The role of neuronavigation-guided functional MRI and diffusion tensor tractography along with cortical stimulation in patients with eloquent cortex lesions

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Abstract

Objective. To effectively combine functional MRI (fMRI), diffusion tensor tractography (both guided by neuronavigation) along with cortical stimulation (CS) for surgery of eloquent cortex (EC) lesions. Materials and methods. Fifteen patients with lesions adjacent to the eloquent motor and sensory cortex were included. Preoperative fMRI and diffusion tensor imaging were performed and then integrated into the neuronavigation system. Intraoperative CS of sensory/motor cortex was performed to localize the EC under awake conditions and this was correlated with areas active on fMRI utilizing neuronavigation. For excision of the deeper structures, CS, and tractography guided by neuronavigation were utilized. Results. A total of 127 cortical sites were evaluated with CS in 15 patients. The overall sensitivity, specificity, and accuracy of fMRI were 79%, 85%, and 82%, respectively, keeping the areas positive on CS as a referential parameter. Tractography helped in resecting the deeper areas of the tumor, but was not very accurate due to brain shift. However, it was useful in roughly assessing the deeper areas close to the long tracts. The risk of developing persistent neurological deficits was 6%. Pathologies included gliomas in ten patients, cavernous malformation in two patients, menigioma in one patient, and focal cortical dysplasia and Dysembryonic neuroepithelial tumor in one patient each. Near total excision was achieved in 7/10 (> 95% excision) gliomas and a total excision in all others lesions. Conclusions. Lesions directly over or immediately adjacent to the motor/sensory area present a surgical challenge because of the high risk of developing neurological deficits due to inadvertent injury due to infiltration of the tumor tissue. Thus, the primary goal of surgery for lesions in EC is to maximize resection without inflicting new neurological deficits, which may be especially challenging in lesions located immediately adjacent to these areas. Functional mapping of the pertinent eloquent areas is an important step toward realization of this goal. It serves the purpose of generating an objective roadmap for the neurosurgeon for surgical planning. For this purpose, various techniques have evolved, including preoperative functional magnetic resonance imaging (fMRI), diffusion tensor imaging (DTI), and intraoperative cortical stimulation and subcortical white matter stimulation.

Keywords: awake surgery; eloquent cortex; epilepsy surgery; functional MRI; neurological deficits; tractography

Introduction

Lesions directly over or immediately adjacent to the motor/sensory area present a surgical challenge because of the high risk of developing neurological deficits due to inadvertent injury due to infiltration of the tumor tissue. Thus, the primary goal of surgery for eloquent sensory/motor cortex lesions (EC), without the use of any imaging modalities has been reported to vary from 13% to 27.5%. However, there have been very few studies showing its actual correlation to areas positive on CS under awake conditions. Such a correlation is important not only to understand the relationship between the two modalities but also to assess the area of actual ‘safe margin’ around the fMRI active zone.

The identification and preservation of subcortical white matter tracts are equally important in preserving the neurological functional integrity of patients undergoing surgery.
resection of EC lesions,15-17 which may be visualized using DTI techniques.2,18-21

All the three above mentioned modalities viz. for localization of EC, that is, fMRI, DTI, and CS have their own limitations and advantages. In the present study, we attempted to effectively combine all these three modalities. Such an integration, we believe may not only enhance the margin of safety for tumor resection, but also provide information on how accurately the functional imaging maps correlate to actual patient stimulation studies.

In addition, the margin of error while resecting the deeper parts of lesion, especially around the white matter tracts, is very less. Neuronavigation-based resection only may not be very accurate due to brain shifts. Hence, a combination with CS along with real time monitoring of the patient’s clinical profile may provide a better input for the surgeon.

Materials and methods

Patient materials

A total of 15 patients with lesions directly over the EC (motor/sensory) and fulfilling the following criteria were included in our study. The study was performed as per the guidelines laid down by the Indian council of Medical Research and after taking clearance from the Ethics committee of the institute.

