Pre- and Intraoperative Tractographic Evaluation of Corticospinal Tract Shift

Andrea Romano, MD*§
Giancarlo D'Andrea, MD‡
Luigi Fausto Calabria, MD*
Valeria Coppola, MD*
Camilla Rossi Espagnet, MD*
Alberto Pierallini, MD§
Luigi Ferrante, MD‡
Luigi Fantozzi, MD*
Alessandro Bozzao, MD*

Departments of *Neuroradiology and ‡Neurosurgery, S. Andrea Hospital, University Sapienza, Rome, Italy; §IRCCS, San Raffaele, Pisana, Rome, Italy

Correspondence:
Andrea Romano, MD,
Department of Neuroradiology,
S. Andrea Hospital,
University Sapienza,
Via di Grottarossa 1035,
00189 Rome, Italy.
E-mail: andrea.romano@uniroma1.it

Received, March 3, 2010.
Accepted, February 16, 2011.
Published Online, April 5, 2011.

BACKGROUND: Magnetic resonance with diffusion tensor image (DTI) may be able to estimate trajectories compatible with subcortical tracts close to brain lesions. A limit of DTI is brain shifting (movement of the brain after dural opening and tumor resection).

OBJECTIVE: To calculate the brain shift of trajectories compatible with the corticospinal tract (CST) in patients undergoing glioma resection and predict the shift directions of CST.

METHODS: DTI was acquired in 20 patients and carried out through 12 noncollinear directions. Dedicated software "merged" all sequences acquired with tractographic processing and the whole dataset was sent to the neuronavigation system. Preoperative, after dural opening (in 11) and tumor resection (in all) DTI acquisitions were performed to evaluate CST shifting. The extent of shifting was considered as the maximum distance between the preoperative and intraoperative contours of the trajectories.

RESULTS: An outward shift of CST was observed in 8 patients and an inward shift in 10 patients during surgery. In the remaining 2 patients, no intraoperative displacement was detected. Only peritumoral edema showed a statistically significant correlation with the amount of shift. In those patients in which DTI was acquired after dural opening as well (11 patients), an outward shifting of CST was evident in that phase.

CONCLUSION: The use of intraoperative DTI demonstrated brain shifting of the CST. DTI evaluation of white matter tracts can be used during surgical procedures only if updated with intraoperative acquisitions.

KEY WORDS: Brain shift, Cortical spinal tract, Diffusion tensor imaging, Dural opening, Presurgical planning, Tractography

Neurosurgery 69:696–705, 2011 DOI: 10.1227/NEU.0b013e31821a8555 www.neurosurgery-online.com

The goal of neurosurgery in the management of brain tumors is to obtain maximal resection with preservation of normal tissue and functions.[1,2] This is particularly important when dealing with "eloquent" brain areas located in the cortex and with the subcortical white matter tracts. It was recently proposed that white matter tracts can be evaluated with diffusion tensor image (DTI) technology, an magnetic resonance (MR) sequence that estimates trajectories compatible with subcortical tracts,[3-8] also in patients affected by brain lesions.[9-11] Moreover, DTI images can be integrated into a neuronavigation system,[12,13] allowing the neurosurgeon to remove a brain lesion while trying to preserve those tracts located in its proximity.

ABBREVIATION: CST, corticospinal tract; **DTI,** diffusion tensor image; **FoV,** field of view; **TE,** time to echo; **TR,** time to repetition

The results of DTI fiber tracking are influenced by the effects of the tumor on the adjacent tissues by infiltration, displacement, or perilesional edema.[14] Other limitations can include the low signal-to-noise ratio, the inability to identify the direction of the fibers, the software used to reconstruct the fibers, which is not standardized yet,[15,16] and operator experience in the process of fiber reconstruction. Another limitation is caused by brain shift[17,18] as the movement of the brain during surgical intervention, especially while opening the dura mater and after tumor resection.

The direction of brain shift depends on many factors: the side of the craniotomy, gravity, and the pressure of the brain mass and of the edema.[19-22]

Using intraoperative MR, it is possible to visualize brain shift, allowing the neurosurgeon to upload newly acquired MR DTI images to the neuronavigation system during surgical procedures, defining new margins of resection. Our hypothesis is that corticospinal tract trajectories, as assessed by DTI, may undergo significant movements during surgical procedures, and that by acquiring pre- and intraoperative DTI images, this shift could be precisely detected. For these reasons the aims of our study were the following: to calculate and define the brain shift of trajectories compatible with the corticospinal tract in patients undergoing glioma resection by using intraoperative MR at different steps in the surgical procedure, and to predict direction of shift of the same tract on the basis of several parameters (craniotomy size, volume of the tumor and edema, and depth of the lesion from the surface of the brain).

METHODS

Patient Population

The data were prospectively acquired from January to December 2009. DTI was acquired in 20 patients (5 female patients, 15 male patients; age range, 35-78 years; mean age, 49.1 years). All patients underwent surgical resection of cerebral tumors. Pathological examination revealed gliomas in all cases (World Health Organization grade II glioma, 1 patient; grade III glioma, 4 patients; grade IV glioma, 15 patients). Clinical conditions pre- and postoperatively were evaluated by a neurologist. The ethical committee of our hospital approved the study, and a signed informed consent was signed by each patient.

Preoperative MRI Study Protocol

In our Department of Neuroradiology, the preoperative MRI study protocol aims at characterizing the lesion and highlighting its relationship with the surrounding structures.

