International Journal of Modern Medicine
VOLUME05 ISSUE03
PUBLISHED DATE: - 30-03-2026
DOI: https://doi.org/10.55640/ijmm-05-03-04
Page 29-36
eISSN: 2156-5198 pISSN: 2156-518X

RESEARCH ARTICLE

MR Tractography In Pediatric Subcortical Brain Tumors as A Tool for Improving Surgical Decision-Making

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Abstract: Magnetic resonance tractography has become an important adjunct in the preoperative assessment of brain tumors, particularly in cases involving functionally eloquent regions. In pediatric patients with subcortical tumors, where anatomical variability and ongoing neurodevelopment complicate surgical planning, tractography provides an additional layer of information for visualizing white matter pathways and estimating the risk of functional deficits. However, its clinical utility remains controversial due to methodological variability, model dependence, and limited reproducibility. This review critically evaluates current evidence on the use of MR tractography in the surgical management of pediatric subcortical brain tumors. A structured literature search was performed across major biomedical databases, focusing on studies published between 2017 and 2025. The analysis emphasizes clinical applications, integration with functional mapping, and methodological limitations affecting interpretation. Available data suggest that MR tractography improves spatial understanding of tumor–tract relationships and may influence surgical approach selection. At the same time, its predictive value for functional outcomes remains inconsistent, particularly in the presence of edema, tumor infiltration, and immature white matter. The lack of standardization and dependence on reconstruction algorithms continue to limit its reliability. MR tractography should therefore be regarded as a supportive rather than standalone modality. Its optimal use lies within a multimodal framework combining anatomical imaging, functional mapping, and intraoperative monitoring. Further standardization and validation studies are required to enhance its role in clinical decision-making.

Key words: MR tractography, diffusion tensor imaging, pediatric brain tumors, subcortical lesions, neurosurgical planning, white matter pathways.

INTRODUCTION

Surgical treatment of pediatric brain tumors remains one of the most technically and conceptually demanding areas of modern neurosurgery, particularly when lesions are in subcortical regions adjacent to functionally critical white matter pathways [1]. In such cases, the surgeon is required to balance maximal tumor resection with preservation of neurological function, often under conditions of limited anatomical clarity.

Conventional magnetic resonance imaging provides detailed structural information and remains the foundation of preoperative evaluation. At the same time, its ability to reflect the functional significance of adjacent brain structures is inherently limited [2]. This limitation becomes more pronounced in pediatric patients, where incomplete myelination, ongoing neurodevelopment, and pronounced interindividual variability reduce the reliability of purely anatomical interpretations [3].

MR tractography, based on diffusion-weighted imaging, has emerged as a method capable of

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reconstructing probable trajectories of white matter pathways. Its clinical adoption has been driven by the need to better understand spatial relationships between tumors and major functional tracts, including corticospinal, language-associated, and visual pathways [4]. In pediatric neurosurgery, this need is particularly acute due to the increased vulnerability of developing neural networks and the higher risk of long-term functional impairment [5].

Despite its expanding use, MR tractography cannot be considered a direct imaging technique. It represents a mathematical model derived from diffusion signal analysis, and its output is influenced by acquisition parameters, reconstruction algorithms, and operator-dependent decisions. These characteristics introduce variability that may significantly affect clinical interpretation, especially in complex anatomical regions. An additional challenge lies in the relationship between tractography findings and actual functional integrity. Clinical observations indicate that apparent tract disruption does not always correspond to neurological deficit, while preserved tractography patterns may coexist with impaired function. Such discrepancies complicate the use of tractography as a predictive tool and raise concerns regarding its reliability in surgical planning. Given these limitations, a critical reassessment of the role of MR tractography in pediatric subcortical tumors is required. The present review focuses on its clinical applications, methodological constraints, and practical implications for decision-making. Attention is paid to its integration into multimodal diagnostic strategies aimed at improving surgical safety and functional outcomes.

METHODS

This review was designed as a narrative analysis of contemporary evidence addressing the clinical role of MR tractography in pediatric subcortical brain tumors. The primary objective was to assess not only its diagnostic capabilities but also its practical contribution to surgical decision-making.

