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Advancements in Imaging and Neurosurgical Techniques for Brain Tumour Resection

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Abstract: ***Brain tumour resection requires achieving maximal tumour removal while preserving neurological function. Recent advancements in neuroimaging and intraoperative neurosurgical technologies have substantially enhanced the precision, safety, and effectiveness of surgical interventions. This review provides a comprehensive overview of contemporary image-guided techniques, including neuronavigation, intraoperative magnetic resonance imaging (iMRI), intraoperative ultrasound (iUS), diffusion tensor imaging (DTI), fluorescence-guided surgery with sodium fluorescein, awake craniotomy, and functional brain mapping. A systematic review of studies published between 2010 and 2023 in PubMed, Scopus, and Web of Science was conducted to evaluate the clinical utility of these approaches, particularly in the management of high-grade gliomas. Current evidence indicates that combining fluorescence-guided surgery with advanced intraoperative imaging improves the extent of safe tumour resection while preserving eloquent brain regions. Nevertheless, limitations such as brain shift, imaging artifacts, and reliance on blood–brain barrier disruption remain significant challenges. Overall, the integration of advanced imaging modalities with modern neurosurgical techniques has improved surgical outcomes and holds considerable promise for advancing personalized brain tumour management.***

Keywords: Brain Neoplasms, Glioblastoma, Neurosurgical Procedures, Magnetic Resonance Imaging, Neuronavigation, Fluorescence-Guided Surgery, Diffusion Tensor Imaging, Intraoperative Imaging

1. Introduction

The management of brain tumors has undergone a significant transformation driven by technological innovations in imaging and surgical instrumentation which collectively aim to maximize the extent of resection while minimising neurobiological morbidity (Mashiach 2025; Richardson 2012). This evolution is particularly critical for glioblastomas, which are considered one of the most lethal cancers in the adult population and brain metastasis, which represents most common intracranial neoplasms (Vadhvekar 2024). Despite the aggressive nature of glioblastoma, the integration of advanced intraoperative technologies such as functional mapping, awake craniotomy and fluorescence-guided spectroscopy surgery has substantially improved the ability to achieve maximal safe resection and preserve neurobiological function (Chaulagain 2023; Vadhvekar 2024). Achieving this delicate equilibrium is paramount, as the maximum extent - of surgical resection is consistently associated with prolonged recurrence-free periods and improved overall survival across various intracranial malignancies, including glioblastomas, low grade gliomas and meningiomas (Belyk 2016). However, the anatomical complexity of these lesions often necessitates that they involve or approach eloquent regions of the brain, creating a critical challenge in balancing oncological control with the preservation of functional integrity (Chaulagain 2023; Wu 2022). To address this challenge, a variety of surgical adjuncts and technological enhancements have been developed to improve the identification and visual discrimination of the tumor-brain interface, thereby assisting neurosurgeons in safely navigating eloquent areas (Chanbour and Chotai 2022). Among these adjuncts, fluorescence-guided surgery using agents such as fluorescein sodium has emerged as a promising technique to enhance the intraoperative visualization of tumor tissue, particularly when integrated with specialized surgical microscopes like the Yellow 560nm filter (Schebesch 2019). This particular filter facilitates the visualization of the residual tumor tissue by accentuating the fluorescence emitted by sodium fluorescein, thereby demonstrating a secure and viable approach to enhance the differentiation between pathological and normal brain parenchyma during the high- grade glioma resection (Schebesch 2022).

