Triple motor mapping: transcranial, bipolar, and monopolar mapping for supratentorial glioma resection adjacent to motor pathways

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OBJECTIVE Maximal safe resection of gliomas near motor pathways is facilitated by intraoperative mapping. The authors and other groups have described the use of bipolar or monopolar direct stimulation to identify functional tissue, as well as transcranial or transcortical motor evoked potentials (MEPs) to monitor motor pathways. Here, the authors describe their initial experience using all 3 modalities to identify, monitor, and preserve cortical and subcortical motor systems during glioma surgery.

METHODS Intraoperative mapping data were extracted from a prospective registry of glioma resections near motor pathways. Additional demographic, clinical, pathological, and imaging data were extracted from the electronic medical record. All patients with new or worsened postoperative motor deficits were followed for at least 6 months.

RESULTS Between January 2018 and August 2019, 59 operations were performed in 58 patients. Overall, patients in 6 cases (10.2%) had new or worse immediate postoperative deficits. Patients with temporary deficits all had at least Medical Research Council grade 4/5 power. Only 2 patients (3.4%) had permanently worsened deficits after 6 months, both of which were associated with diffusion restriction consistent with ischemia within the corticospinal tract. One patient's deficit improved to 4/5 and the other to 4/5 proximally and 3/5 distally in the lower limb, allowing ambulation following rehabilitation. Subcortical motor pathways were identified in 51 cases (86.4%) with monopolar high-frequency stimulation, but only in 6 patients using bipolar stimulation. Transcranial or cortical MEPs were diminished in only 6 cases, 3 of which had new or worsened deficits, with 1 permanent deficit. Insula location ($p = 0.001$) and reduction in MEPs ($p = 0.01$) were the only univariate predictors of new or worsened postoperative deficits. Insula location was the only predictor of permanent deficits ($p = 0.046$). The median extent of resection was 98.0%.

CONCLUSIONS Asleep triple motor mapping is safe and resulted in a low rate of deficits without compromising the extent of resection.

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KEYWORDS motor mapping; stimulation mapping; glioma; oncology

THERE is compelling evidence that more extensive resection improves progression-free and overall survival for patients with glioma.^{1–11} However, this goal must be balanced with the need to avoid postoperative neurological deficits by preserving functional cortex and subcortical tracts.^{12–14} New or worsened postoperative neurological deficits are associated with impaired quality of life¹⁵ and overall survival.^{16,17}

Although preoperative imaging modalities such as blood oxygen level–dependent functional MRI, magnetoencephalography, transcranial magnetic stimulation, and MRI fiber tracking can facilitate surgical planning, direct cortical and subcortical stimulation remains the gold standard for determining function.¹⁸ Of the above techniques, only MRI tractography can reliably identify subcortical motor pathways,¹⁹ however, intraoperative localization of deep

ABBREVIATIONS ADC = apparent diffusion coefficient; dcMEP = direct cortical MEP; EOR = extent of resection; HARDI = high angular resolution diffusion imaging; ISI = interstimulus interval; MEP = motor evoked potential; tcMEP = transcranial MEP.

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pathways using neuronavigation becomes increasingly inaccurate as tumor is resected and brain shift increases.²⁰

Bipolar stimulation is the most well-established technique for motor mapping. Initially described in humans by Wilder Penfield and colleagues in the first half of the 20th century,²¹ the technique has been incrementally improved over the following decades.^{13,22–24} More recently, a growing body of evidence supports the use of high-frequency monopolar stimulation^{25–27} for both cortical and subcortical mapping. While stimulation facilitates identification of functional tissue, motor evoked potentials (MEPs) can be utilized to monitor motor function during resection. This may be performed transcranially (tcMEP)^{28,29} or by direct cortical stimulation via a grid or strip electrode (dcMEP).^{26,28}

While these 3 techniques have been frequently used independently or in various combinations with each other, there is a paucity of data examining postoperative motor deficits when all 3 are used together. We hypothesized that the use of bipolar stimulation, monopolar stimulation, and MEP monitoring in combination would result in a lower rate of postoperative motor deficits when compared with historical controls using one or more techniques separately. Here, we present our initial experience using triple motor mapping during intraaxial tumor resection.

