Optimization of direct cortical stimulation using tibial versus median nerve sensory mapping during midline brain tumor resection: illustrative case

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BACKGROUND During brain tumor resection, neurophysiological mapping and monitoring help surgeons locate, characterize, and functionally assess eloquent brain areas in real time. The selection of mapping and monitoring targets has implications for successful surgery. Here, the authors compare direct cortical stimulation (DCS) as suggested by median nerve (MN) with posterior tibial nerve (PTN) cortical sensory mapping (SM) during mesial lesion resection.

OBSERVATIONS Recordings from a 6-contact cortical strip served to generate an MN and a PTN sensory map, which indicated the strip was anterior to the central sulcus. Responses exhibited an amplitude gradient with no phase reversal (PR). DCS, elicited through a stimulus probe or contact(s) of the strip, yielded larger responses from the corresponding sensory mapped limb; that is, PTN SM resulted in larger lower limb muscle responses than those suggested by MN SM.

LESSONS SM of the MN and PTN is effective for localizing eloquent cortical areas wherein the PTN is favored in surgery for mesial cortical tumors. The recorded amplitude of the cortical somatosensory evoked potential is a valuable criterion for defining the optimal location for DCS, despite an absent PR. The pathway at risk dictates the specifics of SM, which subsequently defines the optimal location for DCS.

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KEYWORDS sensory mapping; motor mapping; phase reversal; direct cortical stimulation; midline tumor; maximum amplitude criteria; case report

The combination of mapping and monitoring cortical structures through intraoperative neurophysiology aims to facilitate maximum tumor resection while preserving function by avoiding eloquent tissue. Brain tumors and other space-occupying lesions, whose mass effects cause anatomical and physiological shifting and/or distortion, pose a particular risk of neural insult during resection.1 Neurophysiological brain mapping techniques provide surgeons with a reliable tool for localization, demarcation, and characterization of the motor and sensory pathways.1,2 They provide critical information for the development of the surgical strategy intraoperatively, for example, by helping to determine a safe point of entry and approach to the lesion, and can also define the tumor boundaries during resection. Intraoperative neurophysiological monitoring (IOM) provides real-time functional assessment, diminishing surgical risk and guiding the extent of tumor resection by allowing intervention ahead of deficit permanence. Monitoring in these cases can use techniques similar to those used for mapping.

Neurophysiological tools include sensory and motor mapping. Sensory mapping (SM) involves a cortical strip or grid electrode used to capture electrocorticographic somatosensory evoked potentials (SSEPs) and often incorporates the determination of an SSEP phase reversal (PR). SSEPs, elicited by activation of a peripheral sensory nerve, have the opposite polarity within the postcentral versus the precentral gyrus. Hence, the polarity, or phase, of the SSEP reverses across the central sulcus (CS), therefore suggesting the location of the CS and the precentral and postcentral gyri.1,2

ABBREVIATIONS CS = central sulcus; DCS = direct cortical stimulation; EEG = electroencephalography; FLAIR = fluid-attenuated inversion recovery; IOM = intraoperative neurophysiological monitoring; MEP = motor evoked potential; MN = median nerve; MRI = magnetic resonance imaging; PR = phase reversal; PTN = posterior tibial nerve; SM = sensory mapping; SSEP = somatosensory evoked potentials.

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In some instances however, there is no observed PR of the SSEP.\(^1\)\(^-\)\(^5\) This indicates, among other things, that the recording electrode is not positioned across the CS. The SSEPs obtained in this case are still informative, as the location of the postcentral or precentral gyrus can be inferred by the amplitude gradient of the SSEP responses obtained along the cortical electrode.\(^1\)\(^-\)\(^4\)\(^,\)\(^6\) In any case, the waveforms obtained during SM further serve as important indicators of the optimal location for subsequent motor mapping through direct cortical stimulation (DCS) of the primary motor cortex.\(^5\)\(^-\)\(^9\) DCS is a neurophysiological tool used for mapping the proximal motor pathway. It involves electrical stimulation of the cortex itself through a handheld probe or a cortical strip/grid electrode with concomitant recording of motor evoked potentials (MEPs) from muscles or the distal motor tracts. Although initially used for mapping, DCS also serves as a powerful tool to continuously monitor motor function during resection by leaving the cortical electrode in place after the mapping. Through a contact(s) of the cortical electrode at or near the location suggested by SM and subsequently validated by DCS motor mapping, an optimized stimulus is delivered to the cortex to repeatedly elicit responses in appropriate targets for the duration of the resection. In instances in which the lesion is superficial, the depth of penetration of the stimulus must be well controlled to avoid eliciting responses by activation of the motor pathway distal to the location of a possible insult.

