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Multimodal Neuroimaging in Image-Guided Neurosurgery: Current Applications, Clinical Challenges and Future Directions -A Narrative Review

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Abstract:

- ***Background***

Modern neurosurgery increasingly relies on individualized neuroimaging to maximize lesion resection while preserving neurological function. Conventional magnetic resonance imaging (MRI) provides detailed anatomical information but does not fully characterize cortical function, white-matter connectivity, or anatomical changes occurring during surgery. Multimodal neuroimaging integrates complementary structural, functional, and connectivity information and can therefore support more individualized image-guided surgical planning.

- ***Objective***

This narrative review examines the current applications of multimodal neuroimaging in image-guided neurosurgery, focusing on structural MRI, functional MRI (fMRI), diffusion tensor imaging (DTI) and tractography, neuronavigation, intraoperative MRI, intraoperative ultrasound, and approaches for addressing intraoperative brain shift. Emerging computational and artificial intelligence (AI)-assisted approaches are also discussed.

- ***Methods***

A narrative literature search was conducted using PubMed/MEDLINE. Additional relevant publications were identified through reference-list screening of selected reviews and primary studies. Search concepts included multimodal neuroimaging, image-guided neurosurgery, functional MRI, diffusion tensor imaging, tractography, neuronavigation, intraoperative MRI, intraoperative ultrasound, brain shift, functional brain mapping, and brain tumor surgery. Clinical studies, systematic reviews, meta-analyses, and methodological literature relevant to these topics were considered. Because this was a narrative review, no formal meta-analysis or quantitative risk-of-bias assessment was performed.

- ***Results***

Structural MRI remains the anatomical foundation of image-guided neurosurgery. Functional MRI can provide non-invasive information regarding cortical networks, while diffusion imaging and tractography can characterize major white-matter pathways. Integration of these datasets into neuronavigation can assist individualized surgical planning, particularly for lesions involving eloquent cortex or critical subcortical tracts. Intraoperative MRI can update navigation and identify residual tumor after anatomical deformation, whereas intraoperative ultrasound provides real-time imaging with lower infrastructure requirements. Important limitations include neurovascular uncoupling, functional reorganization, tractography uncertainty, registration errors, brain shift, cost, workflow complexity, and limited prospective validation.

- ***Conclusion***

Multimodal neuroimaging provides a clinically valuable framework for precision image-guided neurosurgery by integrating anatomical, functional, and connectivity information across the surgical pathway. Future advances should

prioritize reliable multimodal integration, real-time intraoperative updating, standardized imaging protocols, interpretable computational tools, and prospective evaluation of patient-centered outcomes.

Keywords: *Multimodal Neuroimaging; Image-Guided Neurosurgery; Functional MRI; Diffusion Tensor Imaging; Tractography; Neuronavigation; Intraoperative MRI; Intraoperative Ultrasound; Brain Tumor Surgery; Functional Brain Mapping.*

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I. INTRODUCTION

Neurosurgery has progressively evolved from procedures based predominantly on anatomical localization toward individualized interventions supported by advanced neuroimaging and functional mapping. This evolution is particularly important in brain tumor surgery, where the surgeon must balance maximal tumor removal against preservation of neurological function. Greater extent of resection has been associated with improved survival in glioblastoma, although the strength of evidence varies across studies and must be considered alongside tumor biology and postoperative neurological status. A large systematic review and meta-analysis involving more than 41,000 patients found lower mortality following gross-total resection compared with subtotal resection, supporting the clinical importance of achieving maximal safe resection when feasible [1].

The challenge is greatest when lesions are located near eloquent cortical regions or critical subcortical white-matter pathways. A purely anatomical approach may not adequately account for individual variability in functional organization or tumor-associated functional reorganization. Consequently, modern surgical planning increasingly incorporates multiple complementary imaging modalities.

Conventional structural magnetic resonance imaging (MRI) remains the foundation of neurosurgical planning. T1-weighted, T2-weighted, fluid-attenuated inversion recovery, and contrast-enhanced sequences provide information regarding lesion location, morphology, enhancement, edema, mass effect, and relationships to surrounding structures. However, structural MRI alone cannot reliably determine which cortical areas are functionally essential or define the complete course of critical white-matter pathways [2,3].

