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Advanced Imaging Techniques in Preoperative Planning for Brain Tumor Resection: Evaluating the Impact on Surgical Precision and Neurological Outcomes

Técnicas avanzadas de imágenes en la planificación preoperatoria para la resección de tumores cerebrales: evaluación del impacto en la precisión quirúrgica y los resultados neurológicos

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ABSTRACT

This study investigates advanced imaging techniques and their impact on surgical precision and neurological outcomes in preoperative planning for brain tumor resections. Selected studies include large human sample sizes, peer-reviewed research, systematic reviews, and meta-analyses focusing on advanced imaging techniques and their impact on surgical precision and neurological outcomes. Latest imaging modalities experiments on animal studies are considered. Systematic review of recent literature on advanced imaging modalities—such as MRI, fMRI, PET, and DTI—and their application in preoperative planning. Our findings suggest advanced imaging techniques, including Functional MRI, Ultra-High Field MRI, Diffusion Tensor Imaging (DTI), PET/CT and Deuterium Magnetic Resonance Spectroscopy (2H MRS) improve surgical precision and neurological outcomes in brain tumor resections by enhancing tumor targeting, reducing morbidity, and improving resection accuracy. Future advancements should focus on integrating and optimizing these technologies to further improve preoperative planning and patient-specific treatment strategies.

Keywords: advanced imaging, brain tumor resection, surgical precision, neurological outcomes, preoperative planning

RESUMEN

Este estudio investiga técnicas de imagen avanzadas y su impacto en la precisión quirúrgica y los resultados neurológicos en la planificación preoperatoria para resecciones de tumores cerebrales. Los estudios seleccionados incluyen muestras humanas de gran tamaño, investigaciones revisadas por pares, revisiones sistemáticas y metanálisis centrados en técnicas de imagen avanzadas y su impacto en la precisión quirúrgica y los resultados neurológicos. Se consideran los últimos experimentos en modalidades de imágenes en estudios con animales. Revisión sistemática de la literatura reciente sobre modalidades avanzadas de imágenes, como MRI, fMRI, PET y DTI, y su aplicación en la planificación preoperatoria. Nuestros hallazgos sugieren que las técnicas de imagen avanzadas, que incluyen resonancia magnética funcional, resonancia magnética de campo ultraalto, imágenes con tensor de difusión (DTI), PET/CT y espectroscopia de resonancia magnética de deuterio (2H MRS), mejoran la precisión quirúrgica y los resultados neurológicos en las resecciones de tumores cerebrales al mejorar la localización del tumor. , reduciendo la morbilidad y mejorando la precisión de la resección. Los avances futuros deberían centrarse en la integración y optimización de estas tecnologías para mejorar aún más la planificación preoperatoria y las estrategias de tratamiento específicas del paciente.

Palabras clave: imágenes avanzadas, resección de tumores cerebrales, precisión quirúrgica, resultados neurológicos, planificación preoperatoria

INTRODUCTION

Brain tumors encompass over 100 types, each affecting the brain uniquely, with symptoms ranging from cognitive impairment to psychological changes. Despite ongoing research, survival rates for brain cancer have stagnated, impacting about 94,390 Americans annually, with approximately 1 million currently living with the condition. (*Brain Tumor Facts - National Brain Tumor Society*, 2024)

Glioblastoma multiforme (GBM), recognized as the most lethal form of brain cancer, typically limits survival to just 12–16 months following diagnosis. Although its annual occurrence is relatively modest—around 3.19 cases per 100,000 in developed regions—its prevalence is gradually rising in certain areas due to demographic shifts toward aging populations and advances in detection methods. (Obrador., 2024) Generally diagnosed at an average age of 64, with the highest occurrence seen between 75 and 84 years, GBM is traditionally identified through histopathological analysis. However, contemporary diagnostic strategies now incorporate a range of imaging modalities including Functional MRI, Ultra-High Field MRI, Diffusion Tensor Imaging (DTI), PET/CT in conjunction with Brain MRI, Deuterium Magnetic Resonance Spectroscopy (2H MRS), Intraoperative MRI, and 3D Imaging and Mapping, all of which offer in-depth tumor profiling and surgical guidance (Thakkar et al., 2014).

Novel modalities of neurological imaging technologies transformed preoperative planning for brain tumor resections by enhancing the precision and efficacy of surgical interventions. High-resolution MRI has evolved with advanced sequences and increased spatial resolution and is offering unparalleled detail of brain anatomy and enabling precise tumor localization and characterization. Functional MRI (fMRI) is advanced in temporal and spatial resolution which allow detailed mapping of brain activity and vital functional areas, critical for avoiding damage to regions responsible for essential functions such as speech and motor control. Diffusion Tensor Imaging (DTI) improves higher resolution and more accurate tractography algorithms while providing detailed visualization of white matter pathways and helping to navigate around critical neural networks to minimize postoperative deficits. Positron Emission Tomography (PET) imaging is when combined with MRI (PET-MRI) which is being used to enhances differentiation of tumor tissues from normal brain tissue based on metabolic activity aiding in more accurate tumor delineation and characterization. Magnetic Resonance Spectroscopy (MRS) has advanced with better spectral resolution and more comprehensive metabolite profiling and is assisting in distinguishing between different tumor types and grades based on their unique metabolic signatures. Intraoperative MRI systems are now more sophisticated because they are offering real-time imaging with improved spatial and temporal resolution for immediate adjustments to the surgical approach based on intraoperative findings. 3D Imaging and Mapping is also integrated with high-definition modeling and augmented reality and is providing surgeons with detailed, interactive views of the brain's structure and tumor, thus facilitating enhanced surgical navigation and planning. Novel advancements up to 2024 include the incorporation of AI and ML algorithms to automate and refine image analysis, improve diagnostic accuracy, and predict surgical outcomes. All these technological innovations are playing their role in enhancing preoperative planning by improving tumor localization, preserving neurological functions, and ultimately optimizing surgical outcomes. (Martucci., 2023) (CE et al., 2023) (Jian., 2022)

