Identification of motor pathways during tumor surgery facilitated by multichannel electromyographic recording

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Object. The goal of this study was to determine the usefulness of electromyographic (EMG) recording in locating motor pathways near the central sulcus or internal capsule during surgery.

Methods. Multichannel EMG recordings were compared with visual observation of contralateral body movement that was elicited by direct cortical or subcortical stimulation used to identify motor pathways before and during tumor resection. The EMG recordings were more sensitive than visual observation alone in identifying motor responses: in 30% of cases, responses were identified by EMG recording alone at some point during the operation and, in 9% of cases, EMG responses were the only responses observed. Additionally, EMG recordings often detected seizure activity resulting from electrical stimulation of the cortex that could not be appreciated on visual inspection. No new motor deficits were seen postoperatively in 88% of the patients in this series.

Conclusions. Using EMG recording in addition to motor pathway mapping results in greater sensitivity, allowing the use of lower stimulation levels and facilitating detection of stimulation-induced seizure activity.

KEY WORDS • electrophysiological monitoring • cortical stimulation • brain neoplasm • motor cortex • electromyography

Surgery for resection of supratentorial tumors or other lesions near the sensorimotor strip and/or internal capsule carries an associated risk of damage to cortical or subcortical motor pathways, which can result in postoperative paresis or paralysis. However, it is desirable to resect such lesions aggressively to the greatest extent possible to improve the patient’s chance of survival and postoperative quality of life. To obtain the most extensive resection possible, intraoperative stimulation mapping is often performed to identify functional motor regions. This is accomplished using either monopolar or bipolar stimulation and carefully observing the body contralateral to the operative side for any movement associated with stimulation of cortical or subcortical areas.

It is possible to perform tumor resections during craniotomies in patients given local anesthetic agents. This allows the patient to assist in the detection of stimulation-induced movements. The “awake” technique also allows identification of sensory pathways by the patient’s report of stimulation-induced paresthesias. However, there are disadvantages to the use of awake craniotomies. First, the experience of undergoing major surgery while awake is not a pleasant one, and the option of general anesthesia increases comfort and decreases anxiety for the patients. In addition, intrinsic brain tumors are often quite large before being detected; with such mass lesions it is important to be able to control ventilation mechanically and keep PCO₂ low. Although the ability to detect sensory as well as motor pathways is potentially useful, in our experience the risk of morbidity from disruption of cortical sensory pathways is limited (unpublished data). The loss of pain and temperature sensation is often transient, recovering in 1 to 2 months, possibly by increased participation of thalamic mechanisms. Limited proprioceptive loss is tolerated well enough that it does not seem to warrant the increased discomfort and risk of an awake craniotomy. In contrast, motor deficits can have devastating functional consequences and every effort should be made to avoid such complications whenever possible.

Although the technique of observing overt movements elicited by electrical stimulation has proved useful for intraoperative localization of motor pathways, it is not without problems. It is difficult to observe the entire contralateral body at once, especially when the extremity to be mapped is positioned prone or laterally. Thus, a small movement may be missed while attention is focused on another site. This becomes an issue during subcortical stimulation because the topography of the motor pathways may not be as orderly as it is at the cortical surface. Also, because EMG activity precedes visually observed motor activity, it is possible that stimulation may weakly activate motor pathways enough to elicit EMG responses and yet not recruit a sufficiently large pool of motor neurons to produce a visible movement.

To overcome these problems and improve the sensitivity of motor mapping, we recorded multichannel EMG activity during cortical and subcortical stimulation in a se-
Motor pathway mapping using EMG recording

ries of patients undergoing craniotomies for resection of tumors located near sensorimotor cortex or subcortical motor tracts. Our results indicate that EMG recording is often more sensitive than observations of gross movement, and thus facilitates identification of functional pathways during surgery. In this report we will describe the methods for motor mapping using EMG recordings and compare the EMG results with those obtained by visual observation of gross movements.

