ACNS Guideline: Transcranial Electrical Stimulation Motor Evoked Potential Monitoring

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Motor evoked potentials (MEPs) are electrical signals recorded from neural tissue or muscle after activation of central motor pathways. They complement other clinical neurophysiology techniques, such as somatosensory evoked potentials (SEPs), in the assessment of the nervous system, especially during intraoperative neurophysiologic monitoring (IONM). Somatosensory evoked potentials directly assess only a part of the spinal cord, the dorsal columns (Emerson, 1988), and also the medial lemniscus, the thalamocortical radiations, and somatosensory cortex. Because they provide indirect surveillance of the motor tracts, their use has been shown to improve neurologic outcomes during spinal surgery (Nuwer et al., 1995). However, SEPs can fail to detect damage to the spinal cord motor pathways when the dorsal columns are spared (Ben-David et al., 1987; Ginsburg et al., 1985; Jones et al., 2003; Krieger et al., 1992; Legatt et al., 2014; Zornow et al., 1990); this led to the development of techniques for directly monitoring the central motor pathways. Most often, this is accomplished using transcranial electrical stimulation (TES) of the brain and recording of evoked neural or myogenic activity caudal to the area that is at risk during surgery (Legatt, 2002). During TES, high-intensity stimuli must be delivered to the scalp to stimulate the brain through the intact skull, with stimulus voltage and current levels far above those used to elicit SEPs. If a craniotomy permits direct stimulation of motor cortex by electrodes placed on the brain surface, low-intensity direct cortical stimulation can also be used to elicit MEPs for IONM (Szelényi et al., 2007b; Taniguchi et al., 1993). Direct cortical stimulation is outside the scope of this guideline, but the recommendations herein for the recording of the MEPs that are elicited by transcranial electrical brain stimulation would also apply to recording of MEPs elicited by direct cortical stimulation.

Transcranial magnetic stimulation has also been used to elicit MEPs by inducing electrical current flows within the brain tissue without passing large amounts of current through the scalp. This reduces stimulation of pain fibers in the scalp, skull, and meninges and makes it a practical technique for MEP studies in awake subjects (Chen et al., 2008). However, transcranial magnetic stimulation is not the optimal MEP technique for IONM because of the anesthetic suppression of transcranial magnetic stimulation–MEPs which are generated mainly by eliciting I-waves (see section on Definitions and Physiology, below) and difficulties in maintaining a constant position of the coil relative to the patient's head (Legatt, 2004). Neither TES with single stimulus pulses nor transcranial magnetic stimulation consistently produces robust myogenic MEPs suitable for IONM. The commercial availability of stimulators that can deliver trains of high-intensity electrical pulses has made reliable MEP monitoring using TES possible in most patients. At this time, the techniques for recording and interpreting TES-MEPs have become sufficiently well established to warrant the formulation of these guidelines. Personnel performing TES-MEP monitoring must be cognizant of the technical challenges and risks of the technique.
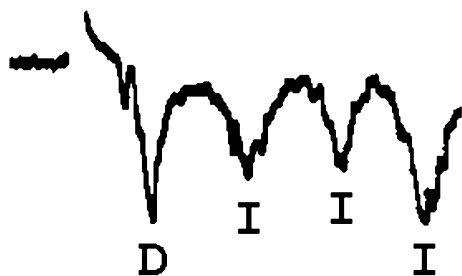
TERMINOLOGY: DEFINITIONS AND PHYSIOLOGY

Corticospinal tract activity elicited by stimulation of cerebral cortex, either electrical or magnetic, consists of "D-waves," which reflect *direct* activation of the pyramidal cell axons that leave the cortex and comprise the corticospinal tract, and "I-waves," which reflect *indirect* activation of these pyramidal neurons by synaptic transmission from activated cortical interneurons (Amassian et al., 1987) (Fig. 1). There may be multiple I-waves, at roughly equal intervals, reflecting the number of synapses (and synaptic delays) between the interneurons that are initially activated by the stimulus and the pyramidal neurons that give rise to the corticospinal tract. Since I-waves are mediated by cortical synaptic activity, they are markedly suppressed by surgical levels of anesthesia. However, D-waves remain and can be recorded along the course of the corticospinal tract. When used for IONM, they are recorded from the spinal cord caudal to the region that is at risk during the operation. Recordings of D-waves from the spinal cord rostral to the region at risk can also be performed as a control to assess the adequacy of corticospinal tract stimulation.

