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Q-Ball high-resolution fiber tractography: Optimizing corticospinal tract delineation near gliomas and its role in the prediction of postoperative motor deficits– A proof of concept study

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ABSTRACT

Introduction: After resection of eloquent gliomas, impacting motor pathways, patients frequently harbour pronounced motor deficits (MD), predominantly attributed to damage to the corticospinal tract (CST).
Research question: This study compares the results of conventional DTI-FT and q-ball (QBI)-high resolution FT with patient's postoperative morbidity, relating postoperative MD with the nearest distance from the lesion to the CST (nD-LCST).
Materials and methods: In this ongoing prospective trial, we utilized probabilistic High-Resolution Fiber Tracking (HRFT) through q-ball imaging (QBI-FT) and conventional Diffusion Tensor Imaging Fiber Tracking (DTI-FT), based on equal and standard diffusion-weighted MRI. Our analysis focused on the normalized Distance from the lesion to the CST-FT (nD-LCST), compared with MD evaluated via standardized clinical examination.
Results: Post-surgery, 4 patients developed new MD or deteriorated respectively. Among these, one patient was diagnosed with glioblastoma, one with diffuse astrocytoma, one with anaplastic astrocytoma, and one with oligodendroglioma. QBI-FT analysis revealed that patients with MD had a significantly lower median nD-LCST (−0.4 IQR = 2.1), in contrast to those without MD (8.4 IQR = 3.9; $p = 0.029$). Median values of QBI-FT were located within the tumor outlines, when MD deteriorated. Patients with postoperatively impaired MD had larger tumor volumes compared to those without MD.
Discussion and conclusion: Our preliminary findings suggest that QBI-FT may offer advantages over DTI-FT in predicting postoperative motor deficits, potentially enhancing neurosurgical planning. However, due to the small sample size of our study, these results are exploratory, and further research with larger patient populations is necessary to confirm the benefits of QBI-FT. QBI-FT shows promise as a complementary tractography technique suitable for clinical purposes alongside standard DTI-FT.

1. Introduction

The resection of eloquent gliomas impacting the motor system frequently leads to pronounced postoperative motor deficits (MD), predominantly attributed to damage of the corticospinal tract (CST). The presence of gliomas can alter, infiltrate, or even eradicate the standard structure and pathways of white matter fiber tracts. Consequently, surgeries targeting areas in proximity to crucial structures like the CST are fraught with challenges. Nevertheless, technological innovations have significantly enhanced the efficacy of these surgical interventions (Becker et al., 2022; Krieg et al., 2012; Kuhnt et al., 2013a). In light of these challenges, fiber tractography (FT) has surfaced as a pivotal tool in preserving or minimizing postoperative neurological setbacks.

Anatomically, the CST engages with the spinal interneuron, notably

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the Rexed grey matter lamina IV layer. It also interfaces with the anterior horn motoneuron, pivotal for trunk and limb movements, and ultimately converges at the anterior horn motor cells of the spinal cord. These cells regulate the nuanced motions of skeletal muscles, encompassing the intricate activities of the hands, feet, and other small muscle groups. Gliomas situated near the CST region invariably compromise the motor system. Notably, the strength of limb muscles emerges as a reliable metric for projecting clinical trajectories and gauging the quality of life in afflicted individuals (Cavers et al., 2012). In this milieu, efforts are unwaveringly directed towards curbing post-surgery complications, emphasizing the preservation of essential white matter tracts integral to extensive neural networks.

Diffusion-weighted MRI, augmented by fiber tractography (FT), has been lauded for its potential in optimizing glioma excision while retaining neurological integrity. This approach invariably leads to improved survival rates and a heightened quality of life (Vassal et al., 2013). In particular, diffusion tensor imaging (DTI)-anchored FT is adept at identifying and mapping functional territories at the cortical stratum and delineating the routes of essential fascicles within the white matter (Basser et al., 2000; Park et al., 2015). While DTI is intuitive and aligns effortlessly with navigational paradigms, it occasionally falters in precisely ascertaining the genesis and termini within the white matter. To circumvent these DTI-associated constraints, sophisticated methodologies based on the representation of so called high-angular-resolution diffusion imaging (HARDI) signals have been proffered. However, the clinical application of HARDI is mired in contention, primarily owing to protracted acquisition phases necessitated by an augmented array of diffusion-encoding gradients or a demanding postprocessing procedure (Anderson, 2005; Michailovich and Rathi, 2010; Tuch et al., 2002).