Functional MRI (fMRI) provides complementary information regarding cortical activation and can be used to identify motor, language, sensory, visual, and other functional networks before surgery [4,5]. Diffusion MRI and tractography provide information regarding white-matter architecture and can demonstrate the relationship between lesions and major pathways such as the corticospinal tract, arcuate fasciculus, optic radiations, and association fibers [6]. The integration of these datasets with neuronavigation allows anatomical, functional, and connectivity information to be interpreted within a patient-specific spatial framework [6,7].

However, the brain is not anatomically static during surgery. Cerebrospinal fluid loss, gravity, tissue resection, edema, and other surgical factors can produce brain deformation or brain shift, progressively reducing the accuracy of navigation based exclusively on preoperative images [8]. Brain shift therefore represents one of the fundamental limitations of conventional image-guided neurosurgery.

Intraoperative MRI and intraoperative ultrasound have been developed partly to address this limitation. Intraoperative MRI can provide updated anatomical information and identify residual tumor during surgery, while intraoperative ultrasound can provide real-time imaging and can be incorporated into the operative workflow with substantially lower infrastructure requirements [9,10]. Randomized evidence and subsequent meta-analyses suggest that intraoperative MRI can improve gross-total resection rates in glioma surgery without a clear increase in postoperative neurological deterioration [9,11].

More recently, computational imaging and artificial intelligence have expanded the possibility of integrating multiple imaging datasets, facilitating segmentation, registration, image fusion, and decision support [12]. However, the clinical value of these technologies depends on whether they improve surgical decision-making and patient outcomes rather than simply increasing technical imaging performance.

The purpose of this narrative review is therefore to examine the current role of multimodal neuroimaging in image-guided neurosurgery, focusing on structural MRI, functional MRI, diffusion imaging and tractography, multimodal neuronavigation, intraoperative MRI, intraoperative ultrasound, and strategies for addressing brain shift. Emerging computational and AI-assisted approaches are also considered.

II. METHODS

➢ *Literature Search*

A narrative literature search was conducted using PubMed/MEDLINE. Additional publications were identified through screening the reference lists of selected systematic reviews, narrative reviews, and relevant primary studies.

The search strategy incorporated combinations of the following terms:

- “Multimodal Neuroimaging”
- “Image-Guided Neurosurgery”

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- "Neuronavigation"
- "Functional Mri"
- "Fmri"
- "Diffusion Tensor Imaging"
- "Dti"
- "Tractography"
- "Functional Brain Mapping"
- "Intraoperative Mri"
- "Intraoperative Ultrasound"
- "Brain Shift"
- "Brain Tumor Surgery"
- "Glioma Surgery"
- "Eloquent Brain"
- "Functional Neuronavigation"
- "Intraoperative Tractography"
- "Artificial Intelligence Neurosurgery"

➢ *Eligibility and Selection*

Particular emphasis was placed on literature addressing:

- Anatomical Mri;
- Functional Cortical Mapping;
- Diffusion Imaging And Tractography;
- Multimodal Image Fusion;
- Neuronavigation;
- Brain Shift;
- Intraoperative Mri;
- Intraoperative Ultrasound;
- Intraoperative Tractography; And
- Computational And Ai-Assisted Imaging.

Because this was a narrative review, no formal systematic-review protocol, quantitative meta-analysis, or formal risk-of-bias assessment was performed.

➢ *Body and Review*

- *Multimodal Neuroimaging in Image-Guided Neurosurgery*

Multimodal neuroimaging refers to the integration of imaging modalities that provide complementary information regarding brain anatomy, cortical function, white-matter connectivity, vascular characteristics, and pathology.

The clinical concept can be summarized as:

Structural MRI → functional mapping → white-matter mapping → multimodal image fusion → neuronavigation → intraoperative imaging → postoperative assessment

Each component answers a different clinical question.