In this review, we will be focusing on 1). Functional MRI (fMRI), 2) Intraoperative MRI, 3) High-Resolution MRI, 4) Diffusion Tensor Imaging (DTI), 5) 3D Imaging and Mapping, 6) Deuterium Magnetic Resonance Spectroscopy (2H MRS), and 7) Positron Emission Tomography (PET). Each of these approaches is integral in refining surgical precision and optimizing treatment strategies.

Hypotheses or Research Questions

Hypothesis: Advanced imaging techniques improve surgical precision and reduce postoperative neurological deficits.

Research Questions: 1), How do various imaging modalities contribute to tumor localization and surgical planning? 2), What is the impact of these techniques on postoperative neurological outcomes?

METHOD

Inclusion and Exclusion Criteria

We prioritize studies with large human sample sizes. We added studies that have followed rigorous methodologies such as systematic reviews and meta-analyses that adhere to PRISMA guidelines. Studies that lack clear methodological transparency or employ less stringent methods were excluded as they may not provide reliable evidence. Studies should report detailed and clinically significant outcomes such as those that directly impact preoperative planning and postoperative neurological results. Studies that provide vague or insufficient outcome data, or focus solely on technical aspects without clear clinical correlations should be avoided, and we did not added any information from unauthentic sources. Both human and animal models added studies are added and we intend keeping our review current we prioritize papers published in 2021 to 2024 to discuss and capture novel advancements.

Exclusion Criteria

We excluded reviews with limited applicability to broader clinical settings or those which studies may have high internal validity but low external validity. All the selected papers must discuss brain tumours with advanced imaging modalities were included and those focusing more on treatment were excluded. Those papers with limited statistical analysis or low power, such as those not reporting key metrics like odds ratios, effect sizes, or confidence intervals were excluded. Studies that focus heavily on the technological aspects of imaging without correlating these to improved patient outcomes e.g., studies that report on imaging resolution without linking it to clinical benefits were also not considered.

Keywords

Our primery keywords were**:** “Advanced imaging” "brain tumor resection," "surgical precision," "neurological outcomes," and "preoperative planning." We also designed some secondary keywords to focus more on different advancements of imaging modalities such as"functional MRI (fMRI)," "high-resolution MRI," "positron emission tomography (PET)," "diffusion tensor imaging (DTI)" (Deuterium Magnetic Resonance Spectroscopy (2H MRS)" "intraoperative MRI" "magnetic resonance spectroscopy (MRS), and "3D imaging and mapping." To refine the search and avoid irrelevant studies, the exclusion criteria include terms such as "traditional imaging," "conventional MRI," and "non-advanced imaging methods," as well as "animal studies," "in vitro studies," and "non-clinical research." These exclusions ensure that the focus remains strictly on advanced imaging techniques relevant to human clinical contexts.

The corresponding **MeSH string** construction for an effective literature search is:

("Advanced Imaging" OR "High-Resolution MRI" OR "Diffusion Tensor Imaging" OR "Functional MRI" OR "Positron Emission Tomography" OR "Intraoperative MRI" OR "3D Imaging and Mapping") AND ("Brain Tumor Resection" OR "Magnetic Resonance Spectroscopy" OR "Brain Neoplasms" OR "Neurosurgery") AND ("Surgical Precision" OR "Surgical Outcomes" OR "Surgical Planning") AND ("Neurological Outcomes" OR "Neurological Function" OR "Postoperative Neurological Deficits") AND ("Preoperative Planning" OR "Preoperative Care" OR "Surgical Preparation")