All MRI examinations were performed on a 1.5-T magnet (Magnetom Sonata, Siemens AG, Medical Solutions, Erlangen, Germany). T2-weighted sequences (time to echo [TE]/time to repetition [TR] = 105/2200 ms; matrix = 157 × 320; field of view [FoV] = 250 mm; slice thickness = 5 mm), fluid-attenuated inversion recovery sequences (TE/TR/inversion time = 125/10 000/2005 ms, matrix = 144 × 256, FoV = 250 mm, slice thickness = 5 mm), and isotropic volumetric magnetization-prepared rapid gradient echo T1-weighted sequences (TR/TE = 4.38/1780 ms; matrix = 256 × 256; FoV = 250 mm; slice thickness = 1 mm) were acquired before and after intravenous administration of paramagnetic contrast medium and 6 motion-probing gradient directions. The DTI study was carried out through 12 noncollinear directions (b value = 0 and 1000 s/mm^2) with echo-planar sequences (TE/TR = 92/9400 ms, matrix = 128 × 128, FoV = 230 mm, slice thickness = 1.9 mm, bandwidth = 1502 Hz/pixel, slices = 60, no gap, acquisition time = 6.18 min, 3 NEX [number of excitations]).

The tractography processing was carried out by planning software iPlan 2.6 (BrainLAB AG, Feldkichen, Germany). The corticospinal tract was chosen in our study because of its deep location, reduced sensitivity to artifacts derived from opening the skull, and fixation pins. Color maps were utilized to define an appropriate region of interest (ROI) for the following tractographic procedure. The fiber-tracking technique contemplates the 3D reconstruction of white matter trajectories of corticospinal tract (CST) by using a fractional anisotropy threshold of 0.17 and a processing angle above 55°. The posterior arm of the internal capsule and precentral gyrus identified by functional MRI for the pyramidal tract were chosen as the site of the positioning of the ROIs (always using the same size of ROI: 50 pixels). Tracking was initiated in both the retrograde and orthograde directions according to the direction of the principal eigenvector in each voxel of the region of interest. The trajectories reconstructed were transformed into tridimensional objects. Compared with the previously reconstructed trajectories, the outer margins of these objects were automatically enlarged by the software by 2 mm in every direction (Figure 1). Dilating the 3D reconstructed trajectories allowed registration errors to be minimized (usually below 3 mm) and a safer margin for surgery to be introduced. Tractographic processing was performed by the same operator.

The trajectories were considered suitable for the surgical planning if there were no interruptions on any of the layers at the level of the lesion.

All tractography results were saved in a file that included *x*/*y*/*z* coordinates for each tract. These data were imported (together with b = 0 diffusion images) into the navigation software (iPlan 2.6, BrainLAB AG, Feldkichen, Germany). After rigid registration of b = 0 images with a volumetric anatomical dataset and after ensuring data consistency (discrepancies ≤3 mm) in the tumor area, trajectory reconstructions can be visualized within anatomical images. The margins of the fiber are then segmented to permit their definition as "objects" within the neuronavigation system and their visualization during surgery. This processing is usually performed the day before the procedure and takes approximately half an hour.

Preoperative MRI Evaluation in the Brain Suite

To facilitate MRI data registration in the neuronavigation system, a multichannel head coil—incorporating stereotactic "markers" (supplied by BrainLAB) that are "read" by the neuronavigation infrared camera—was used. The automatic image registration software "merged" the acquired images with tractographic processing and the whole dataset was sent to the neuronavigation system.

In the Brain Suite (equipped with the same MR unit as was used for standard preoperative imaging), volumetric, isotropic T1-weighted images were acquired, with the same characteristics to those previously obtained except without the administration of paramagnetic contrast medium. These sequences represent the "baseline" for the subsequent merging with preoperative images and are aimed at the identification of the markers.

The total acquisition time of presurgery images for operating theater planning is therefore very limited, approximately less than 10 minutes. Tractographic reassessment required during the neurosurgical procedure (for a reevaluation of the tumoral margins with respect to specific myelinated fibers) was repeated (with the same sequence parameters and identical MRI equipment by the same operator that performed the presurgical planning) and resent to the neuronavigation system to update the anatomical parameters. In 11 of 20 patients, DTI data were also acquired after dural opening and before tumor removal. These data were used to update the neuronavigation system and used for continued surgery and further resection of the tumor.

Brain Shift Evaluation

Pre-, intraoperative, and if acquired after dura mater opening DTI were registered with automatic image fusion software (iPlan 2.6, BrainLAB AG,