SSEPs derived from median nerve (MN) stimulation are most common during SM and the PR evaluation. In this instance, the polarity of early sensory components, the N20 and the P20, which localize to the postcentral and precentral gyri, respectively, are compared. The representation of the MN in the sensory cortex is lateral;\(^2\) thus, this method has proven to be very useful for localizing the CS during surgery for lateralized lesions or lesions that require a lateral approach. The results of this kind of SM set the stage well for DCS to localize and/or continuously monitor the lateral motor cortical regions such as those that modulate function of the hand, arm, and face. However, upper extremity–derived SM and PR can be less useful for lesions located medially and away from the hand representation in the homunculus.\(^2\) In these circumstances, PR of SSEPs corresponding to activation of a nerve in the lower extremity is applicable and better supports localization via DCS of the corresponding motor cortical regions modulating function of the lower extremity. Reports of mapping using SSEP PR after stimulation of the femoral nerve, peroneal nerve, or posterior tibial nerve (PTN) have demonstrated their utility specifically during surgery for the resection of tumors located in the paracentral lobule.\(^3\)\(^-\)\(^6\)\(^,\)\(^9\)\(^,\)\(^10\)

The foot sensory representation is located deep down the longitudinal fissure.\(^10\)\(^,\)\(^11\) Consequently, a clear PR may be difficult to identify. Therefore, the use of DCS for localization is an indispensable complementary tool for identification of the precentral gyrus in surgery for medialized lesions. Furthermore, the localizing benefits of DCS are integral for subsequent continuous monitoring of motor function, particularly when stimulation is provided through an electrode that is parked on the same cortical location throughout resection.\(^2\)\(^,\)\(^4\)\(^,\)\(^10\)

Here we present a case report directly comparing our DCS results using the “optimal” stimulation location suggested by SM of MN- versus PTN-derived SSEPs during resection of a lesion in the paracentral lobule. We demonstrate that at a similar stimulus intensity, defined lower extremity motor responses were elicited via DCS at the location suggested by the PTN SM, thus enabling protection of the tissue at greatest risk for surgical infringement. In contrast, poor lower motor responses were elicited at locations suggested by the MN SM. These observations highlight the importance of accurate evaluation of SM, particularly when there is no PR. They also emphasize the need to include a lower extremity nerve in the SM when confronted with medial lesions or surgical points of cortical entry. All of this has direct implications for effective protection of the cortical motor pathway.

Illustrative Case

Examination and Diagnosis

A 53-year-old right-handed male presented with a sudden loss of vision in his right eye. During workup for an ophthalmic artery occlusion, magnetic resonance imaging (MRI) with and without contrast revealed an approximately 2-cm right frontal mesial fluid-attenuated inversion recovery (FLAIR) abnormality without abnormal enhancement (Fig. 1). Expansion of the involved gyrus was noted on the MRI. He underwent further workup for demyelinating disease; however, it was negative. Based on all this, the decision was made to surgically excise the tumor by a right frontal craniotomy.

Surgery

The dura was opened in a curvilinear fashion and reflected toward the midline, exposing the falx. Consistent with the imaging, the involved gyrus appeared grossly expanded. A cortical strip electrode was inserted posteriorly, under the edge of the cranium, to overlay both the exposed cortex and the obscured cortex posterior to the craniotomy. DCS via a hand-held stimulating probe resulted in a lack of motor responses, indicating no exposure of the precentral gyrus and

![FIG. 1. MRI showing abnormality located in the right mesial superior frontal convolution: axial T2-weighted (A), axial FLAIR (B), coronal FLAIR (C), and sagittal FLAIR (D) sequences.](image-url)
no involvement of the primary motor cortex. Utilizing both direct observation and stereotactic guidance, the abnormality was dissected circumferentially around its edges. Based on intraoperative observation and postoperative MRI results, it was determined that gross-total resection of the FLAIR abnormality was achieved. The pathology was consistent with increased cellularity and mild atypia, negative for p53, Ki-67, and IDH1. The patient’s neurological examination was unchanged after surgery.