Methods

Patient Selection and Characteristics

We queried our institution's prospective registry of all resections using motor mapping to identify consecutively treated patients in whom triple modality mapping (defined as bipolar and monopolar stimulation in conjunction with tcMEPs and/or dcMEPs) was utilized for glioma resection. The decision to perform awake surgery with bipolar mapping or asleep surgery with triple motor mapping was based on the site and size of the tumor, patient preference, and whether other functions were also at risk. All patients were treated at the University of California, San Francisco Medical Center between January 2018 and August 2019. Intraoperative mapping data were extracted from the registry and operative and neurophysiologists' notes. Additional demographic, clinical, pathological, and imaging data were extracted from the patients' electronic medical records. All patients with new or worsened postoperative motor deficits were followed for at least 6 months. Deficits were considered permanent if they persisted at 6 months. All motor deficits were included, regardless of severity. IRB approval was granted by the University of California, San Francisco.

Anesthetic Protocol

All motor mapping was performed under general anesthesia. One patient had awake speech mapping and was then placed under general anesthesia for motor mapping. A short-acting neuromuscular blockade was used during induction. The patient was then maintained on 50%–70% nitrous oxide and a volatile halogenated anesthetic (sevoflurane, desflurane, or isoflurane, less than 0.5 minimum alveolar concentration) with remifentanyl. Propofol was prepared and placed in line but was only used if needed

to suppress stimulation-induced seizures. Bite blocks were placed bilaterally around the endotracheal tube. The patient's temperature was maintained above 36°C during motor mapping. All lines were placed in the ipsilateral limb when possible, and the contralateral face, arm, and leg were exposed during motor stimulation. Mechanical venous thromboembolism prophylaxis was not applied to the contralateral leg.³⁰

Surgical and Mapping Technique

All cases were performed using neuronavigation with overlaid corticospinal tractography. After registration, corkscrew electrodes were applied over the ipsilateral primary motor cortex based on navigation landmarks. Subdermal needle electrodes were placed in the contralateral face, upper arm, forearm, hand, upper leg, lower leg, and foot. High-frequency tcMEP monitoring was performed at intervals ranging from 1 to 5 minutes (0–200 V, 50- to 500- μ sec pulse duration, 0–9 pulses at 1- to 4-msec interstimulus interval [ISI]), depending on the amount of muscle movement generated by stimulation (Fig. 1A).

Bipolar cortical mapping was performed using the Ojemann stimulator (Radionics Inc.) with a 5-mm bipolar probe, delivering a biphasic square-wave pulse of 1-msec duration at 60 Hz. During stimulation, a neurophysiologist looked for electromyography changes, and all team members directly observed the patient. Stimulation commenced at 4 mA, and the current was incremented to a maximum of 16 mA. Where possible, a 4-contact strip electrode was passed subdurally for dcMEP monitoring (0–20 mA, 50- to 500- μ sec pulse duration, 0–9 pulses at 1- to 4-msec ISI) after optimizing the stimulation site and parameters to elicit responses from as many electromyography channels as possible (Fig. 2B). In some cases, we were not able to perform dcMEP because of scarring from previous operations, the distance from the craniotomy to the primary motor cortex, or brain shift. We reported any reduction in MEPs by > 20%.

Subcortical monopolar mapping was performed using high-frequency monopolar (0–20 mA, 500- μ sec pulse duration, 5 pulses at 4-msec ISI) and bipolar stimulation (Figs. 1B and 2C). Subcortical bipolar stimulation using the above parameters was used if deemed appropriate. In general, resection was ceased if monopolar stimulation thresholds of 5 mA or lower were encountered. In general, the goal of resection was to remove all the contrast-enhancing tumor for enhancing lesions and the FLAIR abnormality for nonenhancing tumors. For enhancing tumors, we attempted to remove as much of the FLAIR abnormality as possible based on functional limitations.