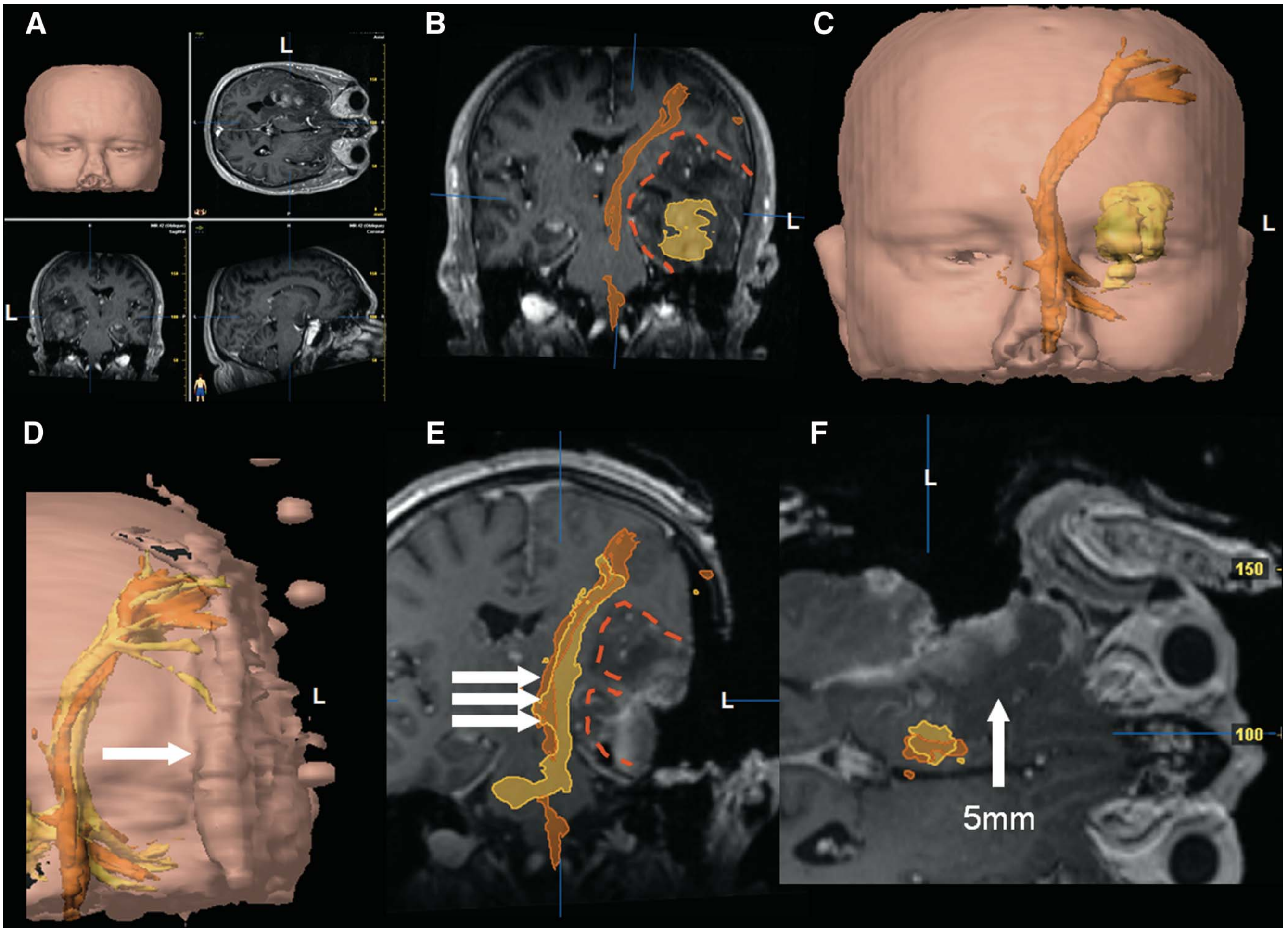

FIGURE 1. *Outward brain shifting. Patient 15: Left temporobasal lobe glioblastoma multiforme (***A***). In* **B** *and* **C***, the indirect mass effect of tumor due to the peritumoral edema (red dotted) on the corticospinal tract (orange) dislocated medially is evident. After tumor resection, an outward shifting (arrows) of corticospinal tract (yellow) is noted (***D–F***). There is no greater collapse of the surgical cavity due to the presence of residual share of peritumoral edema (***E***, red dotted).*

Feldkichen, Germany), which is used to perform semiautomatic rigid registration. After registration, the images could be displayed side by side or in an overlay mode. The extent of shifting was considered as the maximum distance between the preoperative and intraoperative contours of the trajectories of CST on identical/registered axial slices where the shift was considered to be maximum. Positive or negative values were assigned according to the direction of the shift, with reference to the craniotomy opening. A positive value was assigned if movement was outward (toward the surface), and negative value was assigned if movement was inward. Shifting of the CST was always considered in relationship to preoperative data. Although DTI was acquired in all patients after tumor resection, it was evaluated after dural opening and before tumor resection only in 11 patients. Because DTI acquisition increases surgical time, we decided to collect these data only in those patients in which dural opening determined a visible change of brain position. This was decided by the neurosurgeon and neuroradiologist.

Peritumoral edema and tumor volume were measured using the same software as for planning. The software has a tool that calculates the volume by using a threshold of signal intensity. The craniotomy size and the distance of the tumor from the cortical surface were calculated using the same software as well. Linear regressions, receiver operating characteristic curve, and independent sample *t* test among tumoral parameters and CST shift were obtained.

RESULTS

Preoperative and intraoperative DTI-based fiber tracking were technically feasible in all patients. The integration of tractographic data into the volumetric dataset for neuronavigation was technically possible in all cases. In the areas of interest (areas of anatomical relationship between the trajectory and the tumor), there was correspondence between b = 0 and 3D images, with a deviation that never exceeded 3 mm. This deviation had a tendency to increase in more cranial and caudal cerebral portions that, however, did not interfere with the aim of our study. Table 1 summarizes the general data of the patients, volume, location of the tumor, volume of peritumoral edema, and craniotomy size.

An outward shift was observed during surgery in 8 patients (40%) (Figure 1), and an inward shift was observed during surgery in 10 patients (50%) (Figure 2). In the remaining 2 patients (10%), no intraoperative displacement was detected (Table 2).

The maximum intraoperative shifting of the CST ranged from an inward of 9.7 mm (5.2 ± 2.5 mm; mean ± standard deviation) to an outward of 11 mm (5.5 ± 2.4 mm; mean ± standard deviation).

Only peritumoral edema showed a statistically significant correlation in the amount of shift ($P = .001$; Spearman correlation), with an R value of 0.691 (Figure 3), indicating a more pronounced outward shift in those patients with larger edema.

In a comparison of patients showing inward and outward shifting, statistically significant differences were evident. Peritumoral edema was more pronounced in patients with outward shifting ($P < .001$), as well as the craniotomy size ($P = .038$) (Table 3). No statistically significant differences were evident when comparing the tumor sizes between 2 groups.

A shift of 2.5 mm was obtained with a sensitivity of 100% and a specificity of 80% in the presence of a median value of peritumoral edema of 42 mL and a sensitivity of 100% and a specificity of 66% in the presence of a median craniotomy size of 57 mm (Figure 4).

In 11 patients (Table 2) DTI also was acquired after dura mater opening (shift range from −7 to +8 mm) (Figure 5). In the greater part of the group, an outward shifting was evident (7 patients). A direct correlation was evident between craniotomy size and shifting after dura mater opening ($P = .05$, $R = 0.69$) (Table 4). Eighteen of 20 patients were affected by motor deficits in the preoperative phase.