Inclusion criteria

1. Focal lesions adjacent to eloquent motor/sensory cortex. ‘Lesions’ in the study included intra-axial tumors such as gliomas and cavernomas and certain extra-axial tumors such as meningiomas and also chronic non-tumoral lesions presenting with drug refractory epilepsy.
2. Patients able to perform the functional MRI tasks.
3. Karnofsky’s performance score of 80% or above.

Pathologies included gliomas in ten patients, cavernomas in two patients, meningioma in one patient, focal cortical dysplasia (FCD) and Dysembryonic neuroepithelial tumor (DNET) in one patient each.

Exclusion criteria

1. Patients unable to perform fMRI tasks (e.g. hemiplegic patients).
2. Lesions separated by a bridge of normal parenchyma from the motor/sensory cortex or fMRI active area separated from the tumor by a bridge of normal parenchyma.

Preoperative fMRI and DTI

In all patients, preoperative fMRI and DTI were performed under image guidance protocol after applying fiducial markers over the scalp.

MRI acquisition

MRI was performed on a 3-T MR unit (Achieva; Philips Medical Systems, Netherlands) by using a 32-channel head coil.

In brief, the BOLD signals were measured employing an echo-planar technique (TE, 52 ms; TR, 3 s; section thickness, 4 mm; and matrix size, 128 × 128). A total of 120 frames of 25 axial sections (acquisition time per frame, 3 s) were acquired through the motor cortex during repeated motor task periods (30 s) and resting periods (30 s). The patient practiced the paradigm multiple times before the scan. The patient was observed to make sure that he/she performed the paradigm accurately during acquisition of the fMRI imaging data.

DTI was performed by using a single-shot echo-planar sequence with the array sensitivity-encoding technique. Motion-probing gradient orientations were applied along 32 directions, and the b factor was set at 1000 s/mm2. The acquisition parameters used were as follows: TR/TE, 8,000/83.3 ms; bandwidth, 143 kHz; matrix size, 128 × 128; section thickness, 2 mm without intersection gap; FOV, 30 × 30 cm; and NEX, 2.

High-resolution anatomic imaging was performed by using a volumetric T1-weighted 3D GE sequence (TR/TE/TI, 1640/2.28/552; flip angle 12 degree; number of sections 160; and isovoxel resolution of 1X1X1 mm3).

Data processing

Nordic ICE (Nordic Neuro Lab, the Netherlands) was used to calculate the activation maps; the statistical significance of changes in signal intensity was calculated on a voxel-by-voxel basis employing the Student t test. The task paradigm consisted of 43 s of rest and 30 s of self-paced hand grasping; this task-rest cycle was repeated six times.

Acquired diffusion-sensitized and reference image sets were transferred to an Intel Pentium Windows-based operating system (Microsoft) for further data analysis. Tensor calculation and tractography were performed by using nordic ICE software. All diffusion-weighted and non-diffusion-weighted images were first realigned by affine transformation by using the automated image registration program, to further minimize eddy current and potential small bulk motions that may have occurred during the scans. The six elements of the diffusion tensor were calculated for each pixel by using multivariate linear fitting. After diagonalization, three eigenvalues and three eigenvectors were obtained. The eigenvector associated with the largest eigenvalue was used as an indicator of fiber orientation.

Tractography was performed on the basis of fiber assignment by continuous tracking. A brute force fiber tracking was initially performed for the whole brain. The fiber propagation was stopped at a fractional anisotropy threshold of < 0.2 or an angle threshold > 50°. The Neuronordic software allows isolation of tracts passing through a single region of interest (by using the inclusive “OR” operator) or multiple regions of interest (by using the exclusive “AND” operator). The CST was isolated by drawing an “OR” region of interest around the CST in the brain stem (was identified as a blue color bundle [i.e., a bundle running in the superior—inferior direction] in the anterior part of the brain stem) and an “AND” region of interest around the corona radiata in the direction-coded color axial sections. Unrelated fibers, such as fibers going to the contralateral side, cerebellum, or thalamus, were removed by using a “NOT” region of interest. To be included into the study and for further analysis, the CST has to be continuous from the brain stem to the motor cortex. If it is not continuous, it will be considered...
as unidentifiable, and it was concluded that DTI failed to isolate that particular CST (Fig. 1).