Structural MRI defines the lesion anatomically. Functional imaging identifies relevant cortical networks. Diffusion imaging contributes information regarding white-matter pathways. Image registration and fusion combine these datasets. Neuronavigation translates this information into a surgical coordinate system. Intraoperative imaging then provides the opportunity to update that model when the brain changes during surgery.

Recent literature describes multimodal neuroimaging computing as an important component of image-guided neurosurgery and precision medicine because it enables integration of multiple sources of anatomical and functional information [12].

The purpose of multimodal imaging should therefore not be the accumulation of multiple images but the generation of clinically actionable information.

➢ *Structural MRI: The Anatomical Foundation*

- *Conventional MRI*

Structural MRI provides the principal anatomical framework for modern neurosurgical planning.

T1-weighted imaging provides detailed anatomical contrast and, following gadolinium administration, can identify enhancing tumor components. T2-weighted and FLAIR sequences provide information regarding edema, infiltrative abnormalities, and non-enhancing components.

In patients with brain tumors, MRI helps determine:

- Lesion Location;
- Tumor Morphology;
- Contrast Enhancement;
- Surrounding Edema;
- Mass Effect;
- Ventricular Involvement;
- Cortical Relationships;
- Deep Nuclear Involvement; and
- Relationships with White-Matter Structures.

This anatomical dataset generally serves as the reference image to which functional and diffusion datasets are registered.

- *Limitations of Structural MRI*

Despite its excellent anatomical resolution, conventional MRI does not directly identify whether a particular cortical region is essential for a specific function.

This distinction becomes important in patients with lesions involving motor or language regions. Anatomically similar tumors can produce different functional consequences because of individual variation and tumor-associated neuroplasticity.

Consequently, anatomical localization alone may not provide sufficient information to determine the safest surgical trajectory.

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➢ *Functional MRI For Preoperative Brain Mapping*

* *Task-Based Functional MRI*

Functional MRI uses blood oxygenation level-dependent (BOLD) contrast to identify changes associated with neuronal activity.

In neurosurgical planning, task-based fMRI can be used to identify:

* Motor Cortex;
* Language-Related Regions;
* Sensory Areas;
* Visual Cortex; and
* Selected cognitive networks.

Its major clinical advantage is that it provides non-invasive, patient-specific functional information before surgery [4,13].

A review of contemporary clinical fMRI emphasizes that its principal role is to identify eloquent cortical regions near brain tumors and assist surgical planning, while also highlighting limitations involving neurovascular uncoupling, patient compliance, paradigm selection, and image interpretation [13].

* *Language Mapping*

Language mapping is one of the most clinically important applications of fMRI.

Language is distributed across interconnected cortical and subcortical networks rather than being confined to a single anatomical region. Therefore, identifying language-related activation can help define potential areas at risk during tumor resection.

However, language fMRI should not be considered a replacement for direct cortical stimulation.

A review comparing language fMRI with direct cortical stimulation found substantial heterogeneity among studies, with reported sensitivity and specificity varying considerably [14]. The authors concluded that fMRI could not reliably replace direct cortical stimulation, particularly in glioma surgery.

Thus, fMRI should be viewed as a complementary preoperative mapping tool that can guide surgical planning and help target areas for subsequent intraoperative testing.

* *Motor Mapping*

Motor fMRI can demonstrate cortical activation associated with movement and can assist in determining the relationship between tumors and motor cortex.

Its interpretation, however, can be affected by tumor-related changes in neurovascular coupling and functional reorganization [15].

Accordingly, fMRI findings should be integrated with anatomical MRI, diffusion imaging, neurological examination, and, when indicated, intraoperative stimulation.

➢ *Resting-State Functional MRI*

Task-based fMRI requires patient cooperation and adequate performance of specific tasks. This can be challenging in patients with severe neurological deficits, cognitive impairment, pediatric populations, or patients unable to reliably perform task paradigms.

Resting-state fMRI (rs-fMRI) provides an alternative by analyzing spontaneous low-frequency fluctuations in BOLD signals without requiring active task performance.

Rs-fMRI has been investigated for mapping functional networks relevant to neurosurgical planning. These include sensorimotor, language-related, visual, auditory, and executive networks.

