Subcortical stimulation mapping of descending motor pathways for perirolandic gliomas: assessment of morbidity and functional outcome in 702 cases

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OBJECTIVE Herein, the authors report their experience with intraoperative stimulation mapping to locate the descending subcortical motor pathways in patients undergoing surgery for hemispheric gliomas within or adjacent to the rolandic cortex, with particular description of the morbidity and functional outcomes associated with this technique.

METHODS This is a retrospective analysis of patients who, in the period between 1997 and 2016, had undergone resection of hemispheric perirolandic gliomas within or adjacent to descending motor pathways. Data regarding intraoperative stimulation mapping and patient postoperative neurological status were collected.

RESULTS Of 702 patients, stimulation mapping identified the descending motor pathways in 300 cases (43%). A new or worsened motor deficit was seen postoperatively in 210 cases (30%). Among these 210 cases, there was improvement in motor function to baseline levels by 3 months postoperatively in 161 cases (77%), whereas the deficit remained in 49 cases (23%). The majority (65%) of long-term deficits (persisting beyond 3 months) were mild or moderate (antigravity strength or better). On multivariate analysis, patients in whom the subcortical motor pathways had been identified with stimulation mapping during surgery were more likely to develop an additional and/or worsened motor deficit postoperatively than were those in whom the subcortical pathways had not been found (45% vs 19%, respectively, $p < 0.001$). This difference remained when considering the likelihood of a long-term deficit (i.e., persisting > 3 months; 12% vs 3.2%, $p < 0.001$). A higher tumor grade and the presence of a preoperative motor deficit were also associated with higher rates of motor deficits persisting long-term. A region of restricted diffusion adjacent to the resection cavity was seen in 20 patients with long-term deficits (41%) and was more common in cases in which the motor pathways were not identified (69%). Long-term deficits that occur in settings in which the subcortical motor pathways are not identified seem in large part due to ischemic injury to descending tracts.

CONCLUSIONS Stimulation mapping allows surgeons to identify the descending motor pathways during resection of tumors in perirolandic regions and to attain an acceptable rate of morbidity in these high-risk cases.

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KEYWORDS motor mapping; stimulation mapping; subcortical mapping; oncology

GLIAL tumors involving the motor cortex or descending subcortical motor fibers present a unique set of challenges. With the main objective of achieving maximal resection with minimal morbidity, the neurosurgeon's ability to safely and reliably identify and preserve the motor cortex as well as its associated descending white matter tracts is a crucial step in surgical management.^{4,12,17} The utility of stimulation mapping to localize and confirm

eloquent structures and minimize neurological morbidity during resection of gliomas has been well established and adopted as the standard of care at many centers.¹⁰ Advances in preoperative imaging modalities, including positron emission tomography, functional MRI, magnetoencephalography, and diffusion MRI fiber tracking (DMRI-FT), offer additional methods to facilitate identification of functional brain in relationship to tumor.²⁹ Information gath-

ABBREVIATIONS CST = corticospinal tract; DMRI-FT = diffusion MRI fiber tracking; DWI = diffusion weighted imaging.

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ered with these modalities can also be loaded into neuro-navigational systems to help localize functional tissue. In the case of DMRI-FT, the path of white matter fibers such as the corticospinal tract (CST) can be modeled and displayed by the navigation system in 3D space.³⁴ However, these techniques are still susceptible to the consequences of brain shift and loss of navigational accuracy.²⁰ In addition, reconstruction of motor fibers using DMRI-FT is highly user and technique dependent, and the depicted fibers may not be an accurate representation of the true functional fibers.^{1,18} A false-negative absence of DMRI-FT streamlines can occur in edematous or tumor-infiltrating regions,^{2,6} or false-positive streamline bundles can be seen when pathways are displaced by growth. Intraoperative MRI can address some of these challenges but requires significant added time and resources, and evidence supporting a robust correlation with intraoperative functional mapping data is currently lacking.^{22,24} Given the current state of technology, we have continued to rely on stimulation mapping as the gold-standard for localizing functional tissue. In this paper, we report our experience in using subcortical motor mapping to localize and preserve descending motor fibers during tumor resection. We describe the utility of this technique in a high-risk cohort of patients harboring gliomas involving the motor cortex or its descending fibers as well as the short- and long-term functional outcomes of the patients. Having previously described the use of subcortical mapping during glioma surgery,¹⁰ we present this follow-up analysis of just over 700 cases, showing that this technique continues to be reliable and robust and reduces injury to the subcortical motor tracts during glioma surgery.