When brain stimulation causes muscle contractions, the compound muscle action potentials, or myogenic MEPs, can be recorded from multiple muscles simultaneously following a single

Stimulation within motor cortex

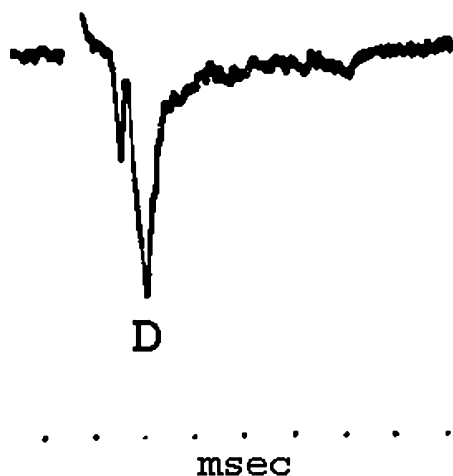## Stimulation within subcortical white matter

FIG. 1. Corticospinal tract activity elicited by stimulation within or below motor cortex, recorded from the ipsilateral lateral column between C1 and C2, in a monkey. Intracortical stimulation (upper trace) produces a D-wave and a series of I-waves; stimulation within the subcortical white matter (lower trace) only produces a D-wave (Modified from Patton HD, Amassian VE. Single- and multiple-unit analysis of cortical stage of pyramidal tract activation. *J Neurophysiol* 1954;17:345–363).

train of transcranial stimuli. Train stimulation is needed to reliably elicit myogenic MEPs under anesthesia. The excitatory postsynaptic potentials in the anterior horn cells summate to bring them to threshold and fire them. Both D-waves and myogenic MEPs can be used for IONM (Fig. 2).

Transcranial electrical stimulation predominantly generates D-waves under the stimulating anode and therefore predominantly generates myogenic MEPs in muscles contralateral to the stimulating anode (Fig. 3). However, in rare patients with congenital motor tract nondecussation, TES produces predominantly anode-ipsilateral myogenic MEPs (MacDonald et al., 2004). Myogenic

MEPs may also be elicited by stimulation of cortex under the TES cathode, but such responses are less stable and may disappear in the absence of corticospinal tract pathology (Legatt, 2006).

Mention should be made of a technique using stimulation of the rostral spinal cord and recordings from peripheral nerves in the legs, which has sometimes been labeled "neurogenic motor evoked potentials" (Owen et al., 1988). Collision studies (Toleikis et al., 2000) have shown that the signals recorded using this technique are mediated by retrograde conduction within the dorsal columns, not anterograde conduction within the corticospinal tracts. Also, these signals may be preserved in the face of corticospinal tract damage that causes paraplegia (Minahan et al., 2001). This technique may be useful for IONM of the dorsal columns, but it should not be construed to be an MEP monitoring technique. Similarly, myogenic MEPs after rostral spinal cord stimulation could be partly mediated through retrograde activation of the dorsal columns, whose collateral branches form excitatory synapses with alpha motor neurons (MacDonald, 2006), and recording of these signals should not be considered a reliable method for corticospinal tract monitoring.