Clinical Material and Methods

Patient Population

Participants in the study were a consecutive series of 66 patients (33 males and 33 females) who underwent surgery for supratentorial lesions. Fifty-four of these patients were right handed and four were left handed. Hand dominance was not available in eight patients because of age (three patients) or inadequate records (five patients). Ages of the patients ranged from 6 months to 72 years, with a mean age of 40 years.

Monitoring Technique

After induction of anesthesia with thiopental or propofol and an initial neuromuscular block with vecuronium or rocuronium to facilitate intubation, anesthesia was maintained by a 70%-30% mixture of nitrous oxide/oxygen, supplemented by isoflurane (0.25–0.5% end-tidal concentration) and fentanyl (1–4 µg/kg). Propofol (0–100 µg/kg/minute) was administered as necessary to supplement the above agents to maintain a low end-tidal concentration of isoflurane. Intraarterial blood pressure, esophageal temperature, oxygen saturation, and end-tidal concentrations of oxygen, carbon dioxide, nitrogen, nitrous oxide, and isoflurane were measured continuously throughout the operation. Esophageal temperature was maintained at above 35.5˚C by using forced warm air (Bair Hugger; Augustine Medical, Inc., Éden Prairie, MN). In general, light surgical anesthesia was maintained, relying on opioid agents to provide adequate analgesia while minimally suppressing cortical responsiveness. Before mapping commenced, a standard twitch monitor was used to confirm the absence of any residual paralysis. An ankle jerk reflex was also elicited to confirm that the anesthesia was sufficiently light to obtain EMG responses because spinal motor neurons are also suppressed by volatile anesthetic agents.

Patients were positioned to provide adequate surgical access, either supine or prone with a bolster elevating the ipsilateral shoulder, with the head fixed in a three-point Mayfield head rest. The operating table was oriented with the anesthesiologist on the side contralateral to the craniotomy, using a Phelan scrub table over the patient to permit visualization of the entire contralateral side. Whenever possible, all drapes, monitors, and intravenous and intraarterial catheters were placed ipsilateral to the craniotomy to minimize restriction, maximize visibility of movement, and prevent any problems that might arise as a result of movement in the event of seizure activity following stimulation. No compression stockings were used on the contralateral leg so that movements would not be obscured.

Before the patient was draped, subdermal needle electrodes were inserted into 12 to 16 muscles chosen to provide broad coverage of the appropriate body region. The exact montage varied somewhat from patient to patient. For example, if the lesion was clearly limited to the midline near the falx, greater emphasis would be placed on lower extremity muscles. For lesions located more laterally near hand or face representations, the converse would be true. Because the aim of the EMG recordings was to sample as many muscles as possible, the two electrodes connected to each differential amplifier input were not placed in the same muscle, which normally would be done. Instead, they were placed in different muscles in the same region of the body (Fig. 1). This arrangement minimized artifact sensitivity by maximizing common mode rejection while allowing up to twice as many muscles to be monitored as the number of recording channels. A typical configuration thus might be orbicularis oris–orbicularis oris (face), trapezius–deltoides (shoulder), triceps brachii–biceps brachii (upper arm), flexor carpi radialis–extensor digitorum (forearm), abductor pollicis brevis–flexor digiti minimi brevis manus (hand), vastus lateralis–biceps femoris (upper leg), tibialis anterior–gastrocnemius (lower leg), and abductor hallucis–abductor digiti minimi pedis (foot). Although in some cases the two muscles for a given channel may have similar or identical innervation, phase cancellation in the differential recording is unlikely to be a problem because EMG responses (unlike evoked potentials) do not show stereotyped phase locked activity, but instead are complex and multiphasic, depending on the exact geometrical relationships among the recording sites and the neuromuscular junctions activated, as well as the complex structure of the descending cortical activation.