Methods

Patient Selection and Characteristics

The study cohort includes all patients with hemispheric gliomas within or adjacent to the rolandic cortex and descending motor fibers who underwent resection during which cortical and subcortical stimulation mapping was used. All patients were treated at the University of California, San Francisco Medical Center by the senior author (M.S.B.) between 1997 and 2016. Patients were initially identified by querying a prospectively collected brain tumor registry, which contained findings related to intraoperative cortical and subcortical mapping results. Additional data regarding the patients' baseline demographic and clinical characteristics, tumor histology, and pre- and postoperative neurological status were collected through a review of the medical center inpatient and outpatient records, operative reports, and pathology reports. All patients with a new or worsened postoperative motor deficit were followed up for at least 3 months postoperatively, and, for purposes of the functional outcome evaluation, the deficit was considered long-term if it remained at 3 months. The study was conducted with the approval of the local Committee on Human Research.

Mapping Technique

The technique for subcortical mapping has been described in prior reports.^{4,11,13,17} The Ojemann stimulator

(Radionics, Inc.) was used with a bipolar probe with 5-mm spacing between electrodes to deliver a biphasic square-wave pulse of 1-msec duration at 60 Hz. For awake patients, visualized motor response with verbal confirmation from the patient was used to determine a positive motor response, and multichannel electromyography recordings were used in asleep patients.^{13,35} Following dural opening, the cortical motor region was stimulated and identified using serially increasing currents in increments of 1 mA, starting at 2 mA for awake patients (to maximum of 6 mA) and at 4 mA for asleep patients (to maximum of 16 mA). Then the same current applied at the cortex was used for the subcortical mapping to localize the descending motor pathways. Subcortical stimulation mapping was started when the resection was carried to the depth on level with the bottom of a sulcus. Serial subcortical stimulation was performed with each advancing 2–3 mm of resection. When cortical motor sites could not be identified due to safety of access (e.g., from scar tissue preventing adequate exposure), subcortical mapping was still performed in an attempt to identify the motor pathways using a current between 10 and 16 mA for asleep patients and between 4 and 6 mA for awake patients.

Imaging

For patients who developed a postoperative deficit, the early postoperative MRI (within 72 hours) was reviewed for any regions of abnormality on diffusion-weighted imaging (DWI). For our analysis, the degree of abnormality was arbitrarily considered significant when the area of restricted diffusion along the resection cavity was greater than 2 mm in thickness. Patients in the two illustrative cases underwent a high angular resolution diffusion imaging (HARDI) sequence on a 3-T General Electric Medical Systems scanner (Discovery MR750) both during the presurgical MRI and the early postoperative MRI with the following parameters: TR 6425 msec, TE 80 msec, axial slices 50, in-plane 2.2 mm² (subsampling to 1.1 mm²), slice thickness 2 mm, b value 2000 sec/mm², diffusion gradients 55, minimally diffusion-weighted image 1.

Illustrative Cases

Two illustrative cases were selected to explore damage to the CST by modeling the pathway using tractography (Fig. 1). The first case was a 62-year-old female with a recurrent right frontal anaplastic astrocytoma who underwent repeat resection after presenting with worsening left-sided weakness and headaches. The repeat resection revealed glioblastoma on pathological analysis. The patient in this case suffered a long-term deficit, but the subcortical pathway was not identified by stimulation. The second case was a 38-year-old male with a recurrent left parietal low-grade astrocytoma who had new, worsening enhancement on imaging concerning for a high-grade recurrence. Repeat resection was undertaken, and pathological analysis demonstrated anaplastic astrocytoma. In this case, the subcortical pathway was identified, and the patient went on to suffer a long-term deficit. In each of these illustrative cases, the presurgical CST was modeled with residual bootstrap Q-ball probabilistic tractography using

FIG. 1. Two illustrative cases used to explore mechanisms of injury to the descending motor pathways. To explore possible motor tract injury due to mechanical and/or ischemic injury, two cases were selected from a cohort of patients who had suffered a long-term deficit. Preoperative images (**A and E**) demonstrate the relationship of the modeled fibers to the tumor, and postoperative images (**B and F**) demonstrate the resection cavity and the region of restricted diffusion. The technique of motor fiber modeling is described in *Methods*. The volume of tissue with restricted diffusion (green) and the resection cavity (pink) on postoperative images were manually segmented (**C, D, G, and H**). Portions of the DMRI-FT motor fibers (blue) overlapping with the resection cavity are displayed in pink, and portions overlapping with the region of restricted diffusion are shown in green. In the first case (**A–D**), the patient suffered a long-term deficit, but the subcortical fibers were never identified by stimulation. Interestingly, the DMRI-FT CST did not overlap with the resection cavity, but a large portion of the motor fibers is seen running through the region of postoperative restricted DWI. In contrast, in the second case (**E–H**), motor tracts were identified by subcortical mapping during surgery, and the patient experienced persistent motor deficits. As expected, a significant portion of the descending motor fibers is seen running through the resection cavity. Figure is available in color online only.