No patients showed new symptoms in the postoperative phase; 15 of 20 patients demonstrated a clinical improvement.

DISCUSSION

Diffusion tensor imaging is an MR technique introduced several years ago, but its clinical use in neurosurgery is still limited. The main problems are related to the experience needed for reconstructing trajectories of white matter tracts (introducing an operator-dependent bias) and to continuous software evolution with use of different probabilistic or deterministic algorithms. In addition, technical difficulties arise from cerebral tumor modification induced on the adjacent white matter tracts (mass effect and fractional anisotropy modification due to peritumoral edema) and from the intraoperative evaluation of white matter tracts. In particular, although color-coded fractional anisotropy is usually a technique to visualize fiber tracts, the color of each tract can be

TABLE 1. General Data

Patient	Sex	Tumor, WHO Grade	Location	Tumor Volume, mL	Peritumoral Edema Volume, mL	Craniotomy Size, mm	Tumor Depth, mm
1	M	IV	Right temporobasal lobe	10	49	57	16
2	F	IV	Right temporobasal lobe	79	52	56	0
3	F	IV	Left temporobasal lobe	11	65	54	0
4	M	IV	Left temporobasal lobe	95	26	86	0
5	M	IV	Right temporal lobe	19	7	42	10
6	M	IV	Right temporobasal lobe	40	80	70	25
7	M	IV	Right temporoparietal lobe	70	78	64	0
8	M	IV	Left temporobasal lobe	18	121	32	0
9	M	IV	Left temporobasal lobe	15	40	53	0
10	F	IV	Right occipitoparietal lobe	27	91	60	6
11	M	III	Left frontal lobe	81	26	42	0
12	M	IV	Left temporobasal lobe	20	109	93	23
13	F	IV	Left frontotemporal lobe	113	143	82	0
14	M	II	Right frontal lobe	27	19	49	0
15	M	IV	Left temporobasal lobe	16	44	59	16
16	M	III	Right temporobasal lobe	149	0	58	17
17	M	III	Left temporobasal lobe	17	0	52	30
18	M	III	Right basal ganglia	12	0	51	24
19	F	IV	Right temporobasal lobe	21	38	68	24
20	M	IV	Left temporoinsular lobe	4	0	66	0

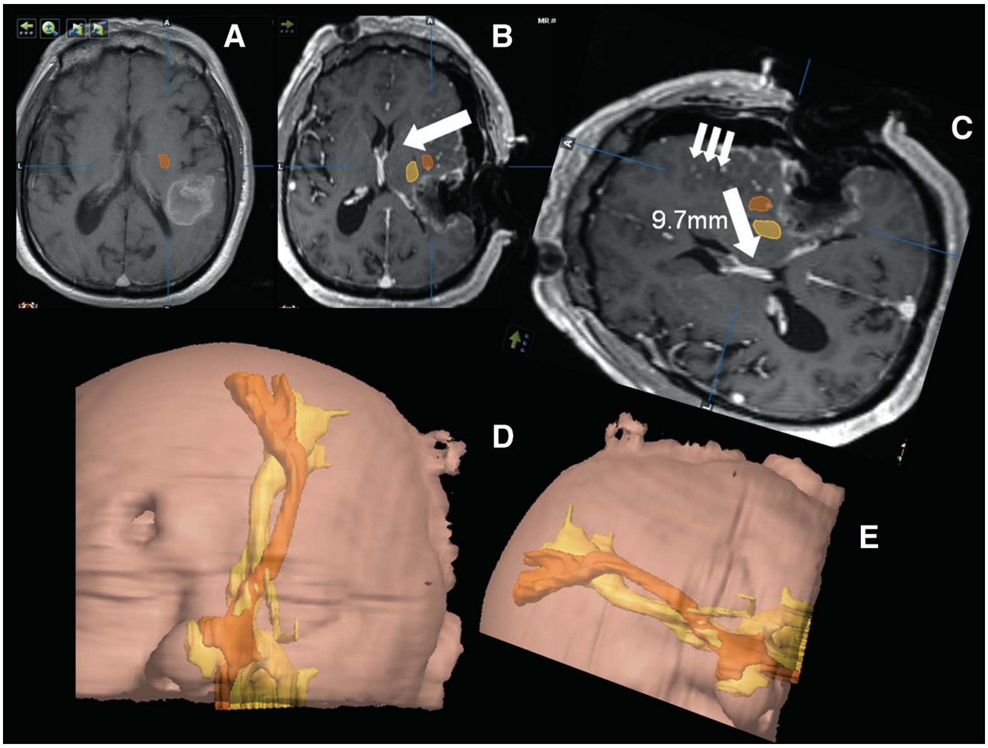

FIGURE 2. *Inward brain shifting. Patient 5: Right temporal lobe glioblastoma multiforme. No significant share of peritumoral edema or lesion mass effect on corticospinal tract (orange) is evident (***A***). After tumor resection, a significant inward shifting (arrows) of corticospinal tract (yellow) is noted (***B–E***).* **C** *and* **E** *are aligned in the direction of gravity. The overhanging surface collapses into the cavity and the midline is deformed toward the contralateral side. The new position of the corticospinal tract is located close to the surgical cavity (***B*** *and* **C***).*

abnormal in the intraoperative color code fractional anisotropy, and may appear disorientated because the patient's head is usually fixed facing to the right or left, depending on the position of the lesion.[23] Artifacts deriving from the opening of the skull and fixation pins may also cause image distortions on echoplanar images.[23,24] Despite this, Nimsky et al[24] reported that no major image distortion occurred in areas of interest near the resection of the tumor border; in confirmation of this assessment, DTI-based fiber tracking was technically feasible in all our patients.