Imaging

All patients underwent postoperative MRI within 48 hours of resection. The examination was performed on a 3.0T scanner (GE Healthcare) and included 3D T1- and T2-weighted sequences as well as a high angular resolution diffusion imaging (HARDI) sequence with the following parameters: TR 6425 msec, TE 80 msec, 50 axial slices, 2-mm slice thickness, b value = 2000 sec/mm², and 55 diffusion gradients.

FIG. 1. Illustrations of the triple motor mapping technique. **A:** Illustration of monitoring with tcMEP and dcMEP electrodes. **B:** Illustration of subcortical mapping and current spread from bipolar and monopolar probes. Copyright Kenneth X. Probst. Published with permission.

Preoperative and postoperative tumor volumes were calculated using the Brainlab Elements SmartBrush tool (version 2.6). For contrast-enhancing tumors, the enhancing component on the T1-weighted sequence was measured, whereas for nonenhancing tumors, volumes were measured using the FLAIR signaling abnormality.

For patients with postoperative deficits, the postoperative MRI scan was reviewed to identify any areas of diffusion-weighted imaging and corresponding apparent diffusion coefficient (ADC) abnormality to suggest ischemic injury.

Corticospinal tractography was performed using methods we have previously published.³¹ In brief, HARDI data and anatomical sequences were analyzed offline using the AW Server (General Electric). A seed region of interest and a target region of interest were placed on the cerebral

peduncle and primary motor cortex ipsilateral to the surgical cavity; fiber tracking employed a fractional anisotropy threshold of 0.15 and a tract angular change of 60°. Tracked white matter fibers were included as an object on the 3D T1-weighted MR images, and the shortest distance between the tract and surgical cavity was determined by a neuroradiologist (J.E.V.M.).

Statistical Analysis

The statistical significance of univariate predictors of postoperative deficits was determined using the Fisher exact test. The Student t-test and the Mann-Whitney U-test were used for parametric and nonparametric continuous variables, respectively. Pearson's correlation coefficient was used to determine the strength of the relationship be-

FIG. 2. Example case of triple motor mapping. **A:** Axial contrast-enhanced T1-weighted MR image demonstrating a precentral tumor in a 60-year-old patient with progressive left leg weakness and focal seizures, with overlaid corticospinal tractography. **B:** Intraoperative photograph before resection, demonstrating a positive bipolar stimulation site (3) and a 4-contact electrode for dcMEP. **C:** Intraoperative photograph demonstrating subcortical monopolar mapping during tumor resection.

tween monopolar stimulation and the distance to the corticospinal tract. All statistical analyses were performed in R (version 3.5.3, r-project.org).

Results

Patient Characteristics and Mapping Details

Between January 2018 and August 2019, 59 operations utilizing triple motor mapping were performed in 58 patients. One patient underwent a second operation for recurrence 14 months after their initial operation. Patient demographics are presented in Table 1. Only 2 patients (3.4%) had intraoperative seizures, which were terminated rapidly with cold irrigation. In both cases, mapping could resume after termination of the event.

Although tcMEP monitoring was performed in all cases, dcMEP monitoring was possible in only 45.8% of cases. The use of dcMEP was limited by scarring from previous operations, by the distance from the craniotomy to the primary motor cortex, or brain shift. MEPs were noted to irreversibly diminish in 6 cases (10.2%). One patient had loss of foot responses that were associated with transiently worsened mild weakness (patient 4, Table 2). In the other cases, the stimulation amplitude had to be increased 20%–40% for the same effect. One of these patients had mild transient weakness (patient 2), and another had moderate permanent weakness related to an infarct (patient 6). The other 3 changes in MEPs were likely artifactual, related to brain shift away from the inner table. The negative predictive value for MEP monitoring was 94.3%, but the positive predictive value was only 50%.

Subcortical mapping was performed using a combina-

tion of bipolar and monopolar stimulation. Descending motor pathways were identified using monopolar stimulation in 51 cases (86.4%). No deficits occurred in patients in whom a monopolar threshold could not be identified. Subcortical bipolar stimulation was utilized in 20 cases but was only positive in 6 (30%), all of whom had monopolar stimulation thresholds of less than 10 mA. Using a distance threshold of 5 mm, the positive and negative predictive values of monopolar stimulation were 49.0% and 88.0%, respectively.