the preprocessing parameters previously described.^{5,18} The region of restricted diffusion and the resection cavity on postoperative images were manually segmented in Track-Vis (trackvis.org). A rigid registration was performed with FLIRT (FMRIB's Linear Image Registration Tool, FSL) to bring the restricted diffusion and surgical cavity regions of interest into the preoperative space so that the preoperative CST could be targeted to infer potential damage attributed to resection (pink) and restricted diffusion (green).^{14,15}

Statistical Analysis

Comparisons of the likelihood of developing any or long-term deficits postoperatively between groups were performed using the chi-square test or Fisher's exact test. Multivariate analysis was performed using a logistic regression analysis (JMP 13, SAS Institute Inc.). A *p* value < 0.05 was considered significant for all analyses.

Results

Table 1 depicts demographics of the surgical cohort in addition to rates of new or worsened and long-term postoperative deficits. The age of the patients ranged from 18 to 84 years (median 44 years). There were 276 patients with low-grade tumors (WHO grade I or II) and 426 patients with high-grade tumors (WHO grade III or IV). One hundred ninety-two patients (28%) underwent an awake mapping procedure. A motor deficit was present in 89 patients (13%) prior to surgery. Subcortical stimulation mapping

was performed in all patients, and subcortical motor tracts were successfully identified in 300 cases (43%). A total of 210 patients (30%) developed a new or worsened motor deficit within 24 hours after surgery. Of these patients, 161 (77%) recovered to normal or their preoperative baseline function by the 3rd postoperative month. The remaining 49 patients, representing 7.0% of the entire cohort, were considered to have a long-term deficit.

Patients in whom the subcortical motor pathways were localized by stimulation mapping were more likely to develop a new or worsened motor deficit postoperatively than those in whom the subcortical mapping did not identify the pathway (45% vs 19%, respectively, *p* < 0.001). When only long-term motor deficits were considered, the group in which the motor pathways had been identified continued to be associated with higher rates of postoperative deficits (12% vs 3.2%, respectively; *p* < 0.001). Patients who had an existing baseline motor deficit were also more likely to develop a new or worsened deficit than were those who did not have a preoperative deficit (65% vs 25%, respectively; *p* < 0.001). This difference remained when considering only long-term deficits (16% for those with preoperative deficits vs 5.7% for those without; *p* = 0.003). A frontal lobe location was also associated with significantly higher rates of postoperative deficits. On univariate and multivariate analysis, tumor location, preoperative motor deficit, and identification of the subcortical pathway intraoperatively were significantly associated with a new or worsened postoperative neurological deficit. However, only identification of the subcortical pathway intraop-

TABLE 1. Patient and tumor characteristics and univariate analysis of those who underwent resection of perirolandic gliomas

Parameter	Total	New/Worse Deficit	p Value	Long-Term Deficit	p Value
No. of patients	702	210 (30%)		49 (7.0%)	
Mean age (yrs)	44.9 ± 13.5	*		†	
Sex			0.62		0.93
Male	411 (58.5%)	120 (29.2%)		29 (7.1%)	
Female	291 (41.5%)	90 (30.9%)		20 (6.9%)	
Side			0.88		0.50
Lt	302 (43.0%)	89 (29.5%)		20 (6.6%)	
Rt	398 (56.7%)	119 (29.9%)		28 (7.0%)	
Bilat	2 (0.3%)	2 (100%)		1 (50%)	
Tumor location			<0.001		0.25
Frontal	279 (39.7%)	110 (39.4%)		24 (8.6%)	
Temporal	73 (10.4%)	10 (13.7%)		2 (2.7%)	
Parietal	131 (18.7%)	37 (28.2%)		10 (7.6%)	
Insular	94 (13.4%)	14 (14.9%)		3 (3.2%)	
Multilobular	125 (17.8%)	39 (31.2%)		10 (8.0%)	
WHO grade			0.47		0.17
I	4 (0.6%)	0 (0%)		0 (0%)	
II	272 (38.7%)	85 (31.3%)		12 (4.4%)	
III	216 (30.7%)	60 (27.8%)		18 (8.3%)	
IV	210 (30.0%)	65 (31.0%)		19 (9.0%)	
Anesthesia‡			0.76		0.18
Asleep	484 (71.6%)	152 (31.4%)		31 (6.4%)	
Awake	192 (28%)	58 (30.2%)		18 (9.4%)	
Preop motor deficit			<0.001		<0.001
Yes	89 (12.7%)	58 (65%)		14 (16%)	
No	613 (87.3%)	152 (25%)		35 (5.7%)	
Subcortical pathway found			<0.001		<0.001
Yes	300 (42.7%)	135 (45%)		36 (12%)	
No	402 (57.3%)	75 (19%)		13 (3.2%)	