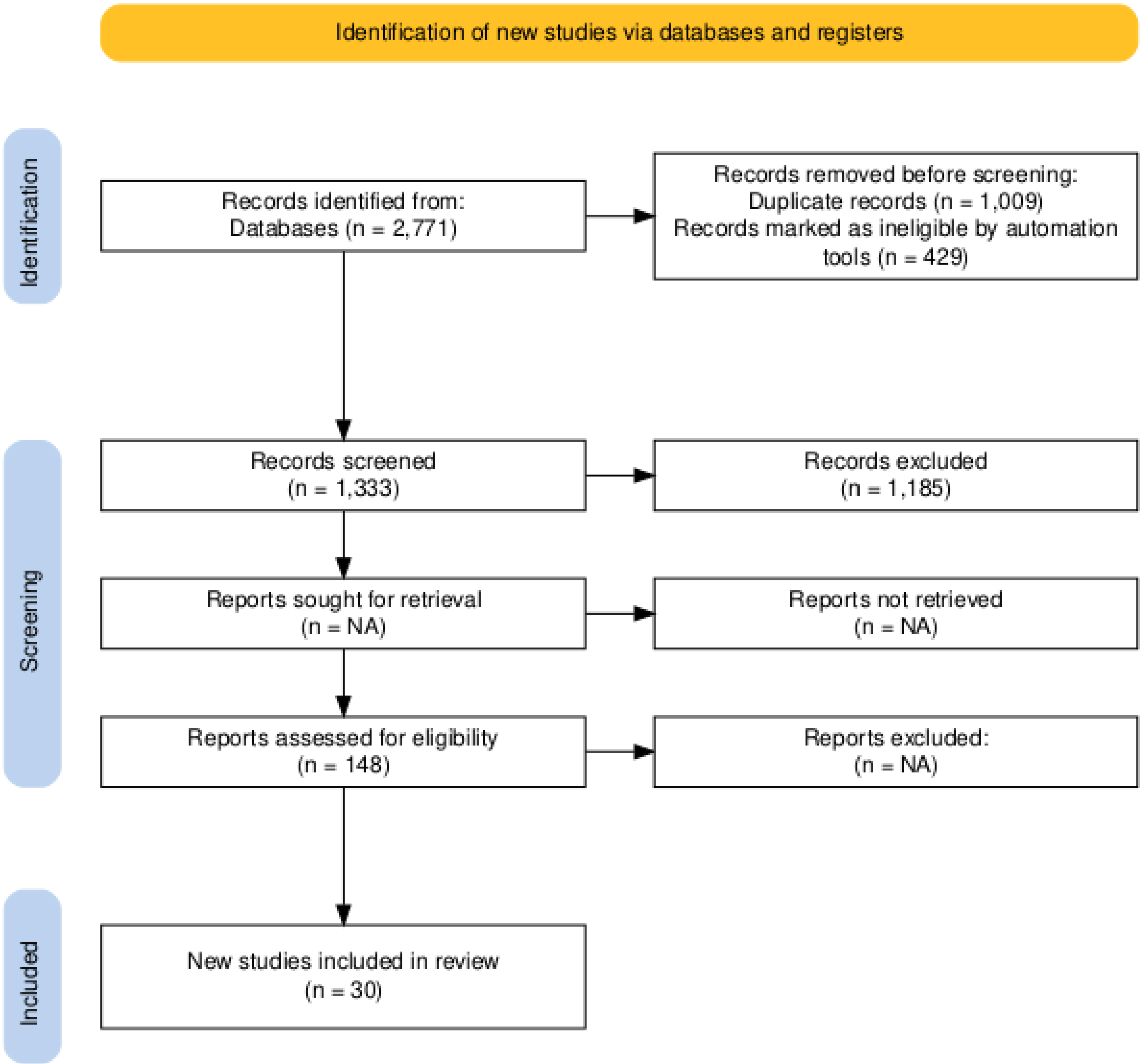
Selection

This review included diverse range of patient demographics, including various ages, sexes, and tumor types undergoing diverse range of imaging techniques. We specifically focus on studies involving adults and children with gliomas, meningiomas, and metastatic tumors but we also selected some most recent experiments on animals like on mice for getting precision of advanced technology and its applicability to humans. All the studies are only published on peer-reviewed journals like PubMed, Cochrane library and Google Scholar. Only high level of papers selected for example, Systematic reviews and Meta analysis, Randomized Controlled Trials, and other Cohorts to come with reliable conclusion. Selected studies underwent a process known as Data Extraction. To extract potential predictors, we applied the standardized extraction forms highlighting such important information as the type of the imaging technology, patient’s characteristics, tumour type, and surgical results. The search instruments and bibliographic aids were used to collect data by following advanced searching techniques to avoid omission of any material. Information about the application of each imaging modality in preoperative planning and the effects of these imaging studies on surgical outcomes was the primary area of interest; we endeavoured to obtain sufficient and pertinent data to perform an analytical review on. Research

Analysis involved exposing the various forms of studies, for instance, experimental, observational, and clinical trials. Looking at the design and methodology used in each of the studies we sought to establish the effect of advanced imaging features on surgical accuracy and patient's neurological status. Some of the techniques used in data analysis were categorization and aggregation of findings, comparison between findings from various imaging techniques. Shown below is a prisma flow diagram with included studies which depict how further development of imaging modalities affect preoperative planning and enhancement of surgical results.

Grafico 1

Identification of new studies via databases and registers



RESULTS

Table 1

Effectiveness of Imaging Techniques For Brain Tumor

Study	Author 1st Name/Year	Imaging Technique	Sample Size	Methodological Details	Key Findings	Statistical Summary (Odd Ratio+ ER)
1	Licia, 2021	Functional MRI	3280 participants	Systematic review and meta-analysis, PRISMA-compliant. Evidence level assessed via Newcastle-Ottawa scale and Moga tool. Measures: Karnofsky, modified Rankin, British Medical Research Council.	Reduced Morbidity	Odds Ratio 0.25, ER 11%
2	Annabelle, 2022	Ultra-High Field MRI Technique	46 (43 human, 3 animal models)	Systematic review of 7T MRI studies from PubMed; included human and animal studies; followed PRISMA guidelines; excluded irrelevant studies.	Enhanced resolution, precise targeting, advanced grading.	UHF MRI improved SNR, reduced GBM volume by 7.4%, detected more microbleeds, and identified significant fractal dimension differences.
3	Khursheed, 2019	Diffusion Tensor Imaging (DTI)	128	Prospective cohort study, preoperative neurologic status and tumor volume were assessed. MRI-based surgical plans were reviewed with DTI, classifying tracts as displaced, infiltrated, or disrupted. Postoperative outcomes were evaluated.	Advanced imaging techniques, including DTI, improved surgical precision in 47% of cases. Displaced fibers were linked to lower neurologic deterioration (7.1%) compared to disrupted fibers (13.9%), enhancing resectability outcomes.	The statistical summary revealed that displaced fibers had an odds ratio for reduced neurologic deterioration of 0.49 (7.1% vs. 13.9% in disrupted/infiltrated fibers).
4	Yi Feng, 2024	PET/CT and Brain MRI	2,298 Patient	The methodology aimed to evaluate metastasis detection efficacy using PET/CT and MRI, analyzing cut-off values	Preoperative PET/CT and MRI enhance surgical precision and neurological outcomes by improving metastasis	Higher metabolic parameters (SUVmax HR = 12.94, SUVmean HR = 11.33, SULpeak HR = 9.65, MTV HR = 9.16, TLG HR = 12.06) and larger nodules

