Advanced MRI Techniques in Brain Tumor Diagnosis and Neurological Oncology

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Abstract*—Advanced MRI modalities—such as diffusion imaging (DWI, DTI, DKI), perfusion imaging (DSC, DCE, ASL), MR spectroscopy (MRS), functional MRI (fMRI), susceptibility-weighted imaging (SWI), quantitative relaxometry (T1/T2 mapping), and quantitative radiomics/AI—are increasingly indispensable in neuro-oncology. They provide metabolic, vascular, and cellular information that complements conventional MRI, enabling more accurate tumor grading, differentiation of tumor recurrence vs. treatment effects, prediction of molecular markers (IDH, 1p/19q, MGMT), and monitoring of therapy. Recent studies and consensus guidelines highlight the added value of these methods: for example, perfusion MRI (DSC/DCE) shows high sensitivity/specificity (~90%/85%) in distinguishing tumor recurrence from radiation necrosis, and combined MRS and perfusion yields ~92% specificity for differentiating neoplasms from non-neoplastic lesions. Radiomics and machine learning leveraging multimodal MRI (and PET/MRI) can predict key genotypes with accuracies around 80–90%. We synthesize the recent literature (past decade) and consensus guidelines to present an in-depth review of each modality, including technical principles, typical acquisition parameters, diagnostic performance, applications to grading and molecular subtyping, roles in posttreatment monitoring, limitations, and future directions. We also provide comparative tables of protocols and performance metrics, and a flowchart for multimodal imaging decision-making (Figure 1). Our findings support an integrated imaging approach: for instance, international recommendations advise routine use of perfusion MRI for gliomas lacking clear high-grade features. In conclusion, advanced MRI techniques significantly enhance neuro-oncologic imaging and support personalized management, but standardized protocols and further validation are needed to fully realize their potential in clinical practice.

***Keywords*—Brain tumors, advanced MRI, diffusion imaging, perfusion MRI, MR spectroscopy, functional MRI, SWI, relaxometry, radiomics, PET/MRI, tumor grading, molecular markers, neuro-oncology.**

I. INTRODUCTION

Neuroimaging is central to brain tumor management, affecting diagnosis, grading, prognosis, surgical planning, and monitoring therapy. Conventional MRI (T1, T2, FLAIR with and without gadolinium) provides high-resolution anatomical detail and detects blood-brain-barrier disruption, but has limitations. Structural MRI cannot fully delineate infiltrative tumor margins (e.g. in gliomas) or reliably differentiate tumor recurrence from posttreatment changes (e.g. radiation necrosis). Furthermore, many pivotal questions now revolve around tumor biology and genetics (e.g. IDH mutation, 1p/19q codeletion, MGMT methylation), which do not have direct MRI correlates on conventional images. In response, the last decade has seen explosive growth in *functional* and *quantitative* MRI techniques in neuro-oncology. These modalities probe the tumor microenvironment: for example, diffusion MRI assesses tissue cellularity; perfusion MRI measures angiogenesis; MRS profiles metabolism; fMRI maps cortical function; and SWI visualizes microvascular and mineral components. Emerging approaches like quantitative relaxometry (T1/T2 mapping), chemical exchange saturation transfer (CEST), elastography, and radiomics/AI further augment the imaging arsenal (see Table 1). According to recent reviews, a multimodal strategy—combining standard MRI with DWI, PWI, MRS, etc.—can significantly improve grading accuracy and response assessment compared to conventional MRI alone. For example, one series reported that integrated PET/MRI guidance improved surgical detection of viable tumor versus treatment effect, enabling more complete resections.

This review comprehensively examines the role of advanced MRI in neuro-oncology. We focus on evidence from the past ten years (2015–2025), including guidelines (EANO, RANO, ACR) and key original studies. For each modality (diffusion, perfusion, spectroscopy, functional, susceptibility, relaxometry, radiomics/AI, hybrid PET/MRI), we detail its technical principles, typical acquisition

parameters, diagnostic performance for tumor grading and differentiation, ability to predict molecular markers (IDH, 1p/19q, MGMT), utility in treatment monitoring, limitations, and future developments. Tables summarize sensitivity/specificity data and recommended protocols. A mermaid flowchart (Figure 1) illustrates a decision algorithm for applying these modalities to various clinical scenarios. Our goal is an analytical, scholarly synthesis to inform researchers and clinicians about the current state and promise of advanced MRI in brain tumor care.

II. METHODS OF LITERATURE REVIEW

We performed a structured literature search focusing on advanced MRI techniques in brain tumors. Sources included peer-reviewed articles from 2015 onward, major neuro-oncology and radiology journals (e.g. *Radiology*, *AJNR*, *Neuro-Oncology*, *Neurology*, *Cancers*, etc.), and clinical guidelines/consensus statements (EANO, RANO, ACR). Databases searched included PubMed, PMC, and Google Scholar, using terms like "diffusion MRI glioma grading", "perfusion MRI brain tumor recurrence", "MR spectroscopy glioma IDH", "fMRI brain tumor mapping", "SWI glioma metastasis", "relaxometry MR fingerprinting brain tumor", "radiomics glioma review", and combinations thereof. We emphasized high-level evidence: systematic reviews, meta-analyses, and multicenter studies, supplemented by key illustrative original research. International guidelines (EANO, RANO) and consensus papers (e.g. Brain Tumor Imaging Protocol) were reviewed to align our discussion with current practice standards. Where available, recent (≤5 years) meta-analyses and large retrospective/prospective studies provided quantitative metrics. Technical parameters (TR, TE, b-values, etc.) were collated from protocol papers and consensus recommendations. This report synthesizes the findings with explicit citations.