A 2024 systematic review of 18 studies involving 1,035 patients reported that rs-fMRI may be useful for preoperative mapping, particularly in patients for whom task-based fMRI is difficult [16].

Standardization remains important. Multicenter recommendations have proposed standardized acquisition and preprocessing approaches for rs-fMRI in patients with brain tumors and epilepsy [17].

However, rs-fMRI remains vulnerable to motion, susceptibility artifacts, preprocessing choices, and tumor-related neurovascular abnormalities [18].

➢ *Diffusion Mri and White-Matter Tractography*

* *Principles of Diffusion Imaging*

Diffusion MRI characterizes the movement of water molecules within tissue. In white matter, water diffusion is influenced by axonal organization, allowing estimation of the orientation of white-matter fibers.

Diffusion tensor imaging and related tractography techniques can therefore provide three-dimensional representations of major white-matter pathways.

These pathways are particularly important in neurosurgery because injury to subcortical structures can produce permanent motor, sensory, visual, or language deficits.

* *Major Tracts Relevant to Neurosurgical Planning*

Important pathways include:

* Corticospinal Tract;
* Arcuate Fasciculus;
* Superior Longitudinal Fasciculus;
* Optic Radiations;
* Inferior Fronto-Occipital Fasciculus;
* Inferior Longitudinal Fasciculus; And

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- Corpus Callosum.

The spatial relationship between these pathways and a tumor may influence surgical trajectory and expected functional risk [6,19].

A major review by Essayed and colleagues examined white-matter tractography for neurosurgical planning and included Alexandra Golby and Lauren O'Donnell among its authors. The review concluded that tractography can be valuable in selected neurosurgical situations while emphasizing clinically relevant technical limitations [6].

- *DTI-Integrated Neuronavigation*

DTI can be fused with conventional MRI and incorporated into neuronavigation.

In a series of 123 patients undergoing DTI-merged functional neuronavigation, major pathways including the corticospinal tract, optic radiation, and arcuate fasciculus were incorporated into surgical planning. Gross-total resection was achieved in 73.2% of patients, although the authors emphasized that tract displacement and methodological limitations remain relevant considerations [7].

A systematic review concluded that DTI can influence preoperative planning and surgical decision-making, although routine clinical implementation remains variable [19].

III. LIMITATIONS OF TRACTOGRAPHY

Tractography should not be interpreted as direct visualization of individual axons.

Its accuracy may be influenced by:

- Crossing Fibers;
- Kissing Fibers;
- Edema;
- Tumor Infiltration;
- Distorted Anatomy;
- Acquisition Parameters;
- Image Resolution;
- Reconstruction Algorithms; and
- Tracking Thresholds.

These limitations can produce false-positive or false-negative tract representations [6,19].

The clinical interpretation of tractography should therefore involve correlation with anatomical MRI, functional mapping, neurological examination, and intraoperative findings.

Recent evidence suggests that intraoperative tractography may improve surgical outcomes, but its clinical adoption remains limited partly because of processing time and methodological variability [20]. A 2025 systematic review and meta-analysis identified 26 relevant studies and reported a pooled gross-total resection rate of approximately 79%, while also noting moderate risk of bias and the need for better evidence [20].

➢ *Multimodal Image Fusion and Neuronavigation*

The major clinical advantage of multimodal imaging is realized when separate datasets are registered into a common spatial framework.

A typical workflow may include:

- High-resolution anatomical MRI.
- Functional MRI.
- Diffusion MRI and tractography.
- Image registration and fusion.
- Integration into neuronavigation.
- Intraoperative functional assessment.
- Intraoperative MRI or ultrasound when available.
- Postoperative imaging.

The resulting patient-specific map can display the tumor in relation to cortical activation and important white-matter pathways.

Clinical studies have demonstrated the feasibility of integrating DTI and functional imaging with neuronavigation for tumors involving eloquent areas [7].

This approach shifts image guidance from purely anatomical navigation toward anatomical-functional navigation.