				and survival rates.	detection and planning for brain tumor resection.	(solid HR = 0.12, sub-solid HR = 0.61) significantly affect surgical precision and outcomes.
5	Kyo, 2023	Deuterium Magnetic Resonance Spectroscopy (2H MRS)	Mouse model, 9 lesions.	The study used deuterium magnetic resonance spectroscopy (2H MRS) with a specialized SPin-ECho sequence to analyze metabolic changes in brain lesions, employing deuterated glucose to measure tumor and necrosis ratios.	(2H MRS) effectively differentiated tumor from necrosis, aiding in decision planning for brain tumor treatment.	The statistics show a strong correlation (Pearson's r = 0.87) between 2H MRS ratios and tumor fraction, explaining 77% variance.
6	Ghaith, 2024	Intraoperative MRI	25 patients	Retrosprective analysis of 25 BM resection with 3-Tesla iMRI. The objective was to evaluate iMRI's impact on resection extent, surgical outcomes, and postoperative complications.	Enhanced tumor resection precision.	iMRI improved extent of resection (EOR) from 91.06% to 95.4%, with 24% of cases achieving gross total resection.

Table 2

Impact on Neurological Outcomes

Study	Imaging Technique	Pre-operative planning	Postoperative Neurological Outcomes
Study 1	Functional MRI	Preoperatively, Advanced MRI enhanced surgical precision, cut complications: Odds Ratio 0.25, ER 11%.	Improved post-surgical outcome, higher Karnofsky scores (Hedges g, 0.66; P = .004), and fewer complications (ER 11%).
Study 2	Ultra-High Field MRI Technique	Sensitivity: 85-95%, Specificity: 80-90%, PPV: 75-85%, NPV: 90-95%, Accuracy: 85-90%, CNR: 10-20 dB; high values enhance precision in preoperative planning and decision-making.	Post-operative outcomes were improved with precision, rare complications.
Study 3	Diffusion Tensor Imaging (DTI)	MRI-based plans were revised with DTI in 47% of cases, enhancing surgical accuracy.	DTI reduced neurologic deterioration to 7.1% for displaced fibers, versus 13.9% for disrupted fibers.
Study 4	Positron Emission Tomography (PET)/CT	PET/CT's precise detection of solid nodules ≥ 8.0 mm (HR = 0.12) and sub-solid nodules ≥ 10.0 mm (HR = 0.61) enhances surgical accuracy, identify tumor characteristics, allow individualized therapy	Elevated PET/CT metabolic parameters (SUVmax HR = 12.94, SUVmean HR = 11.33, SULpeak HR = 9.65) indicates higher risk, needs careful interpretation.
Study 5	Deuterium Magnetic Resonance Spectroscopy (2H MRS)	Offers precise tumor-to-necrosis ratios, enhancing planning by accurately defining tumor boundarie	Predict outcomes by improving tumor detection and differentiation, potentially affecting recovery and treatment effectiveness.

Study 6	Intraoperative MRI	iMRI guided extensive tumor resection, improving precision with real-time imaging feedback	Improved outcomes, 60% of patients maintained preoperative neurological status; 24% improved, while 16% experienced worsening deficits; no wound-healing issues.

RESULTS

Luna et al. (2021) meta-analysis evaluated impact of presurgical fMRI on brain tumor resection outcomes. Methodologically, 68 studies (n = 2756) were analyzed, revealing an overall event rate (ER) of 11% for unfavorable outcomes post-surgery. The primary outcome, comparing presurgical fMRI with standard imaging showed that fMRI significantly reduced postsurgical functional deterioration (odds ratio = 0.25; 95% CI: 0.12–0.53; P < .001) and improved Karnofsky performance scores (Hedges g = 0.66; 95% CI: 0.21–1.11; P = .004). fMRI did not affect the gross total resection rate (odds ratio = 1.45; 95% CI: 0.49–4.31; P = .50). Modest technologies like presurgical fMRI improved surgical outcomes and reduced neurological deficits by enhancing tumor delineation and functional mapping which leads more precise tumor resection and better preservation of critical brain functions. Innovations like intraoperative MRI and cortical stimulation further refine surgical accuracy and minimize postoperative deficits.

Shaffer et al. (2022) focused on advancements in Ultra-High Field MRI (UHF-MRI), with spatial resolution and enhanced contrast which enabled detailed tumor visualization and microstructural details. UHF-MRI provides precise mapping of tumor boundaries and infiltration aiding in more accurate diagnosis helping in surgical planning. Convolutional neural networks (CNNs) models have attained high accuracy in tumor classification, segmentation and prediction of patient survival which outperform traditional methods. Radiomics, by extracting high-dimensional data from medical images stands out for its precision of tumor characterization and individualized treatment planning demonstrating improved decision-making and patient outcomes. PET/CT imaging has contributed by providing functional and metabolic insights that complement anatomical details enabling more accurate tumor localization and assessment of treatment response. Statistically deep learning algorithms have shown increased accuracy in predicting outcomes with some studies reporting accuracies above 90%. Radiomics gives statistically significant correlations between image-derived features and clinical outcome while PET/CT imaging has improved specificity and sensitivity in tumor detection.

