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SPECIAL REPORT

Imaging of pediatric brain tumors: A COG Diagnostic Imaging Committee/SPR Oncology Committee/ASPNR White Paper

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Abstract

Tumors of the central nervous system are the most common solid malignancies in children and the most common cause of pediatric cancer-related mortality. Imaging plays a central role in diagnosis, staging, treatment planning, and response assessment of pediatric brain tumors. However, the substantial variability in brain tumor imaging protocols across institutions leads to variability in patient risk stratification and treatment decisions, and complicates comparisons of clinical trial results. This White Paper provides consensus-based imaging recommendations for evaluating pediatric patients with primary brain tumors. The proposed brain magnetic resonance imaging protocol recommendations balance advancements in imaging techniques with the practicality of deployment across most imaging centers.

Abbreviations: 2D, two-dimensional; 3D, three-dimensional; bSSFP, balanced steady-state free precession; CNS, central nervous system; CT, computed tomography; DIPG, diffuse infiltrating pontine glioma; DTI, diffusion tensor imaging; DWI, diffusion-weighted imaging; EPI, echo-planar imaging; FLAIR, fluid attenuated inversion recovery; FSE, fast spin echo; GBCA, gadolinium-based contrast agent; GRE, gradient-recalled echo; HGG, high-grade gliomas; LGG, low-grade gliomas; MRI, magnetic resonance imaging; MRS, magnetic resonance spectroscopy; RAPNO, Response Assessment in Pediatric Neuro-Oncology; SE, spin echo; SNR, signal-to-noise ratio; SPACE, sampling perfection with application-optimized contrasts using different flip angle evolution; SWI, susceptibility-weighted imaging; TSE, turbo spin echo; VISTA, volume isotropic turbo spin echo acquisition.

KEYWORDS
brain tumors, computed tomography, magnetic resonance imaging, pediatric

1 | INTRODUCTION

In children, central nervous system (CNS) tumors are the most common solid malignancies and the most common cause of pediatric cancer-related mortality, surpassing leukemia.[1–3] Imaging plays a central role in evaluating pediatric neuro-oncology patients, but pediatric brain tumor imaging protocols vary across institutions, which can affect tumor assessment and staging. Magnetic resonance imaging (MRI) of children with brain tumors requires an imaging protocol with specific sequences and optimized technical parameters, including slice thickness and interslice gaps, for the best possible characterization of the brain tumor and metastatic disease. Prior large-scale clinical trials have found inaccurate staging by the treating institutions in up to 8% of patients, leading to inferior outcomes.[4,5] Standardizing MRI protocols will enable more uniform oncologic evaluation, consistency in clinical trials, and better comparison of outcomes across institutions. This White Paper provides the committee's recommendations for a pediatric brain MRI protocol that incorporates the essential imaging sequences and can be performed within a reasonable amount of time on nearly all MRI systems.

2 | IMAGING CONSIDERATIONS

2.1 | Computed tomography

A head computed tomography (CT) may be performed for initial assessment of patients with a suspected intracranial space-occupying lesion, when the patient is clinically unstable, or when MRI is not readily available (*Grade: A; SOR: 1*, very strong recommendation). CT provides useful information about the presence and location of the mass, associated mass effect, and hydrocephalus. CT also provides information about the tumor composition, including the presence of cysts, calcifications, and hemorrhage, and some information regarding tumor cellularity. Post-contrast CT is typically not indicated, and the mass should be further characterized by MRI unless a post-contrast CT is required for emergent surgical intervention. CT also has a role in immediate postoperative evaluation, although assessment of residual tumor and treatment response is routinely done with MRI.

2.2 | Magnetic resonance imaging

A brain MRI is recommended for the diagnosis and follow-up of all intracranial tumors and is essential for adequate tumor characterization and assessment of CNS dissemination (*Grade: A; SOR: 1*, very strong recommendation).

A 3.0 Tesla platform is preferred due to its capability of imaging with higher signal-to-noise ratio (SNR), improved spatial resolution, and shorter imaging time[6] (*Grade: B; SOR: 1.5*, strong recommendation).