Preoperative neurological assessment
Patients underwent a detailed neurological assessment in the preoperative period and the presence of any neurological deficits was recorded. Muscle power was assessed and a grade was assigned according to the Medical Research Council, UK. Patients with lesions close to leg area were tested also by being asked to walk on a straight line, on toes and heels. A mock drill was provided so that the patient understands completely what was expected of him/her at the time of surgery.

Integration of functional and DTI data with neuronavigation system
Neuronavigation during surgery was performed using Medtronic Stealth frameless stereotactic system, which allows multiple MR or CT volumes to be loaded simultaneously during a surgical procedure. A T1-weighted thin slice morphometric scans were obtained (fast 3D gradient echo with rapid sampling time, high signal intensity, and image contrast while approaching steady state). These were first loaded to serve as the primary reference for neuronavigation. Functional results from the fMRI and DTI data analyses were then integrated into the neuronavigation system as the second and third volume by overlaying the activated voxels on a structural scan and converting the new volume to Digital Imaging and Communications in Medicine format, using the headers from the raw structural images.

Other investigations
In patients presenting with drug refractory epilepsy with lesions such as DNET or focal cortical dysplasia, additional work up included an inter-ictal EEG, video EEG. Ictal SPECT (subtracted and superimposed on MRI) was performed if indicated (for FCD). All patients with intractable epilepsy were discussed at a joint conference and underwent a full presurgical epilepsy evaluation.

Awake craniotomy
Patients were counseled and explained in detail about the procedure of awake craniotomy before surgery. In the operation theater, intravenous access was established by the anesthetist, an oxygen mask was applied and pulse oximetry and end-expiratory CO₂ concentration were monitored. Patients were kept under light anesthesia before the start of surgery. Local anesthesia with a combination of 0.5% bupivacaine and epinephrine (1:200,000) was infiltrated as ring block to block the nerves supplying the scalp (supraorbital, zygomaticotemporal, auriculotemporal, greater occipital, and lesser occipital nerves) and around the insertion site of the pins of the Mayfield head-frame. The neuronavigation system (Medtronic stealth) was registered and the lesion location was mapped to plan the location of the skin incision. Skin incision site was also infiltrated with local anesthetic agent. Scalp incision was made and subgaleal flap was raised followed by elevation of the bone flap. Dura was covered initially with lignocaine-soaked cottons and then the dura was opened. The fMRI-active areas were then identified using the MRI images in the image-guidance system. These areas were then marked using small sterile markers. CS (as described below) was used to stimulate the areas identified with fMRI and the response was recorded. Initially, a wide area was stimulated as a screening procedure. Following this, the areas close to the fMRI positive areas were divided into blocks of 10 × 10 mm. Response to CS for each block was recorded, and its relationship to fMRI-active areas was noted. Once resection was commenced, deeper sub-cortical areas were stimulated meticulously before

Fig. 1. Case 1 (see manuscript) Contrast MRI (a) axial section and (b) sagittal section showing left motor cortex glioma. fMRI and tractography images integrated on the neuronavigation system showing the functional area (white arrows) and tracts (arrow heads) in relation to the tumor in (c) axial and (d) sagittal views. Intraoperative photographs showing mapped motor strip (square cottons and black arrows) and (e) its close relation to the tumor; (*) before excision of the lesion and (f) after excision. Postoperative MRI (g) axial section and (h) sagittal section showing near complete excision of the tumor.
proceeding with excision of every piece of tissue, especially so with caution when the neuronavigation showed these areas close to the tracts.