A structured literature search was performed using PubMed, Scopus, and Web of Science databases. The search covered publications from January 2017 to January 2025 and was restricted to English-language studies. The search strategy included combinations of the following terms: «MR tractography», «diffusion tensor imaging», «pediatric brain tumors», «subcortical lesions», «white matter pathways», and «neurosurgical planning» [6].

Selection of studies was guided by their clinical relevance. Priority was given to original clinical studies, systematic reviews, and meta-analyses evaluating the use of tractography in preoperative planning, intraoperative navigation, and postoperative outcome assessment [7]. Attention was paid to studies involving pediatric populations and tumors located in eloquent or subcortical regions, where functional preservation is a critical component of treatment strategy. Studies focusing exclusively on technical aspects without clinical correlation were excluded, as were experimental and animal studies. Case reports were included selectively when they provided insights into clinically meaningful applications of tractography, particularly in complex surgical scenarios [8].

Data extraction was performed with emphasis on several domains, including indications for tractography, its integration with functional mapping techniques, its influence on surgical strategy, and its association with postoperative neurological outcomes. In addition, methodological factors affecting reliability were analyzed, including diffusion models, reconstruction techniques, and the impact of pathological changes in white matter. Due to heterogeneity in study design, imaging protocols, and outcome measures, a qualitative synthesis approach was adopted. The analysis aimed to identify recurring patterns of clinical use, key limitations, and areas of uncertainty that continue to influence the interpretation of tractography in clinical practice.

RESULTS

Clinical Applications of MR Tractography in Pediatric Brain Tumors

The use of MR tractography in pediatric neuro-oncology is primarily driven by the need to

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better understand spatial relationships between tumor tissue and functionally critical white matter pathways. This requirement becomes particularly relevant in subcortical tumors, where deep localization and complex anatomy limit the ability of conventional MRI to accurately estimate functional risk. In preoperative planning, tractography is most frequently applied to assess the displacement, deformation, or possible involvement of major projection pathways, including the corticospinal tract, as well as associative and commissural fibers. This information contributes to defining the surgical corridor, estimating the permissible extent of resection, and anticipating the likelihood of postoperative neurological deficit [9]. In lesions located near motor or language areas, visualization of white matter pathways may shift the balance toward more conservative, function-preserving strategies, although the degree of influence varies depending on the reliability of tract reconstruction.

A particularly important development has been the integration of tractography with functional mapping techniques. The combination of diffusion-based structural reconstruction with functional MRI or navigated transcranial magnetic stimulation provides a more comprehensive representation of brain organization, incorporating both anatomical and functional components [10]. This multimodal approach is especially valuable in pediatric patients, where neuroplasticity and variability of cortical representation may obscure the relationship between structure and function. At the same time, discrepancies between tractography and functional mapping are not uncommon, and in such cases functional data are generally considered more reliable for surgical planning [11].

Intraoperatively, tractography data are often incorporated into neuronavigation systems, allowing visualization of reconstructed pathways during tumor resection. In selected cases, particularly in eloquent regions, this integration may contribute to increasing the extent of safe resection while reducing the likelihood of permanent deficits [12]. However, the clinical utility of intraoperative tractography is limited by brain shift, which progressively alters spatial relationships during surgery and reduces the accuracy of navigation based on preoperative imaging [13]. For this reason, intraoperative neurophysiological monitoring remains indispensable. Tractography also plays a role in the interpretation of postoperative outcomes. Changes in specific white matter pathways, such as the dentato-thalamo-cortical tract, have been associated with the development of neurological syndromes, including cerebellar mutism [14]. In such situations, tractography serves primarily as a tool for retrospective anatomical analysis rather than a predictive modality. The assessment of visual pathways represents another clinically relevant application. Probabilistic tractography has demonstrated the ability to reconstruct optic radiations and evaluate their integrity in patients with tumors affecting the visual system [15]. Some studies report correlations between tract integrity and visual function, although these relationships are variable and depend on methodological factors as well as the underlying pathology.