DTI has been instrumental in mapping white matter tracts by modeling water diffusion along axonal fibers (Basser et al., 1994). However, its assumption of a single diffusion direction per voxel limits its accuracy in regions with complex fiber architectures, such as areas where fibers cross or diverge (Jeurissen et al., 2013; Tournier et al., 2011). This limitation is particularly problematic near gliomas, which often disrupt normal white matter structures, leading to potential inaccuracies in tractography and misinterpretation of neural connectivity. Q-Ball HRFT addresses these challenges by capturing multiple fiber orientations within a single voxel (Tuch et al., 2002). Utilizing High Angular Resolution Diffusion Imaging (HARDI), it reconstructs an Orientation Distribution Function (ODF), providing a detailed representation of complex fiber configurations (Descoteaux et al., 2009). This advanced technique enhances the visualization and delineation of neural tracts, which is crucial for surgical planning in glioma cases. By integrating diffusion-weighted sequences, suitable for Q-Ball HRFT into our imaging protocol, we aim to improve the precision of CST mapping adjacent to gliomas, offering neurosurgeons more reliable tractographic information than conventional DTI. This advancement is essential for minimizing the risk of postoperative motor deficits and optimizing surgical outcomes (Yeh et al., 2021).

Existing literature posits that DTI-centric fiber tracking, particularly when navigating gliomas near the CST, offers considerable value across preoperative planning, prognostic forecasting, intraoperative navigation, and outcome enhancement (Fekonja et al., 2021; Gao et al., 2017; Yu et al., 2019). Nevertheless, the efficacy of HARDI-anchored FT in generating comprehensive insights to mitigate or pre-empt postoperative motor deficits resultant from CST injury remains a matter of debate.

In view of these uncertainties, our research is delineated to: 1) Evaluate the practicality of employing DTI and QBI-HRFT in the presurgical schematics for patients harboring lesions adjacent to the CST, 2) Establish correlations between fiber tracking outcomes and preoperative motor impairments, 3) Probe the nexus between postoperative fiber tracking determinants and subsequent patient prognoses. 4) Evaluate the impact of other crucial tumor factors on FT-results, correlated to motor outcome.

2. Methods

Over a five-year span from April 2017 to February 2022, this study systematically gathered clinical and imaging data. It adhered to the ethical guidelines outlined in the Declaration of Helsinki and received approval from the relevant ethics committee (approvals S-146/2017 and S147/2017). Participation was contingent upon each patient's written consent, following ethical protocols. The study focused on adult patients (18 years or older) suspected of having a glioma near the corticospinal tract (CST), according to conventional, preoperative MRI and neuroradiological examination. Enrollment criteria included a compulsory preoperative MRI, specifically incorporating Diffusion Weighted (DW) imaging sequences by default, at this time only compulsory for eloquent gliomas and awake craniotomy conditions. A key factor for inclusion was the lesion's proximity to critical fiber bundles, defined as being less than 20 mm away. Exclusion criteria were set for individuals below 18, those lacking complete MRI data, or those with contraindications for undergoing MRI.

2.1. Motor assessment

Motor function was assessed one or two days before surgery and at the day of discharge. The motor function status at discharge was considered for the evaluation.

2.2. Impacting factors

Moreover analyzed was the impact of the following:

- Tumor volume: The tumor volume was automatically calculated after manual segmentation of tumor outlines. For high-grade gliomas, the outlines were drawn according to the contrast enhancing boundaries, for non-contrast enhancing tumors, hyperintense areas according to FLAIR-sequences were chosen. The outlines were manually drawn across all slices.
- Superficial tumor localization was defined for tumors associated to the grey matter. Deep tumors were defined to be located within the white matter.
- Precentral or postcentral localization of the tumor.
- Peritumoral edema: Likewise the tumor segmentation, edema volume was automatically calculated after manual segmentation of FLAIR-hyperintense areas for high-grade tumors.
- MGMT-methylation present or not present
- Surgical approach directly destined to the tumor via transcortical approach or other

3. Imaging data

Up to three days before the surgical procedure, a preoperative MRI dataset was obtained using a 3 T scanner (Magnetom Prisma, Siemens, Erlangen, Germany). The study required the following sequences: a T1-weighted three-dimensional (3D) magnetization-prepared rapid gradient-echo (MPRAGE) with gadolinium, featuring a repetition time (TR) of 1790 ms, an echo time (TE) of 3.7 ms, a field of view (FoV) of 250 mm, a slice thickness of 1 mm, 160 slices, acquired in the sagittal plane, with a duration of 3 min and 29 s; a fluid-attenuated inversion recovery (FLAIR) sequence with a TR of 8500 ms, a TE of 136 ms, a FoV of 230 mm, 25 slices, lasting 2 min and 52 s; and a diffusion-weighted imaging (DWI) sequence with a TR of 6600 ms, a TE of 87 ms, a FoV of 256 mm, 56 slices, utilizing a number of excitations I, b-value of 1000 s/mm^2, 64 noncollinear diffusion-encoding gradients, a voxel size of 2 $\times$ 2 $\times$ 2 mm^3, with an acquisition time of 7 min and 50 s. The overall duration of the MRI session was approximately 25 min. As it can be seen, the MRI protocol, equally used for DTI-FT and QBI-FT is adapted to patient's preoperative requirements.