**Intraoperative CS**

Intraoperative CS of sensorimotor cortex was performed. CS (alternating current of 60 Hz, 2 ms, 1–10 mA peak) with a bipolar electric probe of a cortical stimulator (Ojemann, model OCS-1, Radionics, France) was performed. The amplitude of current was progressively increased by 1 mA. Biphasic square-wave pulses of 2 ms at 60 Hz, with maximal duration of a pulse of 2 s, were used for the stimulation. The whole of the exposed cortex was stimulated, including the planned area of resection. The patient was instructed to report immediately if any of the following was noticed: [1] involuntary tonic contraction of the hand/leg or the whole limb, [2] Clonic movements, [3] Loss of control of voluntary movements, [4] Presence of any sensation or ‘numbness,’ and [5] any other response, which the patient found peculiar. The anesthetist performed neurological examinations during the stimulation. The comparison between CS-tested areas and functional MR imaging-activated areas was made only on the exposed cortical surface. Therefore, functional MR imaging-activated foci away from the craniotomy were not tested with CS. Cold saline (temperature between 3 and 6°C) was kept ready to be irrigated over the brain in case the patient developed a seizure during the procedure.

**Response recording**

As mentioned earlier, the area of the cortex close to the fMRI-positive area was divided into blocks (each of area of 10 × 10 mm). Each ‘block’ was labeled depending on the response as given below. Division of the cortex into blocks was so performed so as to allow objective assessment of each area:

1. **Response I:** fMRI(+); CS(+): if the area showed an activity on fMRI as per neuronavigation-based localization and also showed positive response on cortical stimulation.
2. **Response II:** fMRI(+); CS(–): if the area showed a positive activity on fMRI as per neuronavigation-based localization but did not show any positive response on cortical stimulation.
3. **Response III:** fMRI(–); CS(–): if the area did not show activity on fMRI as per neuronavigation-based localization and also on cortical stimulation.
4. **Response IV:** fMRI(–); CS(+): if the area does not show activity on fMRI as per neuronavigation-based localization but showed positive response on cortical stimulation.

**Electrocorticography**

The three patients with drug refractory epilepsy underwent intraoperative electrocorticography as per the technique described by us earlier.22,23

**Excision of the lesion**

After identification of the eloquent areas, the lesion was accessed through the non-EC either through a transsulcal or transcortical approach. The lesion was resected using the standard microsurgical techniques (bipolar cautery, ultrasonic aspirator, etc.). At the depth of the dissection, the tracts were identified using neuronavigation-guided imaging of the diffusion tensor tractography. Similar to the cortical stimulation, subcortical areas identified with DTI as per neuronavigation-based localization were stimulated and then response was recorded in a way as described above for functional cortical areas. All the deeper areas were stimulated and correlated with the neuronavigation-based tractography.

In the depths of resection, the excision proceeded meticulously in a step by step manner, removing the tumor piecemeal. At every step, neuronavigation and CS were used to identify the tracts and also the patient was continuously assessed neurologically for development of any deficits.

The end of the procedure was defined as when
1. The excision was completed or
2. The patient developed a significant motor/sensory deficit.

**Postoperative neurological assessment**

Patients underwent a detailed neurological assessment in the immediate postoperative period, at 24 h after surgery and after 3 months. The presence of any neurological deficits was recorded and then compared with the preoperative neurological status. A repeat MRI with contrast was performed at the follow up between 1 and 3 months.

**Results**

Fifteen patients with lesions directly over the EC were included in the study. The age of the patients ranged from 18 years to 66 years with a mean of 35 ± 11.8 years. All except one patient were males.

**Symptoms**

Seizure was the most commonly presenting complaint among our patients with 67% patients having had seizures before presentation. Three patients presented with intractable epilepsy and underwent the complete protocol for epilepsy surgery work up.22 Other presentations included headache, vomiting, and neurological deficits. Five patients had neurological deficits (hemiparesis/dysphasia) at the time of presentation.