It was recently assessed that MR tractography may impact surgical planning, leading to changes in the surgical approach and in the limits of resection.[25] However, it is also known that during surgical removal of a brain tumor, modifications of white matter tract positioning may occur. Shifting of deep structures, the so-called subsurface shifting, seems to be much more relevant[26,27] than the shifting of cortical structures, which is clearly visible during surgery.

The knowledge of the course of major white matter tracts located close to a tumor during the surgical procedure can be useful to avoid postoperative neurologic deficits.[19]

To verify and understand this phenomenon we studied a prospective group of patients affected by cerebral gliomas undergoing surgery in an operating theater supplied with an intraoperative MR scan at 1.5 T. This allowed intraoperative MRI updates used for navigation, which also included DTI images to evaluate white matter tract deformations. In our study, DTI was acquired preoperatively and intraoperatively with a high-field MR unit, and a rigid registration of data was used because we did not need to compensate for brain deformation. For this reason, our data differ from those reported by others[28] using a nonrigid alignment of preoperative DTI MRI acquired with high-field unit (3T) and intraoperative data acquired with low-field magnet (0.5 T).

In this study, we documented that shift involving the CST can be observed in 90% of cases during surgery. This percentage is similar to those reported in other studies.[23,24,29] In their study, Hastreiter et al[18] highlight several causes of brain shift, ranging from the characteristics of tissue to the deformation of tissue following gravity. The direction of shifting can be different. Nimsky et al[24] described an outward shifting

TABLE 2. Corticospinal Tract Shifting Values Obtained After Tumor Resection (Intraoperative Shift) and After Dura Mater Opening[ab]

Patient	Intraoperative CST Shift	After Dura Mater Opening CST Shift
1	4	4
2	−2.6	0
3	0	0
4	−4.2	4.3
5	−9.7	\
6	6.5	3.5
7	5	2.8
8	0	\
9	−5	4.7
10	11	4
11	−3	−7.3
12	4	7.5
13	3	\
14	−5.4	0
15	5	\
16	−9.1	\
17	−5	\
18	−2.3	\
19	4	\
20	−5.8	\

[a]CST, corticospinal tract; DTI, diffusion tensor image.
[b]In all cases, the preoperative DTI was considered as a reference. A positive value was assigned if movement was outward from the surface, and negative value was assigned if movement was inward.

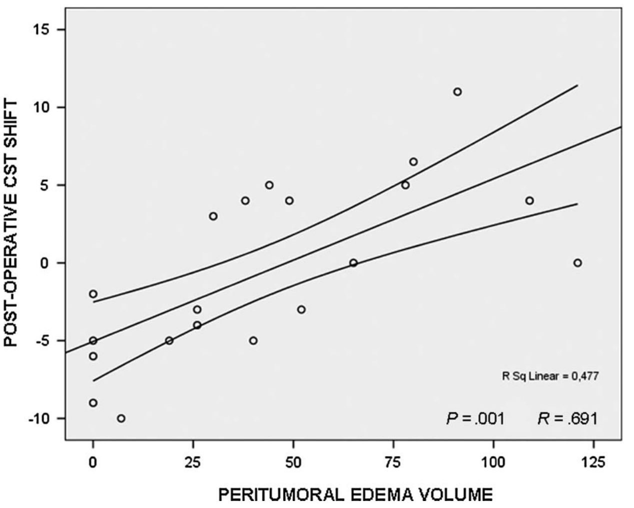

FIGURE 3. *Linear regression between peritumoral edema and corticospinal tract shifting. Shifting values correlate significantly with peritumoral edema; the linear regression is depicted as a straight solid line with upper and lower 95% confidence boundaries.*

in 59% and an inward shifting in 30% of cases evaluated; shift ranged from −8 to +15 mm. Dorward et al[29] indicated outward shifting in 72% of cases. In a study of Ozawa et al,[23] the magnitude of the CST displacement due to the tumor resection varied from −8 to +8.7mm (59% outward, 41% inward). In our study, shifting ranged from −9.7 to +11mm (40% outward, 50% inward), and 2 patients did not show CST displacement (10%).

In our experience, parameters predicting that CSTs shift independent of direction were the amount of peritumoral edema and the craniotomy size.

A shift of 2.5 mm was obtained with a sensitivity of 100% and a specificity of 80% for a median value of peritumoral edema of 42 mL and a sensitivity of 100% and a specificity of 66% for a median value of craniotomy size of 57 mm.

As mentioned, shifting is not necessarily unidirectional. The subsurface motion during tumor resection is driven not by external pressure, but by the relief of weight and intraparenchimal pressure.[19,27,30] The direction of white matter tract shifting, whether in the outward or inward direction in respect to the craniotomy opening, seems to be unpredictable.[23,26] For larger lesions, the shifts do not reach a steady state during surgery, but

TABLE 3. Summarized Data of Different Parameters Analyzed Among Patients Showing Inward, Outward, and No Shifting After Tumor Resection

After Tumor Resection		Tumor Volume, mL	Peritumoral Edema, mL	Craniotomy Size, mm	Tumor Depth, mm
10 patients with inward shifting	Mean	**49.8**	**17**[a]	**55.5**[a]	**8.1**
	Standard deviation	*48.295*	*18.785*	*12.878*	*11.59*
8 patients with outward shifting	Mean	**39.63**	**64.88**[a]	**69.13**[a]	**13.75**
	Standard deviation	*35.12*	*28.482*	*12.518*	*10.457*
2 patients without shifting	Mean	**14.5**	**93**	**43**	**0**
	Standard deviation	*4.95*	*39.598*	*15.556*	*0*

[a]Statistically significant differences comparing patients showing inward and outward shifting.