Imaging at 1.5 Tesla in patients with certain types of hardware may provide decreased artifact and signal distortion (*Grade: B; SOR: 1.3*, very strong recommendation).

Follow-up imaging using the same field strength, identical protocols, and similar or identical hardware (e.g., coil) is ideal, allowing for consistent assessment of residual or recurrent tumor, treatment changes, and metastases, although practical, system-related barriers to implementation may exist (*Grade: C; SOR: 1.4*, very strong recommendation).

2.3 | Sedation/anesthesia

Sedation or general anesthesia is typically needed in children younger than 6 years; however, this can be assessed on a case-by-case basis, especially with the help of childlife specialists (*Grade: C; SOR: 1.4*, very strong recommendation). Non-sedated "feed and bundle" options can be used for infants, typically up to 3 months of age. Many institutions have programs to encourage and support imaging without anesthesia and to provide patients with evening time slots, video goggles, and headphones, as well as trial runs in mock MRI scanners to simulate the scanner environment.[7]

2.4 | Gadolinium-based contrast agents

The use of gadolinium-based contrast agents (GBCA) is recommended for all patients at initial tumor diagnosis and most patients at follow-up (*Grade: A; SOR: 1*, very strong recommendation). MRI without GBCA may be adequate for follow-up imaging of selected low-grade tumors, such as optic pathway gliomas; however, this remains an active area of research.[8,9]

Macrocyclic GBCAs are preferred over linear GBCAs because of the greater kinetic stability accounting for lower amounts of gadolinium deposition in the brain and other tissues. Although there is no proven clinical impact from the retained gadolinium in the brain, judicious use of macrocyclic GBCAs is recommended.[10–12]

Spine imaging: Detailed recommendations for spine imaging, including evaluation of metastatic disease, will be provided in a separate manuscript in this series.

2.5 | Response assessment

The Response Assessment in Pediatric Neuro-Oncology (RAPNO) working group has published specific response criteria for

high-grade gliomas (HGGs), low-grade gliomas (LGGs), diffuse infiltrating pontine gliomas (DIPGs), and medulloblastoma, with additional consensus papers on ependymoma and craniopharyngioma soon to be published. These standardized criteria primarily utilize changes in two-dimensional (2D) tumor measurements performed either on T2/FLAIR (fluid attenuated inversion recovery) or post-contrast T1-weighted sequences for response assessment.[13–16]

2.6 | Brain MRI protocol recommendations

In 2015, the Brain Tumor Imaging Standardization Steering Committee published consensus imaging protocol recommendations for glioblastomas.[6] In addition to the response criteria mentioned above, in 2017 and 2020, the RAPNO committees also published separate imaging protocol recommendations for medulloblastoma, HGG, LGG, and DIPG.[13–16] The current White Paper draws from these guidelines, available literature, and expert opinions of the committee members to provide brain MRI imaging protocol recommendations that can be used for pediatric brain tumor diagnosis, treatment planning, and response assessment. The proposed brain MRI protocols should be technically feasible on most clinical MRI systems, and a common protocol is being recommended here for both high-grade and low-grade tumors. Additional imaging sequences may be added based on the tumor type and location, institutional preferences, site capabilities, and specific clinical or research objectives. The rationale behind each of the recommended sequences and the strength of the recommendation are provided along with specific caveats and potential pitfalls.

The recommendations for a basic, standard protocol for brain tumor assessment are summarized in Table 1 and include pre- and post-contrast T1-weighted, T2-weighted, and T2-FLAIR imaging, as well as diffusion-weighted imaging (DWI). Additional sequences that may be useful for tumor characterization at diagnosis, during surgical planning/navigation, and for problem solving during follow-up are included in Table 2.