Intraoperative Neurophysiological Monitoring

Modalities

SSEPs elicited from the MN and PTN, MEPs elicited transcranially by stimulation at C3 and C4 from the left brachioradialis, abductor pollicis brevis, medial gastrocnemius, tibialis anterior, and abductor hallucis muscles bilaterally, and electroencephalography (EEG) from 8 channels were performed according to their standard application, as defined by the respective published guidelines. 

Baseline SSEP and transcranial MEP responses and EEG data were obtained prior to incision and were maintained throughout the procedure but will not be discussed further.

Anesthesia Regimen

Anesthesia was induced with 20 mg propofol and 20 mg succinylcholine and maintained using a total intravenous regimen. Propofol infusion was initially at a rate of 150 µg/kg/min and maintained throughout the procedure at 200 µg/kg/min starting shortly after incision. The remifentanil infusion was at a rate of 0.1 µg/kg/min.

Sensory Mapping and Phase Reversal

After the craniotomy and opening of the dura, SM was performed by recording averaged SSEP responses from a 1 × 6 cortical strip electrode (Adtech) placed by the surgeon. The cortical strip remained in the same location and orientation during MN stimulation and during PTN stimulation. Each contact of the cortical strip was referred to a scalp electrode located at Fpz. Low-cut and high-cut filter settings were 30 and 1500 Hz, respectively. Standard SSEP scalp derivations were included in the mapping montage as a control. Responses for SM were elicited by alternately stimulating the left MN and left PTN with 50-mA, 500-µsec pulses at 2.71 Hz.

Direct Cortical Stimulation

During DCS for motor mapping or motor monitoring, trains of anodal 250-µsec pulses consisting of 4 pulses per train with a 4-msec interpulse interval (250 Hz) were delivered at 0.76 Hz. For motor mapping, stimuli were delivered through a surgeon-held, 3-mm, ball-tipped stimulating probe. The surgeon used a hunting algorithm and moved the stimulating probe over the surface of the brain around the border of the tumor and evaluated motor responses to find a safe nonmotor entry point. Motor responses were absent during this phase of DCS at stimulation intensities as high as 20 mA. Once a safe surgical entry point was defined, DCS for motor monitoring was elicited through a contact of the strip electrode, which remained in the same cortical location where the SM was performed. DCS MEPs were recorded from the same muscles as indicated for Transcranial Motor Evoked Potentials, and responses favoring the lower extremity were stable throughout the resection.

Patient Informed Consent

The necessary patient informed consent was obtained in this study.

Discussion

Observations

To satisfy the surgical requirements, neurophysiological sensory and motor mapping was performed. SSEP responses were obtained from all 6 cortical strip recording channels after stimulation of the MN or PTN; however, no PR was observed. Downward deflecting MN responses decreased in amplitude from contact 2 to contact 5, suggesting that the entire electrode was anterior to the CS and contacts 1 and 2 were presumed to be nearest to the precentral gyrus (Fig. 2A). Upward-deflecting PTN responses were largest under contacts 3 and 4, suggesting that they were nearest to the precentral gyrus, and the response polarity was consistent with the suggestion from the MN SM that the electrode was anterior to the CS (Fig. 2B).

Based on the insights gained via SM, we initiated DCS for motor mapping with a targeted stimulus ramping paradigm. Stimulating at 11.4 mA through contact 2, the contact demonstrating the highest amplitude from MN SM, resulted in robust responses of the left upper extremity and small responses in the left lower extremity (Fig. 3A). Stimulating at 11.4 mA through contact 3, the contact demonstrating the highest amplitude from PTN SM, resulted in robust responses from the left lower extremity and small responses in the left upper extremity (Fig. 3B). This stimulus intensity was applied throughout motor monitoring.