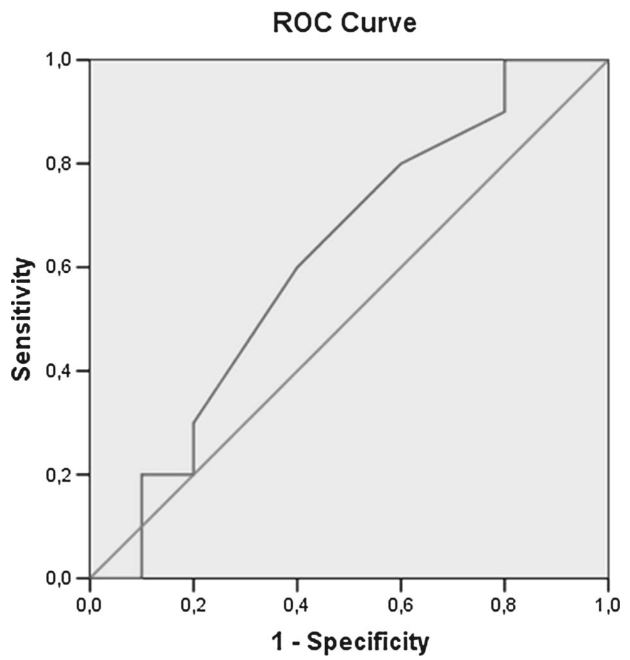

FIGURE 4. *Receiver operating characteristic curve. Predictive shift of 2.5 mm in presence of median value of peritumoral edema of 42 mL.*

dominate initially as surface deformations and subsequently as subsurface deformations.[19]

In our study, an outward shifting of the CST was mostly related to the presence of a large amount of edema and to a large craniotomy size, but in patients showing inward shifting, tumor size plays the most important role, although it is not of statistical significance. This second possibility might be related to gravity and intraoperative positioning of the head of the patient.

Our observations are not in agreement with those proposed by Nimsky et al[26] These authors assessed that the size of the craniotomies did not correlate with the extent of brain shift. They suggested that opening the ventricular system, as well as patient positioning (direction of gravity), had the greatest affect on brain shift. In our group of patients, no patient underwent opening of the ventricular system during the surgical procedures. As opposed to other studies,[23,24,29] an inward shifting was observed in our patients more frequently than an outward one (50% vs 40%). This phenomenon might be related to the anatomical position of most of our tumors. Nabavi et al[19] reported that, in temporal lobe tumors, the temporal lobe shifts, during surgery, toward the midline and limits other motion. In 65% of our patients a temporal component of the tumor was observed and thus, as reported by Nabavi et al, an inward shifting could be expected.

As suggested by Nabavi et al,[19] brain shift tracking may require even more frequent or, if possible, continuous imaging. Only serial imaging with high spatial resolution allows the elucidation of deformation patterns and reveals brain compartments with differing reactions to surgical manipulations.

As we expect, and as described previously, most patients who underwent DTI acquisition after dura mater opening also showed cortical spinal tract outward shifting. This event suggests that, after dural opening, a dynamic group of events may begin that leads to modification of the anatomical organization of surface and subsurface structures, involving white matter tracts and tumor position. In these patients, we noted an outward shifting that ranged from 2.8 to 8 mm, leading to a potential loss of validity of preoperative planning. Despite the low number of cases evaluated and the bias related to the fact that we chose only a subset of patients with visible shift, we confirm this phenomenon as reported by other authors[19]; the dural opening causes cortical bulging and propagates this effect to subsurface structures, especially in the presence of edemigenous tumors. The role of DTI in neurosurgical procedures of tumor resection has been widely discussed in the literature,[25] and its ability to influence surgery has been demonstrated. In the present study we were interested in CST shifting during

TABLE 4. Summarized Data of Different Parameters Analyzed Among Patients Showing Shifting After Dural Opening or Not

After Dural Opening		Tumor Volume, mL	Peritumoral Edema, mL	Craniotomy Size, mm	Tumor Depth, mm
7 patients with outward shifting	Mean	**39.57**	**67.57**	**69**	**10**[a]
	Standard deviation	*29.029*	*35*	*20.921*	*10.615*
1 patients with inward shifting	Mean	**81**	**26**	**42**	**0**
	Standard deviation	\	\	\	\
3 patients without shifting	Mean	**39**	**45.33**	**53**	**0**[a]
	Standard deviation	*35.553*	*23.714*	*3.306*	*0*

[a]Statistically significant differences comparing patients showing outward shifting vs patients without shifting.