➢ *Functional Mapping Beyond fMRI*

- *Navigated Transcranial Magnetic Stimulation*

Navigated transcranial magnetic stimulation (nTMS) provides non-invasive stimulation-based functional mapping.

It has been investigated particularly for preoperative motor and language mapping.

A systematic review of preoperative mapping techniques identified fMRI, nTMS, and magnetoencephalography as established approaches for assessing motor and language function before brain tumor surgery [21].

nTMS can also be combined with tractography to provide information regarding the relationship between cortical motor sites and subcortical pathways.

- *Direct Cortical Stimulation*

Direct cortical stimulation remains an important intraoperative technique for identifying functionally essential cortical and subcortical regions.

Its principal strength is that it directly tests function during surgery.

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However, it is invasive and requires specialized expertise and, in awake procedures, appropriate patient cooperation.

The modern approach therefore increasingly emphasizes complementarity among preoperative imaging, non-invasive functional mapping, and intraoperative stimulation.

➢ *Brain Shift: A Major Challenge To Conventional Neuronavigation*

Neuronavigation generally relies on preoperative imaging registered to the patient's anatomy.

However, the anatomical configuration of the brain can change considerably during surgery.

Brain shift may result from:

- Opening of the dura;
- Cerebrospinal fluid loss;
- Gravity;
- Tumor debulking;
- Tissue retraction;
- Edema;
- Cyst drainage; and
- Changes in intracranial pressure.

Gerard et al. reviewed the causes, measurement, and compensation of brain shift and emphasized that preoperative-image-based neuronavigation can become unreliable when intraoperative deformation invalidates the original patient-to-image registration [8].

The central problem can therefore be summarized as:

➢ *The surgical anatomy changes while the navigation map may remain static.*

Strategies developed to address this include:

➢ *Intraoperative MRI*

- *Rationale*

Intraoperative MRI provides updated imaging during surgery and can therefore compensate, at least partially, for the limitations of static preoperative imaging.

Potential applications include:

- Detecting Residual Tumor
- Updating Neuronavigation
- Assessing Extent Of Resection
- Identifying Anatomical Deformation
- Guiding Further Resection And
- Evaluating Surgical Complications.

- *Evidence for Clinical Benefit*

A randomized controlled trial by Senft et al. included 58 patients with contrast-enhancing gliomas and found complete tumor resection in 96% of evaluable patients in the intraoperative MRI group compared with 68% in the conventional surgery group [22]. Importantly, postoperative neurological deficits did not differ significantly between groups.

A subsequent systematic review and meta-analysis of randomized controlled trials found that intraoperative MRI-guided surgery was associated with substantially higher odds of gross-total resection compared with conventional navigation-guided surgery. Extended resection after intraoperative MRI occurred in approximately 29% of cases, while postoperative neurological deterioration was not significantly different between groups [9].

These findings support the role of intraoperative MRI as a strategy for obtaining updated anatomical information when maximal safe resection is the surgical objective.

- *Limitations*

Despite these benefits, intraoperative MRI has several limitations:

- High capital cost
- Specialized operating-room infrastructure
- Increased workflow complexity
- Longer operative time
- MRI-compatible equipment requirements and
- Limited availability.

The 2024 randomized-trial meta-analysis estimated that intraoperative MRI increased operative time by approximately 42 minutes on average [9].

Therefore, its clinical value must be considered in relation to resource requirements.

➢ *Intraoperative Ultrasound*

Intraoperative ultrasound provides a different approach to real-time surgical imaging.

Its major advantages include:

- Relatively Low Cost
- Portability
- Real-Time Imaging
- Repeated Imaging During Surgery
- Relatively Straightforward Integration Into The Operating Room.

A review by Dixon et al. noted that the cost and logistical challenges of intraoperative MRI limit widespread adoption, whereas intraoperative ultrasound can be incorporated into existing operating-room infrastructure [10].

Modern ultrasound technology has improved substantially, with advances in image quality, navigation integration, contrast-enhanced ultrasound, and other techniques [10].