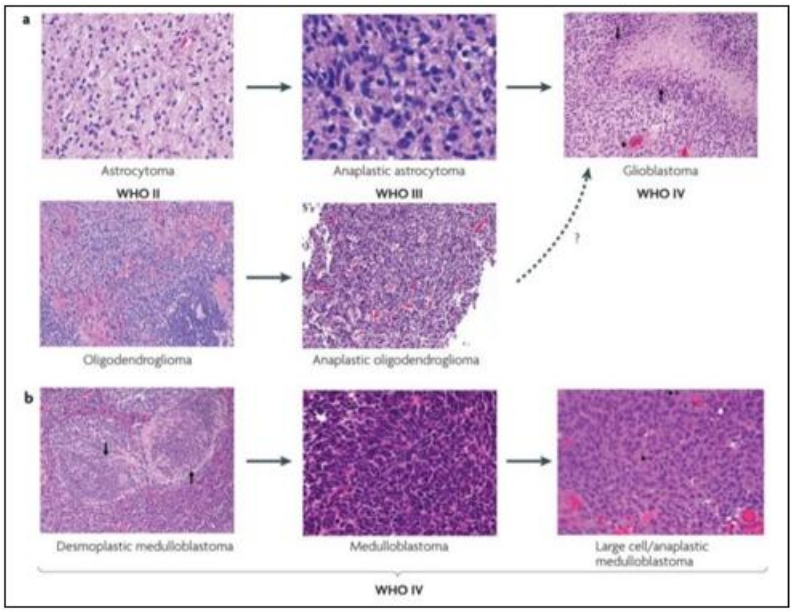
2. Literature Review

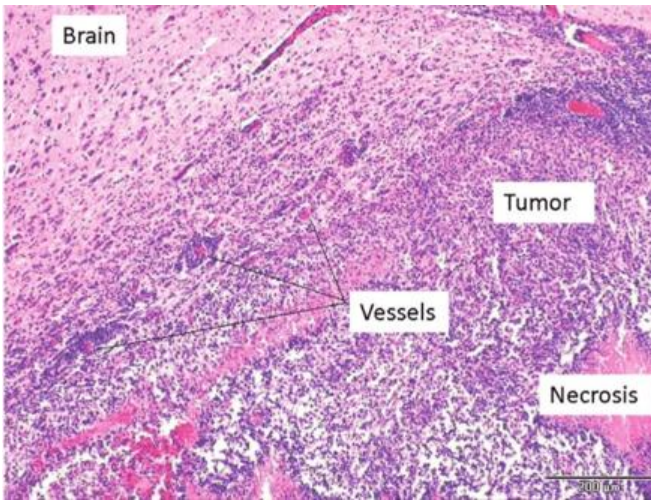
The literature highlights a paradigm shift in neurosurgical oncology, where exceptional technological progress in neuroimaging and the implementation of intraoperative strategies are revolutionising the management of glioblastoma by enabling accurate anatomo- functional, metabolic, genomic and transcriptomic definition (Bonosi 2023). These improvements are backed by an increasing variety of biomedical engineering devices, including as neuro-navigation systems, intraoperative CT and MRI and intraoperative ultrasound, which are frequently deployed to enhance tumor visibility and guide the resection process (Lus 2023; Yang 2023). Advanced imaging techniques, including diffusion tensor imaging, enhance this capability by enabling surgeons to visualize white matter tracts and evaluate their proximity to the tumor, thereby promoting a more thorough comprehension of the lesion's association with adjacent brain structures (Chaulagain 2024).These advancements are backed by a growing array of biomedical engineering devices including as neuro-navigation systems, intraoperative CT and MRI and intraoperative ultrasound, which are commonly implemented to enhance tumor visibility and guide the resection process(Lua 2023; Yang 2023). Advanced imaging methods, like diffusion tensor imaging, improve this ability by helping surgeons see white matter tracts and evaluate how close they are to the tumor. This allows for a better understanding of how the lesion relates to nearby brain structures (Chaulagain 2024). Despite these improvements in structural visualization, traditional neuronavigation systems are limited by their reliance on preoperative images, which may not account for intraoperative brain shift and tissue

deformation that occur after dural opening and tumor debulking (Li 2020).

3. Methodology

This review employed a comprehensive search strategy across PubMed, Scopus and Web of Science, identifying studies published from January 2010 to June 2023 (Chen 2023; Schebesch 2016). The focus was on evaluating the efficacy and safety of fluorescein sodium-guided resection in high grade glioma patients. Fifteen studies met the inclusion criteria. Pooled data revealed that 83% of patients undergoing fluorescence-guided surgery achieved over 95% resection, with 29.8% subtotal and 17% partial reactions (Villa 2017). Emerging studies suggest that a low intravenous dose of 5mg/kg sodium fluorescein optimizes intraoperative fluorescence, increasing resection extent (Xiao 2024). Its mechanism involves accumulation at disrupted blood-brain barrier sites, with intensity directly proportional to tumor invasiveness (Xiao 2024). Conversely, 5-aminolevulinic acid utilizes metabolic pathways to identify malignant cells by distinct biochemical products, offering high sensitivity for detecting cellular infiltration at tumor margins (Xiao et al., 2024). Furthermore, multimodal frameworks that integrate 5-aminolevulinic acid with real-time neurophysiologic mapping and fiber tracking have demonstrated superior preservation of neurological function in eloquent areas compared to solitary visualization methods. Recent studies highlight that combining 5-aminolevulinic acid with intraoperative stimulation mapping significantly enhances the resection of contrast-enhancing tumors within eloquent regions, achieving complete resection rates of up to 73.3% (Peters et al., 2023).