**Lesion characteristics**

Eleven patients had lesions on left side and in four patients, the lesions were on right side. Pathologies included gliomas (10), cavernous malformation (2), meningioma (1), FCD (1) and DNET (1). Among the patients with gliomas, five patients had Grade II, two patients had Grade I, two patients had Grade III, and one patient had Grade IV astrocytoma on histopathological examination.

**Extent of resection**

Among the patients with glioma, near total excision (defined as > 95% excision) was achieved in seven patients (70%)
and in the other three patients, the procedure had to be stopped due to the development of intraoperative deficits. In two patients, this was because of the lesion extending on to the motor cortex and in one patient, this was because of tract consideration (Case 3 of illustrative cases, see below). Among the patients with pathologies other than gliomas, complete excision was achieved in all the patients.

Patient outcome
All patients tolerated the awake surgery and cooperated well for CS. Preoperatively, five patients had neurological deficits in the form of monoparesis or hemiparesis. In the immediate postoperative period, neurological deterioration was observed in four patients. Among these patients, three patients had reversible neurological deficits that recovered completely over a period of 24–72 h. In one patient, the deficits were persistent and still present 3 months after surgery. 26% developed transient neurological deficits, and 6% persistent. Improvement in neurological function was observed in three patients.

Comparison of fMRI and CS
A total of 127 cortical ‘blocks’ (10 mm × 10 mm) were evaluated with cortical stimulation. Among these 127 areas, 68 (54%) showed an active response to CS and 59 (46%) did not show any response to CS. Among the 68 areas active on CS, 54 (79%) were active on fMRI-based neuronavigation as well. Similarly, 63 functionally active areas were identified using fMRI-based neuronavigation, out of which, 54 (86%) were active on fMRI-based neuronavigation as well. The results of comparison between fMRI and CS were reported as sensitivity, specificity, negative predictive value, positive predictive value, and accuracy with a 95% confidence interval. The overall sensitivity, specificity, positive predictive value, negative predictive value, and accuracy of fMRI were 79%, 85%, 85%, 78%, and 82%, respectively, (Table I) keeping CS as the referential.

Tractography-guided resection
It was not possible to objectively compare the CS and tractographic localization, as this was much deeper and was associated with brain shift. However it was useful in roughly providing the surgeon information on areas, where he/she should proceed more cautiously and utilize CS more frequently.

Complications
One patient developed an intra-operative seizure, which was well controlled with cold saline irrigation. There were no other complications.

Illustrative cases
Case 1 (Fig. 1)
A 28-year-old male patient presented with a glioma directly over the left motor strip and had preoperative weakness in right upper limb (power- 3/5 MRC grade). Intraoperatively, eight blocks were identified after CS, of which, three showed a positive response on CS and were fMRI active based on neuronavigation, four areas were inactive on both CS- and fMRI-based neuronavigation, one area was active on CS and inactive on fMRI-based neuronavigation. Similarly, a good correlation was found between subcortical stimulation and neuronavigation-based tractography. White matter tracts were displaced postero-medially by the tumor. Near total excision of the tumor was achieved. Patient did not develop any neurological deficits intra-operatively. Postoperatively, patient had improvement in power in right upper limb from 3/5 to 4/5. Histopathological examination revealed glioblastoma multiformis WHO Grade IV.