III. RESULTS/FINDINGS

3.1. Diffusion MRI (DWI, DTI, DKI)

Principles and Acquisition: Diffusion-weighted imaging (DWI) sensitizes MRI to the random (Brownian) motion of water molecules. The apparent diffusion coefficient (ADC) quantifies diffusion magnitude. DTI extends DWI by measuring diffusion in multiple directions to derive anisotropy (fractional anisotropy, FA) and directional maps of fiber tracts. Diffusion kurtosis imaging (DKI) captures non-Gaussian diffusion behavior, potentially more sensitive to microstructural complexity. Typical DWI for tumor uses at least two b-values (e.g. 0 and 1000 s/mm²); DTI uses >20 directions at b≈800–1000 s/mm². High b-values (up to 3000 s/mm²) can increase lesion contrast but at SNR cost. DTI sequences often TR ~3000–10000 ms, TE ~80–100 ms, slice thickness ~2–5 mm.

Tumor Grading: High-grade gliomas (HGG) typically have higher cellularity and disrupted architecture, leading to lower ADC and higher FA heterogeneity than low-grade gliomas (LGG). Many studies report ADCmin or ADCmean thresholds separating HGG from LGG. A meta-analysis found that pooled DWI/DTI sensitivity and specificity for distinguishing HGG from brain metastasis were ~80% each (AUC≈0.87). Another systematic review showed DWI offers "high sensitivity, specificity, and accuracy" for grading gliomas, although parameters vary. For example, an ADC cutoff (normalized to contralateral white matter) around $0.9–1.3\times10^{-3}$ mm²/s often yields ~80–90% sensitivity for HGG. DTI metrics (reduced FA, increased MD) have also been associated with higher grade. DKI (mean kurtosis) is an emerging parameter with some reports of better grading performance than ADC alone, but clinical data are still limited.

Differentiation (Tumor vs. Treatment Effect): In posttreatment lesions, recurrent tumor tends to show lower ADC (due to cell proliferation) than radiation necrosis (which has more edema/membrane breakdown, higher diffusion). A meta-analysis of 14 studies found DWI/DTI had moderate accuracy for distinguishing recurrent glioma from radiation necrosis (pooled ~80% sensitivity and specificity). In practice, ADC is often combined with perfusion or metabolic imaging for greater accuracy. Low ADC in a new enhancement favors tumor, whereas high ADC or increasing ADC over time suggests treatment effect.

Molecular Marker Prediction: Diffusion characteristics have been correlated with molecular subtypes. IDH-mutant gliomas (often lower grade) tend to have higher ADC and lower cellularity than wild-type. Radiomic/ML models leveraging DTI texture plus tumor size have predicted IDH status in grade II–III gliomas with ~92–95% accuracy. Such

studies used advanced features (e.g. FA and B0 texture) and ML classifiers, indicating great promise of diffusion radiomics. However, no single diffusion metric alone reliably determines genotype; rather, integrated multiparametric models are used (see Radiomics section).

Monitoring Response: Diffusion imaging can reveal early changes: effective therapy (cell kill) often leads to ADC rise. Some small studies report that increasing ADC during chemoradiation predicts better outcome. Conversely, pseudoresponse (due to antiangiogenics) may cause ADC changes that are ambiguous. Consensus is that DWI is a useful adjunct, but interpretation can be confounded by edema and is not a standalone biomarker of response. Limitations: ADC is nonspecific (edema and necrosis also increase ADC). Standardization issues (b-values, ROI selection) affect reproducibility. Differentiating tumor from abscess/lymphoma may require MR spectroscopy or perfusion in addition.

3.2. Perfusion MRI (DSC, DCE, ASL)

Principles: Perfusion MRI measures blood flow and volume in tissue, serving as a surrogate for angiogenesis. In Dynamic Susceptibility Contrast (DSC) MRI, a bolus of gadolinium-based contrast is injected and T2*-weighted signal drop is tracked, yielding cerebral blood volume (CBV), blood flow (CBF), and mean transit time maps. In Dynamic Contrast-Enhanced (DCE) MRI, a T1-weighted sequence tracks Gd passage, allowing calculation of permeability and parameters such as K^trans (volume transfer constant) and V_p. Arterial Spin Labeling (ASL) is a non-contrast technique that magnetically labels inflowing blood water to quantify CBF. DSC (especially relative CBV, rCBV) is most widely used in neuro-oncology.