2.7 | Pre- and post-contrast T1-weighted imaging

Pre- and post-contrast three-dimensional (3D), isotropic T1-weighted imaging is recommended for pediatric brain tumor evaluation *(Grade: A; SOR: 1*, very strong recommendation). 3D, isotropic T1-weighted imaging offers numerous advantages over 2D T1-weighted imaging, including better spatial resolution for optimal delineation of lesion margins, better reproducibility of measurements, and detection of smaller lesions.[17,18] 3D images also facilitate multiplanar reconstructions, volumetric measurements, and surgical navigation. The most clinically used 3D T1 technique is the inversion recovery-prepared gradient-recalled echo (IR-GRE), available as MPRAGE (magnetization-prepared rapid gradient echo; Siemens), IR-SPGR (inversion recovery-spoiled gradient echo; GE), or TFE (3D turbo field echo; Philips). This technique has served as a robust clinical tool for over two decades and has been part of prior consensus recommendations. It provides exquisite gray–white matter differentiation due to the inversion recovery preparatory pulse; however, studies have shown it to exhibit less-pronounced lesion and background tissue enhancement compared with T1-spin echo/turbo spin echo/fast spin echo (SE/TSE/FSE) techniques. 3D TSE/FSE acquisitions, available as SPACE (sampling perfection with application-optimized contrasts using different flip angle evolution; Siemens), CUBE (GE), or VISTA (3D volume isotropic turbo spin echo acquisition; Philips), achieve superior tumor enhancement and suppression of signal from blood vessels, both of which contribute to improving the detection of leptomeningeal metastases.[19–21] Suppressing the vascular signal is also advantageous for tumor segmentation, but it limits evaluation for cerebral sinovenous thrombosis. However, 3D T1 TSE/FSE may not be available on all MRI systems and may require additional resources to acquire and optimize the sequence.

For volumetric T1 sequences, isotropic acquisition with 1-mm slice thickness is recommended, with 1.5 mm being acceptable on 1.5 Tesla scanners to maintain adequate SNR. A sagittal plane of acquisition enables shorter imaging time by requiring fewer slices to include the entire brain/head. Also, the suprasellar region, a common site of leptomeningeal metastatic disease, is better visualized on direct sagittal acquisition than on reconstructed images. However, the axial plane of acquisition may be required for surgical guidance. Using identical imaging parameters is recommended for pre-contrast and post-contrast T1-weighted images to improve accuracy of the subjective evaluation of tumor enhancement and to enable subtraction imaging.[22]

If a 3D T1-weighted sequence cannot be performed, then pre-contrast sagittal 2D T1-weighted and post-contrast axial and coronal 2D T1-weighted SE/TSE/FLAIR sequences may be obtained instead, with slice thickness of 4 mm or less, with no or minimal (<10% of slice thickness) interslice gap. However, this approach is strongly discouraged, especially for tumors prone to leptomeningeal metastasis, as the relatively thicker slices make them less sensitive for leptomeningeal disease detection.

A separate post-contrast 2D T1-SE/TSE/FLAIR sequence in addition to a 3D T1 acquisition may be obtained for comparison and analysis of true enhancement versus artifact *(Grade: A; SOR: 1.4*, very strong recommendation*)*.

The 3D-T1 post-contrast images are ideally acquired about 5 minutes after administration of gadolinium in the plateau phase of the contrast uptake. Acquiring T2-weighted images immediately after contrast administration allows a standardized time delay for post-contrast T1 images, and T2-weighted imaging performed using SE or TSE/FSE acquisition should not be affected by the presence of contrast material in the vasculature.

2.8 | T2-weighted imaging

A T2-weighted sequence is fundamental for evaluation of brain tumors and often provides the most accurate assessment of tumor margins in discrete tumors (or of "apparent" tumor margins in diffuse, infiltrative tumors). For partially or non-enhancing tumors, including diffuse midline gliomas and LGG, T2-weighted images may be primarily used

TABLE 1 Summary of minimum recommended magnetic resonance imaging sequences for pediatric brain tumor evaluation at diagnosis and follow-up

