Blood oxygen-level dependent (BOLD) functional MR imaging (fMRI) is the most widely used noninvasive technique to identify the location of the cortical primary motor areas (PMA) preoperatively. The site of activation on magnetic resonance imaging (MRI) data and diffusion tensor (DT) tractography can be used to evaluate the spatial relationship between the hand and foot fibers of the CST and tumor borders.

**BACKGROUND AND PURPOSE:** Our goal was to improve the preoperative assessment of the corticospinal tract (CST) in patients with brain tumors. We investigated whether the integration of functional MR imaging (fMRI) data and diffusion tensor (DT) tractography can be used to evaluate the spatial relationship between the hand and foot fibers of the CST and tumor borders.

**MATERIALS AND METHODS:** We imaged 10 subjects: 1 healthy volunteer and 9 patients. Imaging consisted of a 3D T1-weighted sequence, a gradient-echo echo-planar imaging (EPI) sequence for fMRI, and a diffusion-weighted EPI sequence for DT tractography. DT tractography was initiated from a seed region of interest in the white matter subjacent to the maximal fMRI activity in the precentral cortex. The target region of interest was placed in the cerebral peduncle.

**RESULTS:** In the healthy volunteer, we successfully tracked hand, foot, and lip fibers bilaterally by using fMRI-based DT tractography. In all patients, we could track the hand fibers of the CST bilaterally. In 4 patients who also performed foot tapping, we could clearly distinguish hand and foot fibers. We were able to depict the displacement of hand and foot fibers by tumor and the course of fibers through areas of altered signal intensity.

**CONCLUSION:** Incorporating fMRI into DT tractography in the preoperative assessment of patients with brain tumors may provide additional information on the course of important white matter tracts and their relationship to the tumor. Only this approach allows a distinction between the CST components, while visualization of the CST is improved when fiber tracking is hampered by tumor (infiltration) or perifocal edema.

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Incorporating Functional MR Imaging into Diffusion Tensor Tractography in the Preoperative Assessment of the Corticospinal Tract in Patients with Brain Tumors

**ORIGINAL RESEARCH**

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fMRI activation areas as seed regions of interest for DT tractography yields useful preoperative information to evaluate the spatial relationship between the hand and foot fibers of the CST and the tumor borders.

Materials and Methods

Subjects

Ten subjects were included in this study. Table 1 presents the characteristics of the study subjects. To assess the feasibility of the study, we imaged 1 healthy volunteer. All other subjects (n = 9) were patients who required neurosurgery for an intracranial lesion. Eight patients were diagnosed with a primary intra-axial brain tumor, and 1 patient, with a symptomatic arteriovenous malformation. All patients were referred for preoperative assessment of the PMA and the CST. All brain lesions were located near the presumed location of the PMA and the CST. In all patients, neurosurgical excision of the intra-axial brain lesion was performed. Histopathologic examination confirmed the presence of a malignant tumor in 7 of the 8 patients with an expected malignancy. Clinical information on the patients’ pre- and postoperative neurologic status was obtained from medical records and neurosurgical reports. The volunteer study received institutional review board approval, and written informed consent was obtained. Ethics committee approval was not required for the clinical work-up of the patients or tumor.

MR Imaging Data Acquisition

Imaging was performed on a 1.5T scanner (Signa CV/I; GE Healthcare, Milwaukee, Wis). An 8-channel head coil was used for reception of the signal intensity. For anatomic reference, a high-resolution T1-weighted 3D fast radio-frequency spoiled gradient-recalled acquisition in the steady state with an inversion-recovery prepulse sequence was used (TR/TE/TI, 9.9/2.0/400 ms; parallel imaging [ASSET] acceleration factor, 2; matrix, 320 × 224; FOV, 24 cm; section thickness, 1.6 mm; 86 contiguous sections). Acquisition time was 3:10 minutes. For functional imaging, a T2*-weighted gradient-echo-planar imaging (EPI) sequence was used (TR/TE, 3000/40 ms; matrix, 64 × 96; FOV, 24 cm; section thickness, 3.5 mm; 35 contiguous sections). Acquisition time was 3:15 minutes per functional run, including 5 dummy scans that were discarded from analysis. The DTI sequence was a single-shot diffusion-weighted spin-echo EPI sequence (TR/TE, 8000/68.7 ms; applying parallel imaging [array special sensitivity encoding technique] with acceleration factor 2; matrix, 96 × 64; FOV, 21 cm; section thickness, 3.5 mm; 38 contiguous sections). Maximum b value was 1000 s/mm² in 25 noncollinear directions. Acquisition time was 3:44 minutes.