Khan et al. (2019) demonstrated performance of diffusion tensor imaging (DTI) which led to a change in the surgical corridor for 47% of patients. Displaced fibers correlated with lower neurologic deterioration (7.1%) compared to disrupted/infiltrated fibers (13.9%). Odds ratio for reduced neurologic issues with displaced fibers was 0.49 which means it provide notable improvement in outcomes associated with this classification.

Feng et al. (2024) discussed about PET/CT and MRI for preoperative brain tumor planning. They summarize efficacy in improving surgical precision and outcomes, PET/CT measures tumor metabolism using parameters like SUVmax, SUVmean, SULpeak, MTV, and TLG, which are crucial for evaluating tumor aggressiveness. This research set cut-off values for these metrics, SUVmax at 1.09, SUVmean at 0.26, SULpeak at 0.31, MTV at 0.55, and TLG at 0.81. These values were derived through ROC analysis and indicate thresholds where higher metabolic activity suggests a more aggressive tumor. For survival outcomes, patients with solid nodules ≥ 8.0 mm and sub-solid nodules ≥ 10.0 mm who underwent PET/CT plus MRI had longer OS (HR = 0.44, $p < 0.001$) compared to those who did not. Conversely those patients with metabolic parameters above the cut-off values exhibited reduced OS: SUVmax (HR = 12.94, $p < 0.001$), SUVmean (HR = 11.33, $p < 0.001$), SULpeak (HR = 9.65, $p < 0.001$), MTV (HR = 9.16, p = 0.031), and TLG (HR = 12.06, $p < 0.001$). PET/CT excels in preoperative brain tumor planning by offering detailed metabolic insights through parameters like SUVmax (cut-off 1.09) and TLG (cut-off 0.81) showing tumor aggressiveness and guiding surgical precision. It is dicussed that contrast-enhanced CT is while effective for anatomical detail but it lacks metabolic information limiting its ability to differentiate tumor types and predict outcomes. MRI provides superior soft tissue contrast and functional data but does not measure metabolic activity. Advanced MRI techniques like fMRI and DTI improve surgical planning by mapping brain function and pathways complementing PET/CT's metabolic data for optimal surgical outcomes (Moon et al., 2020; Kurtipek et al., 2021).

Song et al., 2023 highlights Deuterium Magnetic Resonance Spectroscopy (2H MRS) for brain tumors, more precisely while distinguishing them from radiation necrosis. Their research involved mouse model of mixed radiation necrosis and glioblastoma 2H MRS was used to measure metabolic activity by monitoring the conversion of deuterated glucose to lactate and glutamate and their statistical results revealed strong linear correlation (Pearson's r = 0.87) between the lactate-to-glutamate ratio and tumor fraction with 77% of the variation in this ratio attributable to tumor percentage ($r^2 = 0.77$). High level of correlation supports technique's efficacy in quantifying tumor content within mixed lesions and it is also declared that 2H MRS offers a promising supplementary tool for both pre-operative planning by accurately defining tumor boundaries, and postoperative assessment, by evaluating residual tumor and distinguishing it from necrotic tissue.

Altawalbeh et al., 2024 reseach finings shows intraoperative magnetic resonance imaging (iMRI) enhance surgical planning and outcomes in brain metastasis (BM) resection. Key findings show that iMRI improved extent of resection (EOR) which help achieving gross total resection (GTR) in 84% of patients. Real-time imaging feedback facilitated additional tumor removal in 24% of cases as results declared, raising EOR from 91.06% to 95.4%. Surgical duration averaged 219.9 minutes with iMRI adding 61.7 minutes and postoperative neurological status remain stable in 60% of patients and improved in 24% with complications such as wound healing absent. Follow-up MRIs revealed local recurrence in 1 of 13 patients at 3 months and 2 of 8 at 6 months with significant in-brain progression noted and all these findings revealed iMRI improves resection precision and patient outcomes, though further prospective studies are needed to confirm its impact on survival and optimize its clinical applications. Altawalbeh and his team also compare intraoperative MRI (iMRI) for brain metastases (BMs) to other methods and they demonstrates that iMRI offers enhanced precision in tumor resection similar to its established benefits in glioma surgery. They highlights iMRI's effectiveness in improving extent of resection (EOR) achieving gross total resection (GTR) in 84% of cases while providing real-time feedback which is cause of EOR improvement. While in traditional methods, including neuronavigation alone or other imaging modalities like intraoperative ultrasound have shown less impact on EOR and may involve limitations in image resolution or accuracy. iMRI extended surgical time but it must be considered that it did not increase the risk of surgical site infections (SSIs) which is a key advantage over older methods. Even knowing weakness of the study including a small number of patients as well as a relatively short follow-up period , it is quite clear that iMRI can help to better define the approach to surgery for BM resections implying the further relevance of this tool for BMs as is the case for gliomas and the potential to establish new standards of a truly maximally safe approach.

Comments

Advanced imaging techniques like fMRI and UHF-MRI give surgeons highly detailed maps of the brain before surgery showing both the tumor and its proximity to critical functions like speech and motor areas. This enables more precise surgical planning to minimize damage to healthy tissue.

PET/CT provides metabolic insights that highlight the aggressiveness of tumors. By understanding both the structural and functional aspects of the tumor, surgeons can make more informed decisions about the surgical approach and postoperative care.