In 42 cases, eight channels of EMG responses were recorded using a Nicolet Viking IV P system (Nicolet Biomedical, Madison, WI) with a bandpass of 30 to 1000 Hz and a display gain of 200 V/division. If the electrocardiographic artifact was prominent on a given channel (such as...
Stimulation was applied for approximately 1 second at each site, with the surgeon announcing each time the stimulation was applied and removed. During stimulation, the patient was carefully observed by the anesthesiologist, who reported any stimulus-related movement. Simultaneously, the multichannel EMG display was observed for any stimulus-related EMG activity, which was also reported. If no movement or EMG activity was noted, the stimulating electrode was moved to the next site to be surveyed and the process was repeated. If movement and/or EMG activity was noted at any site, a sterile labeled marker was placed at that location before proceeding. If movement or EMG activity continued after removal of the stimulating electrode, cold lactated Ringer’s solution was irrigated onto the exposed cortex. If this was insufficient, methohexital sodium was administered to terminate the activity. Electrocortigraphy was not used to monitor afterdischarge potentials in this series.

Once initial mapping was concluded, a transparent plastic drape was placed over the identified motor region to mark the motor cortex and to prevent dislodgment of the sterile markers. Depending on the location of the tumor in relation to the motor area, a handheld bipolar stimulator was sometimes used to stimulate white matter at the borders of the resection to identify motor pathways within the internal capsule and corona radiata. At the conclusion of tumor resection, the previously marked sites were usually restimulated to confirm integrity of the motor pathways before dural closure. Intraoperative photographs were obtained to document the locations of the sites producing motor responses in relation to other anatomical landmarks and the location of the tumor.

Results

Pathological studies of specimens obtained during the 66 operations confirmed 24 glioblastomas, 15 oligoastrocytomas, seven anaplastic astrocytomas, four oligodendrogliomas, three low-grade astrocytomas, three cases in which there were gliosis and radiation necrosis, two metastatic carcinomas, two cases of cortical dysplasia, one ganglioglioma, one primitive neuroectodermal tumor, one lymphoma, one meningioma, one arteriovenous malformation, and one case of tuberous sclerosis. Forty-five craniotomies were performed on the right side, 20 on the left side, and one bilaterally.

In 29 cases (44%) the lesions were primarily located anterior to the motor cortex, in 15 cases (23%) the lesions were mainly posterior to the central sulcus, and in 22 cases (33%) the lesions were more deeply situated and mapping was primarily used for identification of subcortical motor pathways, such as the internal capsule or cerebral peduncle.

Adequate outcome data could not be obtained from a review of charts in two patients and, thus, these patients were not included in the outcome analysis. Forty (63%) of the remaining 64 patients had no motor deficits before surgery; 35 (55%) of 64 exhibited no new postoperative deficits. Ten of these 35 patients underwent gross-total tumor resection and the rest underwent subtotal resection. Twenty-four patients (38%) had preexisting motor deficits at the time of operation; 21 were unchanged postoperatively.
Taken together, 56 (88%) of 64 patients had no new deficits postoperatively. Eight patients (12%) demonstrated new postoperative deficits. Three of these new deficits were slight worsening of preexistent hemipareses (two from precentral lesions and one primarily subcortical), whereas the other five constituted new deficits in patients whose strength previously had been normal. Of these five patients, one patient, whose lesion was primarily subcortical and had been previously irradiated, demonstrated a new dense left hemiparesis caused by an infarction in the lenticulostriate distribution; one patient with a precentral lesion demonstrated a new lower-extremity monoparesis that resolved during the next few months, leaving only a residual weakness in toe extensors; and three patients (two with precentral and one with subcortical lesions) demonstrated new slight hemipareses (graded 4/5 at the time of discharge from the hospital).

In 20 (30%) of the 66 operations, motor responses during mapping were noted at least once on EMG recording, although they were not apparent on visual inspection. In six cases (9%) EMG activity was the only indication of motor response. In four (6%) of the 66 operations, movement occurring in response to stimulation at some point during the operation was appreciable on visual inspection but not on EMG monitoring. These were always small movements such as extension of a single finger by a muscle that was not in the recording montage. In no case was visual inspection the only indication of a motor response throughout the operation. In 14 (21%) of the 66 cases no motor responses were detected by either EMG monitoring or visual inspection. None of the patients with new postoperative deficits were in this last category.