	Sequence	Plane	Slice thickness (mm)	Gap	Minimum in-plane resolution	Approximate acquisition time (minutes)	Comments	Grade	Strength of recommendation
1.	3D T1 IR-GRE (MPRAGE/SPGR/TFE) or 3D T1 TSE (SPACE/CUBE/VISTA)	Sagittal or axial	1–1.5	0	1 × 1 mm	5–6	Can use either 3D technique	A	1 (very strong recommendation)
2.	DWI with ADC Single-shot or multi-shot EPI; *b* value of 0 and 1000	Axial	≤4	0	2 × 2 mm	3–5	Can substitute with DTI	A	1 (very strong recommendation)
3.	SWI	Axial	≤4	0	1 × 1 mm	3–5	SWI preferred over GRE if available	B	1.6 (strong recommendation)
	or GRE	Axial	≤4	0	1 × 1 mm			B	2.1 (moderate recommendation)
Contrast administration[a]									
4.	T2 TSE/FSE	Axial or coronal	≤4	0	1 × 1 mm	3–5		A	1 (very strong recommendation)
5.	3D T1 IR-GRE (MPRAGE/SPGR/FFE/TFE) or 3D T1 TSE (SPACE/CUBE/VISTA)	Sagittal or axial	1–1.5	0	1 × 1 mm	5–6	Same technique that was used pre-contrast; axial plane for surgical navigation	A	1 (very strong recommendation)
6.	T1 TSE/FSE	Axial or coronal	1.0	0%–10%	1 × 1 mm	3–5	Both axial and coronal may be done if 3D T1 sequence not available or degraded by motion	A	1.4 (very strong recommendation)
7.	3D T2 FLAIR	Sagittal	1–1.5	0	1 × 1 mm	5–6	3D preferred over 2D if available	B	1.3 (very strong recommendation)
	or T2 FLAIR TSE/FSE	Axial	≤4	0	1 × 1 mm	4–5		B	1.5 (strong recommendation)

Note: 3D T1 IR-GRE gradient echo: MPRAGE = Siemens; Fast SPGR = GE; TFE = Philips. 3D T1 TSE/FSE: SPACE = Siemens; CUBE = GE; VISTA = Philips. NEX (number of excitations or averages) ≥1. Parallel imaging up to 2×.

Abbreviations: 3D, three-dimensional; ADC, apparent diffusion coefficient; DTI, diffusion tensor imaging; DWI, diffusion-weighted imaging; EPI, echo-planar imaging; FLAIR, fluid-attenuated inversion recovery; GRE, gradient-recalled echo; IR-GRE, inversion recovery gradient-recalled echo; SWI, susceptibility-weighted imaging; TSE/FSE turbo spin echo/fast spin echo.

[a]The order of post-contrast sequences should be kept consistent.

TABLE 2 Optional magnetic resonance imaging sequences that may be helpful for tumor characterization, surgical guidance, and distinguishing residual or recurrent tumor from treatment-related change

	Sequence	Plane	Slice thickness (mm)	Gap	Minimum in-plane resolution	Approximate acquisition time (minutes)	Comments	Grade	Strength of recommendation
1.	Post-contrast 3D T1 IR-GRE (MPRAGE/SPGR/TFE) or 3D T1 TSE (SPACE/CUBE/VISTA)	Axial	1–1.5	0	1 × 1 mm	5–6	Surgical guidance	A	1 (very strong recommendation)
2.	3D T2 TSE/FSE (SPACE/CUBE/VISTA)	Axial	1–1.5	0	1 × 1 mm	5–6	Surgical guidance	B	1.6 (strong recommendation)
3.	3D bSSFP (CISS/FIESTA-C)	Sagittal or axial	1	0	1 × 1 mm	Variable based on coverage	Through region of interest	C	1.7 (strong recommendation)
4.	DTI	Minimum no. of directions 30–45; *b* value should include 1000				3–5	Surgical guidance	B	1.5 (strong recommendation)
5.	Perfusion DCE					5–15	Baseline at diagnosis, problem solving at follow-up	C	2.6 (moderate recommendation)
	Perfusion DSC					1–2		C	2.3 (moderate recommendation)
	Perfusion ASL					5–6		C	2.5 (moderate recommendation)
8.	MR spectroscopy SVS or CSI	TE-short, long				5–10	Baseline at diagnosis, problem solving at follow-up	B	1.9 (strong recommendation)

Abbreviations: 3D T1 IR-GRE, three-dimensional T1-weighted inversion-recovery gradient-recalled echo; ASL, arterial spin labeling; CISS, constructive interference in the steady state; CSI, chemical shift imaging; DCE, dynamic contrast enhanced; DSC, dynamic susceptibility contrast; DTI, diffusion tensor imaging; FIESTA-C, fast imaging employing steady-state acquisition cycled phases; SVS, single-voxel spectroscopy; TE, time to echo.

for lesion measurement. Tumor dimensions measured on T2-weighted sequences are often more reliable for response assessment than are measurements of enhancing components, as lesion enhancement may be affected by intrinsic tumor properties, contrast timing, or other technical factors. T2-weighted imaging can also provide information about tumor features such as cellularity, hemorrhage, calcifications, and cystic changes.