* OR = 1.00, 95% CI 0.99–1.02.

† OR = 1.01, 95% CI 0.99–1.04.

‡ Data for 26 patients unavailable.

eratively was associated with long-term motor deficits on both univariate and multivariate analysis (Table 2).

Among the 49 patients with persistent long-term deficits, 30 had a mild deficit, i.e., 4/5 strength or better or isolated facial weakness. In 2 patients the deficit was moderate (3/5, antigravity strength), and in 17 patients the effects were severe (unable to move against gravity). Tables 3 and 4 describe the severity of deficits and the distribution of affected body groups among the patients with long-term deficits.

Significant regions of DWI restriction were seen on the immediate postoperative scan in 20 (41%) of the 49 patients with long-term deficits. Among the 13 cases in which the subcortical pathway was never identified with stimulation yet the patients went on to develop a long-term deficit, 9 patients (69%) had DWI restricted regions on the postoperative scans. The presence of this DWI abnormality was significantly more common among the patients in whom subcortical pathways were not identified and went on to have a long-term deficit, as compared to those in whom subcortical pathways were found and a long-term deficit occurred (69% vs 31%, respectively; Table 5).

Discussion

Diffuse gliomas, by nature, invade and infiltrate white matter tracts, and injury to functional subcortical pathways can be responsible for a large portion of morbidity encountered when surgically removing tumors near functional tissue.^{8,26,30} Safe resection of tumors near functional areas necessitates intraoperative identification of functional sites both at the cortical and the subcortical levels. Techniques for subcortical stimulation mapping using biphasic bipolar 60-Hz stimuli for glioma surgery have been described by our group and others.^{4,11,12,17} More recently, monopolar high-frequency stimulation parameters have been increasingly used and studied, taking advantage of the more predictable pattern of current spread. In theory, the amount of current needed to stimulate a white matter tract can be used to estimate the distance to the stimulated tract.^{3,23} A number of studies have evaluated the relationship of stimulation intensity with the distance between the stimulation points and the motor fibers modeled by using DMRI-FT.^{2,5,19,23,31,36} There is considerable variability in the reported relationships between the current intensity

TABLE 2. Multivariate analysis

Variable	Total	New/Worse Deficit, OR (95% CI)	p Value	Long-Term Deficit, OR (95% CI)	p Value
Tumor location					
Frontal	279 (39.7%)	1			
Temporal	73 (10.4%)	0.23 (0.11–0.49)	<0.001		
Parietal	131 (18.7%)	0.55 (0.34–0.89)	0.013		
Insular	94 (13.4%)	0.43 (0.23–0.81)	0.006		
Multilobular	125 (17.8%)	0.72 (0.45–1.17)	0.18		
WHO grade					
I	4 (0.6%)			NA	NA
II	272 (38.7%)			1	
III	216 (30.7%)			2.17 (0.99–4.74)	0.051
IV	210 (30.0%)			2.29 (0.99–5.33)	0.054
Anesthesia					
Asleep	484 (71.6%)			1	
Awake	192 (28%)			1.67 (0.86–3.25)	0.13
Preop motor deficit					
Yes	89 (12.7%)	3.16 (1.95–5.17)	<0.001	2.10 (0.99–4.42)	0.052
No	613 (87.3%)	1		1	
Subcortical pathway found					
Yes	300 (42.7%)	3.17 (2.23–4.54)	<0.001	7.94 (3.52–17.4)	<0.001
No	402 (57.3%)	1		1	

NA = not applicable.

and the measured distance to the DMRI-FT motor fibers; some authors have proposed a linear relationship of 1 mA of current being able to stimulate structures 1 mm away, while others have shown that this relation is not strictly linear.^{16,21,24} Some of this variability may be due to differences in techniques, both in the stimulation protocol (e.g., probe type, stimulation parameters) and the DMRI-FT methodologies, which have well-documented reproducibility concerns (e.g., operator dependence, sequence, tractography algorithm, parameter choice, etc.).^{9,32,33} In addition, these studies tend to estimate distances to reconstructed fiber tracts based on preoperative or postoperative DMRI studies, which are susceptible to brain shift and loss of navigational accuracy.