Comparison of D-wave and Myogenic MEP Monitoring

D-waves to single-pulse TES are typically recorded as they pass through the corticospinal tract within the spinal cord using near-field electrodes, such as epidural or subdural electrodes. Because there are no synapses between the stimulated cortical pyramidal neurons and the MEP recording site, multipulse stimulation is not required, although a high stimulus intensity is still required to stimulate the brain through the intact skull. The lack of synapses makes D-waves relatively insensitive to anesthesia. D-waves tend to be highly consistent from run to run but are generally small enough to require averaging a small number of responses (≤20) per run to improve the signal-to-noise ratio. The D-wave amplitude corresponds to the number of rapidly conducting corticospinal tract axons within the spinal cord at the level of the recording. Since some corticospinal tract axons terminate at each segmental level, D-waves are of higher amplitude in the cervical region than in the thoracic spinal cord. D-wave monitoring is usually not practical below the T10 bony level because of the small number of corticospinal tract fibers that remain.

Myogenic MEPs are large and do not require signal averaging. Moreover, they often display substantial run-to-run variability (Fig. 4), so that signal averaging should not be used to record them. Generating a myogenic MEP requires synaptic transmission at the anterior horn cell, which is facilitated by a train of stimulus pulses. A train of multiple stimuli also facilitates the production of I-waves, further increasing the potency of the train (Deletis et al., 2001b). The interposed synapse at the anterior horn cell makes myogenic MEPs highly sensitive to anesthetic effects (Fig. 5) and likely accounts for most of their run-to-run variability (MacDonald, 2006). Each stimulus train activates only a small fraction of the anterior horn cells; a varying subset of the lower motor neuron pool is recruited with each run, causing the variability in the response waveforms from run to run.

D-waves, myogenic MEPs, or a combination of both may be used for monitoring the spinal cord. Each has advantages and disadvantages (Legatt, 2004), as described in the following list. In the United States, most centers routinely perform myogenic MEP monitoring.

- Anesthesia: D-waves are relatively insensitive to anesthesia. Myogenic MEPs are easily suppressed by anesthesia,
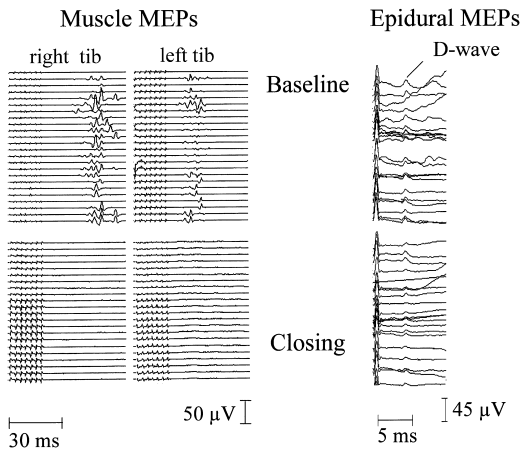
Muscle MEPs   Epidural MEPs

FIG. 2. Concurrent monitoring of myogenic motor evoked potentials (MEPs) (left) and D-waves (right) during surgery for a spinal cord tumor. The myogenic MEPs disappeared, but the D-waves persisted. The patient awoke with new neurologic deficits that subsequently cleared (From Deletis V, Kothbauer K. Intraoperative neurophysiology of the corticospinal tract. In: Stålberg E, et al., eds. *Spinal cord monitoring.* Wien: Springer, 1998:421–444).

especially by inhalational anesthetics (Fig. 5), which sets limits on the anesthetic regimen that can be used during MEP monitoring of myogenic MEPs (Sloan and Heyer, 2002).

- Neuromuscular blockade (NMB): neuromuscular blockade does not affect D-waves, but total NMB eliminates myogenic MEPs. Omitting NMB permits straightforward myogenic MEP monitoring but TES-induced patient movements may necessitate careful stimulus timing to avoid unacceptable patient movements that can interfere with the surgery. Partial NMB may dampen but not eliminate these movements and can complicate interpretation of myogenic

MEPs. Some centers generally omit NMB whereas others tend to use partial NMB. If used, partial NMB should be done with continuous infusion of the paralytic drug (Adams et al., 1993); bolus injections yield a level of NMB that is too variable.