fMRI Stimulation Paradigm

The stimulation paradigm consisted of a blocked design of finger tapping, foot tapping, or lip pouting versus rest (30 seconds per block; 10 blocks per scanning session). Finger tapping was performed either with the right or the left hand separately or with both hands simultaneously and consisted of self-paced consecutive opposition of the thumb to each of the other fingers of the hand. Foot tapping was always performed with both feet simultaneously and consisted of self-paced dorsal and plantar flexion of the feet. The lip motor task consisted of self-paced repetitive lip pouting. Subjects were instructed to perform each of the tasks consciously and to limit head motion. During the rest condition, the subject was instructed to stop performing the task and to relax. Instructions “start” and “rest” were presented auditorily at the start of the active and rest conditions, respectively.

Table 1 gives an overview of the fMRI tasks performed by each subject. The choice of motor tasks to be performed by the subject was based on the location of the tumor and its presumed proximity to the PMA. Irrespective of tumor location, a finger-tapping task with real-time analysis is routinely performed at the start of each fMRI examination in our department, to enable assessment of possible limitations of the fMRI examination (eg, due to medication, poor comprehension/cooperation, and so forth). Each subject performed a minimum of 1 and a maximum of 5 tasks.

Table 1: Subject characteristics and fMRI tasks performed by each subject

| Subject | No./Sex/ Age | Pathologic Diagnosis | Preoperative | Postoperative | Type of Motor Task |
|---------|-------------|----------------------|--------------|--------------|--------------------|
| 1/F/27  | N/A         | N/A                  | N/A          | L, R         | Finger Tapping     |
| 2/F/42  | Anaplastic oligoastrocytoma | Severe left-sided hemiparesis | Unchanged | L, R         | Foot Tapping       |
| 3/M/56  | High-grade oligodendroglioma | Minor left-sided hemiparesis | Unchanged | L, R B       | Lip Pouting        |
| 4/F/55  | Anaplastic oligoastrocytoma | No deficit | Minor left-sided hemiparesis | L, R Y       |
| 5/F/48  | WHO grade II astrocytoma | Minor paresis, left hand | Additional minor paresis, left leg | L, R B       |
| 6/F/31  | Low-grade astrocytoma | No deficit | Subtle disturbances of fine motor skills, right hand | R |
| 7/M/44  | Low-grade oligodendroglioma | No deficit | No deficit | L, R |
| 8/F/42  | No certain pathologic diagnosis* | No defect | No defect | R B |
| 9/F/35  | Low-grade glioma | No deficit | Minor paresis, left hand | B B |
| 10/M/58 | Arteriovenous malformation | No deficit | No deficit | B Y |

Note: F indicates female; M, male; N/A, not applicable (healthy volunteer); B, task performed on both sides simultaneously; R, task performed with right body side; L, task performed with left body side; Y, task performed. WHO, World Health Organization.

*Possibly resolving ischemic infarction.
response function. A t-contrast was then calculated for the “active” minus the “rest” condition.

DTI data were processed and analyzed off-line. DT tractography was performed with the freely available software dTV for MR-DTI analysis (University of Tokyo Hospital, Tokyo, Japan) by using the fiber assignment by continuous tracking (FACT) method. Both the DTI and the fMRI data were loaded into the software package, which enabled us to perform seed region-of-interest selection driven by the locations of the coregistered fMRI activations.

To compare fiber tracking by means of this fMRI-based seed region-of-interest placement with the more conventional fiber tracking approach by using region-of-interest placement based on anatomic landmarks only, we performed DT tractography with these 2 approaches in all subjects.

For the fMRI-based approach, fiber tracking was initiated in both retrograde and antegrade directions from a manually selected freeform seed region of interest that was chosen in the white matter area immediately subjacent to the maximal fMRI activity in the precentral cortical gray matter. The entire cerebral peduncle was chosen as a target region of interest. For the conventional fiber tracking approach, a freeform seed region of interest was manually placed in the entire cerebral peduncle, from which fiber tracking was initiated in both retrograde and antegrade directions. The cerebral peduncle is an anatomically well-known and reliable location of the CST that was least likely to be influenced by potential mass effect of intra-axial lesions. For the conventional fiber-tracking approach, we chose not to use a target region of interest, placed, for example, in the internal capsule or PMA, because these areas were often displaced by the mass effect of the lesion, which would render region-of-interest placement unreliable. For both approaches, diffusion tensors, eigenvalues, and eigenvectors were computed from linearly interpolated diffusion tensor images at each iteration, and tracking was terminated when it reached given threshold values of fractional anisotropy (FA) and angle (60°) between consecutive vector lines. The FA threshold was by default 0.20, but it was lowered in cases in which no tract was visualized by using the default settings, because the FA values in the tract could be decreased by the edema and/or tumor infiltration. The tracked fibers were assessed in 3D by using multiple orthogonal projections overlaid on the high-resolution T1-weighted images, to determine their actual and apparent relationships to the brain tumor.