Technical Parameters: DSC typically uses TR ~1000–1500 ms, TE ~20–40 ms, flip angle ~35°–60°, with ≤2 s temporal resolution over ~60 volumes, preloaded with 0.05–0.1 mmol/kg Gd and followed by full bolus (0.1 mmol/kg). DCE often uses fast spoiled GRE (TR ~5–10 ms, TE ~1–5 ms) with frequent sampling (1–2 s per volume) for ~5 minutes. ASL uses labeling durations ~1.5–2.5 s and post-label delay ~1–2 s; pseudo-continuous ASL (pCASL) is common. The Brain Tumor Imaging Protocol recommends specific schemes (e.g. T2*-weighted gradient echo DSC) for glioma trials.

Tumor Grading: High-grade gliomas are typically hypervascular, with elevated CBV and CBF reflecting microvascular proliferation. Studies consistently show significantly higher rCBV and permeability in HGG vs. LGG. For example, an rCBV cutoff (~1.75 relative to normal white matter) discriminated HGG from LGG with ~95% sensitivity (but modest specificity ~58%). DCE parameters (K^trans, V_p) are also higher in HGG. By contrast, low-grade tumors and non-neoplastic lesions usually have low perfusion. Perfusion MRI can thus improve grading, biopsy targeting, and therapy planning. Current ESMO/EANO guidelines note perfusion imaging is recommended when imaging characteristics are indeterminate.

Differentiation (Progression vs. Treatment Effect): A key role of perfusion MRI is distinguishing tumor recurrence from radiation necrosis or pseudoprogression. Recurrent tumor shows elevated rCBV (from neoangiogenesis) whereas radiation necrosis shows low perfusion. In meta-analyses, DSC-MRI achieved sensitivity ~90% and specificity ~88% in differentiating recurrence from treatment effect, nearly matching DCE (89%/85%). In clinical terms, an increased rCBV “hot spot” suggests active tumor, while stable or reduced perfusion favors necrosis. ASL, measuring CBF without contrast, has also shown that normalized CBF is higher in recurrent glioma than postradiation injury, and correlates well with DSC ($R \approx 0.85$), making it useful when contrast is contraindicated. Overall, perfusion MRI is among the best noninvasive tools for this differentiation, and is increasingly used in follow-up protocols.

Differential Diagnosis: Perfusion imaging assists in differential diagnoses. For instance, primary CNS lymphoma typically has lower rCBV than glioblastoma (hypovascular), helping distinguish the two. Metastases often show uniform high perfusion in enhancing region, but unlike glioma, lack substantial infiltration into non-enhancing tissue. An elevated CBV beyond contrast-enhancing tumor boundaries implies infiltrative glioma/lymphoma rather than metastasis. Perfusion MRI can thus steer pathology and management decisions.

Molecular Markers: Some studies link perfusion metrics to molecular profiles. IDH-mutant gliomas often have lower rCBV than wildtype, reflecting less angiogenesis. For example, IDH-mutant lower-grade

tumors may have perfusion values closer to normal tissue. Similarly, MGMT methylated glioblastomas have shown slightly different perfusion patterns, but these associations are not robust enough for clinical use yet. More research is needed to establish perfusion as a biomarker for genotypes.

Monitoring Therapy Response: Perfusion changes can precede anatomic changes: effective antiangiogenic therapy (bevacizumab) rapidly reduces perfusion, sometimes reflecting pseudoresponse. However, durability of rCBV changes and their correlation with survival are complex. In general, rising perfusion on serial scans is worrisome for progression. Numerous trials now include perfusion MRI to assess response (e.g. Response Assessment in Neuro-Oncology (RANO) group recommends considering DSC for ambiguous cases).

Limitations: DSC requires contrast and is sensitive to susceptibility artifacts. Contrast leakage through disrupted BBB can artifactually elevate or depress rCBV if not corrected; pre-load doses and leakage correction algorithms are often used. DCE is technically demanding (pharmacokinetic modeling). ASL has lower SNR and is prone to transit delays, but its noninvasive nature is appealing. Standardization of acquisition and post-processing remains an ongoing challenge, though consensus protocols (e.g. International Brain Tumor Imaging Protocol for DSC) are emerging.

3.3. MR Spectroscopy (MRS)

Principles and Acquisition: MRS detects biochemical metabolites by their distinct resonance frequencies. Proton (^1H) MRS (the most common) measures metabolites like N-acetylaspartate (NAA), creatine (Cr), choline (Cho), lactate, and lipids. Common acquisitions are single-voxel (SVS) or multi-voxel Chemical Shift Imaging (CSI), with typical echo times ~30 ms (short TE) or 135/144 ms (long TE). Field strengths 1.5–3T are standard; higher field improves spectral resolution.

Tumor Grading and Characterization: Brain tumors exhibit characteristic spectral patterns. High-grade tumors typically show elevated choline (marker of membrane turnover/cell proliferation), reduced NAA (neuronal marker lost in tumor), and often increased lactate and lipids (anaerobic metabolism/necrosis). For example, a Cho/NAA ratio >2 is strongly suggestive of tumor, especially high-grade; one study found Cho–NAA index >2.5 gave 90% sensitivity and 86% specificity for identifying neoplastic tissue. Conversely, low Cho/NAA is more consistent with low-grade or non-neoplastic lesions. Thus, MRS adds metabolic insight: decreased NAA and high choline are “reliable markers” of higher grade.