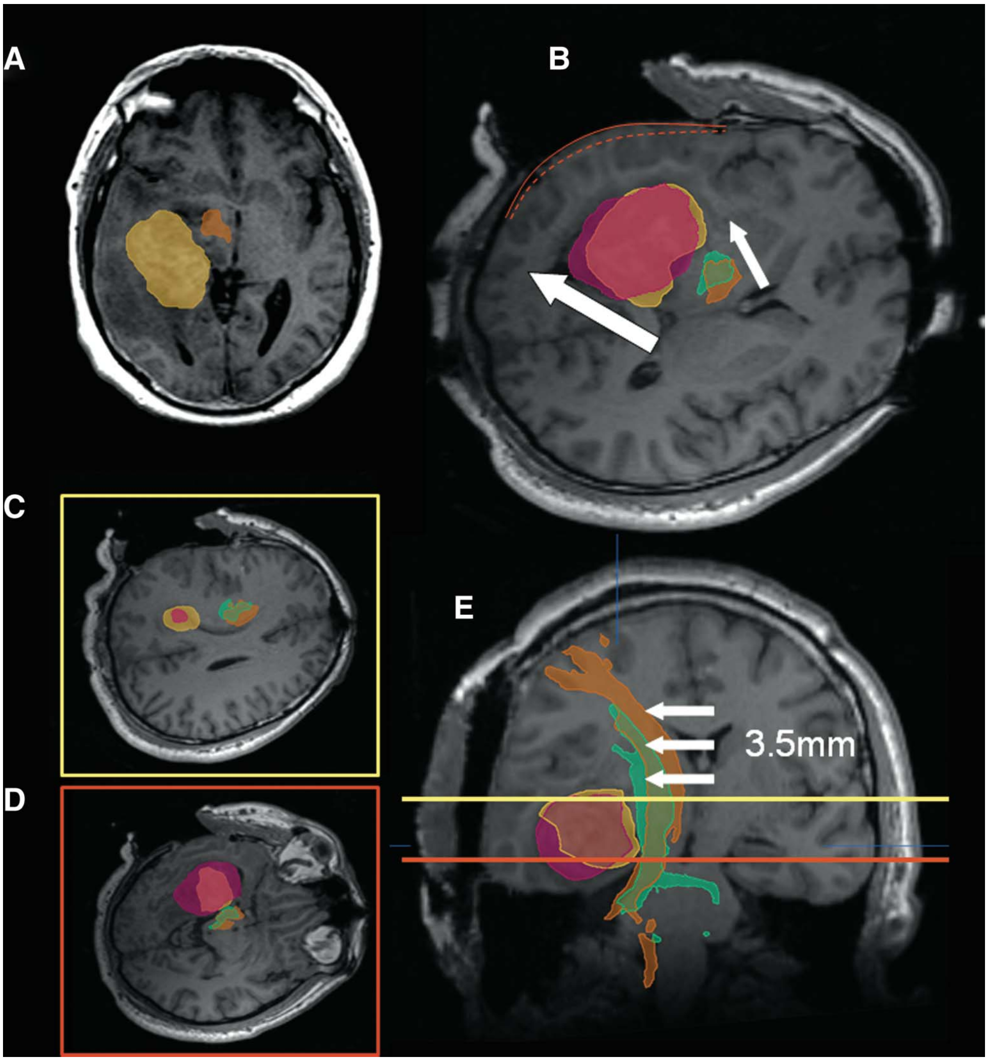

FIGURE 5. *Shifting after dural opening. Patient 6: Right temporobasal lobe glioblastoma multiforme (represented in yellow). Axial images are aligned in the direction of gravity. Direct mass effect of tumor dislocated corticospinal tract medially and anteriorly (orange) (**A**). After dural opening, the surface bulging is evident (**B**, red line) with respect to the primitive position of cortical surface (red dotted); the new position of the corticospinal tract (green) and tumor (red) are shown. An outward shifting (arrows) is documented, laterally and posteriorly concerning to the corticospinal tract and the laterally and inferiorly about the tumor (**B–E**).*

surgery and we did not consider the role of DTI for surgical proposes, which is the real goal of DTI acquisition.

Some limits emerged from our study. First, we did not have the possibility of achieving a deep intraoperative neurophysiological acquisition to confirm the real position of the CST and its functional preservation. The evaluation of the patients' clinical condition and improvement of preoperative symptoms were interpreted as functional preservation of the CST. In the last period we began a new intraoperative experience with neurophysiological procedure, obtaining in a few patient groups successful results of concordance between the postoperative position of CST and registered motor-evocated potentials.

Second, the CST was chosen in our study because of its deep location, less sensitive to artifacts derived from opening of the skull and fixation pins. We retain that analysis of other white matter tracts, as optic radiation or arcuate fasciculus, located closer to cortical surface, may lead to a more difficult evaluation of real anatomic modification of these tracts during different surgical steps.

Third, a strong bias has to be considered in the subgroup of patients, which were scanned right after dura opening. Because of the increase in surgical time related to DTI acquisition, only a subset of patients with visible shift was rescanned after dura opening. In these patients our target was not the definition of a shift per se, but to quantify its amount.

CONCLUSION

The use of intraoperative DTI evaluation to update a navigation system demonstrated brain shift of the CST. This happened not only after tumor resection, but also after dura mater opening. The amount of peritumoral edema correlated with CST shifting when an outward movement of this tract was observed. The dura mater opening per se can also cause significant shift (mostly outward), especially in deeply located neoplasms. DTI evaluation of white matter tracts can be used during surgical procedure only if updated with intraoperative acquisitions.

Disclosure

The authors have no personal financial or institutional interest in any of the drugs, materials, or devices described in this article.