Nonetheless, the overarching theme remains that positive subcortical motor stimulation at low currents likely suggests that the motor pathways are close, while stimulation requiring higher currents indicates greater distance to those functional pathways. When considering the impact on functional outcomes, there is also general consensus in the literature that the resection should be stopped at a safe margin distance from the descending motor pathways. This margin translated into stimulation threshold ranges from 1 to 10 mA, and resection to positive stimulation levels below these currents has resulted in significantly higher rates of postoperative motor deficits.^{16,21,23,24,27,28} At our institution, the Penfield technique of bipolar stimulation mapping has been used with these parameters for

TABLE 3. Incidence of additional postoperative motor deficits

Parameter	Total No.	Long-Term Deficit			p Value
		Mild (4/5 strength or better or isolated face weakness)	Moderate (3/5 strength)	Severe (2/5 strength or worse)	
All patients	49 (7.0%)	30 (4.3%)	2 (0.3%)	17 (2.4%)	
Subcortical pathway					<0.001
Found	36 (12%)	23 (7.7%)	1 (0.3%)	12 (4%)	
Not found	13 (3.2%)	7 (1.7%)	1 (0.2%)	5 (1.2%)	
Histology					0.03
High grade	37 (8.7%)	20 (4.7%)	0 (0%)	17 (4.0%)	
Low grade	12 (4.4%)	10 (3.6%)	2 (0.7%)	0 (0%)	
Preop motor deficit					0.003
Yes	14 (16%)	6 (6.7%)	0 (0%)	8 (9.0%)	
No	35 (5.7%)	24 (3.9%)	2 (0.3%)	9 (1.5%)	

TABLE 4. Types of long-term motor deficits

Effect	No. of Patients					
	Total	Face	Upper Extremity	Lower Extremity	Upper & Lower Extremity	Significant DWI Restricted Area
Mild (4/5 strength or better or isolated face)	30	1 (3.3%)	8 (27%)	7 (23%)	14 (47%)	9 (30%)
Moderate (3/5 strength)	2	0	1 (50%)	0	1 (50%)	1 (50%)
Severe (2/5 strength or worse)	17	0	2 (12%)	1 (5.9%)	14 (82%)	10 (59%)

subcortical stimulation mapping for the last 20 years. This technique is well established in its safety and efficacy, and we have found positive stimulation results to be unambiguous and reliable. Resection is stopped when there is positive stimulation of the descending pathways. We have also found negative results to be informative. According to our prior work, with negative mapping, very low functional morbidity rates (approximately 2%) can be expected.¹⁷

The current analysis expands on our previous report¹⁷ and describes the utility of stimulation mapping of the descending subcortical motor pathways and its impact on postoperative neurological morbidity in a large cohort of 702 patients with peritumoral gliomas. This report again illustrates the high-risk nature of these particular lesions as we encountered a relatively high rate of functional morbidity in the immediate postoperative period (30%).⁷ However, most of these functional morbidities resolved; only a small subset had any motor deficits that persisted long-term (7%), and only 2.4% experienced a persistent severe disabling deficit. Our findings also support prior reports of patients with an existing preoperative motor deficit who are at greater risk for worsening neurological function after surgery.^{17,30} Although histological tumor grade was not associated with the likelihood of developing a new or worsened motor deficit after surgery, higher rates of long-term morbidity were found in high-grade tumors. The DMRI-FT studies have revealed that high-grade gliomas tend to more frequently displace and distort the CSTs, whereas low-grade gliomas tend to infiltrate the motor fibers.¹ Perhaps the greater degree of associated edema and necrosis in high-grade tumors limits the ability of white matter to recover after surgery.

