

Review Article

Diffusion Tensor Imaging of the Corticospinal Tract in Preoperative Planning for Motor Area Gliomas

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Abstract

Background: Gliomas near the rolandic cortex threaten the corticospinal tract (CST), the pathway chiefly responsible for voluntary motor function. Diffusion tensor imaging (DTI) tractography offers a noninvasive way to visualise this tract before surgery.

Objective: To review published evidence on DTI-CST tractography for preoperative planning of motor-area gliomas.

Methods: Narrative review of validation studies, neuronavigation series, comparative imaging studies and outcome cohorts.

Findings: Tractography integrated into neuronavigation increases extent of resection and reduces new motor deficits versus anatomical navigation alone. Validation against direct subcortical stimulation shows tractography approximates, but does not exactly localise, the functional tract, with discordance growing near tumour and oedema. Classifying tumour-tract interaction as displaced, infiltrated or disrupted correlates with resectability and motor outcome. Crossing-fibre regions remain a persistent tensor-model weakness that probabilistic tracking, Q-ball and constrained spherical deconvolution partly address.

Conclusions: DTI-CST tractography is a valuable, imperfect adjunct that should inform, not replace, intraoperative functional mapping.

Keywords: Diffusion tensor imaging; Corticospinal tract; Tractography; Glioma; Preoperative planning

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Keywords: diffusion tensor imaging; corticospinal tract; tractography; glioma; preoperative planning

Introduction

Gliomas located within or adjacent to the primary motor cortex and its descending white-matter output present a defining trade-off in neuro-oncological surgery: maximising the extent of resection, which improves survival, against preserving the corticospinal tract (CST), whose injury produces permanent hemiparesis. Because the CST cannot be seen on conventional structural MRI, surgeons have long relied on intraoperative techniques — direct electrical cortical and subcortical stimulation (DES) with motor evoked potential monitoring — to localise the

pathway in real time [1]. Diffusion tensor imaging (DTI) tractography, which reconstructs putative white-matter trajectories from the directional dependence of water diffusion, was proposed as a complementary noninvasive method that could be obtained before surgery, displayed on the neuronavigation system, and used to plan the trajectory and extent of resection [2].

Over the past two decades, DTI-based CST tractography has moved from a research curiosity to a near-routine adjunct in centres performing eloquent-area glioma surgery [3]. It is now combined with functional MRI, navigated transcranial stimulation and intraoperative MRI in various multimodal pipelines, and it informs decisions ranging from patient counselling and surgical approach selection to the choice between awake and asleep resection strategies. However, tractography is a model-derived reconstruction, not a direct image of axons, and its accuracy has been repeatedly tested against the only available intraoperative ground truth: DES [4]. This review synthesises the published literature on DTI-CST tractography for preoperative planning in motor-area gliomas, organised around six themes: acquisition and neuronavigation integration; validation against DES; patterns of tumour-tract interaction; comparison with functional MRI; correlation with postoperative motor outcome; and the persistent limitations of the tensor model relative to advanced diffusion techniques. Throughout, the emphasis is on evidence quality — prospective controlled trials, correlative validation studies and systematic reviews are weighted more heavily than isolated case descriptions.

Technique and Neuronavigation Integration

CST tractography is typically generated from single-shell diffusion-weighted acquisitions using deterministic streamline algorithms seeded from the precentral gyrus and the cerebral peduncle, then fused onto anatomical MRI within the neuronavigation workstation [5]. Early

feasibility work combined this pipeline with intraoperative cortical stimulation to confirm that reconstructed tracts corresponded to functionally active pathways [2]. A key technical refinement was intraoperative re-acquisition: because brain shift and tissue removal progressively displace the true tract position relative to the preoperative dataset, updating tractography with intraoperative MRI substantially improves its reliability during resection [6]. Similar tractography-integrated navigation, sometimes combined with fence-post catheter marking and continuous motor evoked potential monitoring, has been used to guide staged resection around the pyramidal tract in glioblastoma [7].