- Stimulator: monitoring of myogenic MEPs requires a multi-pulse stimulator; D-wave monitoring does not.
- Recording electrodes: D-wave monitoring requires invasive electrodes placed near the spinal cord, either intraoperatively by the surgeon or percutaneously; monitoring of myogenic MEPs does not.
- Structures monitored: since D-waves must be recorded caudal to the region at risk for IONM, they cannot be used to monitor the lower spinal cord (usually caudal to the T10 bony level). D-waves assess only axonal conduction within the corticospinal tracts. Myogenic MEPs additionally assess the integrity of spinal cord gray matter, which may be more sensitive to ischemia than spinal cord white matter (MacDonald and Dong, 2008) and may also demonstrate nerve root or peripheral nerve dysfunction.
- Desynchronized activity: spinal cord lesions such as tumors may cause temporal dispersion of the descending corticospinal tract volley, which precludes monitoring of D-waves caudal to the lesion. Myogenic MEPs adequate for monitoring may be present in such patients (Fig. 6).
- Detection of unilateral compromise: D-wave monitoring can fail to detect unilateral corticospinal tract compromise because the epidural electrodes record the D-waves generated in the corticospinal tracts on both sides. Myogenic MEP monitoring records from muscles on each side separately.
- Timing of alarm: because myogenic MEPs require not only corticospinal tract conduction but also anterior horn cell transmission and peripheral nerve conduction, they may be lost at a time when D-wave corticospinal tract potentials are still present (Fig. 2). The meaning of this dissociation depends on the surgical circumstances. During descending aortic surgery, acute spinal cord ischemia rapidly disables anterior horn cells, causing
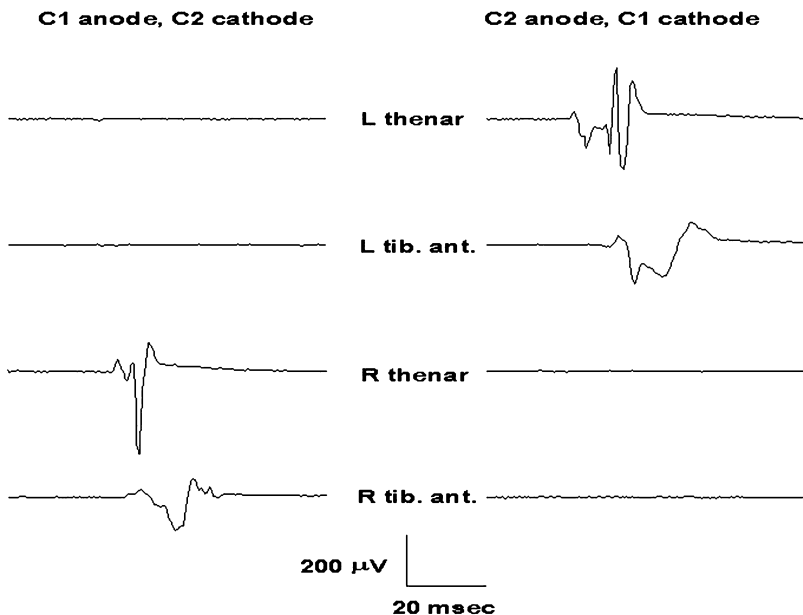