Results

Volunteer

In the healthy volunteer (subject 1), the PMA of the hand, foot, and lip on both sides was successfully established by fMRI. By using fMRI-driven seed regions of interest, we could clearly visualize and distinguish fiber tracts of the hand, foot, and lip on both sides (Fig 1A, -B). Each tract followed a distinct course through the corona radiata and internal capsule with hand fibers coursing anterior and lateral to foot fibers and lip fibers showing the most anterolateral trajectory (Fig 1B).

In contrast, when the conventional fiber tracking approach was used, the lip fibers were not visualized (Fig 1C). Also, the CST fibers were not visualized as far along their course toward the PMA as they were with the fMRI-based fiber tracking approach.

Patients

The PMA could be established with fMRI for all motor tasks of interest in all patients. Table 1 shows that all patients performed finger tapping on at least 1 side; additionally, 4 patients performed foot tapping and 3 patients performed lip pouting.

fMRI-Based DT Tractography Versus Conventional DT Tractography

In all 9 patients, we were able to track the hand fibers of the CST from all PMAs by using the fMRI-based seed region-of-interest approach. In the 4 patients who also performed foot tapping, we could make a clear distinction between the hand and foot fibers. Of the 3 patients who performed lip pouting, the corticobulbar fibers of the lip could be tracked by using fMRI-based seed regions of interest on both sides in 1 patient (subject 10) and on the nontumor side in the other 2 patients (subjects 2 and 4, images not shown).

With the conventional fiber tracking approach, lip fibers
were not visualized in any of the patients. The hand and foot fibers could not be distinguished within the internal capsule or corona radiata, nor could the CST fibers be visualized as far along their course toward the PMA as with the fMRI-based fiber-tracking approach. Furthermore, in 3 patients (subjects 2, 3, and 4), the CST fibers were markedly dispersed, scarce, and prematurely terminated in the hemisphere with the lesion, compared with the unaffected hemisphere (Fig 2).

**fMRI-Based DT Tractography and Clinical Correlates**

In 3 patients (subjects 2, 3, and 6), the PMA of the hand and/or foot as shown on fMRI was displaced by the tumor (Table 2). The tracked CST in these patients was also displaced compared with the other side (Fig 3). In 2 of these patients (subjects 2 and 3), functional neurologic deficit was present preoperatively (Table 1). All 3 patients underwent awake neurosurgical resection of the lesion, during which electroradiological mapping was performed, confirming the proximity of the lesion to the PMA in each case. Postoperatively, the functional neurologic status had remained unchanged in both patients with a pre-existing deficit. In 1 patient (subject 6), subtle disturbances of the fine motor skills of the right hand had developed after resection of the tumor that was located in close proximity to the PMA of the right hand.

In 2 patients (subjects 3 and 5), both the PMA and the CST were located in areas of decreased signal intensity on the T1-weighted images (due to perifocal edema or tumor infiltration, Fig 4). At conventional fiber tracking FA thresholds (0.20), these fiber tracts were not visible. Only by using a lower FA threshold could these tracts be visualized (Fig 5A–C). Both patients had preoperative neurologic deficits (Table 1), and in both patients, neurosurgical resection of the lesion aided by electroradiological stimulation was performed. The functional neurologic status had remained unchanged in 1 patient (subject 3). In the other patient (subject 5), a minor paresis of the left leg had developed postoperatively in addition to the pre-existing minor paresis of the left hand. As shown by DT tractography, the CST fibers of this patient’s left leg ran through an area of perifocal edema or tumor infiltration (Fig 5).

In 1 patient (subject 4), the PMA of the hand was at a considerable distance from the tumor. fMRI-based DT tractography in this patient, however, showed that the hand fibers ran adjacent to the tumor border. This patient, with no preexisting neurologic deficit, developed an ischemic stroke due to increased intracranial pressure postoperatively and was eventually left with a minor left-sided hemiparesis (Table 1). Intraoperative electric mapping had not indicated proximity of the tumor to eloquent brain regions.