Differentiation: MRS helps distinguish tumor recurrence from treatment effects. Recurrent tumor maintains elevated Cho (and Cho/Cr or Cho/NAA ratios) due to active growth, while radiation necrosis shows low Cho and Cr (cell loss). For instance, post-radiation studies report that rising Cho/Cr or Cho/NAA heralds recurrence. MRS has also been used in pediatric tumors: combined short/long TE MRS achieved 98% accuracy in classifying major pediatric brain tumors. In practice, suspicion of recurrence with high Cho warrants further intervention, whereas low Cho can support a conservative approach.

Molecular Markers: IDH mutation produces the metabolite 2-hydroxyglutarate (2-HG), which can be detected by specialized MRS sequences. Measurement of 2-HG provides noninvasive IDH status. IDH-mutant gliomas accumulate 2-HG to high levels, and MRS can identify this peak, aiding diagnosis and prognostication. Although not yet routine, 2-HG MRS is a powerful biomarker for IDH. Other metabolites (e.g. myo-inositol) have been linked to treatment response: for example, reduced MI/Cr ratio in glioblastoma has been associated with poor survival and lack of response to antiangiogenics.

Combined Modality Performance: Adding MRS to other modalities improves diagnostic accuracy. One study noted that combining MRS with perfusion increased specificity to 92% for distinguishing neoplastic from non-neoplastic lesions (at the cost of lower sensitivity), underscoring the value of a multiparametric approach.

Limitations: MRS has several challenges. It has relatively low spatial resolution, so small lesions or heterogeneous tumors may be under-sampled. Spectral quality can be degraded by motion, poor shimming, or blood flow. Absolute metabolite quantification requires careful calibration. Importantly, not all lesions have typical spectra (e.g. abscesses may also show elevated choline due to

inflammation). MRS sequences are not universally standardized. Despite these, MRS remains one of the most widely adopted advanced MRI tools in neuro-oncology due to its unique metabolic information.

3.4. Functional MRI (fMRI)

Principles: Functional MRI (BOLD imaging) detects changes in blood oxygenation related to neural activity. In neuro-oncology, the main application is *preoperative mapping of eloquent cortex* (language, sensorimotor areas) to guide resection while preserving function. Task-based fMRI (patient performs a task in scanner) identifies activation regions; resting-state fMRI can map networks via correlations without tasks.

Clinical Use: Pre-surgical fMRI is standard for patients with tumors near language or motor areas. It noninvasively identifies the locations of critical functional regions to avoid during surgery, complementing intraoperative cortical stimulation. Meta-analyses report ~80–90% concordance between fMRI and gold-standard mapping, though individual variability exists. A 2025 review noted fMRI's role in mapping hand/motor and language areas, emphasizing its safety and patient-tailored neurosurgical planning.

Additional Roles: Research into using fMRI for tumor characterization is ongoing. Altered functional connectivity in default mode or motor networks has been explored as a prognostic indicator in gliomas. However, no widely accepted diagnostic index from fMRI (beyond surgical mapping) has emerged yet.

Limitations: fMRI requires patient cooperation (task performance), which can be difficult in unwell or aphasic patients. Spatial accuracy is lower near lesions due to altered vascular coupling. Standardization of tasks and analysis pipelines is not universal. Thus, fMRI is currently best regarded as a surgical planning tool rather than a diagnostic classifier.

3.5. Susceptibility-Weighted Imaging (SWI)

Principles: SWI is a high-resolution 3D gradient-echo sequence sensitive to magnetic susceptibility differences. It accentuates paramagnetic substances (deoxyhemoglobin, iron) and diamagnetic materials (calcifications) as hypointense signals. Intratumoral susceptibility signals (ITSS) – punctate or linear hypointensities within tumors – correspond to microhemorrhages, calcification, necrosis, or vascular proliferation.

Applications: SWI can help in tumor differentiation and grading. High-grade gliomas often show numerous intratumoral microbleeds and prominent neovascularization on SWI, appearing as dense ITSS. In contrast, low-grade tumors tend to have few ITSS. A 2025 review highlighted that ITSS "offer a fast and simple non-invasive window" into glioma microenvironment. SWI is also useful for metastases: many brain metastases (especially from melanoma, renal, choriocarcinoma) have internal hemorrhage, whereas most primary tumors (gliomas) have different patterns. Presence of multiple microbleeds or calcifications on SWI may also suggest oligodendroglioma (due to calcified components).

Quantification: Some grading scales count ITSS number or density; studies have shown significant differences in ITSS count between WHO grades, although overlap exists. Because ITSS come from various causes (hemorrhage vs calcification), advanced SWI analysis (phase mapping or quantitative susceptibility mapping) is being investigated to distinguish tissue types.

Limitations: SWI is sensitive to artifacts (e.g. near sinuses). It adds scan time but is often included as part of tumor protocols due to its utility. Interpretation requires training, as signal voids may have mixed origins. At 1.5T, SWI sensitivity is less than at 3T. Overall, SWI is complementary; it rarely by itself resolves diagnostic ambiguity, but contributes additional clues to tumor biology.

