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Role of Artificial Intelligence in Intraoperative Margin Detection during Glioblastoma Resection

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Introduction

Accurate intraoperative margin detection is critical for optimizing tumor removal while preserving neurological function. Traditional methods-such as intraoperative MRI, neuronavigation and fluorescent-guided surgery using 5-ALA-have significantly improved the surgeon's ability to distinguish tumor from normal brain tissue. Nevertheless, these modalities have limitations, including cost, logistical complexity, time delays and limited sensitivity in certain contexts. In recent years, Artificial Intelligence (AI) has emerged as a transformative force in medical imaging and surgical decision-making. AI-driven techniques, particularly those based on deep learning and machine learning algorithms, offer the potential to enhance intraoperative guidance by providing real-time, accurate and interpretable assessments of tumor margins. This explores the role of artificial intelligence in intraoperative margin detection during glioblastoma resection. By examining current technologies, key algorithms, clinical validation studies and future directions, we aim to provide a comprehensive overview of how AI is revolutionizing the surgical landscape for GBM [1].

Description

Glioblastoma Multiforme (GBM) is the most aggressive and lethal form of primary brain tumor in adults, characterized by rapid proliferation, extensive infiltration and resistance to standard therapies. Despite advancements in surgical techniques, radiation and chemotherapy, the median survival for GBM patients remains dismal, typically ranging from 12 to 18 months post-diagnosis. One of the key determinants of prognosis is the extent of Tumor Resection (EOR). Numerous studies have established a positive correlation between greater EOR and prolonged survival. However, achieving maximal safe resection remains a formidable challenge due to the highly infiltrative nature of GBM and its frequent proximity to eloquent brain regions [2].

Glioblastomas are notorious for their diffusely infiltrative growth patterns, often extending microscopic projections well beyond radiologically visible boundaries. During surgery, even under magnification and illumination, tumor tissue can be indistinguishable from edematous or reactive normal brain. The risk of leaving behind residual tumor cells not only diminishes the efficacy of adjuvant therapies but also significantly worsens patient outcomes. Neuronavigation systems uses preoperative imaging to guide resections but may suffer from brain shift during surgery. Provides updated imaging but is time-consuming and requires specialized operating suites. Enhances visualization of tumor tissue but is limited in detecting non-enhancing infiltrative margins. Provide real-time feedback but require specialized training and have variable sensitivity. These limitations underscore the need for intelligent systems that can integrate multimodal data and provide robust, dynamic assessments of tumor boundaries. Artificial intelligence encompasses a range of computational techniques that enable machines to perform tasks traditionally requiring human intelligence. In the context of neurosurgery, AI primarily involves: A subset of ML using neural networks with multiple layers to model complex relationships. AI techniques that enable image analysis and object recognition. Extraction and interpretation of textual data (less relevant intraoperatively but important for clinical documentation) [3].

AI algorithms can process intraoperative image-such as those obtained from Optical Coherence Tomography (OCT), ultrasound, or iMRI-to enhance margin visualization. Convolutional Neural Networks (CNNs) have been particularly effective in classifying tumor vs. normal tissue pixels in real time. Deep learning models can enhance contrast and suppress noise in 5-ALA fluorescence images, improving sensitivity to marginal tumor tissue that might otherwise be missed by the naked eye. Raman spectroscopy provides molecular fingerprints of tissues. AI classifiers trained on Raman spectra can distinguish tumor margins with high specificity and sensitivity. Models such as Support Vector Machines (SVM) and random forests have been used to automate spectral interpretation. HSI captures a wide spectrum of light per pixel, offering rich data for tissue classification. AI models trained on HSI data can detect subtle differences between tumor and healthy brain tissue that are imperceptible to human vision. Some approaches combine data from various modalities (e.g., OCT, MRI, fluorescence, spectroscopy) and use ensemble learning or deep fusion networks to integrate features and improve classification accuracy [4].

Effective implementation of AI-based margin detection tools requires seamless integration into the intraoperative workflow. AI systems must be compatible with existing operating room equipment (microscopes, imaging systems, etc.). Visual outputs (e.g., heatmaps, overlays) should be intuitive and provide actionable insights without disrupting surgical flow. Algorithms must process data in real time to be clinically useful. Systems must be validated through clinical trials and approved by regulatory bodies such as the FDA or EMA. The adoption of AI-driven intraoperative margin detection offers several potential benefits. By identifying tumor infiltration zones that might be missed otherwise, AI can support more complete resections. Precise localization helps avoid unnecessary resection near eloquent cortex. Accurate margin detection decreases the likelihood of early recurrence and the need for additional surgeries [5].

Conclusion

rtificial intelligence is poised to play a transformative role in the intraoperative management of glioblastoma. By enhancing the detection of tumor margins in real time, AI has the potential to improve extent of resection, reduce complications and extend survival for patients with this devastating disease. While challenges remain, including data limitations, ethical considerations and workflow integration, rapid pace of technological advancement and growing clinical validation suggest a promising future. As neurosurgery embraces the era of precision medicine, AI-driven tools will be instrumental in tailoring interventions to individual patients, maximizing oncological outcomes while preserving neurological function. In the fight against glioblastoma, intelligent margin detection may represent a decisive advancement, bridging the gap between surgical intuition and computational precision.

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Conflict of Interest

None.

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