Our observations demonstrated the utility of SM to define the optimal stimulating contact for DCS for interhemispheric tumor removal, even in the absence of a true PR per se. The stimulation intensity was the same at each DCS location, and the strip electrode remained in place after the SM, thus facilitating a direct comparison of the mapping results from the MN versus the PTN. These data informed the surgical strategy, allowing for safe tumor resection by defining a safe entry point, and provided the optimal cortical location and stimulation parameters for continuous monitoring of the motor pathway at risk.

SM is a well-established technique used to localize the CS and the precentral and postcentral gyri, thus linking the anatomical and functional topography. Typically, the generators of the MN are mapped because of their large cortical representation and corresponding large-amplitude, well-documented, archetypal cortical potentials and because these potentials produce a PR across the CS. Although more difficult to obtain, sensory potentials elicited from the lower extremity also reverse phase across the CS, and this is helpful in localizing the CS medial to the cortical generators of upper extremity SSEPs. PR following stimulation of the femoral nerve or PTN has been reported, albeit rarely for the PTN. Femoral nerve cortical SSEPs originate from the superior lip of the interhemispheric fissure, medial to the representation of the upper extremity, yet lateral to the representation of the distal lower extremity. Thus, despite their often smaller potentials, femoral nerve SSEPs for mapping the CS in locations medial to the representation of the upper extremity may be preferred. The source of the cortical representation for the distal lower extremity such as for the PTN is situated in the interhemispheric fissure and therefore may lead to variable SSEP distributions. Further complicating their utility, the temporal dispersion of the action potentials associated with the long pathway of the
PTN may make it difficult to record PTN SSEPs particularly to localize the CS. Our case indicates that for the true interhemispheric lesion, SM via PTN SSEPs proved versatile. Occasionally, sensory potentials do not display a PR, even following MN stimulation. This could be due to the position and orientation of the electrode, anatomical distortion, or physiological rearrangement of the brain tissue due to a space-occupying lesion and may be impacted by limitations imposed by the exposure. Other studies have also shown that the N20 does not necessarily reverse phase when mapping away from the hand area. The absence of an observed PR of PTN SSEPs has also been previously reported. Wood et al. reported no observed PTN SSEP PR in 6 of 6 cases during mapping for midline tumors. Alba and Seki reported a PR in 1 of 4 cases in which the PTN was used to identify the CS in surgery for interhemispheric tumors wherein the grid was applied to the upper mesial surface of the hemisphere. In the other 3 cases was inconclusive. Subsequent reports have corroborated the difficulty in obtaining PR with the PTN. In contrast, Kombos et al. reported successful PR after PTN stimulation in 3 of 3 patients. We did not observe a PR of either the MN or PTN SSEP, and the strip seemed to be located anteriorly; that is, all the observed potentials were out of phase with those obtained at the scalp (Fig. 2). Therefore, the strip location on the cortex explains this lack of PR, which is consistent with the imaging data (Fig. 1). Because surgical restrictions excluded further manipulation of the strip in our case, we switched to the maximum amplitude criterion to identify optimal stimulation contacts for DCS.

The CS can also be indicated by the contact giving the highest amplitude SSEP as nearest to the CS. This is particularly helpful when a PR is absent or indiscernible. In an early report on PTN SSEPs for SM, Wood et al. suggested using the amplitude criterion for CS localization. Several authors have corroborated the amplitude criterion in subsequent reports.

SM is an initial step in motor functional localization. Because SM implies and does not directly distinguish function, it is recommended to follow SM with motor mapping regardless of the presence or absence of a PR. As previously reported, the contact with the largest amplitude from the SM was chosen for DCS. Stimulation from contact 3, as suggested by the PTN map (Fig. 2B), resulted in robust responses from muscles of the lower limb (Fig. 3B). This is consistent with the medial distribution of sensory and motor cortical components of the lower extremity. Importantly, selecting contact 3 allowed efficient monitoring of the motor pathways at risk during the resection. Stimulation through contact 2, as suggested by the MN map (Fig. 2A), yielded robust responses semiselectively from the upper limb muscles (Fig. 3A). This is consistent with the lateral anatomical and somatotopic organization of the median nerve. It has been demonstrated that the hand representation on the cortex is located 6 to 7 cm lateral to the midline. The shift between stimulating at contact 2 and contact 3 (10 mm apart) based on the results of the different sensory maps was crucial for discriminating and monitoring the surgical target tissue. This difference in the activated muscles during DCS is attributable to the position and/or orientation of the strip but also could have resulted from anatomical and functional rearrangement of the brain structures due to the lesion. Because motor functional areas can be elucidated through