In 4 patients (subjects 7–10), both the PMA and the tracked fibers showed no relation to the tumor border, though in 3 of these patients (subjects 7, 8, and 9), the lesion was in close proximity to the supplementary motor area. In these 3 patients, electroradiological mapping was performed intraoperatively, whereas in the remaining patient (subject 10), the lesion was neurosurgically resected with the patient under general anesthesia (ie, without electroradiological mapping). All of these patients were neurologically intact preoperatively. In 1 patient (subject 9), minor paresis of the left hand had developed postoperatively (Table 1).

**Discussion**

We showed that incorporating the fMRI-assessed information on cortical activation areas into DT tractography for fiber tracking of the motor tracts is feasible not only in the healthy brain but also when intra-axial lesions are present. In the preoperative assessment of patients with brain tumors, this can provide essential information not only on the location of eloquent cortical areas but also on the course of important subcortical white matter tracts. This information cannot be obtained from conventional anatomic MR imaging or from conventional DT tractography based on anatomic landmarks.

The integration of both high-resolution anatomic (T1-weighted) data with fMRI data in the fiber-tracking procedure makes an evaluation of the spatial relationship between tracked fibers and tumor borders possible. Also, this coregistration of anatomic, functional, and DTI data facilitates the potential intraoperative use of the data, for example in devices for stereotactic surgical navigation.

In contrast to intraoperative cortical mapping, the electric stimulation of the subcortical white matter during surgery is not very successful for reliably identifying functional white matter tracts. Also, in deep subcortical tumors, the normal position of the PMA may be preserved, whereas only the CST or a few fiber bundles of the CST may be displaced. In such cases, the PMA cannot be used as a landmark for the CST. Therefore, a method to noninvasively visualize the important fiber tracts and their subcomponents would be of great benefit for presurgical planning and guiding the operative procedure. We showed that tracking of the CST directly from the fMRI activation area can be used to visualize and distinguish the different components of the CST, especially the hand and foot fibers. In a healthy volunteer, the presented method showed that the tracked hand, foot, and lip fibers follow a distinct course, the foot fibers coursing postero-medially to the hand fibers within the posterior limb of the internal capsule (PLIC). This distribution within the corticospinal tract confirmed previous findings by Holodny et al, who also studied the CST by using DT tractography and found the same location and internal organization of the separate CST components within the PLIC. Both our study and that of Holodny
et al indicate that the hand and foot fibers are organized along the short (left-right) axis of the PLIC, rather than along the long (anteroposterior) axis of the PLIC, as has been previously assumed.30

In patients with a brain tumor, the (deviated) course of the white matter tract and its relationship to the tumor may be depicted by our integrated fMRI–DT tractography method. This is extremely useful in cases in which the PMA is located away from the tumor, but the CST runs closely by the tumor area. We showed that tracking the CST based only on anatomic landmarks may not be sufficient to visualize reliably the CST and that fMRI-based seed region-of-interest placement may be necessary to visualize the CST in its entirety. With fMRI-based DT tractography, the CST fibers could be followed farther along their course toward the PMA than when DT tractography was performed on the basis of anatomic landmarks only. Furthermore, DT tractography of the CST was seen to be hampered in cases of anatomic distortion due to a mass effect of the lesion or in cases of altered diffusivity due to tumor infiltration or perifocal edema in the region of the CST. Tracking improved when the fMRI-based seed region-of-interest approach was used, thus providing more reliable preoperative information.

Recently, other authors have described methods to combine the information on functional cortical areas assessed by fMRI with information on the course of the CST as visualized by DT tractography.20,22,31-33 However, to our knowledge, only 2 studies used a real fMRI-based seed region-of-interest selection procedure for fiber tracking, and these were limited only to identifying the hand fibers within the CST.20,31 Not only have we identified the hand fibers but our method was also successful in distinguishing other fibers both in a healthy volunteer and in patients with tumor, by using fMRI-based region-of-interest selection. This distinction may provide additional presurgical information, in particular allowing a more specific risk estimate before neurosurgical resection of a lesion as well as guiding electric stimulation of the subcortical white matter intraoperatively. Within the CST, the hand and foot fibers run together, such that they are indistinguishable with DT tractography without the placement of a region of interest in a location specific to each of these fibers.16 Although the known somatotopic distribution within the precentral gyrus may allow specific region-of-interest placement in the PMAs