Despite these applications, the overall impact of MR tractography on surgical decision-making remains heterogeneous. In some clinical scenarios, it provides critical information that directly influences the surgical approach, while in others it functions as an adjunct without altering operative strategy. This variability reflects both the technical limitations of the method and the complexity of pediatric brain organization. Taken together, MR tractography enhances anatomical understanding and contributes to preoperative planning, but its clinical value is realized primarily when it is integrated into a broader diagnostic framework. Its role is complementary rather than definitive, particularly in cases where conventional imaging alone is insufficient to estimate functional risk.

Limitations and Sources of Variability of MR Tractography

Despite its widespread clinical adoption, MR tractography remains fundamentally limited by its model-based nature. Unlike conventional

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MRI, it does not directly visualize white matter structures but reconstructs probable pathways based on diffusion signal characteristics. This distinction is critical, as it defines tractography not as an anatomical image but as an interpretative model subject to multiple sources of variability. One of the primary determinants of variability is the choice of diffusion model and reconstruction algorithm. Deterministic and probabilistic approaches often yield divergent representations, particularly in regions with complex fiber architecture such as crossing or branching tracts. Even minor differences in region-of-interest placement, tracking thresholds, and termination criteria can lead to substantial changes in tract configuration, reducing reproducibility and limiting inter-study comparability [16, 17].

Pathological alterations in brain tissue further complicate interpretation. Edema, tumor infiltration, and compression significantly affect diffusion properties, frequently leading to reduced anisotropy and incomplete tract reconstruction. In such contexts, apparent tract disruption may reflect reversible microstructural changes rather than true axonal damage. Conversely, preserved tractography patterns do not necessarily indicate functional integrity, creating a persistent mismatch between imaging findings and clinical outcomes. In pediatric populations, these limitations are amplified by developmental factors. Ongoing myelination, evolving connectivity, and pronounced anatomical variability influence diffusion metrics and reduce the stability of tract reconstruction. As a result, interpretation frameworks derived from adult populations cannot be directly applied, and age-specific variability must be considered in clinical decision-making. Technical parameters related to image acquisition represent an additional source of heterogeneity. Variations in magnetic field strength, diffusion directions, and signal-to-noise ratio directly affect data quality and reconstruction accuracy. Differences in acquisition protocols between institutions further limit standardization and complicate the development of unified clinical guidelines [18].

Intraoperative factors introduce further uncertainty. Brain shift alters the spatial relationship between anatomical structures during surgery, reducing the accuracy of navigation systems based on preoperative imaging. This limitation is particularly relevant in large tumors and procedures involving significant cerebrospinal fluid loss, where tractography-based navigation may diverge from actual anatomy [19].

The absence of universally accepted standards for acquisition, processing, and interpretation remains a major unresolved issue. Although multiple approaches to standardization have been proposed, no consensus has been reached, reflecting both technological variability and incomplete validation of tractography against functional or histological reference standards. Taken together, these limitations indicate that MR tractography should not be interpreted as an objective representation of white matter anatomy but rather as a probabilistic construct influenced by technical, biological, and methodological factors. Its clinical use requires cautious interpretation and integration with complementary diagnostic modalities.

MR Tractography in Surgical Decision-Making

Within the context of pediatric subcortical brain tumors, MR tractography is most appropriately used as part of a structured, multimodal decision-making process rather than as an independent determinant of surgical strategy. Its value lies in refining anatomical understanding and supporting risk estimation rather than providing definitive guidance. At the preoperative stage, tractography contributes to the assessment of tumor–tract relationships and facilitates stratification of surgical risk. Patterns such as tract displacement, compression, or apparent disruption may influence the choice of surgical corridor and the anticipated extent of resection. Displacement of well-organized tracts is generally associated with a more favorable functional prognosis, whereas infiltration or loss of tract continuity introduces greater uncertainty and often necessitates a more conservative approach [20].

The integration of tractography with functional mapping remains a critical element of its clinical application. Concordance between structural

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and functional data increases confidence in surgical planning, whereas discrepancies highlight the limitations of tractography and shift decision-making toward functional assessment. In such situations, functional mapping is typically considered the more reliable indicator of eloquent cortex and pathway integrity [21].