The clinical value of this integration was tested directly in a prospective, controlled trial of 238 patients with gliomas involving the pyramidal tract, comparing DTI-based functional neuronavigation with conventional anatomical neuronavigation. The DTI-guided group achieved greater extent of resection, better postoperative motor function, and longer survival [8]. This trial remains the strongest outcome-level evidence that preoperative tractography changes surgical behaviour in a way that benefits patients, and it underpins the routine adoption of DTI-based planning described in subsequent applications reviews [3].

Validation Against Direct Subcortical Stimulation

Because tractography is inferential, its spatial accuracy has been checked repeatedly against DES, which remains the reference standard for functional localisation. Early correlative work found that the tractography-defined tract boundary and the nearest DES-positive stimulation site were spatially related but not identical, with measurable discrepancies of several millimetres [9]. Subsequent series comparing DTI-CST reconstructions with subcortical stimulation in intrinsic tumour surgery confirmed a consistent, if modest, spatial offset that tended to increase

closer to the tumour margin [10]. Correlative studies combining intraoperative MRI with DES similarly showed that tractography approximates but systematically under- or overestimates the true functional margin, particularly where oedema or infiltration distorts local diffusion signal [11].

Table 1: Selected studies correlating DTI-based corticospinal tract tractography with intraoperative direct subcortical stimulation [2,9,10,12,13,11,14,15,16]; N = 9 sources.				
Study (year)	Comparator	Tumour population	Design	Key theme
Berman 2004	Intraoperative cortical stimulation	Gliomas near motor cortex	Correlative feasibility	Tractography overlays functionally active cortex
Berman 2007	Subcortical stimulation + magnetic source imaging	Brain tumours near CST	Correlative accuracy	Measurable offset between tract and stimulation site
Zolal 2012	Direct subcortical stimulation	Intrinsic brain tumours	Correlative accuracy	Offset increases near tumour margin
Zhu 2012	Direct subcortical stimulation	Cerebral glioma	Prospective cohort	Tractography-DES concordance predicts motor outcome
Ostrý 2013	Subcortical CST mapping	Gliomas near CST	Intraoperative 3T DTI	Intraoperative re-acquisition narrows discordance
Javadi 2017	Intraoperative MRI + subcortical stimulation	Gliomas near CST	Correlative accuracy	Systematic bias near oedema/infiltration
Bozzao 2010	Subcortical stimulation	Tumours near pyramidal tract	Correlative series	Tractography approximates tract course
Münnich 2019	Intraoperative MRI + subcortical stimulation	Tumours near CST	Large correlative series	Confirms general accuracy, margin caution urged
Li 2023	Pooled subcortical mapping studies	Glioma (mixed)	Systematic review/meta-analysis	Good but incomplete concordance overall

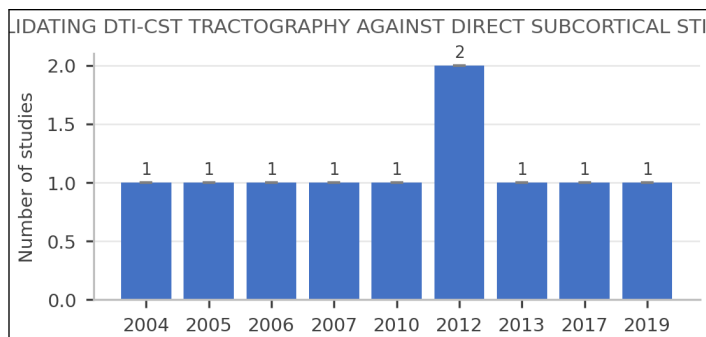


Figure 1: Studies cited in this review that validate DTI-based corticospinal tract tractography against intraoperative direct subcortical stimulation, by publication year [2,5,6,9,14,10,12,13,11,15].