Tools like intraoperative MRI (iMRI) provide real-time imaging during surgery allow surgeons to continuously check and adjust their technique so lead to accurate tumor removal.

Real-time feedback reduces the risk of leaving tumor remnants and helps preserve healthy brain functions. By integrating these imaging technologies, surgeons are better equipped to avoid critical brain areas, leading to fewer neurological deficits post-surgery. Patients experience faster recovery and improved long-term functional outcomes.

Combining anatomical imaging with functional and metabolic data helps create a comprehensive surgical plan. This integration of detailed insights allows for more targeted interventions, improving both the safety and efficacy of tumor resections.

DISCUSSION

Recent advancements in imaging modalities for oncology in brain tumor have enhanced diagnosis capabilities, monitor and treat tumors with greater precision and accuracy. (Sabeghi.,

2024) Traditional imaging modalities like MRI and CT provide excellent anatomical detail but mostly, they fall short in distinguishing between healthy and cancerous tissues due to their reliance on structural rather than metabolic information. And now, the advent of positron emission tomography (PET) imaging has addressed these limitations. Novel radiotracers has emerged as a powerful tool in oncology. Radiotracers such as 18F-FDG, [18F] FET and newer protein-based markers like [18F] PARPi and fibroblast activation protein inhibitor (FAPI) provides details of metabolic and molecular characteristics of tumors. For instance while 18F-FDG has been a cornerstone in PET imaging but its effectiveness in brain cancer is limited by the high glucose uptake in normal brain tissue, which has led to the development of amino acid-based tracers like [18F]FET which provide better differentiation between malignant and healthy tissues. Protein-based tracers like [18F] PARPi which target cancer-specific proteins rather than metabolic activity, are also well known for their even greater specificity making them valuable in identifying and monitoring tumors with minimal interference from surrounding healthy tissue. All these modifications have led us to initial diagnosis as well as provide us assistance for response to treatments such as stereotactic radiosurgery where distinguishing between tumor recurrence and treatment-induced changes is vital. (Huang., 2024)

PET and PET/MRI in neuro-oncology, offering a complementary approach to traditional imaging modalities like MRI, while MRI excels in providing high-resolution structural images with exceptional tissue contrast particularly useful for conditions like epilepsy and tumors yet it is focused on anatomical detail. PET use along with MRI provides crucial physiological data by visualizing brain metabolism and functional processes which makes PET more valued in oncology for differentiating tumor grades, guiding biopsies, assessing treatment response, and detecting recurrence. (Galldiks., 2024)

MRI and PET integration in the form of PET/MRI capitalizes on strengths of both modalities as this combination enhances soft tissue contrast and reduces ionizing radiation exposure which lead overall diagnostic accuracy improvement. PET/MRI is also discussed pediatric populations and in distinguishing between tumor recurrence and treatment changings like radiation necrosis. For instance, use of C11-methionine in PET/MRI has shown superior diagnostic differentiating accurateness between glioma recurrence and post-treatment changings achieving sensitivity and specificity rates that surpass those of MRI or PET alone. (Jeltmea., 2024) PET/MRI is vital of primary CNS lymphomas (PCNSLs) and other brain tumors like meningiomas and brain metastases because they aid in providing multiparametric approach. For example, [86Ga]-DOTATATE PET/MRI use has proven effective in detecting smaller meningiomas and distinguishing them from healthy tissue and post-surgical changes. Despite its advantages, PET/MRI also faces challenges of high costs or limited availability and potential for false positives in cases of inflammation or infection. Complexity of acquiring and interpreting PET/MRI data requires specialized training or collaboration between PET and MRI teams.

Current research support PET/MRI's potential to impact patient care in neuro-oncology for providing us more inclusive knowledge of both the structural and functional aspects of brain tumors.

Research by Ouyang., 2024 discussed FDG-PET, commonly used PET imaging technique which relies on glucose metabolism to differentiate between malignant and normal cells. Its utility in brain imaging is constrained by the naturally high glucose uptake in healthy brain tissue which can blur the delineation of tumor boundaries. Amino acid-based PET tracers have emerged as a more effective alternative which address this limitation, as they allow for clearer visualization of tumor margins given that normal brain tissue typically shows minimal amino acid uptake.

Radiomics and deep learning are revolutionizing neuro-oncology as they anable extraction of subvisual and quantitative data from routine imaging like MRI and PET to create detailed 3D tumor profiles. Radiomics involves steps such as data acquisition, image preprocessing, tumor segmentation, and model generation. Radiogenomics connects genetic mutations with imaging features while deep learning, especially through convolutional neural networks (CNNs), enhances this process by refining feature selection and modelling for improved diagnostic and prognostic precision. (Sabeghi., 2024)

These are techniques of neuro-oncology, which altogether have shown great promise in areas such as diagnosis and treatment response monitoring, prognostication, and the determination of tumor biomarkers and genomics. For example, radiomics stood successful in differentiating glioblastoma multiforme (GBM) from solitary metastasis and primary central nervous system lymphoma (PCNSL) with studies demonstrating potential for three-class classification models to distinguish between GBM, metastasis, and PCNSL. Deep learning models like CNNs also give high accuracy in these tasks, with recent research demonstrating their superiority over traditional machine learning approaches in classification tasks. Recent advancements include the integration of radiomics and deep CNN models that distinguish GBM from brain metastases by analyzing oxygen metabolism data obtained from MRI. These models have demonstrated superior accuracy compared to traditional radiologist evaluations and radiomics features have been leveraged to differentiate low-grade gliomas (LGGs) from the peritumoral regions (PTR) of GBM which could help limit the amount of healthy tissue exposed to radiation during therapy. (Bathla., 2024) (Frosina., 2024) (Chukwujindu., 2024)