Postoperative HARDI tractography was available in 50 cases (84.7%), and the motor pathways could be stimulated in 43 (86.0%) of these. All resections stopped at least 2 mm away from the corticospinal tract based on postoperative tractography. In the 7 cases in which motor pathways could not be stimulated (up to 20 mA), the mean distance to the corticospinal pathway was 19.0 mm (range 15–22 mm). There was a strong linear relationship between the amplitude required for monopolar stimulation and the distance from the resection cavity to the motor pathways (Pearson's correlation coefficient 0.77, $p < 0.0001$; Fig. 3). Using the derived regression formula, stimulation at 5, 10, 15, and 20 mA equated with distances of 5.7, 9.5, 13.3 and 23.8 mm, respectively.

Postoperative Neurological Deficits and EOR

Patients in 6 cases (10.2%) had new or worse immediate postoperative motor deficits. However, only 2 patients (3.4%) had deficits that did not recover back to baseline by 6 months (Table 2). All 4 transient deficits were mild at discharge. The persistent deficits in the 2 patients were initially severe; however, they improved substantially. At

TABLE 1. Patient demographics and tumor characteristics

Characteristic	Value
Total no. of patients	58
No. of operations	59
Sex	
Female	28 (48.3)
Male	30 (51.7)
Median (range) age at op, yrs	50 (17–81)
Side of tumor	
Lt	15 (25.4)
Rt	44 (74.6)
Site of tumor	
Frontal	18 (30.5)
Temporal	11 (18.6)
Parietal	12 (20.3)
Insula	7 (11.9)
Multilobe*	11 (18.6)
Preop motor deficit	
Yes	22 (37.3)
No	37 (62.7)
WHO grade	
I	1 (1.7)
II	12 (20.3)
III	9 (15.3)
IV	37 (62.7)
Histology	
Glioblastoma	37 (62.7)
Anaplastic oligodendroglioma	4 (6.8)
Anaplastic astrocytoma	4 (6.8)
Oligodendroglioma	7 (11.9)
Diffuse astrocytoma	4 (6.8)
Other†	3 (5.1)

Values represent the number (%) unless stated otherwise.

* Six cases included the insula.

† Ependymoma, anaplastic pleomorphic xanthoastrocytoma, and anaplastic pilocytic astrocytoma.

last follow-up, patient 5 had a facial droop, with 4/5 upper-limb weakness and normal lower-limb power. Patient 6 had 4+/5 upper-limb and 4/5 lower-limb weakness proximally and 3/5 distally and was ambulant with an orthosis and able to perform on tandem gait testing. Both patients with permanent deficits had new areas of diffusion restriction in or adjacent to the corticospinal tracts on postoperative imaging (Fig. 4).

Insula location ($p = 0.001$) and reduction in MEPs ($p = 0.01$) during resection were the only univariate predictors of a new or worse postoperative deficit (Table 3). Insula location ($p = 0.046$) was the only predictor of permanent deficits.

Postoperative volumetric imaging was available for all patients. The median extent of resection (EOR) was 98.2%. Overall, 100% resection, > 90% resection, and >