Larger prospective cohorts applying tractography-guided DES mapping in cerebral glioma surgery found that concordance between the two methods correlated with postoperative motor outcome: cases with close tractography-DES agreement had lower rates of new deficit than cases with wide discordance [12]. Whether intraoperative re-acquisition at high field further narrows this gap has also been examined directly, with 3T intraoperative DTI shown to track subcortical stimulation findings more closely than preoperative-only imaging in some series [13]. Two independent correlative series pairing intraoperative MR tractography with subcortical stimulation reached comparable conclusions: tractography reliably approximates the pyramidal tract's general course but requires stimulation confirmation at the resection margin [14,15]. A systematic review and meta-analysis pooling these and related studies concluded that DTI tractography shows good but incomplete concordance with intraoperative subcortical mapping, supporting its use as a planning adjunct rather than a stand-alone functional map [16].

Tumour-Related Tract Displacement, Infiltration, and Disruption

Tumour growth alters the CST in at least three recognisable ways: pure mechanical displacement of an intact tract, infiltration of the tract by tumour cells with

partially preserved diffusion anisotropy, and frank disruption with loss of coherent fibre orientation. Histopathological correlation work established that reduced fractional anisotropy at the tumour-tract interface corresponds to biopsy-confirmed infiltration rather than simple oedema, validating fiber tracking as a marker of tract integrity rather than only tract location [17]. Building on this, a recent diffusion-MRI-based three-tier classification formally separates displaced, infiltrated and disrupted tract segments and demonstrates that this classification carries prognostic and surgical-planning relevance, including association with resectability and postoperative function [18].

These patterns matter clinically because the same tumour can displace the tract at one pole while infiltrating it at another, so a single global accuracy figure understates the heterogeneity of risk along the tract's course. Reviews of tractography for neurosurgical planning emphasise that clinicians should interpret the reconstructed tract as a probability map, denser in regions of high anisotropy and less reliable in infiltrated or oedematous zones, rather than a binary present/absent structure [1]. This distinction directly informs how much resection margin is considered safe at each point along the tract's trajectory near the tumour, and it explains why two tumours of similar size and location can carry very different motor risk depending on whether the tract is merely pushed aside, infiltrated but still partially functional, or already structurally disrupted before surgery begins.

Comparison with Functional MRI and Multimodal Planning

Functional MRI (fMRI) and DTI address complementary questions: fMRI localises eloquent cortex through blood-oxygenation-dependent activation, while DTI-CST tractography localises the descending subcortical pathway connecting that cortex to the spinal cord. Combining the two was shown to be feasible by using fMRI-derived motor

activation as a seed or waypoint region for CST tractography, improving anatomical plausibility of the reconstructed tract compared with anatomically seeded tracking alone [19]. More recent comparative work directly tested preoperative fMRI combined with tractography against tractography alone for predicting iatrogenic motor deficit, finding that the combined multimodal approach improved prediction of postoperative motor decline relative to either modality in isolation [20].

This complementary relationship reinforces a broader theme in the literature: no single preoperative imaging modality substitutes for intraoperative functional confirmation, but combining modalities narrows the zone of uncertainty that intraoperative mapping must then resolve, potentially shortening operative time in eloquent-area cases [3].

Postoperative Motor Outcome Correlation

Several of the validation studies above extend into outcome analysis, and their consistent message is that tighter DTI-DES concordance and greater preserved tract integrity both associate with better postoperative motor status. The prospective neuronavigation trial found lower rates of new postoperative motor deficit in the DTI-guided arm [8], while the large tractography-DES cohort explicitly linked spatial concordance between the two methods to motor outcome [12]. Tractography-integrated navigation combined with continuous motor evoked potential monitoring during staged resection near the pyramidal tract has likewise been associated with favourable rates of motor preservation in glioblastoma series [7]. The multimodal fMRI-tractography approach similarly improved outcome prediction accuracy over single-modality imaging [20]. Taken together, these outcome-linked studies support DTI-CST tractography as a planning tool with measurable downstream benefit, while cautioning that its predictive value is strongest

when combined with intraoperative confirmation rather than used in isolation.