FIG. 3. Motor evoked potentials to transcranial electrical stimulation between electrodes at positions C1 and C2, recorded bilaterally from thenar and tibialis anterior muscles during an occipitocervical fusion.
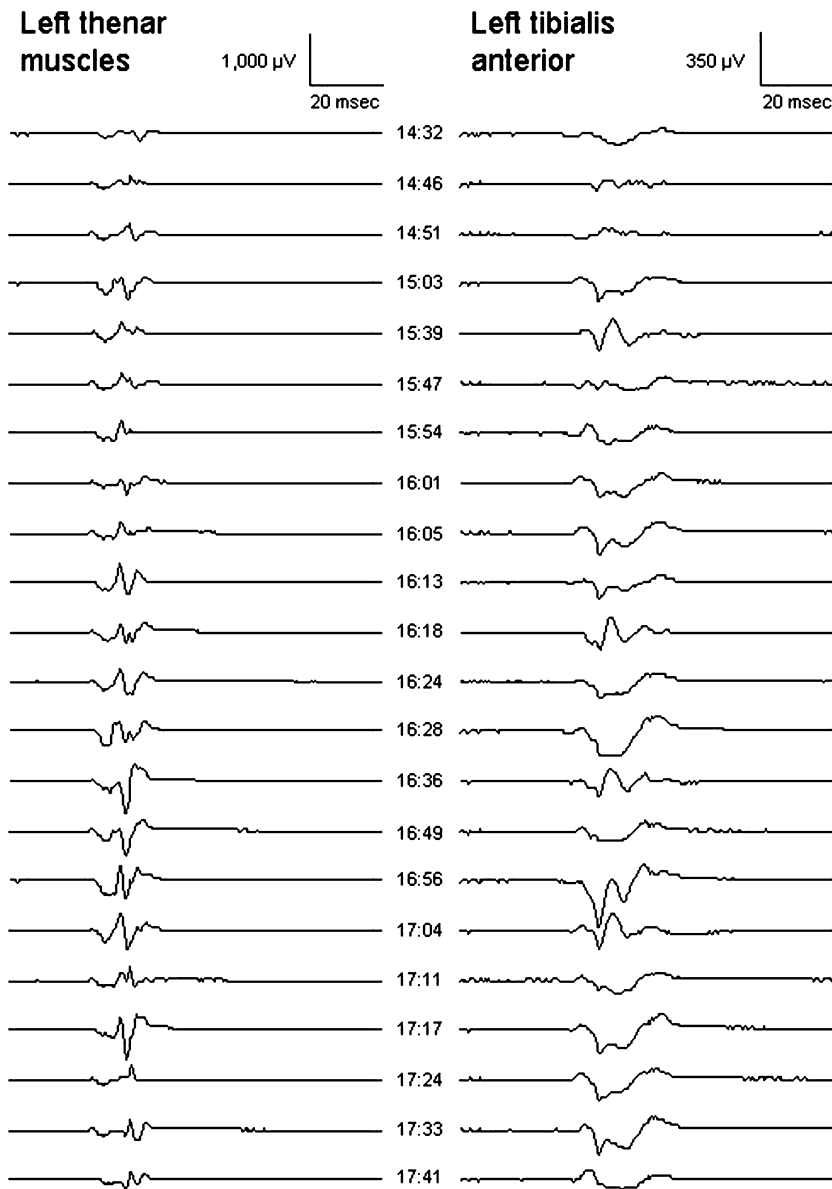
FIG. 4. Myogenic motor evoked potentials recorded from the left tibialis anterior and thenar muscles after multipulse transcranial electrical stimulation with the anode over the right hemisphere, over a 3-hour period during an occipitocervical fusion. Note the large run-to-run variability of the motor evoked potential amplitudes and waveshapes. The numbers in the middle are the clock times of each run (From Legatt AD, Ellen R. Grass Lecture: Motor evoked potential monitoring. *Am J Electroneurodiagnostic Technol* 2004;44:223–243).

loss of myogenic MEPs, while corticospinal tract conduction and D-waves may be unaffected or begin to fail after a delay (MacDonald and Dong, 2008). In these surgeries, persistent loss of myogenic MEPs correlates with a substantial risk of cord infarction and permanent motor deficits (Keyhani et al., 2009). In contrast, during surgery for intramedullary spinal cord tumors, patients in whom myogenic MEPs are lost but D-waves persist generally have transient postoperative weakness or paralysis; the myogenic MEP changes may reflect disruption of propriospinal systems that render intact alpha motor neurons unexcitable, with functional compensation for the loss of these facilitatory inputs during the postoperative period (Deletis, 2002; Sala et al., 2006). Patients in whom D-waves are lost or attenuated by more than 50% during intramedullary spinal cord tumor surgery generally suffer permanent weakness (Deletis and Kothbauer, 1998). Thus, combined D-wave

and myogenic MEP monitoring particularly suits these operations.