TABLE 2. Patients with new or worse postoperative motor deficits

Pt No.	Age (yrs)	Presentation	Previous Resection	Location	Preop Deficit	Worst Recorded Postop Deficit	Permanent Neurological Deficit	Monopolar Subcortical Stimulation Threshold (mA)	Time Until Resolution	MEP Changes	Postop Ischemia	Histology
1	26	Seizure	No	Frontotemporoinsula	None	Mild facial droop	None	13	6 days	No	No	Diffuse astrocytoma, IDH mutant
2	32	Headache	No	Temporoinsula	None	Mild facial droop & 4+/5 hand weakness	None	9	3 days	Yes	No	Anaplastic astrocytoma, IDH mutant
3	62	Seizure	Yes	Insula	4+/5 UE; 4+/5 LE	1/5 UE; 1/5 LE	5–/5 UE; 5–/5 LE	5	2 wks	No	No	GBM, IDH mutant
4	28	Seizure	Yes	Precentral gyrus	4+/5 LE	4/5 UE; 4+/5 LE	4+/5 LE	4	3 wks	Yes	No	Ependymoma
5	42	Seizure	Yes	Frontoinsula	None	Facial droop; 4+/5 UE; 0/5 LE	Facial droop; 4+/5 UE; 5/5 LE	7.5	Permanent	No	Yes	Anaplastic oligodendroglioma, IDH mutant & 1p19q codeleted
6	46	Seizure	Yes	Insula	Facial droop & pronator drift	Facial droop; UE 3/5; LE 3/5	4+/5 UE; 4/5 LE	2.5	Permanent	Yes	Yes	GBM, IDH wildtype

IDH = isocitrate dehydrogenase; LE = lower extremity; Pt = patient; UE = upper extremity.

FIG. 3. Monopolar stimulation thresholds and distance to the corticospinal tracts. Scatterplot and regression line (with 95% confidence intervals) demonstrating the relationship between stimulation intensity during monopolar mapping and the distance to the motor fibers, as measured on postoperative tractography. Pearson's correlation coefficient 0.77 ($p < 0.0001$). Figure is available in color online only.

70% resection were achieved in 25 (42.4%), 45 (76.3%), and 54 (91.5%) cases, respectively. There was no difference in EOR between patients with postoperative deficits and those without ($p = 0.65$). Likewise, there was no association between positive mapping and EOR ($p = 0.66$).

Discussion

Major Findings

Our results demonstrate the safety of resecting tumors near motor pathways using triple motor mapping. Overall, patients in 6 cases (10.2%) had new or worsened postoperative motor function. Only 2 patients (3.4%) had permanent postoperative deficits, both of which were attributable to stroke rather than direct motor injury. There were no cases of severe permanent deficits. The risk of a deficit was higher in patients with insular involvement and in those in whom there was a change in tcMEP or dcMEP recordings. Subcortical motor pathways were identified in 86.4% of patients with monopolar stimulation, but in only 30.0% of cases in which subcortical bipolar stimulation was attempted.

Adding Subcortical High-Frequency Monopolar Stimulation

This paper was derived from a dissatisfaction with current methods of motor mapping. In the senior author's recent series of 702 motor mapping cases using bipolar stimulation,¹² descending pathways could only be identified in 43% of cases; 30% of patients had new or worsened motor deficits, and 7% had persistent deficits, one-third of which were severe (2/5 strength or worse). Only 41% of patients with permanent deficits had significant areas of restricted diffusion on postoperative MRI, suggesting that their deficits were due to direct transgression of the motor system. Our current results demonstrate a much greater ability to identify the motor system and to preserve motor function in the asleep setting, although we did not perform a direct statistical comparison.

Current spread from monopolar and bipolar electrodes is distinct. Bipolar charge is transmitted from one arm of the probe to the other. The electrical field rapidly dissipates beyond the probe but activates tissue between the arms (Fig. 1B).³² The technique is ideal for cortical stim-

FIG. 4. Patient 5. Postoperative diffusion restriction in a 42-year-old patient who underwent re-resection of a fronto-insular anaplastic oligodendroglioma and had a permanent deficit. **A:** Preoperative axial FLAIR MR image with overlaid tractography. The primary aim of surgery was to resect a new enhancing nodule, and the FLAIR abnormality was debulked until the subcortical monopolar threshold was 5 mA. **B:** Postoperative axial FLAIR sequence with overlaid tractography, demonstrating resection of the posterior insular nonenhancing tumor and a 4-mm distance from the corticospinal tract to the cavity. **C and D:** Postoperative ADC maps, with (C) and without (D) overlaid tractography, demonstrating ischemia within the corticospinal tract.

ulation where the goal is to answer the binary question: is the underlying cortex functional or not? We utilized bipolar polar cortical stimulation to identify motor cortex for dcMEP monitoring and also to identify function-free corridors to access the tumor.