Limitations: Crossing Fibres and Advanced Diffusion Models

The single-tensor model that underlies conventional DTI tractography cannot resolve more than one dominant fibre orientation per voxel, a limitation that is clinically important wherever the CST crosses the superior longitudinal fasciculus, corpus callosum radiations or other pathways, such as the centrum semiovale and corona radiata. This crossing-fibre problem, combined with partial-volume averaging and diffusion signal changes from peritumoral oedema, produces both false-negative tract terminations and spurious tract deviations [21]. A widely cited critical commentary argued that these failure modes mean DTI tractography remains a research and educational tool rather than a fully validated clinical instrument, given documented cases of clinically significant discordance with intraoperative mapping [22]; a recent point-counterpoint framed this tension explicitly for a neurosurgical audience, concluding that tractography is accurate enough to guide but not to replace surgical decision-making [23].

Table 2: Diffusion modelling approaches for corticospinal tract tractography discussed in this review [21,24,25,26,27,28].				
Approach	Addresses	Key strength	Key limitation	Reference
Single-tensor DTI (deterministic)	Baseline reconstruction	Fast, widely available	Fails at crossing fibres	yang2021
Probabilistic tractography	Uncertainty modelling	Lower distance error near tumour	Wider, less specific tract volume	mandelli2014, bucci2013
Q-ball / constrained spherical deconvolution	Crossing-fibre regions	Resolves multiple fibre populations	Longer acquisition/processing	becker2020, sheng2021
Free-water correction	Peritumoral oedema	Improves accuracy in non-oedematous glioma	Does not resolve crossing fibres	almairac2024

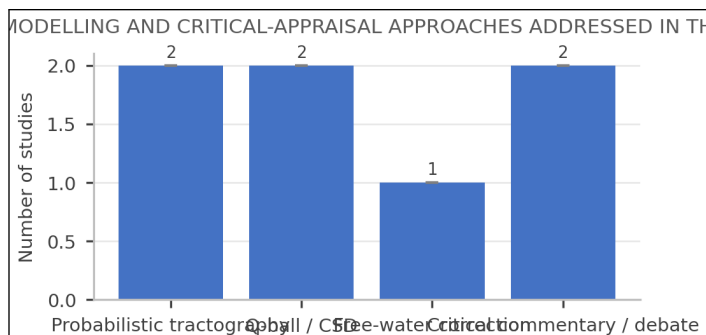


Figure 2: Advanced diffusion modelling and critical-appraisal approaches addressed in the reviewed literature, grouped by category [24,25,26,27,28,22,23].

Quantitative comparisons of deterministic and probabilistic tractography algorithms against DES found that probabilistic methods reduced distance error near the tumour margin at the cost of wider and less anatomically specific tract volumes, illustrating an accuracy-precision trade-off rather than a clean superiority of one method [24,25]. Higher-order diffusion models developed to resolve crossing fibres, including Q-ball imaging and constrained spherical deconvolution (CSD), have been applied specifically to the CST in eloquent glioma surgery and shown improved anatomical continuity through regions where single-tensor tracking fails or terminates prematurely [26,27]. Correcting specifically for free water in the peritumoral compartment, rather than modelling multiple fibre populations, has also been shown to improve tractography accuracy validated against direct stimulation in non-oedematous gliomas, indicating that oedema-related and crossing-fibre-related errors may require different corrective strategies [28].

Conclusion

The published literature supports diffusion tensor imaging tractography of the corticospinal tract as a genuinely useful, but deliberately imperfect, adjunct to preoperative planning for motor-area gliomas. It integrates readily into neuronavigation, improves extent of resection and postoperative motor outcome when

incorporated into structured surgical workflows, and — when interpreted alongside a tumour-tract interaction classification of displacement, infiltration or disruption — helps stratify surgical risk along the tract's course. Its accuracy relative to the intraoperative reference standard, direct subcortical stimulation, is good but not exact, with discordance concentrated near the tumour, in oedema and within crossing-fibre regions such as the centrum semiovale. Advanced diffusion approaches, including probabilistic tracking, Q-ball imaging, constrained spherical deconvolution and free-water correction, meaningfully reduce but do not eliminate these errors, and combining tractography with functional MRI further narrows the zone of uncertainty. The consistent recommendation across validation, outcome and critical-commentary literature alike is that DTI-CST tractography should guide surgical trajectory and counselling, while intraoperative functional mapping remains the final arbiter of the resection margin.

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