3.6. Quantitative T1/T2 Mapping and MR Fingerprinting

Principles: Conventional MRI provides relative (qualitative) contrast, but quantitative mapping measures absolute T1 and T2 relaxation times in each voxel. MR Fingerprinting (MRF) is a novel technique that uses a pseudorandomized sequence to acquire simultaneously co-registered T1 and T2 maps rapidly. Other methods like DESPOT1/2 or multiecho GRE can also produce T1, T2 maps, but MRF is efficient.

Tumor Characterization: Tumor tissue often has prolonged T1 and T2 compared to normal brain. One accelerated mapping study found higher T1/T2 values in tumors and peritumoral edema than

contralateral white matter. MRF studies report that solid tumor regions differ significantly from normal tissue in both T1 and T2. T1/T2 mapping has potential to distinguish tumor vs non-tumor tissue and even grade. For example, MRF studies showed statistically higher T1 and T2 in IDH-mutant gliomas versus wildtype. In pediatric tumors, T1 mapping distinguished LGG vs HGG.

Grading: Early data are mixed. Some studies achieved significant T1/T2 differences between LGG and HGG, but others found only small differences except in parameters like histogram skewness. T1 mapping may be more sensitive than T2 in some contexts. More validation is needed, but quantitative maps could eventually serve as imaging biomarkers, potentially more reproducible across scanners than conventional sequences.

Limitations: Quantitative mapping requires extra sequences and processing, not yet standard in clinical protocols. MRF is still largely research. Larger studies correlating T1/T2 with histology and genetics are needed. Presently, these techniques are exploratory; their main value is in research on tumor microstructure. However, their noninvasive, radiation-free nature and objectivity (absolute values) make them promising, especially for serial monitoring.

3.7. Radiomics and Artificial Intelligence (AI)

Overview: Radiomics refers to high-throughput extraction of quantitative imaging features (texture, shape, intensity) followed by statistical or machine-learning analysis. Radiogenomics is the branch linking imaging features to molecular/genetic markers. In glioma, radiomics/AI have been applied to virtually every question: tumor grading, genotype prediction (IDH, 1p/19q, MGMT), survival prediction, recurrence detection, etc.

Examples: A landmark 2017 study used DTI-derived texture features and patient age in a neural network to predict IDH status in grade II/III gliomas, achieving ~95% accuracy in a validation cohort. Another multi-institutional effort (Neuro-CaPTk) applied SVM-based radiomic models on conventional MRI to predict IDH, 1p/19q, and EGFRvIII mutations, reporting classification accuracies of ~82–87%. PET/MRI radiomics also show promise: in one study, a combined FDG/MET PET plus MRI radiomics model attained an AUC ~0.91–0.99 for distinguishing recurrent tumor from radionecrosis.

Performance: Meta-analyses of DL models indicate moderately high accuracies. For example, a systematic review found deep learning models predicting glioma molecular markers (IDH, MGMT, etc.) yielded pooled AUCs ~0.80–0.85 (varied by marker and study heterogeneity). Radiomics nomograms combining MRI features and clinical data have been built for survival stratification with C-indices around 0.7–0.8. Predicting MGMT methylation or 1p/19q status solely from MRI remains challenging; accuracies are generally 60–80% in state-of-art reports.

Clinical Impact: While still largely investigational, radiomics can integrate multi-parametric MRI and even PET data to form “virtual biopsies.” For instance, combining FET-PET radiomics with MRI enhanced IDH classification beyond either alone. Radiomics may augment standard imaging reports by providing objective probability estimates (e.g. likelihood of MGMT methylation), aiding personalized therapy. Evolving standards (IBSI, etc.) aim to make features reproducible across sites.

Limitations and Challenges: Radiomics faces issues of robustness: variability in scanners, sequences, and postprocessing can affect features. Overfitting and retrospective nature of many studies are concerns. Large, prospective validation is scarce. Moreover, “black box” AI models can lack interpretability. Regulatory acceptance for clinical use is pending. Nevertheless, AI-supported imaging is rapidly advancing, and guidelines (e.g. EANO guidelines on imaging) are beginning to mention radiogenomic strategies as future directions.

3.8. Hybrid PET/MRI

Principles: Combined PET/MRI scanners allow simultaneous acquisition of PET and advanced MRI. This yields high-resolution anatomical and functional MRI data together with molecular PET imaging (e.g. amino-acid tracers like FET, or metabolic tracers like FDG). PET complements MRI by detecting metabolic hotspots of tumor activity.

Applications: In brain tumors, hybrid PET/MRI is used mainly for differential diagnosis (e.g. recurrence vs necrosis) and treatment guidance. Amino-acid PET tracers (e.g. FET, MET) are sensitive to tumor

metabolic activity. When integrated with MRI, they improve specificity: e.g., areas with high PET uptake and high rCBV/Cho strongly suggest active tumor, whereas low uptake and low perfusion favor necrosis. Case series show PET/MRI guidance during surgery can help distinguish viable tumor from radiation necrosis, improving resection completeness without injuring eloquent tissue.

