

wafer use, with median survival times of 16.4 and 9.7 months for newly diagnosed and recurrent GBM, respectively. Histological analysis reveals that most tumor recurrence in high-grade glioma is within 2-3 cm of the tumor margin^{18,19}, while drug penetration from surface erosion of the wafer is only within millimeters of the implant²⁰. Recent efforts in localized drug delivery have therefore focused on increasing local drug penetration to surrounding brain parenchyma. To that effect, much work has been done regarding understanding the brain extracellular matrix/space (ECS).

In addition to size of molecules, diffusion through the ECS is governed by multiple factors, including ECS local geometry, a net fixed negative charge, binding of antigens to receptors, variable degree of dead space, extracellular matrix molecules (hyaluronan), and intratumoral pressure gradients²¹. In order to promote diffusion of chemotherapeutics, nanocarriers such as liposomes and PEGylated nanoparticles have been developed. These surfaces both protect drugs from being prematurely metabolized, as well as provide charge-shielding from the ECS. In fact, studies on rat and human brain have shown that substances of 114 nm were able to diffuse through the ECS when protected from the charge influence of the local environment, as opposed to the previous size of 64 nm when unshielded²². Another important consideration when studying drug distribution in the brain parenchyma and interstitial space is the rate and mechanism of drug clearance from the brain. Recently, a novel, ubiquitous pathway in the brain has been described that facilitates exchange of cerebrospinal fluid (CSF), interstitial fluid (ISF), and the clearance of solutes from the interstitium. Designated the "glymphatic system", this pathway consists of a para-arterial CSF influx route, a trans-parenchymal pathway that is dependent upon the astrocytic aquaporin-4 (AQP4) water channel for astroglial water transport, and finally a para-venous ISF clearance route²³. As understanding of this pathway increases, researchers may be able to better predict the clearance of drug from the interstitial space and therefore tailor dosing of local drug depots. Additionally, knowledge of the glymphatic system and its transport channels may ultimately help to develop novel methods to prolong the half-life of chemotherapeutics and nanocarriers.

Another way to promote local drug penetration through the ECS is by convection instead of relying only on bulk diffusion alone. Indeed, convection-enhanced delivery (CED) of a variety of therapeutics has been a popular topic of drug development and delivery for recurrent glioma in the past decade²⁴⁻²⁶. The CED technique utilizes a catheter that is connected to a pump delivering a pressure head behind the infusion of drug. Studies of CED have shown great promise in terms of penetration of therapy through

the ECS²⁷. Consequently, CED has become among the most popular vehicles for localized delivery in current time, with 52 studies regarding CED for gliomas published in the past year (pubmed) and 5 ongoing clinical trials of convection enhanced delivery for glioma treatment (clinicaltrials.gov).

Unfortunately, most randomized trials related to CED for glioma have been underwhelming²⁸. Perhaps the most notable failure of CED was the PRECISE trial, which did not find any difference in survival when comparing CED of cintredekin besudotox (CB) immunotoxin to gliadel wafers in patients with GBM at first recurrence²⁹. A close examination of that study reveals that inconsistent catheter placement, as well as spread of drug into unwanted areas of low resistance, such as subarachnoid space and the ventricles may have reduced the efficacy of CED. With use of currently available image-guidance technology, these issues may be mitigated in future studies. Additionally, novel methods to track CED infusion of drugs may allow real-time feedback of drug distribution. For example, superparamagnetic iron oxide nanoparticles detectable on T2 MRI imaging have recently been incorporated into brain penetrating nanoparticles, providing ability to track therapeutic in the brain for up to one month after administration³⁰. Radiolabeled therapeutics are also being used to study the volume of distribution of drug after CED, utilizing interval high-resolution positron emission tomography (PET) scanning to evaluate biologically absorbed doses of radiation in specific anatomical distributions³¹. Still, treatment failure of CED in the PRECISE trial may not be fully explained by suboptimal catheter placement alone. In fact, a retrospective review of catheter placement on patient outcomes in the PRECISE trial showed that overall catheter placement scores did not correlate with local tumor control, progression free survival, or overall survival³². The additional issue of infusion backflow also exists in CED, though catheter design has recently been improved with use of multiple ports, backflow-reducing technology, as well as variable injection rates³³⁻³⁶. Overall, the pattern of drug dispersal during CED, especially around inhomogeneous peritumoral tissue, has proven to be unpredictable³⁷, but is steadily improving. Technology development and mathematical modeling may play a future role in determining optimal stereotactic catheter placement, specific to each given tumor and peritumoral environment³⁸⁻⁴⁰. Aside from the infusion and dispersal issues, CED has an additional disadvantage related to connection of the catheter to an outside system, potentially increasing chance of infection with prolonged or repeated infusions. Additionally, in-hospital monitoring is required during infusion, drastically limiting the effective time that drugs can be administered. Subcutaneous reservoirs of drugs for continuous infusion are being explored, but have yet to be optimized for an intracranial application^{25,41}.

Despite their poor parenchymal penetration, polymer designs for local delivery offer a great advantage over CED in that a local depot of drug can be placed one time, which then releases slowly over a period of days to weeks^{20,42,43}. Recently, efforts to pair CED with the use of nanocarriers, including polymers⁴⁴⁻⁴⁶, nanoliposomal drug formulations⁴⁷⁻⁵¹, metallic nanoparticles⁵², liposomally encapsulated radionuclides⁵³, and nanodiamonds⁵⁴, among others, have been explored. With this combination of technologies, CED can effectively deliver nanocarriers to the peritumoral area while the nanocarrier vehicle serves as a “convectible depot” of drug that is released to the local environment over time. The characteristics of polymers as biocompatible depots of drug with controlled, predictable release rate makes them most attractive for this purpose, obviating the need for prolonged infusion times or additional infusions. Furthermore, enhancements to nanopolymer design have allowed for development of smaller carriers, approximately 75 nm in diameter, that are able to penetrate up to sevenfold higher surrounding brain volumes than that of traditional nanopolymer designs of 150-200 nm diameter⁵⁵. Additionally, novel nanopolymer designs can allow for the controlled release of multiple drugs, each with independent release rates to maximize drug synergy⁵⁶. Polymeric nanoparticles have also been successful for use in aiding non-viral gene delivery for GBM treatment, avoiding the pitfalls of viral vector based therapy, and opening a whole new spectrum of therapies for the modality of local drug delivery⁵⁷. Improved kinetics and duration of drug release, increased efficacy, and decreased neurotoxicity is also possible when nanocarrier platforms are utilized for CED⁴⁴. Another advantage of a nanocarrier platform for CED is the ability to incorporate both therapeutic drugs, as well as the diagnostic imaging probe, creating a “theranostic” particle that can be tracked during infusion⁵⁸. A variety of contrast agents can be incorporated for real-time monitoring of infusate distribution, allowing for adjustment of catheter placement or infusion parameters, if necessary⁵⁹. Real-time CED has shown to be safe, highly predictable, and reproducible in animal experiments, and should greatly enhance the characterization of drug distribution in future patient studies⁶⁰.

Overall, treatment for high-grade glioma remains suboptimal; however, knowing that current technology allows for robust peritumoral application of therapeutics, local drug delivery options remain attractive for delivering optimal drug volume to tumor cells while avoiding systemic side effects and circumventing the issue of the blood-CNS barrier. As nanomedicine continues to evolve and the process of CED is refined, we may see an explosion of hopeful options that could one day turn this devastating disease into a manageable entity.

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