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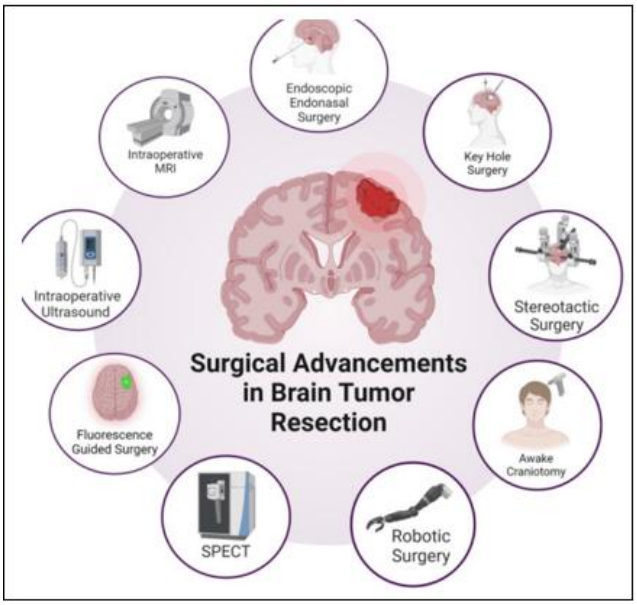

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Overview of radiological and surgical advancements in neurosurgery for brain tumor resection

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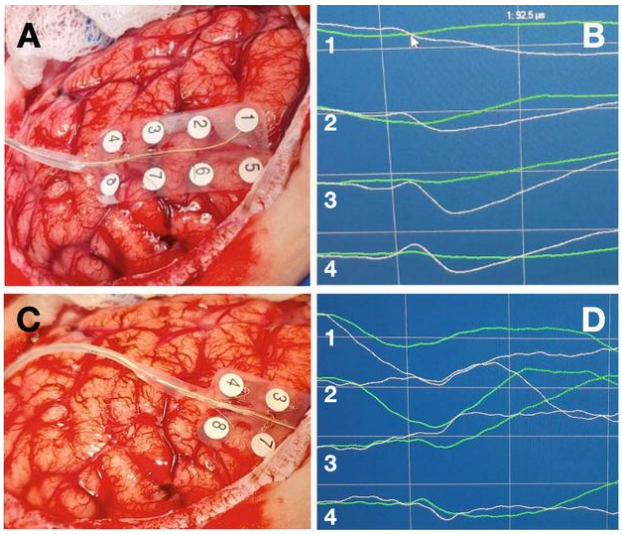

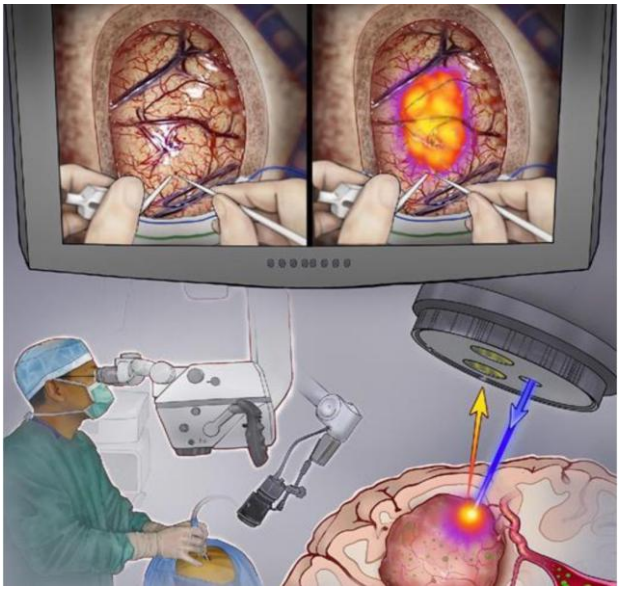

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4. Conclusion

The integration of advanced optical fluorophores and neuronavigation systems marks a significant transition toward personalized neuro-oncological surgery, where real-time molecular visualization supplements conventional anatomical guidance (Belykh & Preul, 2026; Senders et al., 2016). Future clinical strategies should prioritize the standardization of these multimodal workflows to address the spatial heterogeneity of the glioma microenvironment (Ius et al., 2023). Furthermore, investigations into the temporal pharmacokinetics of various fluorophores are essential to optimize the duration of the surgical window, potentially extending the efficacy of resection beyond currently established protocols (Schüpper et al., 2021). Ongoing research into confocal laser endomicroscopy may further bridge the gap in identifying infiltration zones that evade wide-field microscopic detection (Gandhi et al., 2019). Furthermore, the integration of quantitative hyperspectral imaging offers a robust methodology for classifying tissue characteristics based on distinctive spectral signatures, thereby potentially refining intraoperative decision-making. By leveraging these hyperspectral biomarkers, clinicians may eventually reduce reliance on qualitative fluorescence assessment, which often struggles with the subtle transition zones between malignant infiltration and edematous brain parenchyma (Black et al., 2024; Chen et al., 2012).

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