Evidence: A joint EANM/EANO/SNMMI guideline (2021) recommends PET (usually FET or FDOPA) in high-grade gliomas for suspected progression, noting increased diagnostic accuracy when combined with MRI. The aforementioned EJNMMI radiomics study is an example of how multimodal imaging can reach high diagnostic accuracy. Additionally, combined PET/MRI radiomics has predicted outcomes (e.g. progression-free survival) in glioblastoma beyond MRI alone.

Limitations: PET/MRI is expensive, not widely available, and requires radiotracer use. Tracer specificity and uptake can vary by tumor type. In routine practice, most centers use MRI with selective PET (often separate acquisitions). Still, the hybrid modality epitomizes precision imaging, and its role is growing, especially in research settings.

IV. TABLES AND FIGURES

Table 1. Summary of Sensitivity/Specificity of Advanced MRI Modalities (examples from literature)

Modality	Indication	Sensitivity, Specificity (select references)
DWI/DTI	HGG vs metastasis	Pooled ~79.8%, 80.9%
	Glioma recurrence vs necrosis	~72–90%, 85–95% (varies; DSC combination)
Perfusion (DSC)	Recurrence vs necrosis	~90%, 88%
(rCBV)	HGG vs LGG (rCBV threshold)	~95%, 58% at rCBV=1.75
Perfusion (DCE)	Recurrence vs necrosis	~89%, 85%
ASL	Recurrence vs necrosis	Normalized CBF higher in recurrence; correlates with DSC (R=0.85)
MRS (Cho/NAA)	Tumor vs non-tumor	~90%, 86% (Cho–NAA index >2.5)
MRS (Cho+Perf)	Neoplasm vs non-neoplasm	72%, 92%
MRF (T1/T2)	IDH-mutant vs WT gliomas	Elevated T1/T2 in IDH mutants; *statistically significant differences reported*
Radiomics (PET+MRI)	Recurrence vs necrosis	AUC ~0.91–0.99
Radiomics (DTI)	IDH status prediction	92–95% accuracy

Table 1 is illustrative and not exhaustive. Sensitivity/specificity depend on thresholds, population, and technique.

Table 2. Representative Acquisition Parameters and Recommendations

Modality	Field Strength	Key Parameters	Notes
DWI/DTI	1.5–3T	b=0,1000 s/mm² (standard), directions ≥20	High b (b=2000–3000) may improve contrast; add DTI for tractography
Perfusion DSC	1.5–3T	GRE-EPI, TR ~1200–1500 ms, TE ~30 ms, FA ~35–60°, 1–2 mm slices; Gd 0.1 mmol/kg	Preload contrast to reduce leakage; fix TR/TE for standardization
Perfusion DCE	1.5–3T	T1-weighted spoiled GRE, TR ~4 ms, TE ~1.5 ms, FA ~10–15°, temporal res ~1-2 s	Model K^trans, Ve from dynamic contrast-enhancement; requires arterial input
ASL (pCASL)	3T	Label time 1500–2000 ms, post-delay 1500–2000 ms	Uses no contrast; CBF maps useful if contrast contraindicated