The utility and reliability of subcortical mapping is demonstrated by our findings that intraoperative mapping results could predict the likelihood of developing immediate and permanent motor deficits. When the subcortical motor pathways could be identified intraoperatively, there was a significantly higher risk of developing not only a new postoperative deficit, but also a permanent deficit persisting beyond 3 months, compared to cases in which the motor fibers could not be identified. For long-term deficits, there was an almost fourfold increase in the rate of deficits when the subcortical fibers were encountered by stimulation mapping. This suggests that when the resection was done close to the motor fibers, there was an increased risk of injury to these tracts and subsequent morbidity. In addition, it is possible that transected fibers can still be transiently stimulated to evoke a motor response during subcortical mapping. Thus, stimulation mapping provides valuable feedback on when the resection should be

stopped, based on a robust clinical correlation; proceeding without this information could likely result in even higher functional morbidity rates.

Vascular injury to subcortical motor fibers at the time of surgery can also lead to significant deficits that typically do not improve with time.^{21,25,30} In our cohort, significant regions of DWI restriction were observed on the immediate postoperative scan of 41% of patients who experienced a long-term deficit. Interestingly, in this subcohort experiencing long-term deficits, significant regions of DWI abnormality on postoperative imaging were observed much more frequently among the cases in which the subcortical motor pathways were not found than in the cases in which subcortical pathways were found by stimulation. We believe this reflects the two different major causes of long-term morbidity between the groups: mechanical injury to the tracts and vascular injury to the tracts. When the resection is taken close to the tracts, there is greater risk of mechanical injury to the tracts themselves. In cases in which the resection is stopped more distant from the functional pathways, inadvertent injury to the perforating arteries supplying portions of the motor fibers may result in significant morbidity. In two select patients who experienced long-term deficits, volumes of the resection cavity (pink) and regions of restricted DWI (green) on postoperative scans were segmented and overlapped with the preoperative motor fibers modeled by DMRI-FT (blue), to imply possible tract injury due to mechanical and/or ischemic injury. In the first of these illustrative cases (Fig. 1A–D), the patient suffered a long-term deficit, but the subcortical fibers were never identified by stimulation. Interestingly, the DMRI-FT CST did not intersect with the resection cavity, but a large bundle of motor fibers were seen to be located within the region of postoperative restricted DWI. In contrast, in the second case (Fig. 1E–H), intraoperative stimulation did identify the motor tracts, and the patient experienced a persistent motor deficit. As expected, a significant portion of the descending motor fibers can be observed running through the resection cavity (pink).

Conclusions

Resection of tumors within or adjacent to the motor cortex or subcortical tracts can be challenging and is associated with a high rate of immediate postoperative neurological morbidity. In our experience, 30% of patients had a new or worsened motor deficit postoperatively; however, most of these deficits were transient. When the resection was carried close to the motor fibers and direct stimulation localized the descending fibers, the rate of long-term

TABLE 5. Diffusion-weighted imaging abnormalities on postoperative imaging among patients with deficits

Parameter	No. of Patients w/ Long-Term Deficits	No. of Patients w/ Significant DWI Restricted Area	p Value
All patients	49	20 (41%)	
Subcortical pathway			0.049
Found	36	11 (31%)	
Not found	13	9 (69%)	
Histology			0.31
High grade	37	17 (46%)	
Low grade	12	3 (25%)	
Preop deficit			0.75
Yes	14	5 (36%)	
No	35	15 (43%)	

motor deficit was 12% (7.7% mild, 4.3% moderate/severe). If the subcortical pathways could not be identified, the incidence of long-term motor morbidity was 3.2% (1.7% mild, 1.4% moderate/severe). Using stimulation mapping techniques to identify descending motor pathways during resection of tumors in perirolandic regions facilitates the reduction of neurological morbidity to acceptable rates in these high-risk cases. Among the subcohort of patients who experienced a persistent motor deficit and in whom the subcortical pathway could not be localized by stimulation, there was a high incidence of restricted diffusion on postoperative imaging, suggesting that vascular injury to the tracts may be a major contributor to permanent deficits. Further study is needed to directly test the relationship between restricted diffusion and postoperative morbidity, but our results suggest that particular care should be taken to avoid injuring or coagulating perforating vessels while working near subcortical motor pathways.

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Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions

Conception and design: Berger, Han. Acquisition of data: Han, Morshed, Troncon. Analysis and interpretation of data: Berger, Han, Troncon, Jordan, Henry. Drafting the article: Han, Morshed. Critically revising the article: Berger, Morshed, Jordan, Hervey-Jumper. Reviewed submitted version of manuscript: Berger, Han, Morshed, Jordan, Henry, Hervey-Jumper. Statistical analysis: Han. Study supervision: Berger, Han, Henry, Hervey-Jumper.

Supplemental Information

Previous Presentations

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