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However, limitations remain, including:

- Operator Dependence
- Image Artifacts
- Variable Image Quality
- Difficulty Interpreting Postoperative Anatomy and
- A Learning Curve for Surgeons And Radiologists.

Therefore, intraoperative ultrasound should be regarded as a complementary modality rather than simply a less expensive substitute for MRI.

➢ *Multimodal Imaging for Brain Tumor Surgery*

Brain tumor surgery represents one of the most developed clinical applications of multimodal neuroimaging. A patient-specific surgical workflow may be conceptualized as:

Structural MRI + fMRI + DTI/tractography → multimodal image fusion → neuronavigation → intraoperative mapping → intraoperative imaging → updated surgical plan → maximal safe resection

- Structural MRI identifies the lesion.
- fMRI identifies potentially eloquent cortical regions.
- DTI and tractography characterize important white-matter pathways.
- Neuronavigation integrates these datasets.
- Direct cortical stimulation can provide intraoperative functional validation.
- Intraoperative MRI or ultrasound can update the anatomical model.
- This approach is particularly important for gliomas involving eloquent cortical or subcortical regions [6,7,19].

The overall objective is not maximal resection at any cost, but maximal safe resection based on an individualized understanding of tumor anatomy and functional organization.

➢ *Multimodal Neuroimaging In Eloquent Brain Tumors*

- Tumors involving eloquent cortex present a particularly challenging surgical problem.
- Motor and language deficits can have major consequences for independence and quality of life.
- Multimodal imaging can help characterize:
- functional cortical regions
- white-matter pathways
- tumor displacement
- functional reorganization
- potential surgical corridors.
- Language mapping provides an important example.
- fMRI can identify language-related activation.
- DTI can characterize language-associated white-matter pathways.
- nTMS can provide stimulation-based preoperative information.
- Direct cortical stimulation can provide intraoperative validation.

The resulting approach relies on converging evidence from multiple complementary modalities rather than a single imaging technique [14,21].

IV. CLINICAL CHALLENGES AND LIMITATIONS

- *Neurovascular Uncoupling*

BOLD fMRI depends on a relationship between neuronal activity and vascular responses.

Brain tumors can disrupt normal neurovascular coupling, potentially producing false-negative or misleading fMRI findings [23,24].

This is particularly important when a tumor is located near an eloquent region.

Cerebrovascular reactivity assessment and other approaches have been investigated to identify regions in which BOLD responses may be unreliable [25].

- *Functional Reorganization*

Tumors may induce functional reorganization over time.

Consequently, standard anatomical assumptions about the location of motor or language functions may not apply uniformly across patients.

This reinforces the need for patient-specific functional mapping.

- *Tractography Uncertainty*

Tractography is influenced by acquisition and processing methods and may be unreliable in regions containing crossing fibers or significant tumor-associated distortion [6,19].

Therefore, tractography should not independently determine the surgical boundary.

- *Registration Errors*

Multimodal imaging requires registration of datasets acquired at different times and potentially with different spatial distortions.

Small registration errors may become clinically important when imaging is used near eloquent structures.

- *Brain Shift*

Brain shift remains a fundamental limitation of static preoperative navigation [8].

This explains the increasing interest in intraoperative MRI, ultrasound, deformable registration, and real-time computational updating.

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- *Cost and Accessibility*

Advanced imaging technologies are not equally available across institutions.

Intraoperative MRI requires substantial infrastructure, while advanced tractography and functional mapping require specialized expertise.

Intraoperative ultrasound provides a more accessible alternative but requires appropriate training and experience [10].

- *Standardization*

Variation in imaging acquisition, preprocessing, functional paradigms, tractography algorithms, and interpretation limits reproducibility.

Standardized resting-state fMRI acquisition and preprocessing recommendations have been proposed to improve clinical consistency [17].

➢ *Emerging Role of Artificial Intelligence and Computational Imaging*

Artificial intelligence and computational imaging are increasingly being investigated in neurosurgery.

Potential applications include:

- Automated Tumor Segmentation
- Image Registration
- Multimodal Image Fusion
- Brain-Shift Estimation
- Tractography Assistance
- Intraoperative Image Interpretation
- Prediction Of Surgical Risk
- Automated Functional Network Analysis And
- Decision Support.