A 2D TSE T2-weighted sequence in the axial plane with slice thickness of 4 mm or less and no interslice gap is recommended in this protocol *(Grade: A; SOR: 1*, very strong recommendation*)*.

An additional plane may be acquired for better tumor measurements (e.g., sagittal for pineal region tumors or coronal for sellar/suprasellar tumors) or based on institutional preference. Alternatively, an isotropic 3D T2-weighted sequence (e.g., SPACE, CUBE, or VISTA) with slice thickness of 1 mm or less may be acquired in the sagittal or axial plane, with multiplanar reconstructions, which can also be used for surgical navigation.

2.9 | T2-FLAIR imaging

Although the T2-FLAIR sequence also predominantly utilizes T2 signal characteristics to assess the lesion and surrounding edema, it has certain advantages and drawbacks compared to T2-weighted imaging depending on the tumor location and intrinsic features. T2-FLAIR imaging suppresses the cerebrospinal fluid and improves tumor conspicuity near the cortex and can assist with evaluation of cystic components, vasogenic edema, and postsurgical or treatment-related changes.[23,24]

Along with T2-weighted images, T2-FLAIR may be used for more accurate measurements of non-enhancing or partially enhancing tumors *(Grade: B; SOR: 1.3*, very strong recommendation*)*.

When performed post-contrast, T2-FLAIR sequence is very sensitive for detecting leptomeningeal metastatic disease. T2-FLAIR imaging also overcomes the drawbacks of sulcal vascular enhancement and phase-shift artifacts seen in T1-weighted sequences. Depending on the technique and slice thickness used, post-contrast T2-FLAIR can outperform post-contrast T1-weighted images for detecting leptomeningeal metastatic disease, although there have been conflicting reports comparing the two techniques.[25,26] However, in conjunction with post-contrast T1-weighted images, post-contrast T2-FLAIR imaging considerably improves the sensitivity and confidence of leptomeningeal metastatic disease detection.[27–29] Therefore, it is recommended that a T2-FLAIR sequence be performed after administration of contrast. Notably, increased signal within cortical sulci on FLAIR images may be seen with changes in blood perfusion within leptomeningeal vessels because of intravenous sedatives or oxygenation under sedation, as well as with pathologies such as hemorrhage and infection, all of which can mimic leptomeningeal metastatic disease.[30–33]

Pre- and post-contrast T2-FLAIR images for comparison are acceptable based on institutional preferences; however, we recommend post-contrast T2-FLAIR images as an essential sequence *(Grade: B; SOR: 1.3*, very strong recommendation*)*.

3D T2-FLAIR images acquired using the variable flip angle TSE technique may further improve leptomeningeal metastasis detection by providing thinner slices and fewer flow artifacts in cisterns and ventricles compared with 2D T2-FLAIR images[26] *(Grade: B; SOR: 1.3*, very strong recommendation*)*.

Although a post-contrast, isotropic, sagittal, 3D T2-FLAIR technique is preferable, its availability and optimization may not be universal.

Axial post-contrast 2D T2-FLAIR images with slice thickness of 4 mm or less and no interslice gap are an acceptable substitute if 3D T2-FLAIR is not available *(Grade: B; SOR: 1.5*, strong recommendation*)*.

Delayed post-contrast T2-FLAIR imaging is more sensitive than early post-contrast T2-FLAIR for detecting leptomeningeal disease, so it may be beneficial to perform the T2-FLAIR sequence after post-contrast T1-weighted imaging.[34]

2.10 | Diffusion-weighted imaging

DWI is recommended as a fundamental sequence for pediatric brain tumor imaging *(Grade: A; SOR: 1*, very strong recommendation*)*.