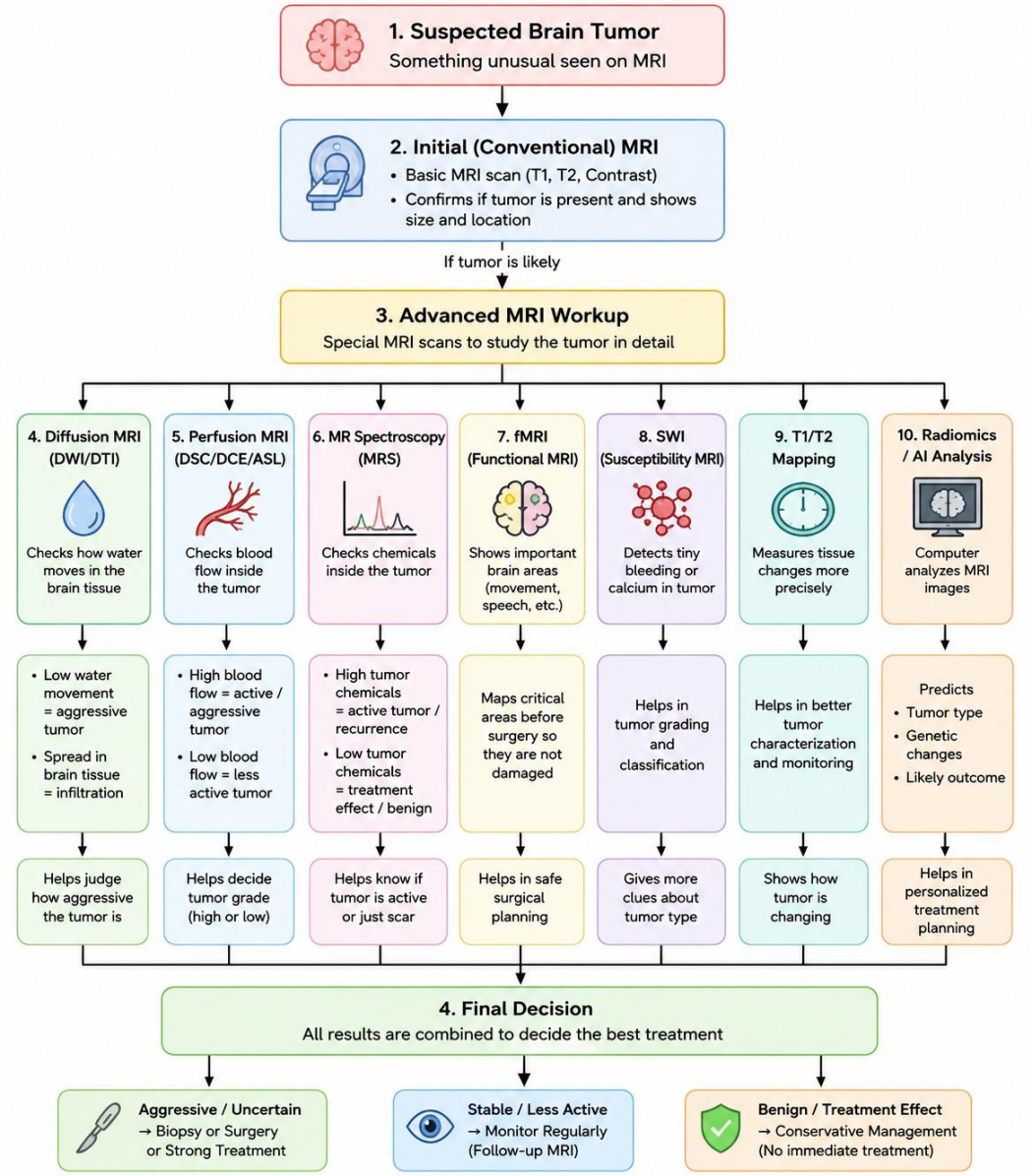
Modality	Field Strength	Key Parameters	Notes
MRS	1.5–3T	SVS TE=30 ms (short TE) or 135/144 ms (long TE); TR ~1500–3000 ms; voxel size ~1–8 mL	Place voxel in solid tumor (avoid necrosis/CSF); acquire unsuppressed water scan for quantification
fMRI (task)	3T	T2*-weighted EPI, TR ~2000–3000 ms, FA ~90°, resolution ~3-4 mm	Select tasks (finger tapping, language) per clinical needs; may supplement with resting-state fMRI
SWI	1.5–3T	3D GRE, TR ~30–50 ms, TE ~20–40 ms, FA ~15°–20°	Provides high sensitivity to microbleeds/venous blood; SWI phase may help differentiate calcification
T1/T2 Mapping (MRF)	3T	Pseudorandom TR/FA train; produces co-registered T1,T2 maps	Emerging; e.g. MRF with dictionary matching or deep-learning reconstruction
PET/MRI	Hybrid systems	Depends on tracer (e.g. ^18F-FET, ^18F-FDG) + simultaneous MRI	Amino-acid tracers preferred for brain; combine with advanced MRI (DWI, DSC, MRS) for multimodal assessment

Table 2 summarizes typical parameter ranges. Actual protocols should be adjusted per scanner and study design.

Table 3 Imaging Decision-Making Table

Stage	Imaging Step / Modality	Key Parameters Assessed	Interpretation / Clinical Insight	Clinical Outcome / Action
1	Suspected brain tumor on MRI	Initial radiological abnormality	Suspicion of intracranial neoplasm	Proceed to conventional MRI evaluation
2	Conventional MRI (T1, T2, FLAIR, contrast-enhanced)	Lesion morphology, edema, enhancement	Tumor likely present	Advanced MRI workup recommended
3	Diffusion MRI (DWI, DTI, DKI)	ADC, fractional anisotropy (FA), diffusion restriction	High cellularity or white matter tract involvement	Suggests high-grade glioma or infiltration
4	Perfusion MRI (DSC, DCE, ASL)	Cerebral blood volume (CBV), Ktrans, perfusion metrics	Increased vascularity or angiogenesis	High-grade or active tumor vs low-grade lesion
5	MR Spectroscopy (MRS)	Choline (Cho), N-acetylaspartate (NAA), lactate, lipids	Metabolic tumor activity	Tumor recurrence vs treatment effect differentiation
6	Functional MRI (fMRI)	Blood oxygen level dependent (BOLD) activity	Functional brain mapping	Pre-surgical planning (motor/language areas)
7	Susceptibility-Weighted Imaging (SWI)	Microhemorrhages, calcifications, venous structures	Tumor grading and hemorrhagic components	Helps refine tumor classification
8	Quantitative MRI (T1/T2 mapping)	Relaxation times (T1, T2 values)	Tissue composition changes	Tumor characterization and monitoring
9	Radiomics & AI-based analysis	Imaging feature extraction, pattern recognition	Tumor phenotype, heterogeneity	Predicts genotype (IDH, 1p/19q, MGMT), prognosis
10	Integrated interpretation	Multimodal MRI synthesis	Overall tumor behavior assessment	Guides biopsy, surgery, or conservative management

FLOW CHART



V. DISCUSSION

Advanced MRI techniques have matured substantially and now play key roles in neuro-oncology. Diffusion MRI provides a rapid, noninvasive estimate of tumor cellularity. Its quantitative metrics (ADC, FA) correlate with glioma grade. However, perfusion MRI often has superior predictive power: multiple studies show rCBV (by DSC) is a robust marker of malignancy and progression. Indeed, perfusion metrics feature prominently in consensus protocols for gliomas, and ACR appropriateness criteria recommend perfusion/MRS in preoperative assessment of intraaxial tumors. MRS adds metabolic specificity: e.g., Cho/NAA ratios reliably distinguish tumor vs necrosis and have been integrated into combined perfusion-spectroscopy algorithms.