When EMG responses were obtained, the response amplitude was proportional to the stimulation intensity (Figs. 2 and 3). At threshold stimulation levels, small responses with discrete, compound muscle-action potentials were often seen; such responses were never accompanied by overt movement. At higher levels, individual action potentials were no longer seen, and the EMG response changed to an interference pattern that tended to be augmented during the 1-second duration of stimulation. Such responses were usually accompanied by obvious movement.

The EMG responses were quite focal in distribution and typically observed in only one or two channels (Figs. 2 and 3). When responses were obtained from more than one cortical stimulation site, their distribution was consistent with the arrangement of the motor homunculus, with face responses obtained at the most lateral sites and hand, arm, leg, and foot responses elicited at progressively more medial sites. With cortical stimulation, responses were never obtained simultaneously from muscles without contiguous cortical representation; that is, hand and forearm responses were often seen together, but never hand and foot. The topography of responses to subcortical (capsular) stimulation was less orderly, but was not examined in detail.

Seizures (defined as movements elicited by stimulation that continued after the end of stimulation) occurred in seven (11%) of the 66 patients undergoing mapping. In addition, subclinical seizures (defined as EMG activity elicited by stimulation that continued after the end of stimulation) were observed in an additional nine (14%) of the 66 patients (Fig. 4). No seizures were detected by gross movement that were not also apparent in EMG recordings. Seizures were terminated by irrigating cold lactated Ringer’s solution onto the exposed cortex or, rarely, by intravenous administration of a 30-mg bolus of methohexital sodium.
Discussion

It is now generally recognized that both chances of survival and quality of life for patients with brain tumors are enhanced by achieving the most extensive surgical resection possible.16,26 However, when tumors are located near motor cortex or subcortical motor pathways, the risk of causing significant motor deficits with aggressive resection is a major concern. The use of electrical stimulation to identify functional motor regions allows resection to proceed as far as possible while minimizing the risk of new postoperative deficits.24,7,8

There is, of course, a tradeoff between achieving total resection and avoiding the production of new deficits. In this series, in only 10 of the 35 patients who presented with no preoperative motor deficit was gross-total resection of tumors achieved. In the remaining patients, resection was halted when functional motor pathways were identified by stimulation mapping. Without the ability to map motor pathways, the surgeon may have to perform an unnecessarily limited resection to spare function or else proceed with tumor resection without the ability to assess potential deficits that may be created. Stimulation mapping provides the necessary intraoperative data for a rational choice between these extremes.

Electrical stimulation of the cortex was first used on a systematic basis during the excision of brain lesions by Fedor Krause in the early 1900s and, since that time, the basic method of visual inspection for assessment of the motor response to stimulation has not changed. The use of EMG monitoring to assess motor responses is thus a fundamental technical advance in motor mapping.

Electromyography has two important advantages over observation of movement during stimulation mapping of motor pathways: it facilitates monitoring of the face, upper extremity, and lower extremity simultaneously, and it can detect motor responses that may not be observed during gross inspection. The ability to monitor multiple body sites easily is particularly important during mapping of subcortical pathways, where the topography is not as orderly as that found at the cortical surface and, thus, small movements might easily be missed by an observer looking at another part of the body. In contrast, it is easy to scan all channels of a cathode-ray tube display simultaneously. Because the traces remain on the screen for 10 seconds before being overwritten, the record can be reviewed to allow identification of subtle responses that otherwise might be missed, but which may be the first indication that the resection is approaching functional tissue.

The ability to elicit EMG responses at lower stimulation levels than are required for visible movements allows mapping to be performed using a lower current and, potentially, there is less likelihood of inducing seizures. The duration of the stimulation can also be diminished. The latency for a visible movement is often a second or more after application of the stimulus to the cortical surface. The EMG response typically shows an augmenting pattern (Figs. 2 and 3) with EMG activity evident before overt movement. The stimulation can be removed as soon as an EMG response is reported; this is particularly useful if the patient has a high incidence of stimulation-induced seizures, which can be minimized by using brief stimulation at the lowest current that elicits an EMG response.