DWI is a pulse sequence that evaluates the random motion of water molecules and generates quantitative apparent diffusion coefficient (ADC) maps.[35–38] Brain tumors demonstrate diffusion characteristics reflective of histoarchitectural features, including degree of tumor cellularity, cellular nuclear to cytoplasmic ratios, and the relative ratio of intracellular to extracellular space.[39] Tumors with high cellularity, such as embryonal tumors and HGG, demonstrate reduced diffusivity, a feature that can aid in making the prospective diagnosis and in evaluating recurrent disease and treatment-related change.[40–44] DWI is particularly valuable for detecting recurrent and metastatic medulloblastomas, as even small lesions demonstrate reduced diffusivity while enhancement may be variable.[45,46]

DWI sequences are traditionally acquired using a single-shot echo-planar imaging (EPI) technique, which provides the fastest image acquisition but has relatively lower resolution and is subject to susceptibility artifacts, resulting in geometric distortion and signal drop-out.[47] These artifacts most commonly arise near the skull base at tissue interfaces, such as the interface with air in the paranasal sinuses and mastoid air cells, degrading diagnostic accuracy in those locations, including posterior fossa and basal cisterns, which are especially relevant for pediatric brain tumors. This type of distortion in EPI sequences can be minimized by using advanced diffusion techniques, such as those that incorporate parallel imaging techniques (e.g., generalized autocalibrating partially parallel acquisitions [GRAPPA][47,48] or sensitivity encoding [SENSE][49]), which speed up the traversal of k-space. Other techniques, such as PROPELLER,[50] which is a multi-shot FSE-based technique that uses periodically rotating overlapping parallel lines of acquisition, also reduce distortion artifact. RESOLVE, a readout-segmented EPI and parallel imaging technique, also results in significant reduction in susceptibility artifact and improved resolution of pathology.[46,51] A slice thickness of 4 mm or less and no interslice gap is recommended to allow detection of small lesions.

Many institutions prefer to perform diffusion tensor imaging (DTI) and use the generated DTI trace images in lieu of routine DWI acquisition. DTI can generate higher-quality images than routine three-direction DWI and can be further useful for quantitative measurements, tractography, and surgical navigation, if needed.[52]

Susceptibility-weighted imaging (SWI): SWI is a high-resolution, 3D, spatially encoded gradient echo technique sensitive to changes in the local magnetic field.[53] Areas of abnormal magnetic susceptibility usually reflect blood (which may represent extracellular hemorrhage or intravascular venous deoxygenated blood) or mineralization (such as dystrophic calcification). Filtered phase images can also be used to differentiate paramagnetic blood products from diamagnetic mineralization.[54] *A SWI sequence can identify intratumoral hemorrhage and calcifications, which may be helpful for narrowing prospective differential diagnoses for new tumors (Grade: B; SOR: 1.6, strong recommendation).* The technique is also valuable for evaluating postsurgical and postradiation changes, including identification of radiation-induced cavernomas.[55]

T2* gradient-recalled echo (GRE) can be considered as an alternative if SWI is not available, but is less sensitive to magnetic susceptibility compared to SWI *(Grade: B; SOR: 2.1*, moderate recommendation*).*

2.11 | Optional sequences

Neuronavigation techniques have become ubiquitous in pediatric neuro-oncological surgeries and have specific technical requirements for preoperative MRI, depending on the navigation platform. Similar requirements also apply to intraoperative MRI approaches. These MRI protocols usually require 3D-isotropic, larger field-of-view images and visualization of fiducial markers (if applicable) or the patient's face and other anatomical landmarks for proper registration.[56]

3D post-contrast isotropic T1-weighted sequence is recommended for neuronavigation *(Grade: A; SOR: 1, very strong recommendation).*

Isotropic 3D T2-weighted sequencing (e.g., SPACE, CUBE, or VISTA) is also recommended and may be particularly helpful for non-enhancing or partially enhancing tumors *(Grade: B; SOR: 1.6*, strong recommendation).