• Effect of spinal deformity correction: during correction of spinal deformities, changes in the anatomic relationship between the D-wave recording electrodes and the spinal cord can produce false-positive results during D-wave monitoring (Ulkatan et al., 2006).

RECOMMENDED STANDARDS FOR TES-MEP MONITORING

Standards for recording equipment, personnel, and documentation are given in the American Clinical Neurophysiology Society Guideline 9A: Guidelines on Evoked Potentials (2006). Additional standards for IONM are given in American Clinical Neurophysiologic Society Guideline 11: Guidelines for Intraoperative Monitoring of Sensory Evoked Potentials (1994a). Personnel involved in the
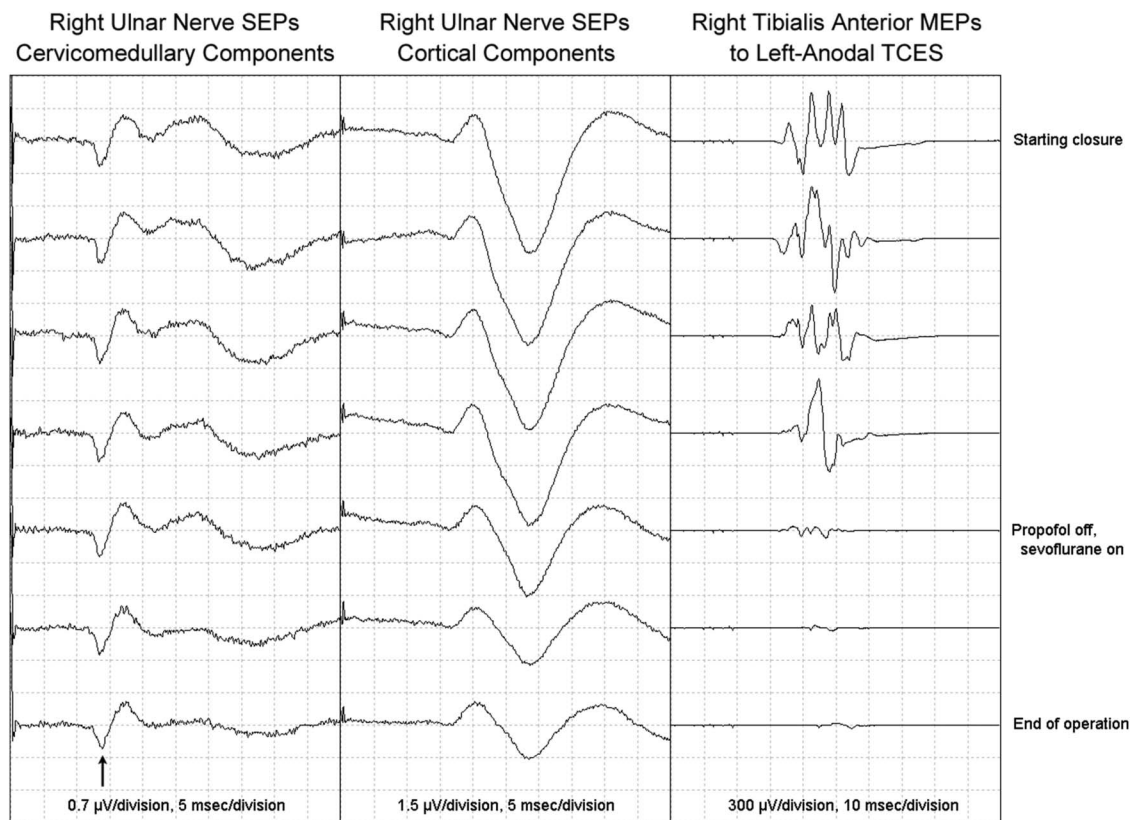
FIG. 5. Effect on different evoked potentials of changing the anesthetic regimen from total intravenous anesthesia with propofol and remifentanil to inhaled sevoflurane during spinal instrumentation surgery for a T11 compression fracture with kyphosis. Subcortical somatosensory evoked potentials (SEPs) (left column, arrow) were essentially unaffected, cortical SEPs (middle column) were attenuated, and myogenic motor evoked potentials (MEPs) (right column) were almost completely eliminated. TCES = trans-cranial electrical stimulation (From Legatt AD. *Intraoperative neurophysiology: Interactive case studies.* New York: Demos Medical Publishers, 2015).