REFERENCES

1. Berger MS, Rostomily RC. Low grade gliomas: functional mapping resection strategies, extent of resection, and outcome. *J Neuroonc*. 1997;34(1):85-101.
2. Sanai N, Berger MS. Glioma extent of resection and its impact on patient outcome. *Neurosurgery*. 2008:62(4):753-766.
3. Jellison BJ, Field AS, Medow J, Lazar M, Salamat MS, Alexander AL. Diffusion tensor imaging of cerebral white matter: a pictorial review of physics, fiber tract anatomy, and tumor imaging patterns. *AJNR Am J Neuroradiol*. 2004;25(3): 356-369.
4. Jones DK. Determining and visualizing uncertainty in estimates of fiber orientation from diffusion tensor MRI. *Magn Reson Med*. 2003;49(1):7-12.
5. Mori S, van Zijl PC. Fiber tracking: principles and strategies—a technical review. *NMR Biomed*. 2002;15(7-8):468-480.
6. Mori S, Crain BJ, Chacko VP, van Zijl PC. Three-dimensional tracking of axonal projections in the brain by magnetic resonance imaging. *Ann Neurol*. 1999;45(2):265-269.
7. Mori S, Frederiksen K, van Zijl PC, et al. Brain white matter anatomy of tumor patients evaluated with diffusion tensor imaging. *Ann Neurol*. 2002;51(3): 377-380.
8. Mori S, Kaufmann WE, Davatzikos C, et al. Imaging cortical association tracts in the human brain using diffusion-tensor-based axonal tracking. *Magn Reson Med*. 2002;47(2):215-223.
9. Berman JI, Berger MS, Mukherjee P, Henry RG. Diffusion tensor imaging-guided tracking of fibers of the pyramidal tract combined with intraoperative cortical stimulation mapping in patients with gliomas. *J Neurosurg*. 2004;101(1): 66-72.
10. Bello L, Gambini A, Castellano A, et al. Motor and language DTI Fiber Tracking combined with intraoperative subcortical mapping for surgical removal of gliomas. *NeuroImage*. 2008;39(1):369-382.
11. Mikuni N, Okada D, Enatsu R, et al. Clinical impact of integrated functional neuronavigation and subcortical electrical stimulation to preserve motor function during resection of brain tumours. *J Neurosurg*. 2007;106(4):593-598.
12. Kamada K, Todo T, Masutani Y, et al. Combined use of tractography integrated functional neuronavigation and direct fiber stimulation. *J Neurosurg*. 2005;102(4):664-672.
13. Nimsky C, Ganslandt O, Fahlbusch R. Implementation of fiber tract navigation. *Neurosurgery*. 2006;58(4 suppl 2):292-304.
14. Schonberg T, Pianka P, Hendler T, Pasternak O, Assaf Y. Characterization of displaced white matter by brain tumors using combined DTI and fMRI. *NeuroImage*. 2006;30(4):1100-1111.
15. Kinoshita M, Yamada, K, Hashimoto, et al. Fiber-tracking does not accurately estimate size of fiber bundle in pathological condition: initial neurosurgical experience using neuronavigation and subcortical white matter stimulation. *NeuroImage*. 2005;25(2):424-429.
16. Basser PJ, Pajevic S, Pierpaoli C, Duda J, Aldroubi A. In vivo fiber tractography using DT-MRI data. *Magn Reson Med*. 2000;44(4):625-632.
17. Nimsky C, Gansalndt O, Hastreiter P, et al. Preoperative and intraoperative diffusion tensor imaging-based fiber tracking in glioma surgery. *Neurosurgey*. 2005;56(1):130-138.
18. Hastreiter P, Rezk-Salama C, Soza G, et al. Strategies for brain shift evaluation. *Med Image Anal*. 2004;8(4):447-464.
19. Nabavi A, Black PM, Gering DT, et al. Serial intraoperative magnetic resonance imaging of brain shift. *Neurosurgery*. 2001;48(4):787-798.
20. Reinges MH, Nguyen HH, Krings T, et al. Course of brain shift during microsurgical resection of supratentorial cerebral lesions: limits of conventional neuronavigation. *Acta Neurochir*. 2004;146(4):369-377.
21. Roberts DW, Hartov A, Kennedy FE, et al. Intraoperative brain shift and deformation: a quantitative analysis of cortical displacement in 28 cases. *Neurosurgery*. 1998;43(4):749-760.
22. Hartkens T, Hill DL, Castellano-Smith AD, et al. Measurement and analysis of brain deformation during neurosurgery. *IEEE Trans Med Imaging*. 2003;22(1): 82-92.
23. Ozawa N, Muragaki Y, Nakamura R, Hori T, Iseki H. Shift of the pyramidal tract during resection of the intraaxial brain tumors estimated by intraoperative diffusion-weighted imaging. *Neurol Med Chir*. 2009;49(2):51-56.
24. Nimsky C, Ganslandt O, Hatreiter P, et al. Intraoperative diffusion-tensor MR imaging: shifting of white matter tracts during neurosurgical procedures-Initial experience. *Radiology*. 2005;234(1):218-225.
25. Romano A, D'Andrea G, Minniti G, et al. Pre-surgical planning and MR-tractography utility in brain tumour resection. *Eur Radiol*. 2009;19(12): 2798-2808.
26. Nimsky, C, Ganslandt O, Cerny S, Hastreiter P, Greiner G, Fahlbusch R. Quantification of, visualization of, and compensation for brain using intraoperative magnetic resonance imaging. *Neurosurgery*. 2000;47(5):1070-1080.
27. Paulsen KD, Miga MI, Kennedy FE, Hoopes PJ, Hartov A, Roberts DW. A computational model for tracking subsurface tissue deformation during stereotactic neurosurgery. *IEEE Trans Biomed Eng*. 1999;46(2):213-225.
28. Archip N, Clatz O, Whalen S, et al. Non-rigid alignment of pre-operative MRI, fMRI, and DT-MRI with intra-operative MRI for enhanced visualization and navigation in image-guided neurosurgery. *Neuroimage*. 2007;35(2): 609-624.
29. Dorward NL, Alberti O, Velani B, et al. Post-imaging brain distortion: magnitude, correlates, and impact on neuronavigation. *J Neurosurg*. 1998;88(4): 656-662.
30. Miga MI, Paulsen KD, Lemery JM, et al. Model-updated image guidance: initial clinical experiences with gravity-induced brain deformation. *IEEE Trans Med Imaging*. 1999;18(10):866-874.

COMMENT

The paper by Romano et al highlights the necessity to compensate for brain shift. As demonstrated before, there is a distinct individually unpredictable shifting of the pyramidal tract during the course of surgery. In case navigation is not only used for craniotomy placement but to guide the extent of a resection and to preserve eloquent brain structures like the pyramidal tract, then some strategy for compensation is mandatory. Mathematical models alone can not solve this challenge alone; at least some kind of intraoperative sparse data have to be obtained to allow a deformation of high-quality preoperative data for brain shift compensation. These sparse data may be obtained by some intraoperative imaging method like contour scanning, or standard imaging approaches like CT, ultrasound, or MRI. Intraoperative high-field MRI not only provides these sparse data on the brain deformation, but also allows to perform intraoperative diffusion tensor imaging, so that brain shift can be compensated for directly. In complicated cases additional intraoperative electrophysiological evaluations might add further safety.

Christopher Nimsky
Marburg, Germany

William Farr, a nineteenth century British epidemiologist, regarded as one of the founders of medical statistics. He was responsible for the collection of official medical statistics in England and Wales. His most important contribution was to set up a system for routinely recording the causes of death. Consequently, for the first time it allowed the mortality rates of different occupations to be compared.