The Medical Imaging Interaction Toolkit's (MITK) open-source software MITK Diffusion, available at https://github.com/MIC-DKFZ/MITK-Diffusion, was utilized for fiber tracking (FT) (source:”"-Medical Imaging Interaction Toolkit: MITK Diffusion Imaging (MITK-DI)”" n. d.). Both diffusion tensor imaging (DTI) and q-ball imaging (QBI) tracking approaches employed the same DW-MRI sequence, as mentioned above. Once the data was imported into MITK Diffusion, a rigid registration was performed between the DW images and T1-weighted sequences or FLAIR-sequences respectively. Subsequent pre-processing of the DW images involved head motion correction and eddy current correction through affine registration to the unweighted volume (Fritzsche et al., 2012). This process was followed by the calculation of tensors for DTI using the Insight Toolkit and dODF for QBI. FT for both DTI- and QBI-based fiber reconstruction was directly conducted using MITK Diffusion. The regions of interest (ROIs) were manually segmented over the precentral gyrus and mesencephal peduncle, as frequently used. False positive fibers were excluded with separate ROIs.

Tractography parameters were set based on common recommendations and for the purpose of comparability. For QBI, the parameters included sharpening of orientation distribution functions (ODFs) (Descoteaux et al., 2009) a GFA-cutoff of 0.15, a step size of 0.5 voxels, For DTI, the parameters comprised an FA cutoff of 0.15, a step size of 0.5 voxels and a minimum tract length of 20 mm (Becker et al., 2020).

4. Statistics

Categorical variables are expressed in terms of their counts and respective percentages. For continuous variables, we present them as median values along with their interquartile range (IQR) deviations. To assess the differences between patients with and without postoperative MD, univariate analysis was employed. A p-value of less than 0.05 was considered to indicate statistical significance.

5. Results

5.1. Overall characteristics

This study included 8 patients with a mean age of 47.5 years (SD = 13.8), all having gliomas near the corticospinal tract (CST). We analyzed 8 gliomas in total. Table 1 provides comprehensive details on the baseline characteristics and histological findings.

The average time required for CST visualization was 6.8 min (SD = 2.1) for DTI-FT and 11.5 min (SD = 6.5) for QBI-FT. Lesion locations were as follows: 7 in the precentral area and 1 in the postcentral area. Five lesions were situated in the deep white matter. Four tumors had a positive MGMT-methylation status, another four tumors were operated via direct and transcortical approach. Only one patient exhibited mild motor deficits before surgery. Table 1 displays the baseline characteristics.

Table 1
Baseline characteristics.

N	8
Age (mean, SD)	47.5 (13.8)
Sex (n, %)	
Male	6 (75.0)
Female	2 (25.0)
Preoperative MD[a] (n, %)	1 (12.5)
Postoperative MD (n, %)	4 (50.0)
Nearest distance by QBI median, IQR (mm)	3.6 (9.3)
Nearest distance by DTI, median, IQR (mm)	4.0 (6.3)
Volume, median, IQR (cm^3)	4.6 (3.8)
Histopathological Findings	
Glioblastoma WHO 4 IDH-negative	4
Anaplastic Oligodendroglioma WHO 3, IDH mutant, 1p71q co-deletion	2
Oligodendroglioma WHO 2, IDH positive, 1p19q co-deletion	1
Anaplastic Astrocytoma WHO 2, IDH mutant	1

[a] MD: motor deficit.

Post-surgery, 4 patients developed motor deficits (MD). The patient with preoperative deficits experienced worsening postoperatively. QBI fiber tracking (QBI-FT) analysis revealed that patients with MD had a significantly lower median normalized Distance from the lesion to the CST (nD-LCST) (−0.4 IQR = 2.1), in contrast to those without MD (8.4 IQR = 3.9; p = 0.029). It has to be noted that the nD-LCST for QBI had mean negative values, showing that QBI-FT fibers were located within the tumor outlines when patients suffered from postoperative MD. A similar significant trend was observed in nD-LCST measurements using DTI-FT. However, the mean nD-LCST here was positive with 2.4 mm, when MD occurred postoperatively.

Patients with postoperatively impaired MD had larger tumor volumes (4.1 IQR = 4.1) compared to those without MD (5.2 IQR = 4.0); however, this difference was not statistically significant (p = 0.486). Edema volume did not impact the neurological outcome in terms of MD. Fig. 1 shows CST-FT based on QBI (right) and DTI (left) for a large frontal tumor with the corresponding CST shift. Differences of the two methods are well depicted. On the contrary, Fig. 2 shows a smaller cortical/subcortical tumor with less edema. CST-FT via QBI (left) and DTI (right) are displayed, showing less obvious differences between the methods. A tumor localization within the deep white matter was associated with higher rates of MD (p = 0.053). Other factors did not determine the postoperative outcome.

When comparing DTI-FT and QBI-FT together with MD, it can be noted that one patient with preoperative MD had a large anaplastic astrocytoma grade II in the frontoparietal lobe. In this case, tumor outlines were located within the CST according to QBI-FT.