interpretation of intraoperative MEP monitoring data should have additional training and experience that provides thorough understanding and direct familiarity with all aspects of TES and of MEP data acquisition, processing, and interpretation. This should include the influence of stimulus and recording parameters, anesthesia, neuromuscular blocking agents, and other factors that may affect the MEPs during IONM; knowledge of anatomic structures, neurophysiologic events and other factors involved in the generation of MEPs; the clinical significance and pathophysiologic correlates of dysfunction of neural pathways demonstrated by evoked potential alterations; and knowledge of which areas of the nervous system are at risk and the mechanisms for that risk during the surgical procedures for which MEP monitoring is used.

Stimulating Equipment for TES

Equipment for TES should be able to deliver brief trains of high-intensity stimuli where the intensity of the stimulus pulses, the number of pulses per train, and the interpulse interval (or equivalently, the pulse rate) within the train can all be adjusted by the operator. Either constant-voltage or constant-current stimulators can be used; specially designed devices of either type are available and some standard SEP stimulators of either type can also be effective (the latter is an off-label use of the SEP stimulator). In constant-voltage stimulation, the stimulus current can vary widely depending on the impedance of the tissue and the electrode–tissue interface. A display of the delivered current is desirable, and the equipment should include circuitry to limit the total current delivered during a stimulus train to a safe level. Isolation and leakage current limitations for evoked potential recording equipment (American Clinical Neurophysiology Society, 2006) also apply to TES stimulating equipment. If the TES stimulator is not contained within the MEP recording equipment, it must have a trigger input and/or output that can be connected to the MEP recording equipment to permit synchronization of stimulus delivery with recording of the MEP responses.

Stimulating Electrodes and Stimulus Parameters

Needle or corkscrew electrodes are most often used for TES, although surface electrodes can also be used. Low impedances, which correlate with a larger contact area between electrode and tissue, help to prevent tissue injury from the high stimulus currents used by limiting current density and energy delivery to the tissue near the electrode. Corkscrew electrodes have lower impedances than needle or EEG cup electrodes (MacDonald, 2006) and are also less likely to become dislodged. When MEPs in the upper limbs are being monitored, stimulating electrodes may be placed at scalp
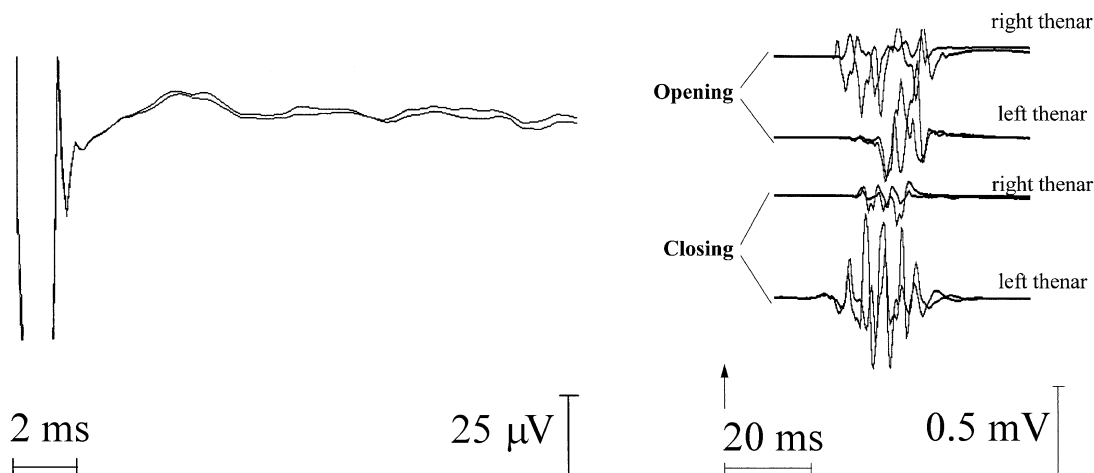
FIG. 6. No clear D-wave is present in epidural recordings caudal to an intramedullary tumor of the cervical spinal cord (left), but transcranial electrical stimulation with brief stimulus trains elicits clear myogenic motor evoked potentials (right) (From Deletis V, Kothbauer K. Intraoperative neurophysiology of the corticospinal tract. In: Stålberg E, et al., eds. *Spinal cord monitoring.* Wien: Springer, 1998:421–444).