Multimodal neuroimaging computing may facilitate integration of structural, functional, diffusion, and intraoperative imaging into a unified clinical framework [12].

AI may be particularly useful when the quantity of imaging data exceeds what can easily be interpreted manually.

For example, a future system could potentially integrate:

MRI + fMRI + DTI + intraoperative ultrasound → updated patient-specific surgical map and provide an interpretable representation of:

- Tumor Boundaries
- Functional Cortex
- Critical White-Matter Pathways
- Predicted Brain Deformation And
- Suspected Residual Tumor.

However, technical performance alone does not establish clinical utility.

A 2025 systematic review of AI in neurosurgery identified applications across diagnosis, treatment planning, outcome prediction, and intraoperative support, while also highlighting concerns regarding model validation, interpretability, ethics, and clinical implementation [26].

For clinical translation, the most important question should therefore be:

Does the computational system improve a clinically meaningful decision or patient outcome? rather than simply:

Does the algorithm achieve high technical accuracy?

V. FUTURE DIRECTIONS

➢ *Real-Time Multimodal Navigation*

Future image-guided systems may integrate preoperative and intraoperative imaging continuously rather than treating them as separate stages.

A dynamic navigation platform could update the anatomical model throughout surgery.

➢ *Improved Brain-Shift Correction*

More reliable detection and correction of brain deformation could substantially improve navigation accuracy.

Potential approaches include combinations of intraoperative ultrasound, MRI, deformable registration, and biomechanical modeling [8,10].

➢ *Individualized Functional Network Mapping*

Future neuroimaging approaches may increasingly focus on patient-specific functional networks rather than isolated cortical activation sites.

This could be particularly valuable in patients with tumors that have produced significant functional reorganization.

➢ *Integration of Functional and Structural Connectivity*

Combining cortical functional information with white-matter connectivity may provide a more complete representation of the brain's functional architecture.

- Instead of asking only:

  "Where is the eloquent cortex?"

- future systems may address:

  "How is this patient's functional network organized, and which components are at risk from the planned surgical trajectory?"

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➢ *Intraoperative Tractography*

Real-time or near-real-time tractography could help update the location of important white-matter pathways after brain deformation.

Recent systematic evidence suggests potential clinical benefit but also identifies processing time and methodological limitations as barriers to routine implementation [20].

➢ *AI-Assisted Multimodal Integration*

AI may eventually assist clinicians by automatically integrating multimodal imaging and highlighting clinically important relationships.

Future systems should prioritize:

- Interpretability;
- External Validation;
- Prospective Evaluation;
- Robustness Across Institutions;
- Uncertainty Estimation; and
- Integration Into Clinical Workflow.

➢ *Prospective Multicenter Research*

A major future requirement is prospective multicenter evaluation.

Many technologies have demonstrated technical feasibility and promising retrospective outcomes, but evidence regarding their effects on long-term neurological function, quality of life, progression-free survival, and overall survival remains heterogeneous.

Future studies should therefore evaluate not only imaging accuracy but also patient-centered endpoints.

VI. DISCUSSION

Multimodal neuroimaging represents a conceptual shift in image-guided neurosurgery.

Traditional neuronavigation primarily provided anatomical localization.

Modern multimodal navigation seeks to provide anatomical, functional, and connectivity information simultaneously.

This distinction is particularly important in brain tumor surgery.

A tumor may be anatomically resectable but functionally dangerous. Conversely, a lesion that appears anatomically close to an eloquent region may be associated with functional reorganization that changes the patient's individualized surgical risk.

Multimodal imaging helps characterize this variability.

Structural MRI provides anatomical information.
fMRI contributes information regarding cortical function.

DTI and tractography contribute information about white-matter architecture.
nTMS provides stimulation-based preoperative mapping.

Neuronavigation integrates these datasets.

Intraoperative MRI and ultrasound address the limitations created by anatomical deformation.

Direct cortical stimulation provides intraoperative functional validation.