Table 2: Overview of the most important findings by fMRI and DT tractography in each subject

| No. | PMA on fMRI | Fiber Tracts on fMRI-Driven DT Tractography |
|-----|-------------|--------------------------------------------|
| 1   | Healthy volunteer: PMAs of hand, foot, and lip on both sides at known anatomic position | Hand, foot, and lip fibers on both sides at known anatomic position |
| 2   | PMA of hand displaced laterally and caudally by tumor | Hand fibers on tumor side displaced compared with healthy side, visualization of lip fibers only on healthy side |
| 3   | PMA of hand and foot displaced by tumor and in area of decreased signal intensity on T1WI | Hand and foot fibers displaced on tumor side, run through area of altered signal intensity on T1WI |
| 4   | PMA at distance from lesion | Hand fibers run very close to tumor border, lip fibers visualized only on healthy side |
| 5   | PMA of hand and foot in area of altered signal intensity on T1WI, near tumors | Hand fibers normal course, foot fibers run through area of altered signal intensity on T1WI, close to tumor |
| 6   | PMA of hand displaced cranially and dorsally | Hand fibers displaced by tumor |
| 7   | PMA not displaced and not related to tumor border | Hand fibers not displaced |
| 8   | PMA not displaced and not related to tumor border | Hand and foot fibers not displaced |
| 9   | PMA not displaced and not related to tumor border | Hand and foot fibers not displaced |
| 10  | PMA not displaced and not related to AVM border | Hand fibers not displaced, visualization of lip fibers on both sides |

Note:—T1WI indicates T1-weighted images; AVM, arteriovenous malformation.

Fig 3. Orthogonal axial/sagittal projection of a T1-weighted MR image with overprojection of the hand PMA and the hand fibers of the CST. In this patient, the left PMA, as shown by fMRI (in orange-yellow), was displaced by tumor, as was the tracked CST (in green).

Fig 4. Axial T1-weighted MR image with fiber tracts projected in color (red and green for the right and left hemispheres, respectively). In this patient, hand fibers ran through an area of altered signal intensity, due to edema or tumor infiltration.
of the hand or the foot in healthy volunteers based on structural anatomic images only, distortion by a mass effect of the lesion renders this approach unreliable in patients with brain tumor. With fMRI, the PMAs are accurately identified and this information allows reliable region-of-interest placement in the hand and foot PMAs within the precentral gyrus. The possibility of distinguishing the hand and foot fibers within the CST is not only relevant in the preoperative assessment of patients with brain tumors but could also be extended to other clinical situations, for example, for planning functional neurosurgery in patients with Parkinson disease and related disorders.

A further strength of our study lies in the clinical applicability of our protocol. The DTI sequence that we used is clinically feasible, with an acquisition time of only 3:44 minutes. Standard presurgical clinical fMRI examinations in patients with brain tumors usually take approximately 20–30 minutes for a protocol consisting of 3–4 motor tasks, including an anatomic T1-weighted scan. The addition of a short DTI sequence takes relatively little time, does not require active patient participation, and may yield important additional information.

Several limitations, however, need to be considered. First, we performed the fMRI and DT tractography combined method in only 1 healthy volunteer and 9 patients. Although this is a limited number of subjects, the fact that the method was successful in distinguishing hand and foot fibers in all cases attests to its robustness and demonstrates its validity for subjects with variable tumor size and location.

Second, we could not identify all lip fibers on the tumor side in the subjects who performed lip pouting. Previous studies suggest that fiber tracking of the motor tracts is inadequate in the lateral portions of the corticobulbar/spinal tract such as the mouth and tongue fiber tracts, and that these tracts can, therefore, not be successfully mapped by DT tractography. Holodny et al reported that the corticobulbar tract (CBT) is probably too small to trace because when fibers cross, the fiber tracking algorithm will preferentially track the larger tract (ie, the CST or the longitudinal fasciculus). However, Thomas et al successfully tracked the CBT in 5 patients with hemiparetic cerebral palsy in both hemispheres, by placing regions of interest in the internal capsule and in the cerebral peduncle and pons and by optimizing the angular deflection threshold.

Although not successful in all patients on the tumor side, our results in a healthy volunteer and 3 patients also demonstrate that tracking of lip fibers is feasible. One possible explanation for the fact that we succeeded in tracking the CBT in our subjects is that we chose a specific region of interest on the basis of the fMRI activation in the cortex and did not track from a region of interest placed in the cerebral peduncle.