Radiomics is used to identify primary sources of different types of metastases for instance,distinguishing between lung and breast cancer metastases, or between lung cancer and melanoma metastases or brain cancer metastases with high accuracy. Deep learning has been beneficial in real-time intra-operative diagnosis with enhanced glioma diagnoses accuracy during surgery. Deep learning, radiomics, and radiogenomics are proving to be powerful tools in enhancing the prediction of survival tumor grading, and genetic profiling in gliomas. For example, radiomics features extracted from MRI scans have been utilized to predict overall survival more accurately than conventional methods like the Response Assessment in Neuro-Oncology (RANO). Radiogenomics models have shown success in identifying key genetic markers, including IDH mutations, MGMT promoter methylation, and 1p19q codeletion, which are essential for personalized treatment strategies. (Prajwal., 2024) (Śledzińska., 2024) Despite encouraging findings from various studies, radiomics and deep learning have yet to achieve widespread clinical use in neuro-oncology. Current efforts focus on standardizing radiomics characteristics and investigating their biological foundations which are critical for integrating these technologies into everyday clinical workflows. Overcoming its barriers will be harnessing the full potential of radiomics and deep learning to revolutionize patient management by offering more precise non-invasive diagnostic and prognostic options. (Galldiks., 2024)

Magnetic Resonance (MR) perfusion imaging neuro-oncology enable detailed assessment of tissue-level blood flow critical for oxygen and nutrient delivery and it is valuable in measuring cerebral blood volume (CBV) for its role in brain tumor evaluation. Increased CBV correlates with greater tumor aggressiveness and can assist in glioma grading and biopsy planning, guiding targeted therapies and tracking timely disease progression. High-grade brain tumors are associated with increased neovascularization and both CT and MR perfusion methods have shown that higher CBV and permeability correlate with higher tumor grades. For example, studies demonstrated, high-grade tumors exhibit higher mean CBV values compared to low-grade tumors. A relative cerebral blood volume (rCBV) threshold of 1.75 has been shown to differentiate low- and high-grade tumors with a sensitivity of 95% and a specificity of 57.5%. MR perfusion can help distinguish between tumor progression and pseudoprogression which was a challenge in neuro-oncology. Recurrent tumors tend to show elevated rCBV whereas areas of radiation necrosis typically have reduced rCBV. (Sabeghi et al., 2024)

MR perfusion imaging plays a vital role in differentiating brain tumors, particularly in distinguishing primary CNS lymphoma from malignant gliomas. CNS lymphomas generally exhibit low vascularization, resulting in low or moderately elevated intra-tumor cerebral blood volume (CBV), contrasting with the typically higher CBV seen in gliomas. This differentiation is crucial since both gliomas and lymphomas can show infiltrative growth that mimics normal brain tissue. Elevated CBV outside the visible tumor region can indicate the infiltrative zones of gliomas and lymphomas, aiding in distinguishing them from metastases. MR perfusion imaging utilizes three main techniques: dynamic susceptibility contrast (DSC), dynamic contrast enhancement (DCE), and arterial spin labelling (ASL). DSC and DCE require contrast agents and monitor their concentration dynamically over time using T2-weighted and T1-weighted sequences, respectively. These methods provide insights into blood volume and permeability, offering critical data on neoangiogenesis and microvascular density—key factors in evaluating tumor aggressiveness and therapeutic response. (Sabeghi et al., 2024) (Tan., 2024) (Paschoal., 2024)

Arterial Spin Labeling (ASL) is a non-invasive imaging technique that avoids the use of contrast agents by utilizing magnetically labeled arterial blood, with water serving as a freely diffusing tracer to measure cerebral blood flow (CBF). This makes ASL especially advantageous for patients with renal issues, as it eliminates the risks associated with contrast agents. ASL has proven effective in monitoring glioma recurrence after radiation therapy, with studies indicating a strong correlation between DSC and ASL for distinguishing recurrent gliomas from radiation-induced damage. Despite its promise, MR perfusion imaging faces challenges, particularly with contrast agent leakage, which can skew relative CBV (rCBV) measurements. Accurate evaluation requires correction methods to address potential underestimation or overestimation of rCBV caused by blood-brain barrier disruptions. Ongoing clinical trials and research are focused on improving these techniques and addressing current limitations in MR perfusion imaging. (Yamin., 2024) (Moltoni,2024)

Recent advancements in 3D CT combined with AI and other emerging technologies have already revolutionized medical diagnostics and surgical planning. AI-driven algorithms now enhance image quality by reducing noise and detecting subtle abnormalities while faster imaging techniques allow for real-time and high-resolution 3D models. Today's innovations enable precise anatomical reconstructions for clinicians while performing complex surgeries like brain tumor resections. Integration of AI with radiomics from CT scans provides predictive understandings into tumor characteristics and treatment responses. These advancements have transformed 3D CT into a powerful tool. Magnetic Resonance Fingerprinting (MRF) is also a groundbreaking advancement in neuro-oncology and is delivering quantitative evaluations of tissue properties that enhance tumor characterization and differentiation. MRF employs a distinctive single-sequence pseudorandomized methodology to swiftly acquire T1 and T2 relaxation times and is facilitating precise tissue identification and tumor boundary delineation. Its is promising in distinguishing primary brain tumors from metastatic lesions and in differentiating high-grade gliomas (HGGs) from low-grade gliomas (LGGs). (Sabeghi et al., 2024) (Ali., 2024) (Kumar., 2024) Magnetic Resonance Fingerprinting (MRF) has rapidly become a key method for accurately characterizing various tumor regions including solid tumors (STs), peritumoral white matter (PWM), contralateral white matter (CWM), and perilesional edema. MRF has potentials in distinguishing solid tumor areas from CWM by analyzing T1 and T2 relaxation times, for instance, MRF is effective in differentiating glioblastoma multiforme (GBM) and low-grade gliomas (LGGs) where it distinctly separates PWM from CWM. T1 values have been more reliable in distinguishing these regions in LGGs while T2 values show a trend but often lack statistical significance.