![FIG. 2. Sensory mapping of the cortical representation of the left MN and PTN. Cortical potentials after left MN stimulation obtained from a strip electrode placed directly on the surface of the brain (A). Although no PR was observed, the response amplitude varied along the strip, increasing from contact A1 to A2 and decreasing systematically from A2 to A6, suggesting contact 2 as optimal for DCS. Cortical potentials after left PTN stimulation obtained from the strip at the same location as in panel A (B). Once again, no PR was observed. The response amplitude increases from contact A1 to A3, decreasing from A3 to A6, suggesting contact 3 as optimal for DCS. In both panels, traces A1 through A6 through FPz are those obtained from the strip, and the two upper traces are scalp recordings that served as reference. The red trace is the baseline. Scale is 10 msec/div and 8 μV.](image-url)
DCS, one may argue that SM is not required in a surgery such as the one described here. However, it is clearly preferred. The surgery benefited from the SM, because it facilitated prompt and directed motor localization. Furthermore, SM helped to make the surgery safe by limiting the overall electrical stimulation of the exposed brain by minimizing the need for a motor cortical hunting approach.

Limitations

This study has several limitations. Repositioning the electrode to find a PR would have benefited our mapping. PR is the best suited SM technique to guide the surgical strategy and allows for subsequent prompt and directed localization of motor cortex with the minimum electrical stimulation of the brain. Our opportunity to reposition was restricted by the surgical exposure. Another caveat of this study is that we did not titrate the stimulus to find response thresholds. The stimulus equivalence at the two locations suggested by the SM permitted a stimulus-matched comparison but without titration a response-matched comparison could not be made. We also want to acknowledge the obvious limitations of our singular illustrative case and, until a series of similar cases can be published, the caution that should be exercised in its interpretation.

Lessons

Despite these limitations, this case affords several important lessons. To optimally address the neuroanatomy at risk, the location of the lesion and its functional effects help to define the corresponding monitoring and mapping approach. Complementary use of the MN and PTN is an effective tool for SM during resection of lesions located in the mesial cortex wherein the PTN SM provided the best guidance for where and how to deliver DCS and to monitor the lower extremity. The shift of the stimulating contact for DCS in our case highlights the importance of correlating the location of the lesion with the monitoring and mapping tools utilized. Finally, we demonstrate that the amplitude criterion of SM of PTN SSEPs is sufficient to define an appropriate cortical location for DCS.

References


FIG. 3. Motor responses elicited by DCS through the strip at 11.4 mA. MEPs obtained from stimulation through contact 2, resulting in robust responses from upper extremity muscles (left [L] adductor pollicis brevis and brachioradialis muscles, [A]), and from stimulation through contact 3, resulting in robust responses from lower extremity muscles (L gastrocnemius, tibialis anterior, and adductor hallucis muscles, [B]). The pattern of maximally activated muscles is consistent with the optimal location for DCS suggested by the sensory map for MN and PTN, respectively. Scale is 10 msec/div and 200 μV. Stimulation was monopolar with the current return placed in the scalp at FPz.


**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: Avshalumov, Mugutso, Pace. Acquisition of data: Avshalumov, Warnecke, Tessler. Analysis and interpretation of data: Avshalumov, Mugutso, Pace. Drafting the article: Avshalumov, Mugutso, Warnecke, Pace. Critically revising the article: Avshalumov, Mugutso, Warnecke, Pace. Reviewed submitted version of manuscript: Avshalumov, Mugutso, Warnecke, Pace. Approved the final version of the manuscript on behalf of all authors: Avshalumov. Statistical analysis: Avshalumov. Administrative/technical/material support: Avshalumov, Pace. Study supervision: Avshalumov.

**Supplemental Information**

**Previous Presentations**

This abstract has been previously presented at the Annual European Congress of Neurosurgery, in Barcelona, Spain, September 24–28, 2023.

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