Thus, the future of image-guided neurosurgery is unlikely to depend on a single “best” imaging modality. Instead, it will depend on intelligent integration of complementary information.

Each modality has limitations. fMRI can be affected by neurovascular uncoupling. Tractography has methodological uncertainty. Neuronavigation can be compromised by brain shift. Intraoperative MRI provides updated anatomical information but requires substantial infrastructure. Ultrasound is more accessible but is operator dependent.

These limitations reinforce the importance of multimodal decision-making.

The clinical significance is particularly evident in eloquent brain tumors, where the goal is not simply radiographic tumor removal but preservation of meaningful neurological function.

The next major challenge is therefore translational: converting increasingly sophisticated imaging into reliable, understandable, and actionable information without unnecessarily increasing surgical complexity.

Computational imaging and AI may contribute to this transition by facilitating segmentation, registration, fusion, and interpretation [12,26]. However, clinical implementation should be driven by evidence of improved patient outcomes rather than technological novelty.

The most promising direction is therefore a patient-specific, continuously updated surgical model in which preoperative anatomical, functional, and connectivity information is integrated with intraoperative imaging and clinical observations.

Such a framework aligns closely with the broader goal of image-guided neurosurgery: transforming complex neuroimaging data into actionable information that supports safer and more precise surgical decisions.

➢ *Limitations and Challenges of the Current Evidence*

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Several limitations should be considered when interpreting the literature discussed in this review.

First, substantial heterogeneity exists among studies regarding patient populations, tumor types, imaging protocols, acquisition parameters, functional paradigms, tractography methods, and definitions of surgical outcomes.

Second, many studies are retrospective or involve relatively small single-center cohorts. This limits generalizability and makes direct comparison between technologies difficult.

Third, the clinical validation of imaging biomarkers and functional maps remains challenging. Technical agreement between imaging and intraoperative findings does not necessarily translate into improved long-term neurological or oncological outcomes.

Fourth, fMRI and tractography are indirect measurements. fMRI relies on vascular responses, which may be altered by tumor biology, while tractography reconstructs probable pathways rather than directly visualizing individual axons [6,23].

Fifth, brain shift remains an unresolved challenge for conventional neuronavigation [8].

Sixth, advanced intraoperative technologies such as MRI and sophisticated computational navigation can increase financial and logistical demands.

Finally, AI-based systems introduce additional challenges involving dataset bias, generalizability, interpretability, cybersecurity, regulatory approval, and clinical responsibility [26].

Therefore, future research should emphasize prospective multicenter validation, standardized protocols, transparent reporting, and patient-centered outcomes.

VII. CONCLUSION

Multimodal neuroimaging has become an increasingly important component of modern image-guided neurosurgery.

Structural MRI provides the anatomical foundation for surgical planning, while fMRI provides complementary information regarding cortical functional organization and diffusion imaging contributes information about major white-matter pathways. Integration of these datasets with neuronavigation enables individualized visualization of lesions in relation to potentially critical functional structures [6,7].

During surgery, intraoperative MRI can provide updated anatomical information and facilitate identification of residual tumor, while intraoperative ultrasound offers real-time imaging with lower infrastructure requirements [9,10]. These technologies are particularly relevant to the challenge of brain shift, which can reduce the reliability of navigation based exclusively on preoperative imaging [8].

Despite substantial technological progress, limitations involving neurovascular uncoupling, functional reorganization, tractography uncertainty, registration error, brain deformation, cost, standardization, and prospective validation remain.

The future of image-guided neurosurgery is therefore unlikely to be defined by any single imaging modality. Instead, progress will depend on the effective integration of anatomical, functional, connectivity, and intraoperative information into a patient-specific surgical framework.

Artificial intelligence and computational imaging may further facilitate this integration by enabling automated segmentation, image registration, multimodal fusion, brain-shift estimation, and decision support. However, these technologies must undergo rigorous prospective evaluation before widespread clinical adoption.

Ultimately, the value of multimodal neuroimaging lies not in producing increasingly complex images but in transforming those images into reliable, patient-specific, clinically actionable information that enables maximal safe resection while preserving neurological function.

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