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Nanomedicine in the targeted treatment of brain tumors.

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Introduction

Brain tumors represent one of the most challenging areas in oncology due to their complex biology, aggressive behavior, and the limitations of current therapeutic approaches. Despite advances in neurosurgery, radiation therapy, and chemotherapy, patient prognosis, especially for malignant gliomas such as glioblastoma multiforme, remains poor. A major barrier to effective treatment is the blood–brain barrier, a highly selective physiological interface that protects the brain from harmful substances but also severely restricts the delivery of most therapeutic agents. This protective shield, while essential for maintaining neural homeostasis, poses a significant obstacle to the penetration of chemotherapeutic drugs, targeted agents, and biologics into tumor tissues. Moreover, conventional systemic therapies often lack selectivity for tumor cells, resulting in damage to healthy brain tissue and systemic toxicities. These challenges have driven the exploration of novel approaches, with nanomedicine emerging as a particularly promising strategy for targeted treatment of brain tumors [1].

Nanomedicine utilizes nanoscale materials—typically in the range of 1 to 100 nanometers—as carriers for therapeutic agents. These nanocarriers can be engineered to improve drug solubility, enhance stability, protect drugs from premature degradation, and facilitate controlled or sustained release. Most importantly, nanomedicine enables targeted delivery to tumor tissues while minimizing exposure to healthy cells, potentially reducing adverse effects. In brain tumor therapy, nanocarriers are being designed to overcome the blood–brain barrier through both passive and active targeting mechanisms. Passive targeting exploits the enhanced permeability and retention effect, a phenomenon in which leaky tumor vasculature and poor lymphatic drainage allow nanoparticles to accumulate preferentially in tumor tissue. Although the EPR effect is more prominent in peripheral tumors than in brain tumors, some degree of vascular abnormality in gliomas can be leveraged for nanoparticle delivery [2].

Active targeting strategies involve functionalizing nanoparticles with ligands such as antibodies, peptides, aptamers, or small molecules that bind specifically to receptors overexpressed on brain tumor cells or the endothelial cells of the blood–brain barrier. Examples include targeting transferrin receptors, low-density lipoprotein receptors, or integrins. Ligand-mediated targeting not only facilitates transport across the blood–brain barrier but also enhances uptake by tumor cells, increasing therapeutic efficacy. Some nanoparticles are engineered to respond to specific stimuli in the tumor microenvironment, such as acidic pH, high enzymatic

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activity, or redox conditions, enabling site-specific drug release [3].

Various types of nanocarriers have been explored for brain tumor therapy. Liposomes, spherical vesicles composed of phospholipid bilayers, can encapsulate both hydrophilic and hydrophobic drugs. Their biocompatibility and ability to be surface-modified with targeting ligands make them a versatile platform. Liposomal formulations of chemotherapeutics such as doxorubicin and irinotecan have shown improved delivery to brain tumors in preclinical studies, and some have entered clinical evaluation. Polymeric nanoparticles, made from biodegradable polymers like poly(lactic-co-glycolic acid), offer tunable drug release kinetics and can be engineered for active targeting. Dendrimers, highly branched synthetic polymers, possess multiple terminal groups that can be functionalized with drugs, imaging agents, and targeting moieties, allowing for multifunctional applications [4].

Inorganic nanoparticles, such as gold nanoparticles, magnetic nanoparticles, and quantum dots, have also been investigated for brain tumor applications. Magnetic nanoparticles, for example, can be guided to tumor sites using external magnetic fields and can serve as both therapeutic carriers and imaging contrast agents. Gold nanoparticles can enhance radiation therapy by increasing local dose deposition in tumor tissues, while also functioning as drug carriers. Multifunctional nanoparticles that combine therapeutic and diagnostic capabilities—known as theranostic nanoparticles—are gaining interest for their potential to enable real-time monitoring of drug delivery, biodistribution, and therapeutic response [5].

Conclusion

In conclusion, nanomedicine offers a promising paradigm shift in the targeted treatment of brain tumors, with the potential to overcome the formidable challenges posed by the blood–brain barrier, tumor heterogeneity, and systemic toxicity of current therapies. Nanoscale drug delivery systems can be engineered to selectively target tumor cells, enhance therapeutic efficacy, and minimize damage to healthy brain tissue. Advances in active targeting, multifunctional theranostic platforms, and novel delivery strategies are paving the way toward more precise and effective interventions.

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