by converting near-infrared light into heat [14]. Zhu et al. recently developed enzyme-responsive nanoparticles, which is another novelty. In reaction to matrix metalloproteinases (MMPs), which are overexpressed in glioblastoma, these nanoparticles release the therapeutic payload. As demonstrated by a significant decrease in tumor growth in animal models, enzyme-responsive devices can enhance treatment targeting for brain malignancies [15].

3.7. Metal Nanoparticles

The fields of photothermal therapy and medication delivery have both made use of gold nanoparticles. By absorbing light and transforming it into thermal energy, these nanoparticles can efficiently cause tumor cells to die [6]. Additionally, gold nanoparticles can facilitate a dual treatment approach by acting as transporters for chemotherapeutic drugs [2]. In addition to being used primarily in magnetic resonance imaging (MRI), iron oxide nanoparticles serve as drug delivery vehicles, enabling real-time therapy efficacy monitoring [2, 3].

3.7.1 Gold nanoparticles: photothermal therapy and drug delivery

In the treatment of brain cancers, gold nanoparticles (AuNPs) have become essential, especially when photothermal therapy (PTT) is used. Because of their unique optical properties, AuNPs can absorb near-infrared (NIR) light and transform it into localized thermal energy, which efficiently destroys tumor cells. Their localized surface plasmon resonance (LSPR), which is precisely tunable according to the size and shape of the gold particles, is responsible for this phenomena [4, 7]. PTT involves the administration of AuNPs into the tumor area, which are then triggered by NIR light. This causes targeted thermal destruction to cancerous cells while protecting nearby healthy tissue. AuNPs can be functionalized to improve drug delivery across the blood-brain barrier (BBB) and raise the

concentration of chemotherapeutic drugs at the tumor location, in addition to their activity in PTT [3, 8].

3.7.2 Iron Oxide Nanoparticles: Imaging and Targeted Drug Delivery

Brain tumors can be treated with iron oxide nanoparticles (IONPs) in two ways. They are commonly used as contrast agents in magnetic resonance imaging (MRI) to enhance tumor margin delineation. Additionally, IONPs can help in magnetically targeted medication delivery, in which the nanoparticles are guided to the tumor site by an external magnetic field. This method lessens systemic negative effects while improving drug delivery precision [3]. These nanoparticles' magnetic characteristics also make it possible to use a technique called hyperthermia, in which the particles are exposed to an alternating magnetic field that produces localized heat and aids in the death of tumor cells [8].

3.8. Carbon-based nanoparticles

3.8.1 Graphene: A High Surface Area Material for Drug Adsorption and Delivery

Because of its large surface area and capacity to adsorb a wide range of pharmacological chemicals, graphene, a carbon-based nanomaterial, has garnered a lot of attention in the field of drug delivery. Combination therapy for brain cancers benefit greatly from its two-dimensional architecture, which offers a wide platform for the inclusion of various therapeutic agents [7]. Additionally, like gold nanoparticles, graphene's exceptional electrical and thermal conductivity can be used for photothermal therapy. Graphene's targeting efficiency can be further improved by functionalizing it with certain ligands, which will encourage greater drug accumulation in tumor tissues [3].

3.8.2 Carbon Nanotubes: Applications in Drug Delivery and Biosensing

One special class of carbon-based nanomaterials with great promise for treating brain cancers is carbon nanotubes (CNTs). Because of their hollow cylindrical shape, medications can be encapsulated, allowing for controlled and prolonged release. Furthermore, CNTs have been investigated as biosensors for tumor marker identification, which aids in early diagnosis and therapy effectiveness evaluation [7]. Similar to graphene, CNTs have remarkable thermal characteristics and can be used in photothermal therapy, which involves heating them with near-infrared light to cause tumor cells to undergo apoptosis [8].

Because of their distinct physicochemical characteristics, carbon nanotubes (CNTs) have demonstrated significant promise in the treatment of brain tumors. For instance, Liu et al. explained how paclitaxel was delivered to glioma cells using CNTs functionalized with transferrin. By enabling CNTs to cross the blood-brain barrier and target tumor cells, the transferrin modification increased the therapeutic index. The hollow tubular shape of CNTs enables controlled release and high drug loading capacity, both of which are essential for delivering potent chemotherapeutic medications with little systemic damage [16-18].

CNTs have been studied as biosensors for detecting tumor biomarkers in addition to their medication delivery capabilities. A CNT-based biosensor was developed by Zhang et al. to detect glioblastoma early. The sensitivity of a sensor that used antibodies to target glioma markers to detect circulating tumor cells in patient samples was very high [19, 20]. CNTs and quantum dots were used by Singh et al. to develop a sensitive biosensor for detecting microRNAs connected to the development of brain tumors [21, 22]. These illustrations show how CNTs are a useful tool for customized brain cancer treatment since they can be used for both therapy and diagnostics.

With nanotechnology, including liposomes, stimulus-responsive nanoparticles, and carbon-based nanomaterials, researchers are making significant strides in the treatment of brain cancers. There is hope that these developments may lead to better patient outcomes and more specialized and efficient therapies for brain disorders.

4. Conclusion

Drug delivery systems based on nanotechnology represent a significant advancement in the treatment of brain tumors, successfully overcoming the challenges posed by the blood-brain barrier (BBB) and the requirement for regulated and targeted drug release. Different nanoparticle systems, such as metallic, liposomal, PLGA, and biomimetic nanoparticles, each have special benefits that show how these platforms may help patients with brain tumors. Furthermore, by combining metal- and carbon-based nanoparticles, new strategies to improve the accuracy, effectiveness, and safety of brain tumor treatments are being developed, which helps to lessen the drawbacks of traditional therapies. For these technologies to be improved and turned into effective treatment choices for brain cancer, ongoing research and clinical trials are essential.

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