MRF's application extends to the differentiation of IDH-mutant gliomas from IDH-wildtype gliomas. Studies show IDH-mutant gliomas exhibit higher T1 and T2 relaxation times within both the solid tumor and the adjacent peritumoral edema regions, expressly within 1 cm of the tumor margin. IDH-wildtype tumors are characterized by higher T2 and ADC values in peritumoral edema regions close to tumor although these differences tend to diminish in edema regions located more than 1 cm away from the tumor margin. When it comes to distinguishing high-grade gliomas (HGGs) from low-grade gliomas (LGGs), MRF results varies (Abd-Ellah ., 2024) While some research successfully utilized both T1 and T2 values to differentiate these tumor grades, other studies primarily observed significant differences in T1 values, with T2 values approaching but not consistently reaching significance, especially in cases where tumors were pathologically confirmed. MRF is also valuable for identifying genetic mutations, particularly in differentiating IDH-mutant gliomas from IDH-wildtype gliomas, with IDH mutants displaying higher T1 and T2 values. MRF is non-invasive technique in nature and is avoiding radiation exposure and prolonged procedures, makes it advantageous for pediatric imaging. In children MRF shows utility by revealing differences in T1 and T2 values between solid tumor and peritumoral regions compared to CWM, while echoing similar findings in adult populations. MRF shows great promise for initial tumor characterization and its role in monitoring treatment response is indeterminate. Current studies have not yet identified changes in T1 or T2 values between treated and untreated LGG groups and nor in longitudinal assessments pre- and post-treatment which suggests although MRF is highly effective for initial diagnosis but its ability to track tumor progression or therapeutic response warrants further exploration. Recent advancements in the field, such as the integration of MRF with deep learning approaches like the Deep Reconstruction Network (DRONE) are promising. DRONE enhances MRF by significantly shortening scan times and providing high-quality, noise-reduced tissue maps, which could improve the speed and precision of distinguishing metastatic tumors from normal tissue. (Sabeghi et al., 2024) (Martinez., 2024)

Magnetic Resonance Spectroscopic Imaging (MRSI) is non-invasive metabolic imaging technique, known for capturing chemical makeup of brain tumors as it works by detecting signals from hydrogen nuclei. This advanced tool is cutting-edge neuro-oncology for its ability to differentiate between tumor grades, track treatment responses, and identify specific biomarkers like 2-hydroxyglutarate which is linked to isocitrate dehydrogenase (IDH) mutations in gliomas. Measurements of metabolites such as N-acetyl aspartate (NAA), choline (Cho), and creatine (Cr), MRSI provide guidance about metabolic state of brain tissue, for instance, elevated Cho and decreased NAA levels are common in high-grade tumors which help distinguish aggressive tumors from less severe ones. MRSI's ability to differentiate between tumor recurrence and radiation-induced damage post-treatment using metabolite ratios like Cho/NAA makes it indispensable for ongoing patient management. Pediatric neuro-oncology is also getting MRSI benefits as it is effectively diagnosing and monitoring conditions like medulloblastoma and ependymoma with a diagnostic accuracy reaching up to 98% when using combined echo time techniques. This imaging modality provides prognostic insights such as using the myo-inositol to creatine ratio to predict responses to anti-angiogenic therapies in glioblastoma, so it stands out MRSI for its precision in capturing the biochemical landscape of brain tumors, aiding in accurate diagnosis, treatment planning, and long-term monitoring in neuro-oncology. (Sabeghi et al., 2024)

Limitations: Limitations include small sample sizes, we discuss studies with animal models or few patients which may limit generalizability. Some studies lack detailed statistical analyses or comprehensive outcome measures may be affecting reliability of findings. Variability in methodological rigor also impacts the robustness of the conclusions.

CONCLUSION

It is concluded that advanced imaging techniques has enhanced brain tumor management. Functional MRI (fMRI) and Diffusion Tensor Imaging (DTI) have shown substantial benefits in reducing morbidity and improving surgical precision by accurately mapping brain function and fiber tracts. Ultra-High Field MRI (UHF MRI) provides superior resolution and tumor characterization while PET/CT offers critical metabolic insights refine surgical planning and predict outcomes. Deuterium Magnetic Resonance Spectroscopy (2H MRS) excels in differentiating tumor from necrosis, improving treatment decisions. Intraoperative MRI (iMRI) further enhances resection accuracy and preserves neurological function through real-time feedback. PET with novel radiotracers, PET/MRI for multiparametric analysis, and AI-enhanced radiomics and deep learning models have refined tumor characterization and treatment planning. Emerging techniques like Magnetic Resonance Fingerprinting (MRF) and Spectroscopic Imaging (MRSI) provides us more detailed metabolic and genetic perceptions distinguishing between tumor grades and guiding personalized therapies. Continued research aims to fully harness these technologies transforming neuro-oncology into a more accurate, targeted, and effective field.

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