In contrast to a bipolar probe, charge from a monopolar electrode spreads radially from the tip, toward a distant reference electrode (Fig. 1B).³² This spread allows the surgeon to modulate the stimulator current to estimate the distance to motor pathways. This both increases the sensitivity of mapping and allows greater spatial resolution.

Szelényi et al.³³ directly compared bipolar and monopolar subcortical stimulation in 20 patients. Stimulation was positive at 92% of sites using monopolar but only at 54% of sites using a bipolar probe. Similarly, we were able to elicit monopolar stimulation in 86.4% of cases; however, only in 30.0% of cases using the bipolar probe and in all cases in which bipolar stimulation was possible was the monopolar threshold less than 10mA.

Several groups have previously demonstrated that the current required for monopolar subcortical stimulation

in milliamps roughly approximates the distance to motor pathways in millimeters.^{34–38} Thus, it provides an earlier warning of proximity to motor pathways and also quantifies the distance. We have demonstrated a high correlation between distance and current using monopolar stimulation, with the 2 numbers being approximately equal.

Subcortical bipolar stimulation does not conform to the same relationship. Zhu et al. demonstrated that the distance of positive bipolar stimulation sites from motor pathways (based on intraoperative tractography) ranged from 2.0 to 14.7 mm with a mean of 5.2 mm.³⁹ Similarly, we found that in most cases subcortical bipolar stimulation was not possible, and, when it was, the distance to motor fibers varied from 2 to 11 mm with a mean of 6.3 mm. Additionally, lack of bipolar stimulation may be falsely reassuring. There were 2 cases in our series with negative bipolar stimulation, despite the stimulation point being within 5 mm of the motor pathways.

Adding tcMEP and dcMEP Monitoring

Although commonly employed for brainstem and spinal cord procedures, there is more limited evidence for the role of MEP monitoring for supratentorial brain tumor resection.

Taniguchi et al.²⁵ utilized direct high-frequency (300–500 Hz) stimulation of the motor cortex, demonstrating that responses could be achieved at much lower voltages than with lower-frequency (50–60 Hz) stimulation. Kombos et al.⁴⁰ performed dcMEP in 70 patients and demonstrated that irreversible changes in latency or loss of potentials was associated with postoperative neurological deficits. Reversible changes in MEPs were often due to retraction or movement of the electrode. Most cases of MEP deterioration are reversible, and permanent loss is associated with a high risk of permanent deficit from stroke.²⁸ This raises the concern that, rather than providing a warning, signal alterations may occur after irreversible damage to motor pathways has already occurred.⁴¹ The high negative predictive value (94.3%) and low positive predictive value (50%) of MEP monitoring emphasize that it should be seen as a screening tool for damage to motor pathways rather than as a diagnostic tool. Thus, the value of MEP monitoring may be that it reassures the surgeons that the motor system is intact and that resection may proceed. However, false negatives (i.e., new deficits occurring despite stable monitoring) may occur in up to 14% of cases.^{29,40} This has been attributed to postoperative edema or hemorrhage. In our study the false-negative rate was 5.7%, with 1 permanent deficit attributable to stroke (which may have occurred after cessation of monitoring) and 2 mild transient deficits without a clear cause. In all 3 cases, monitoring was performed with tcMEP rather than dcMEP.

We utilized tcMEP monitoring more than other groups,^{28,42} possibly because of scarring from previous resections or our preference for small craniotomies and negative mapping, making direct cortical stimulation more difficult.