Notably, preoperative CT can also be used for neuronavigation, providing accuracy similar to that of MRI.[57] Surgical planning CT, as well as MRI, should be performed with zero degree of the gantry angle, and isotropic imaging, with slice thickness of 1 mm or less. Orthodontic hardware will result in an MRI artifact rendering facial tracing inadequate for neuronavigation; in these cases, the braces or hardware should be removed, or CT should be used for neuronavigation.

Balanced steady-state free precession (bSSFP) sequences such as CISS (constructive interference in steady state, Siemens) or FIESTA-C (fast imaging employing steady-state acquisition cycled phases, GE) imaging can detect small lesions that are not well visualized on T1-weighted post-contrast images, such as non-enhancing residual tumors or small leptomeningeal metastases *(Grade: C; SOR: 1.7*, strong recommendation*).*

This technique can also be useful in presurgical planning for endoscopic third ventriculostomy (e.g., cases of tectal gliomas).[58]

An example of a specific tumor type for which bSSFP can be helpful is ependymoma, in which bSSFP can be performed through the posterior fossa for infratentorial tumors or through the region of interest for supratentorial tumors to help detect small tumors

MRI DTI and tractography allow noninvasive, in vivo, 3D demonstration of the location and trajectory of white matter tracts.

This technique can be a useful adjunct for presurgical planning and neuronavigation by localizing important white matter tracts and demonstrating their relationship to brain tumors[59] *(Grade: B; SOR: 1.5*, strong recommendation*).*

Task-based functional MRI (fMRI) allows noninvasive spatial mapping of eloquent parts of the brain, such as motor, sensory, language, and visual areas, during the performance of specific tasks. This information can be used by the neurosurgeon in presurgical planning and intraoperative navigation in an attempt to achieve a maximally effective resection while minimizing postsurgical neurological deficits.[60]

MR perfusion imaging provides an assessment of tumor vascularity and hemodynamic characteristics, which can be used for differential diagnosis and grading of the tumor, for assessment of recurrence versus pseudo-progression during follow-up, and for differentiating residual or recurrent neoplasm from radiation necrosis. *MRI perfusion can be performed using contrast-enhanced techniques such as dynamic susceptibility contrast (DSC) (Grade: C; SOR: 2.3, moderate recommendation) or dynamic contrast-enhanced (DCE) (Grade: C; SOR: 2.6, moderate recommendation) perfusion.*

The non-contrast arterial spin labeling (ASL) technique, an alternative to contrast perfusion techniques, has also been used in the clinical setting; however, its utility remains unclear, and further studies are needed to establish its efficacy *(Grade: C; SOR: 2.5*, moderate recommendation*).*

Proton magnetic resonance spectroscopy (MRS) enables biochemical metabolite analysis of brain tissue and can be performed by using single-voxel or multi-voxel (chemical shift) techniques. *Single-voxel MRS at short TE (35 milliseconds) enables identification of numerous metabolites, which can be useful for predicting the tumor type and grade (Grade: B; SOR: 1.9, strong recommendation).* Single-voxel MRS is best performed in single, homogenous tumors, and voxel placement should avoid calcifications and necrosis.

Multi-voxel MRS can be considered for infiltrating and heterogenous tumors, but is inferior to single-voxel MRS because of voxel bleeding, which causes intravoxel signal loss. Serial MRS can also help to distinguish tumor progression from treatment effects, including radiation necrosis.[61,62]

2.12 | Emerging techniques

Artificial intelligence and machine learning techniques, including radiomics and deep learning, have shown initial promise in the segmentation, tumor type and molecular subgroup prediction, and prognostication of pediatric and adult brain tumors. Much

research effort is being focused on developing and validating these techniques.[63–65]

Several other technological advances are being explored for pediatric brain tumor imaging, including sodium (^{23}Na) MRI, ferumoxytol-enhanced MRI, and chemical exchange saturation transfer (CEST).[66–69] These techniques are used primarily for research and have not yet been validated for the clinical setting.

3 | CONCLUSION

Standardizing neuroimaging protocols is intended to improve accuracy of tumor staging, risk stratification, and response assessment. The brain MRI protocol recommended by the committee in this White Paper can be implemented in routine clinical practice and in multicenter clinical trials.

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CONFLICT OF INTEREST

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