Table 2 summarizes these findings.

6. Discussion and review of the literature

DTI-based FT is a well-known and most frequently used technique to detect white matter tracts according to anisotropy of water diffusion (Mori et al., 1999). Owing to its shortcomings in resolving issues pertaining to extent, origin, and cortical determination, new techniques representing HARDI-signals for HRFT have been developed to overcome these impediments. Among these, the established model QBI for HRFT seems to improve the resolution of white-matter tracts, while still applicable in clinical settings (Becker et al., 2022), which has been a frequent matter of debate for HRFT models because they require longer data-acquisition and postprocessing times. As of now, there hasn’t been a comprehensive analysis regarding the precision in representing the CST near a glioma, in comparison to the DTI-FT technique, also considering influences of other relevant factors, which are impeding the diffusion profile.

Our study represents the first to systematically compare DTI-FT and QBI-FT techniques in assessing lesions adjacent to the CST, with a focus on predicting postoperative motor deficits related to the tumor’s proximity to the FT. Our results indicate that both DTI-FT and QBI-FT effectively reproduce the CST and are correlated with the incidence of postoperative MD. Significantly, QBI-FT reveals that CST fibers were either attached to or intersected by the lesion (given through the negative nd-LCST values), a finding not observed in DTI-FT. This distinction might better explain the observed postoperative decline in neurological function in patients, compared to their preoperative status and indicate favorable FT-results given by HRFT.

In their recent comparative study on CST delineation using DTI- and QBI-based FT in healthy subjects, Suo et al. found that QBI models provided superior diffusion representations for the CST and its branches, particularly noting that the CST’s branches were more accurately generated by QBI than DTI (Suo et al., 2021). They also observed a higher presence of authentic CST fibers and a lower incidence of falsely identified fibers in QBI compared to DTI. Wang et al. concurred, endorsing QBI as a more precise model for FT (Wang et al., 2018), while Zhang et al. specifically recognized the efficacy of QBI models in mapping FT near lesions with peritumoral edema (Zhang et al., 2013). In our