Case 2
A 27-year-old male patient presented with intractable epilepsy. MRI revealed a FCD located anterior to the hand area. The hand motor area was localized using fMRI-based neuronavigation and CS. On CS, patient developed some sensation in right hand along with inability to perform voluntary movements and tonic posturing of the right hand. Hand area localized with fMRI-based neuronavigation exactly correlated with the area identified with CS. Then a grid was placed over the cortex and electrocorticography was recorded. The neurologist interpreted the ECOG and localized the activity to electrodes that corresponded to an area anterior to the hand area, the location of the cortical dysplasia on MRI. fMRI-based neuronavigation identified an area directly over the site of cortical dysplasia that was inactive on CS (false positive). This area was then removed after doing small corticectomy. After excision of the lesion, the electrocorticography was repeated that showed some activity anterior to the resection cavity that area was also excised. Patient developed no neurological deficits and was seizure free postoperatively.

Case 3
A 32-year-old patient with left motor strip glioma presented with 3 seizures. Patient had right hemiparesis (power-4/5) preoperatively. Motor strip was identified with CS and fMRI-based neuronavigation. At the depths of excision of the tumor, when excision was being performed close to white matter tracts (guided by CS and neuronavigation), patient suddenly developed right hemiplegia. The weakness persisted despite waiting for 15–20 min. The procedure was then

Table I. The following table shows the correlation between fMRI activity and cortical stimulation.

<table>
<thead>
<tr>
<th>Cortical stimulation (+) areas</th>
<th>Cortical stimulation (-) areas</th>
<th>Predictive values for fMRI for localizing eloquent areas</th>
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<tbody>
<tr>
<td>fMRI (+) areas</td>
<td>54</td>
<td>79%</td>
</tr>
<tr>
<td>fMRI (-) areas</td>
<td>14</td>
<td>85%</td>
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<td></td>
<td>9</td>
<td>82%</td>
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Sensitivity Specitivity Accuracy
stopped some residual tumor in the depth was left behind. The weakness however improved significantly in the next 24 h. At follow up on 6 months, the patient had mild grip weakness and no other deficit.

Discussion

Identifying cortical areas essential for key brain functions is of critical importance in order to limit neurological deficits from lesion resection. CS is one of the effective ways to localize the eloquent areas intraoperatively. Preoperative mapping with non-invasive techniques such as fMRI and DTI has gained popularity in recent times. However, despite many advantages of preoperative imaging techniques, they do have certain limitations as have already been described and research validating the use of fMRI and DTI mapping is still ongoing.

Jack et al. showed functional MRI to be highly sensitive in the detection of sensorimotor activation in healthy subjects and feasible in patients with lesions around the central sulcus. Based on this, they proposed fMRI for presurgical planning in patients with a focal lesion adjacent to the eloquent cortex. The present study included only lesions adjacent to motor and sensory cortex. We have not performed this study for patients with lesions adjacent to the language areas, as our language protocols have not been properly validated.

Kring et al. studied 103 patients and found that the sensitivity of fMRI in identifying the EC was 85%. Similarly, Hirsch et al. found fMRI to be 95% sensitive in identifying the functional areas.

FitzGerald et al. studied 11 patients with EC lesions. They studied 140 sites and compared the fMRI and cortical stimulation. They found fMRI to be 85% sensitive and 53% specific in identifying the eloquent cortex. They however did not use the diffusion tensor tractography to identify the white matter tracts. Similarly, Roux et al. studied 14 patients with EC lesions. They compared fMRI with CS and found that fMRI was 59% sensitive and 97% specific in identifying the EC sites.

Variation in BOLD studies of fMRI with tumor grade is a possibility. Studies have shown that with increase in tumor grade and age, reduced fMRI signal intensity but this was not significant. It is possible that changes in autoregulation and tumor vasculature may cause a change in BOLD fMRI volumes. Holodny et al. more than a decade ago correlated the fMRI activation volumes in gliomas with neuronavigation and compared it with the normal side. They found that the activation volumes on the side of the tumor were significantly smaller compared with the normal side, especially so in glioblastomas. However no shift of site of fMRI activation was found as compared to the localization correlated on neuronavigation.