As mentioned previously, the single tensor-fitting algorithm often fails at major fiber crossings due to intravoxel averaging of tensor direction. fMRI-based seed region-of-interest placement in itself does not eliminate this problem. However, the main problem with tracking the CBT lies in the fact that it runs together with the CST until it takes a relatively sharp turn at the level just dorsal to the internal capsule. Not only will FA values be reduced at the point where the 2 tracts branch (due to intravoxel tensor direction averaging) but also has the CBT branch a sharply deflecting course. Both of these issues may cause the single tensor-fitting algorithm to fail when one attempts to track the CBT from a seed region of interest placed in the cerebral peduncle, for instance, because intravoxel tensor-direction averaging will favor the course of the larger CST and angle deflection is restricted within, for example, the FACT algorithm. The branching problem is much more easily handled by merging 2 lines instead of splitting a line into 2. In the case of tracking the CBT, merging 2 lines is achieved by initiating fiber tracking of the CBT from a seed region of interest in the primary motor area of the lip, while further constraining its course by a target region of interest in the cerebral peduncle. Our findings demonstrate that the visualization of motor tract components other than hand and foot fibers is possible when basing it on fMRI activation areas.

The inability of the tracking algorithm to detect lip fibers in the tumor hemisphere of 2 patients may reflect the interaction of at least 2 complications. First, fiber tracking is dependent on the diffusion characteristics of the white matter tracts, which will inevitably change during lesion formation (see next paragraph), either due to underlying physiologic change or separation of fiber bundles resulting in enhanced partial volume effects. Second, it is possible that the lip fibers were deviated by

Fig 5. Axial T1-weighted MR images with foot fibers projected in color. Fibers pass through an area of altered signal intensity on T1-weighted images. Varying the FA thresholds for fiber tracking in this patient had a considerable influence on the fibers depicted (A–C, FA thresholds used are shown in each image).
the tumor in such a way that they ran at too sharp an angle to be tracked by the algorithm used here.

Tracking results were found to vary according to the FA threshold. Edema and tumor infiltration typically cause reduction of the FA measured in these voxels.\textsuperscript{23,34} This can cause significant problems in fiber tracking, with fibers terminating prematurely due to crossing the chosen minimal FA threshold.\textsuperscript{20} The optimal tractability threshold of FA for DT tractography of the CST is commonly considered to be around 0.20.\textsuperscript{10} However, this number was derived from patients with stroke and motor deficits, who only showed minor decrease in FA in the affected CST. Lowering the FA threshold for fiber tracking, on the other hand, is expected to introduce erroneous false-positive fiber tracts, in particular when only 1 seed region of interest is used.\textsuperscript{1,14,40} With multiple regions of interest such as we used, the amount of false-positive fiber tracts is reduced by constraining the tract reconstruction,\textsuperscript{14} which makes lowering of FA thresholds, in cases of changed diffusivity due to perifocal edema or tumor infiltration, possible without introducing many erroneous tracts. We show that DT tractography in patients with tumor in a clinical setting needs to be customized because the area of the CST may be edematous or infiltrated by tumor; thus, an FA termination threshold that is set too high may lead to failure of fiber tracking (Fig 4). Specific fMRI-based region-of-interest placement, such as we propose, provides additional a priori information for the tracking and subsequent visualization of the course of the tract and, therefore, facilitates decreasing the FA threshold when required.

The impact of using the proposed integration of fMRI and DT tractography on clinical practice was not formally assessed. Studies formally assessing the impact of implementation of fMRI alone in clinical practice are still scarce,\textsuperscript{41,42} and as far as we are aware, none discuss the integration of fMRI and DT tractography in the preoperative assessment of patients with brain tumors. In fact, the combined use of fMRI and DTI tractography to optimize the presurgical assessment of the cortical motor areas and subcortical white matter tracts in patients with brain tumors. fMRI-based DT tractography is superior to DT tractography on the basis of anatomic landmarks alone, because only with fMRI-based DT tractography is a distinction between the several components of the CST possible. Furthermore, it allows decreasing the FA threshold if necessary and provides an improved visualization of the CST, in particular when fiber tracking is hampered by the presence of tumor or perifocal edema.

**Conclusion**

We propose a clinically feasible protocol of integrating fMRI and DT tractography to optimize the presurgical assessment of the cortical motor areas and subcortical white matter tracts in patients with brain tumors. fMRI-based DT tractography is superior to DT tractography on the basis of anatomical landmarks alone, because only with fMRI-based DT tractography is a distinction between the several components of the CST possible. Furthermore, it allows decreasing the FA threshold if necessary and provides an improved visualization of the CST, in particular when fiber tracking is hampered by the presence of tumor or perifocal edema.

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