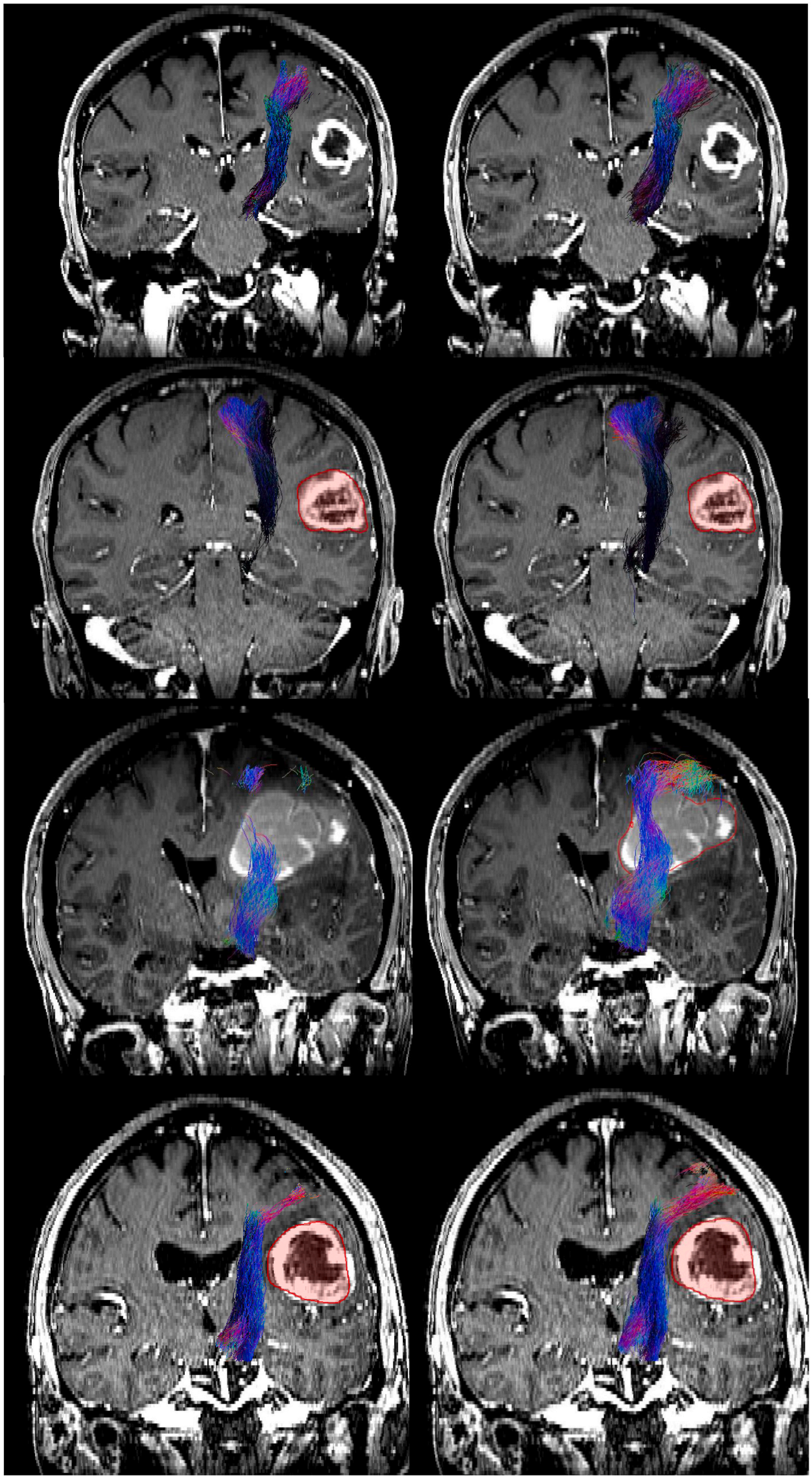

Fig. 1. Fig. 1 presents a side-by-side comparison of DTI and QBI across multiple cases. Each row corresponds to a different patient case, showcasing the DTI-based fiber tracking results on the left and the QBI-based fiber tracking outcomes on the right.

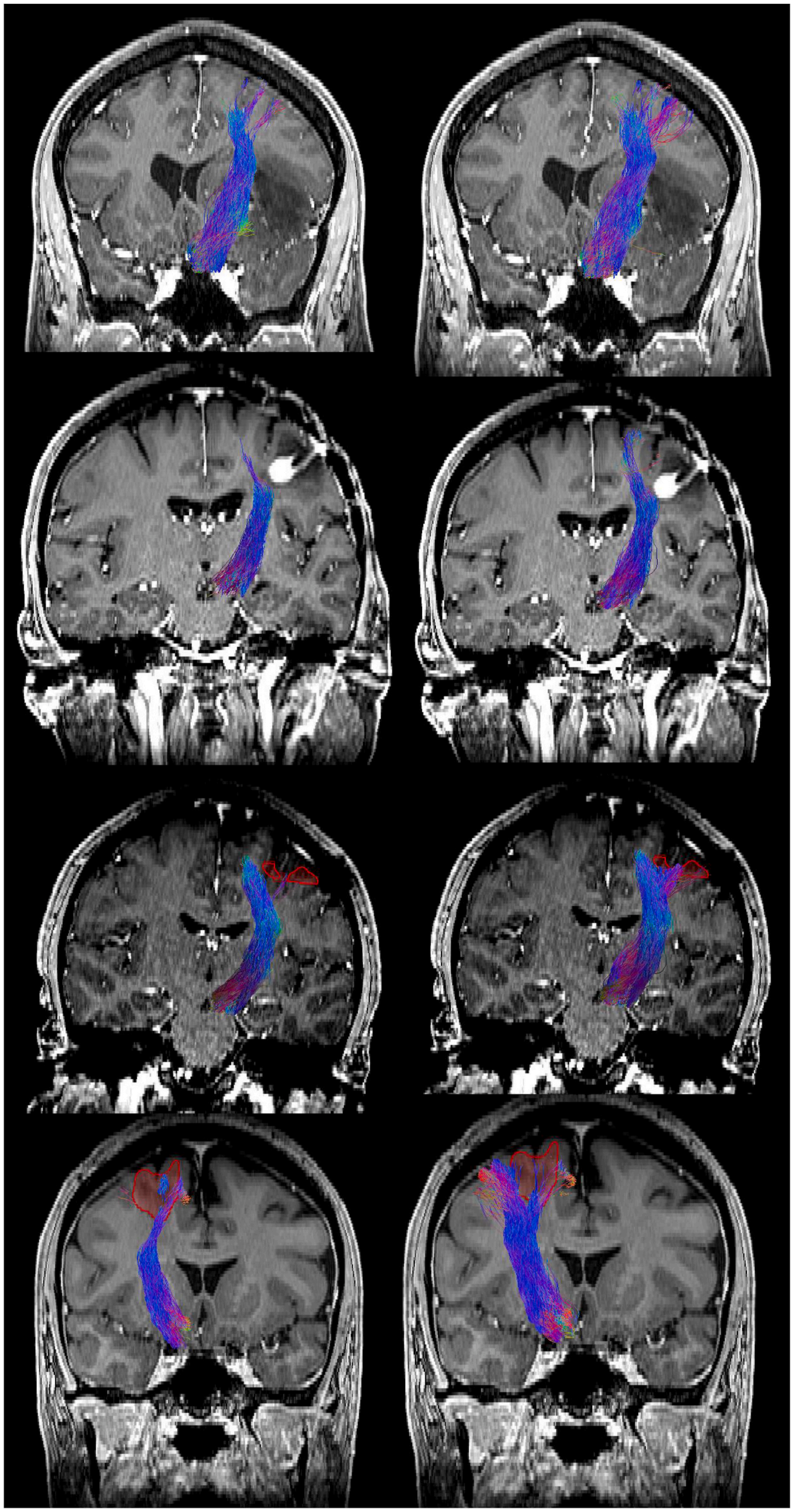

Fig. 2. Fig. 2 extends the visual comparison of imaging techniques with additional patient cases. Similar to Fig. 1, each row in Fig. 2 represents a different case, contrasting Diffusion Tensor Imaging (DTI) on the left with Q-ball Imaging (QBI) on the right for each patient.