Bizzi et al. evaluated the role of fMRI in EC lesions and compared it with the cortical stimulation. They studied 34 patients with a lesion in or adjacent to the eloquent cortex. Preoperative fMRI was done and the EC was mapped at surgery with cortical stimulation. A site by site comparison between fMRI and CS was performed using neuronavigation. A total of 251 cortical sites were tested with cortical stimulation. They found that overall functional MRI sensitivity and specificity were 83% and 82%, respectively.

In the present study, the sensitivity and specificity of fMRI were 79% and 85%, respectively, with CS used as reference. The areas identified with CS did not always correspond to the areas identified with functional MRI. This difference between the two modalities can be explained to an extent by the different nature of these two modalities. Also the areas identified with fMRI may not be directly involved in the execution of a motor task. Another reason for this discrepancy could be due to the brain shifts occurring after craniotomy that can affect the accuracy of neuronavigation.

The risk of neurological deficits ranges depending on the various modalities used: MRI and CS-11% (n = 11, Bizzi et al.), fMRI alone-21% (n = 34, Krishnan et al.), tractography alone with neuronavigation-15.3% (as compared with 32% in controls, n = 238, Wu et al.) and using CS alone-21% (n = 309, Kim et al.).

There are very few studies in literature that combine different modalities in the same patient to localize the eloquent cortex. Berntsen et al. (n = 51 patients) used fMRI and diffusion tensor tractography (DTT) to map eloquent areas and assessed the use of fMRI and DTT for preoperative assessments and also determined whether using these data together with 3D ultrasound enabled safer resection. With this study they demonstrated that preoperative fMRI and DTT had direct consequences for therapeutic strategies and for sparing EC and tracts. They also concluded that functional neuronavigation combined with intraoperative 3D ultrasound can, in most patients, enable resection of brain lesions without jeopardizing neurological function. The risk of neurological deterioration in this study was 12%. However, their patients were operated under general anesthesia and CS was not used for localizing the eloquent cortex.

González-Darder et al. studied 17 patients with lesions in the eloquent motor cortex. They used preoperative fMRI and DTI imaging incorporated into a neuronavigation system. Intraoperatively, the motor cortex was identified using neurophysiological monitoring. Patients were operated under general anesthesia. Though they found a good correlation between the fMRI activity and neurophysiological testing, the rate of fresh neurological deficits in their study was high and persistent neurological deficits were observed in 47.1% of the patients. This high rate of neurological deficits may be because of the fact that the authors operated the patients under general anesthesia.

The low safety margin is especially demonstrated in our illustrative Case 5, where patient developed dense deficits especially while removing the deeper areas. Performing surgery under awake condition provides an immediate feedback, thus allowing the surgeon to stop the surgery. This often results in improvement of the neurological deficit.

Our study is unique in the fact that we combined multimodal techniques (neuronavigation-guided fMRI, tractography, and CS) in awake patients. We found that such a combination, when applied to patients with lesions over or in direct proximity to motor/sensory cortex, provides...
the best possible options to minimize the risk of deficits (this fact is clearly illustrated in Case 5) especially for excising tumor from deeper locations as even minimal intrusion into the areas with tracts can result in dense deficits.

Neuronavigation-based fMRI and tractography-aided resection of tumors is not completely accurate due to brain shift. In addition our study and studies by other authors\(^7,36-39\) have shown that fMRI areas do not completely correspond to areas identified with CS under awake conditions. Also tractography images have a very low margin of error due to high density of fibers, and this can lead to a very high incidence of deficits as is evident from the study by Gonzalez et al.\(^35\)

Therefore, in lesions over eloquent cortex, combined use of multimodal neuronavigation (fMRI and tractography) and CS under awake conditions provides the best option of minimizing the risk of neurological deficits and maximizing tumor excision.

Conclusions

Lesions over the EC present a special surgical challenge. The challenge lies in removing these lesions without producing any deficits. This goal may be better optimized by combined use of multimodal neuronavigation (fMRI and tractography) and CS under awake conditions.

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Declaration of interest:

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