New or Worse Deficits and EOR

Immediate postoperative deficits may occur in up to 60%^{12,28,43} of resections of tumors in or near motor pathways. Indeed, transient deficits may be associated with

TABLE 3. Univariate predictors of new or worse motor deficits (transient or permanent)

Variable	Total	Deficit	p Value
Number of operations	59	6 (10.2)	
Mean age, yrs	50.3	39.6	0.06
Sex			0.67
Female	28 (48.3)	2 (7.1)	
Male	30 (51.7)	4 (13.3)	
Side			>0.99
Lt	15 (25.4)	1 (6.7)	
Rt	44 (74.6)	5 (11.4)	
Site			0.001
Insula	13 (22.0)	5 (38.5)	
Not involving insula	46 (80.0)	1 (2.2)	
Preop motor deficit			0.66
Yes	22 (37.3)	3 (13.6)	
No	37 (62.7)	3 (8.1)	
Previous resection			>0.99
Yes	34 (57.6)	4 (11.8)	
No	25 (42.4)	2 (8.0)	
High-grade glioma			0.60
Yes	46 (78.0)	4 (8.7)	
No	13 (22.0)	2 (15.4)	
Decrease or loss in MEP			0.01
Yes	6 (10.2)	3 (50.0)	
No	53 (89.8)	3 (5.7)	
Monopolar threshold ≤ 5 mA			0.34
Yes	18 (30.5)	3 (16.7)	
No	41 (69.5)	3 (7.3)	

Boldface type indicates statistical significance.

improved survival,¹⁶ likely because of a greater EOR. Permanent deficits, however, may be associated with worse survival^{16,17} and quality of life.¹⁵ Improvements in monitoring and mapping techniques have decreased the rate of permanent deficits. The rate of permanent deficits in studies utilizing a single monitoring or mapping modality has been reported to be between 7% and 12.5%.^{12,28,39} Groups utilizing both MEP monitoring and monopolar subcortical stimulation^{26,41,42} have demonstrated rates of permanent neurological deficits of 5% or less. In the present series utilizing triple modality mapping, permanent deficits occurred in 2 patients (3.4%), both of which were due to ischemia rather than direct transgression of the motor system. Other than insula location, there were no statistically significant predictors of permanent deficits, likely because of the rarity of this event.

We have previously reported median EORs of 96% and 88% for first resection of glioblastoma⁵ and low-grade glioma,⁶ respectively. In this series, we achieved a comparable median EOR of 98.2%, despite the proximity to motor pathways and the high proportion of recurrent tumors.

Limitations and Generalizability

Although cases were identified from a prospective reg-

istry, this is a retrospective study and limited by the quality of data collected within the medical record. Documentation of motor outcome was based on inpatient notes, discharge summaries, and clinic letters written by the treating residents, neurosurgeons, and neurooncologists. It is possible that examination by an independent examiner may have revealed subtle deficits that were missed during these visits. Although we have demonstrated significantly improved clinical outcomes when compared with our previous mapping technique, it is possible that these results are in part due to other factors, such as greater experience or increased use of navigated tractography.

These are the results of subspecialist tumor neurosurgeons, with a dedicated anesthesia and neuromonitoring team working in a high-volume center, and they may thus not be generalizable to all surgeons and institutions. However, the principles utilized may be learned by any experienced neurosurgeon and integrated into practice.

Conclusions

Transcranial and direct cortical MEP monitoring combined with bipolar and monopolar stimulation resulted in improved localization of functional tissue and low rates of transient and permanent deficits. Monopolar stimula-

tion could reliably predict the distance to the corticospinal tract. All permanent postoperative deficits were related to ischemia rather than direct injury to motor pathways. Compared with our previous experience with subcortical bipolar stimulation to localize deep motor tracts, the triad of triple motor mapping is superior in terms of enhancing efficient resection while minimizing motor deficits.

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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: Gogos, Hervey-Jumper, Berger. Acquisition of data: Gogos, Young, Morshed, Avalos, Noss, Villanueva-Meyer, Berger. Analysis and interpretation of data: Gogos, Young, Morshed, Noss, Villanueva-Meyer, Berger. Drafting the article: Gogos. Critically revising the article: Gogos, Young, Morshed, Noss, Villanueva-Meyer, Hervey-Jumper, Berger. Reviewed submitted version of manuscript: Gogos, Young, Morshed, Avalos, Villanueva-Meyer, Hervey-Jumper, Berger. Approved the final version of the manuscript on behalf of all authors: Gogos. Statistical analysis: Gogos. Study supervision: Hervey-Jumper, Berger.

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