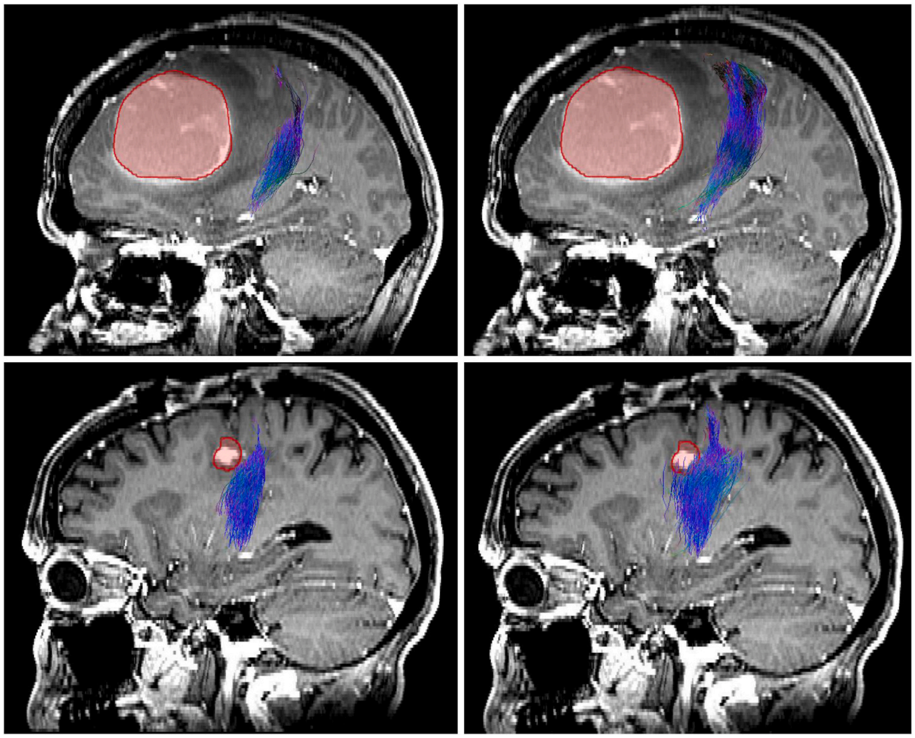

Fig. 3. Fig. 3 provides a detailed visualization of two distinct neurosurgical cases, each depicted with MRI T1-weighted images and corresponding fiber tractography outputs for both QBI and DTI.
First Row: Displays a sagittal view of a patient with a large frontal tumor. The fiber tractography of the CST is illustrated, with DTI results on the left and QBI results on the right.
Second Row: Features a coronal view of a patient with a smaller, cortical/subcortical tumor. The fiber tractography of the CST is illustrated, with DTI results on the left and QBI results on the right.

Table 2
Comparative Analysis of Patients With and Without motor deficits (MD) Regarding Tumor Location and Minimum Tumor Distance Determined by Fiber Tracking (FT) Techniques.

	No MD (n = 4)	MD (n = 4)	p
Nearest distance by QBI median, IQR (mm)	8.4 (3.9)	−0.4 (2.1)	**0.029**
Nearest distance by DTI, median, IQR (mm)	8.6 (3.5)	2.4 (4.8)	**0.031**
Volume, median, IQR (cm^3)	4.1 (4.1)	5.2 (4.0)	0.486
Edema volume, median, IQR (cm^3)	25.5 (16.1)	13.8 (44.0)	0.286
Location, n (%)			0.686
Precental	3 (75.0)	4 (100.0)	
Postcentral	1 (25.0)	0 (0.0)	
Deep seated tumors, n (%)	2 (50.0)	3 (75.0)	**0.053**
MGMT methylation, n (%)	2 (50.0)	2 (50.0)	0.285
Transcortical approach, n (%)	1 (25.0)	3 (75.0)	0.364

Bold p-values indicate significant results.

previous work, we demonstrated that QBI-FT surpasses DTI-FT in delineating CST near tumors, especially in terms of intra- and interrater reliability, achieving substantial agreement as opposed to the moderate agreement observed with DTI-FT (Lenga et al., 2023). This reinforces a broader consensus, as numerous studies (Bauer et al., 2013; Becker et al., 2020, 2022; Descoteaux et al., 2007; Kuhnt et al., 2013a, 2013b) have suggested the superior accuracy and safety margins of different HRFT models in FT delineation for neurosurgical procedures.