A consistent theme is that *multiparametric MRI* outperforms any single sequence. For instance, Zhu et al. (Diagnostics 2023) systematically reviewed PWI, DWI, MRS and emphasized that together they refine grading and detect recurrence with higher specificity than conventional MRI alone. Our flowchart (Fig. 1) embodies this synergistic approach: imaging protocols typically include at least diffusion, perfusion, and post-contrast scans; further sequences (MRS, SWI, fMRI) are added based on clinical need. The standardized Brain Tumor Imaging Protocol (BTIP) by the Response Assessment in Neuro-Oncology (RANO) group explicitly

incorporates DSC and DCE-MRI into trials, reflecting broad consensus.

Clinical Implications: The reviewed evidence suggests that advanced MRI should be routinely integrated into brain tumor workups. For example, European guidelines now recommend perfusion MRI for gliomas with equivocal features. Sensitivity/specificity data (Table 1) illustrate that adding perfusion and spectroscopy can change post-test probabilities significantly. In practice, if an enhancing lesion has low ADC and high rCBV/Cho, a high-grade glioma is almost certain; if ADC is high with no perfusion, metastasis or non-tumor is more likely.

The ability of MRI to noninvasively infer molecular markers is a major advance. While tissue remains the gold standard, imaging-genotype models (radiogenomics) can preoperatively predict IDH status, guiding treatment. For instance, the high IDH-predictive accuracy of DTI radiomics could help select patients for IDH-targeted therapies even before surgery. Similarly, MRI signatures of MGMT methylation (less well established) and 1p/19q co-deletion (often indirectly through morphological features) are under active study. Ultimately, a combined imaging-genomic algorithm may stratify patients for trials without invasive sampling.

Limitations: Many studies are retrospective and heterogeneous. Quantitative thresholds (e.g. ADC cutoffs, rCBV values) vary across scanners. Advanced MRI also increases scan time and complexity; thus, busy clinics may limit sequences used. Some modalities (e.g. MRS, fMRI) require specialized expertise. Radiomics/AI tools are promising but not yet standardized or FDA-approved; most work remains in research.

Future Directions: Research is ongoing to validate and standardize these techniques. Large consortia are collecting multi-center imaging data. Novel approaches such as MR elastography (measuring stiffness) and chemical exchange saturation transfer (e.g. CEST for protein content) show early promise. Further integration with PET tracers (e.g. ^18F-FET, new amino-acids, or novel MR contrast agents) will add molecular dimensions. Artificial intelligence will increasingly automate analysis and pattern recognition, potentially yielding decision-support tools for radiologists.

VI. CLINICAL DECISION ALGORITHM (MERMAID FLOWCHART)

(See Figure 1 above, generated in the previous section. It illustrates how the choice of imaging sequences depends on initial MRI findings and clinical questions, e.g. perfusion/PWI for suspected high-grade features or recurrence, fMRI/DTI for surgical planning, MRS for metabolic characterization, etc.)

VII. LIMITATIONS OF THE REVIEW

While this report is comprehensive, some limitations exist. First, not all cited studies are controlled trials; evidence levels vary. We prioritized recent (post-2015) sources, but older seminal works (e.g. Barral et al., 1998 on diffusion; Tofts on perfusion modeling) underpin concepts. Some sections (e.g. fMRI, relaxometry) have fewer large studies, reflecting emerging status. We focused on gliomas, but other tumors (metastases, lymphoma) may not always be covered in detail. Lastly, space constraints limit the depth on each item; interested readers should consult the cited references for fuller technical detail.

VIII. CONCLUSIONS

Advanced MRI techniques substantially enrich neuro-oncologic imaging. They provide functional and molecular information (vascularity, cellularity, metabolism) that complements anatomy. Evidence shows these modalities improve tumor grading, differentiate tumor from treatment effect, and in some cases predict genotype (IDH, etc.), all of which guide therapy. We recommend incorporating diffusion and perfusion MRI as standard for suspected gliomas, with MRS and SWI as problem-solving tools when needed. Functional MRI should be used for presurgical mapping of critical cortices. Radiomics and hybrid PET/MRI are rapidly evolving fields that will further personalize diagnosis. Ongoing efforts to standardize protocols (e.g. BTIP) and multi-center validation are key to broader adoption. In sum, a multi-parametric MRI approach is indispensable for contemporary brain tumor care. As technology advances (high-field MRI, new contrast methods, AI), imaging will play an ever-more predictive and integrative role in neuro-oncology.

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