Electrocorticography was not used to monitor spike activity or seizures in this series because it was primarily composed of patients with brain tumors rather than seizure disorders per se. Nonetheless, because many such patients experience seizures as one of their presenting symptoms, there is always a possibility of stimulation-induced seizure activity during mapping, which was seen in 11% of the patients in this series. (Subclinical seizures, evident only on EMG recordings, were observed on an additional 14%). Such seizures were never observed following subcortical stimulation, presumably because they arise in intracortical networks, which are only activated by direct cortical stimulation. It is not known whether electrocorticography would be more sensitive at detecting seizure activity than EMG recordings. It is clear from this series that EMG recordings can detect seizures resulting in motor activity with greater sensitivity than observation of movement alone. In more than half of the cases in which EMG activity was observed following cessation of stimulation, it was not accompanied by obvious movements. These delayed responses were presumably the result of ongoing cortical activity and could usually be terminated by cold irrigation of the cortical surface. It is possible that cortical seizures outside the motor area, which would not manifest as EMG activity, could be detected by electrocorticography. It is not clear what the functional consequences of such activity would be; in patients with tumors, otherwise normal brain showing stimulation-induced epileptiform discharges would certainly not be resected.

The central sulcus is considerably more varied in humans than in other primates, and varies in an anteroposterior direction by more than 3 cm.26 Skull base measurements for identification of motor cortex may vary as much as 6 cm,11 and the limited view through a craniotomy adds to the difficulty in identification based on anatomical criteria alone. This is particularly true if the anatomy has been distorted by a significant mass effect. Image-guided surgical navigation techniques, based on intraoperative registration of fiducial landmarks with preoperative magnetic resonance images, can assist in localization of the motor cortex based on anatomical criteria also.5 Nevertheless, functional mapping based on physiological responses remains the gold standard for intraoperative localization.

The importance of physiological rather than anatomical localization is even more pronounced in the identification of subcortical motor pathways. Unlike the cortical surface, there are no obvious anatomical landmarks in the internal capsule. Image-guided surgical navigation techniques cannot compensate for shifting of internal structures as the tumor is debulked. Although they can serve as a rough guide to the extent of tumor resection, they cannot be used to delineate the borders of functional tissue. In contrast, repeated stimulation mapping during subcortical resection can precisely define the boundaries of motor tracts, allowing the maximum resection possible while avoiding interruption of functional pathways.5,17 Furthermore, during subcortical resection, previously identified cortical motor areas can be restimulated to confirm the integrity of their descending connections.

In summary, intraoperative stimulation mapping to identify functional motor pathways can be performed with greater sensitivity and less intense stimulation by multi-
Motor pathway mapping using EMG recording

channel EMG recording in addition to observing overt patient movement. This technique can be applied to both cortical and subcortical motor pathways, in both adult and pediatric patients with brain tumors. The increased sensitivity and lower risk of seizure induction facilitate aggressive surgical resection, helping to maximize tumor removal while minimizing operative morbidity.

Conclusions

Electromyography monitoring enhances the ability to detect the location of primary motor cortex and subcortical pathways with electrical stimulation. In 30% of the cases in this series, EMG monitoring detected motor responses at some point during the operation that otherwise would have gone unnoticed. In 9% of the cases in this series, EMG recording was the only means of identifying motor responses to stimulation. The utility of these techniques is apparent by the fact that 88% of the patients in this series exhibited no new motor deficits postoperatively, despite aggressive tumor resection.

Electromyography also improves the ability to detect seizure activity related to electrical stimulation. In this series, 24% of the patients demonstrated some seizure activity, over half of which was detected by EMG monitoring only. Although EMG recording detected all observed seizures in this series, it is not known how well EMG monitoring compares to electrocorticography as a means of detecting seizures before the onset of motor activity.

Disclosure

None of the authors of this study has any financial interest in any of the instruments or methodologies used in this study.

References


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