Our current findings align with these studies, underscoring that QBI-based FT might predict postoperative deficits more precisely than DTI-FT. This could be attributed to the intersection of CST fibers with the tumor, as indicated by the negative distance—a phenomenon not replicated in DTI-FT. These results further advocate for the adoption of representation techniques based on High Angular Resolution Diffusion Imaging (HARDI) signals, which, as outlined by Berman et al. (2008) and Bucci et al. (2013) offer significant advancements over traditional DTI-based FT. HARDI measures diffusion signals across 60 or more gradient directions, enabling, for instance, the resolution of intravoxel fiber crossings (Colon-Perez et al., 2016). However, it's crucial to acknowledge that QBI-based FT demands substantially more time than DTI and its integration into routine neurosurgical practice remains challenging, primarily due to the lengthy data processing and acquisition requirements.

According to the findings of our study, four patients exhibited a deteriorated motor function postoperatively, with one patient showing an aggravation of pre-existing MD. Notably, QBI models revealed that CST fibers either intersected or were attached to the tumors in these cases. One patient with preoperative MD had a large anaplastic astrocytoma grade II in the frontoparietal lobe, located within the CST according to QBI-FT. This pathology was not discernible using DTI-based fiber tracking, underscoring a critical limitation of this technique (Beppu et al., 2003). Furthermore, ongoing studies highlight the potential limitations of DTI caused by the molecular diagnosis of gliomas. The molecular characteristics of gliomas, such as IDH mutations and 1p/19q co-deletion, significantly influence DTI metrics like FA and MD. This variability can lead to inconsistent interpretations in DTI, impacting the accuracy of fiber tracking in gliomas with complex molecular profiles (Li et al., 2021). The inability of DTI to specifically differentiate tumor-infiltrated white matter from edema or healthy tissue presents considerable challenges in neurosurgical planning. Accurate delineation of tumor boundaries is crucial in glioma surgery to achieve maximum resection while preserving essential brain functions (Conti Nibali et al., 2019). In cases involving high-grade gliomas (HGGs), DTI falls short in providing a comprehensive visualization of the CST. This limitation has been addressed by the development of advanced techniques like multi-level fiber tracking (MLFT). MLFT has shown significant improvements in bundle reconstruction, offering higher radial extent and more complete coverage of the CST compared to conventional DTI methods (Zhylka et al., 2021).

In our study, accurately distinguishing peritumoral edema from tumor infiltration within the FLAIR hyperintense regions posed a significant challenge. This distinction is critical because it directly affects the accuracy of fiber tractography and the delineation of critical structures such as the corticospinal tract (CST). Conventional MRI sequences, including FLAIR imaging, often lack the specificity needed to reliably differentiate between vasogenic edema and infiltrative tumor tissue, particularly in low-grade gliomas where imaging characteristics can be remarkably similar (Kallenberg et al., 2013; Price et al., 2003). This ambiguity may have influenced our tractography results and surgical planning, potentially impacting patient outcomes. Advanced imaging techniques offer potential solutions to this problem. Diffusion tensor imaging (DTI) and diffusion-weighted imaging (DWI) provide microstructural information that can aid in distinguishing tumor infiltration from edema by analyzing parameters such as fractional anisotropy (FA) and apparent diffusion coefficient (ADC) values (Hoefnagels et al., 2014). Tumor infiltration typically disrupts normal white matter architecture, resulting in reduced FA and altered ADC values, whereas vasogenic edema may exhibit different diffusion properties. We did not rely on this information because of the low resolution and artifacts in selected brain regions of the diffusion-weighted sequences. Furthermore, perfusion-weighted imaging (PWI) and magnetic resonance spectroscopy (MRS) offer hemodynamic and metabolic insights, respectively, which can further differentiate tumor tissue from edema (Stadlbauer et al., 2007; Zhang et al., 2013). Integrating these advanced modalities into preoperative imaging protocols could enhance the precision of CST delineation and improve surgical planning by more accurately identifying tumor boundaries and infiltrative regions. This integration would enable more targeted resections while minimizing the risk to critical neural pathways, ultimately contributing to better neurological outcomes for patients. Future studies should consider combining Q-Ball High-Resolution Fiber Tractography with these advanced imaging techniques to address the limitations encountered in the current study and to further refine surgical strategies in glioma management.