During surgery, tractography-based neuronavigation may assist in maintaining orientation and avoiding critical pathways. However, its role remains supportive, as intraoperative brain shift reduces the accuracy of preoperative imaging. Continuous neurophysiological monitoring therefore remains essential, particularly in procedures involving eloquent regions. In pediatric patients, the interpretation of tractography findings must account for neurodevelopmental factors and the potential for functional reorganization. Structural alterations observed on tractography may not correspond directly to functional impairment, and compensatory mechanisms may modify the clinical significance of imaging findings. This further limits the predictive value of tractography when used in isolation. From a practical standpoint, MR tractography is most valuable in complex cases where conventional imaging fails to adequately define functional risk, including deeply located tumors and lesions adjacent to major white matter pathways. In more straightforward anatomical scenarios, its contribution to decision-making is often limited [22, 23].

DISCUSSION

The growing integration of MR tractography into pediatric neuro-oncology reflects a broader shift toward function-oriented surgical planning. While conventional imaging provides detailed anatomical information, it does not adequately address the functional implications of tumor resection, particularly in subcortical regions where white matter pathways play a central role in neurological outcomes. In this context, tractography offers an appealing extension of preoperative assessment by attempting to bridge the gap between structure and function. At the same time, the evidence reviewed in this study indicates that the clinical value of MR tractography is neither uniform nor universally reproducible. Its utility varies considerably depending on methodological factors, tumor characteristics, and patient-specific особенностей. In particular, the inconsistency between structural tractography findings and functional outcomes represents a fundamental limitation that cannot be overlooked. This discrepancy challenges the assumption that visualization of white matter pathways directly translates into reliable prediction of neurological deficits.

A critical observation emerging from the literature is that tractography exerts the greatest influence not as an isolated modality but as part of a multimodal framework. When combined with functional imaging and intraoperative monitoring, it contributes to a more nuanced understanding of brain organization and supports more informed surgical planning. In contrast, reliance on tractography alone increases the risk of misinterpretation and may lead to either overly aggressive or unnecessarily conservative strategies.

The issue of variability remains central to the interpretation of tractography data. Differences in acquisition protocols, reconstruction algorithms, and operator-dependent parameters introduce a level of subjectivity that limits standardization. This problem is particularly pronounced in pediatric populations, were developmental factors further complicate interpretation. As a result, the lack of universally accepted protocols continues to restrict the comparability of findings and the generalizability of conclusions.

From a clinical perspective, the role of MR tractography can be more accurately defined as a tool for reducing uncertainty rather than eliminating it. It provides additional information that refines anatomical orientation and supports hypothesis formation regarding functional risk. However, final surgical decisions must remain grounded in functional assessment and intraoperative findings, which retain greater reliability in determining neurological outcomes. These considerations highlight the need for further research aimed at

improving the standardization and validation of tractography techniques. Future studies should focus on establishing stronger correlations between imaging findings and functional outcomes, as well as developing reproducible protocols that can be applied across clinical settings. Until such advances are achieved, the use of MR tractography should remain cautious, context-dependent, and firmly integrated within a multimodal diagnostic strategy.

CONCLUSION

MR tractography occupies a defined but limited role in the preoperative evaluation of pediatric subcortical brain tumors, where it enhances spatial understanding of tumor–tract relationships and contributes to risk-oriented surgical planning. Its diagnostic value remains conditional due to model dependence, variability of reconstruction, and the inconsistent relationship between structural imaging and functional outcomes. The evidence indicates that tractography is most effective when integrated into a multimodal framework that combines conventional MRI, functional mapping, and intraoperative monitoring, allowing for a more balanced interpretation of anatomical and functional data. In pediatric practice, additional uncertainty related to ongoing brain development and neuroplasticity further restricts the reliability of isolated tractographic findings. Within this context, MR tractography should be regarded as a supportive tool that refines surgical strategy and assists in reducing uncertainty, while definitive decisions must remain grounded in functional assessment and intraoperative verification.

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