In the postoperative assessment, four patients exhibited motor deficits, with variations in the duration and severity reflective of the underlying tumor pathology. The patient with glioblastoma, characterized by its aggressive infiltration into surrounding brain tissue, demonstrated permanent motor deficits. This aligns with findings that glioblastoma disrupts neuronal and glial architecture leading to sustained neurological impairment (Lago-Baldaia et al., 2020). In contrast, the patient with diffuse astrocytoma experienced transient motor deficits. This tumor phenotype is known for its diffuse infiltration, which can disrupt but not necessarily permanently damage local brain circuits, allowing for potential functional recovery post-surgical intervention (Smits et al., 2015). Similarly, the anaplastic astrocytoma patient displayed transient motor deficits, consistent with the tumor's intermediate aggressiveness and its potential for reversible brain tissue displacement upon effective resection (Facchini, 2020; Landers et al., 2023). Lastly, the motor deficits in the patient with oligodendroglioma were transient, corroborating studies indicating that oligodendrogliomas tend to displace rather than invade neural substrates, often resulting in a higher likelihood of recovery of function following surgical management (Bent, 2015; Landers et al., 2023). These cases illustrate the critical influence of tumor histological properties on postoperative neurological outcomes, underscoring the necessity for individualized surgical strategies to optimize functional prognosis.

7. Limitations

The main strength of the current study is that we are the first to examine the merits of DTI and QBI-based FT in presurgical planning for patients with lesions in the proximity to the CST. However, this study has some limitations. A relatively small cohort of patients was examined. It is impossible to make statistical robust statements on the influence of factors like MGMT or IDH on our FT-results in such a limited collective. This study was conducted as a proof-of-concept to assess the feasibility and potential advantages of Q-Ball HRFT in enhancing CST delineation near gliomas. Consequently, it was not structured as a randomized controlled trial (RCT), which is considered the gold standard for establishing the superiority of one method over another. The absence of an RCT is a limitation of our study, as it restricts the ability to draw definitive conclusions about the comparative efficacy of Q-Ball HRFT. This approach was influenced by several factors: ethical considerations against withholding a potentially superior imaging modality from a control group, challenges in recruiting a sufficiently large and homogeneous patient cohort due to the rarity and heterogeneity of gliomas affecting the CST, and the need to first establish preliminary feasibility and optimize imaging protocols for this novel technique. Future research involving larger, randomized studies is necessary to validate our findings and comprehensively evaluate the clinical benefits of Q-Ball HRFT in the surgical management of gliomas. Another limitation of our study is the small sample size, which may affect the generalizability of our findings. This was due to the selective use of the extended Q-Ball HRFT scanning protocol in specific cases where its benefits were most pronounced, ethical considerations regarding prolonged scanning times for patients, strict inclusion criteria focusing on those who would derive the most advantage from advanced imaging, and resource constraints related to specialized equipment and technical expertise. Future research with larger patient cohorts and expanded inclusion criteria is necessary to validate our preliminary results. We are planning to address these limitations by optimizing scanning protocols to reduce imaging times, thereby making it feasible to include a broader range of patients without compromising patient comfort or clinical efficiency. Additionally, due to the small sample size and the distribution of IDH mutation statuses in our cohort, we were unable to perform a comprehensive analysis of how IDH mutation status may have influenced surgical resection outcomes. Another limitation is the involvement of multiple surgeons in performing the procedures. Although all surgeons were highly experienced in glioma surgery and followed standardized protocols, variations in individual surgical technique and decision-making could introduce variability in patient outcomes. Consistency was maintained through adherence to institutional guidelines and regular team discussions; however, we acknowledge that individual differences cannot be entirely eliminated. Future research may benefit from a more controlled surgical environment or analysis of surgeon-specific outcomes to address this variability. Since this topic is still a subject of debate, we believe that our findings provide a real-world picture of the feasibility of both techniques, especially for the prediction of MD after resection of tumors in such deterrent areas. Overall, literature suggests acceptable results for CST-FT, when done with conventional DTI, as opposed to the results for other fiber bundles with a more complex neuroanatomical structure. If QBI-FT really fosters advantages over DTI-FT cannot be answered with the given results. However, our data increases potential and understanding of HRFT in the clinical setting. One of our further future objective is to collect additional patient data to enable a comprehensive evaluation of intraoperative subcortical stimulation outcomes. This data will be analyzed to stratify responses according to tumor type, enhancing our understanding of entity-specific neurophysiological impacts during surgery.

8. Conclusions

Our pilot study suggests that using QBI-based tractography may provide more comprehensive visualization of the corticospinal tract in cases where lesions are near the CST. While the longer data acquisition and post-processing times present challenges for practical application, QBI-based tractography shows potential as a complementary tool to standard DTI-based methods. Implementing QBI-based tractography could contribute to improved surgical planning, but further research with larger patient populations is necessary to evaluate its impact on preserving motor function and enhancing patient outcomes.

Human and animal ethics

Not applicable.

Data material availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Consent to participate

The requirement for informed consent was waived because of the retrospective nature of this study.

Ethics approval

This study was conducted in accordance with the Declaration of Helsinki and approved by the local ethics committee (S-880/2021).

Consent for publication

No individual person's data were included in this studymmc1.

Authors' contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Daniela Becker and Pavlina Lenga. The first draft of the manuscript was written by Pavlina Lenga and DB,RB,PN,JJ,MS,AU, SK commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Conflicts of interest

All authors declare that they have no conflicts of interest.

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