positions C1/C2 or C3/C4 of the 10-10 (expanded 10-20) system (American Electroencephalographic Society, 1994b), with external switching to permit anodal stimulation of either the left or the right hemisphere using the same electrode pair (Szelényi et al., 2007a) (Fig. 7). Since C3/C4 electrodes are closer to facial motor cortex, jaw muscles, and trigeminal nerves than are C1/C2 electrodes, stimulation at C3/C4 can produce stronger biting movements, and C1/C2 electrodes are preferable unless C3/C4 electrodes are required to elicit MEPs (MacDonald, 2006; Szelényi et al., 2007a).

Several different stimulating electrode arrangements can be used to elicit MEPs in the lower limbs. Paired electrodes at C1/C2 or C3/C4 can be used with external polarity switching. Although bilateral leg MEPs are common with these montages, responses still tend to be maximal contralateral to the anode (or rarely ipsilateral in patients with nondecussation). An anode at Cz can be paired with a cathode at Fz (Fig. 7). In some centers, the anode is an electrode at Cz and the cathode is a surface electrode with a very large surface area placed over the front of the head. The C1/C2 and C3/C4 stimulating montages have the advantage that they can stimulate the motor pathways for both upper and lower limbs with a single stimulus train, permitting simultaneous recording of upper-limb and lower-limb MEPs. The Cz/Fz stimulating montage has the advantage that it may more reliably stimulate the motor pathways for the lower limbs bilaterally with a single stimulus. The optimal electrode arrangement for stimulation may vary between patients and surgical circumstances; different stimulation montages can be tested and the best one selected for each patient.

When myogenic MEPs are monitored, multipulse TES is used because under surgical levels of anesthesia, a single D-wave volley is often not sufficient to bring the anterior horn cell to the firing threshold. Multipulse stimulation elicits a train of D-waves, and often some I-waves as well, and the excitatory postsynaptic potentials that they produce in the anterior horn cell summate to above threshold, thus firing the lower motor neuron and generating the myogenic MEP (Legatt, 2004). If the interpulse interval (interval between stimulus pulses in the train) is too long, the postsynaptic potentials do not overlap and the benefit of the temporal summation is lost. If it is too short, stimuli after the first in the train are not as

effective in firing the corticospinal tract axons because of their refractory periods (Deletis et al., 2001a). Interpulse intervals between 2 and 4 ms (i.e., intratrain pulse repetition rates of 250–500 Hz) are typically optimal for myogenic MEP monitoring. A train of 3 pulses will suffice in some patients; others will require more. Both constant-current and constant-voltage stimulators can be used for TES; different machines have different ranges of options for pulse width and stimulus intensity. Intraoperative neurophysiologic monitoring services typically establish a standard set of stimulus parameters (pulse width, stimulus intensity, number of pulses per train, and interpulse interval/pulse rate) for the initial recordings under anesthesia, and then adjust the parameters as necessary and appropriate to obtain MEPs adequate for IONM in each individual patient.

Transcranial electrical stimulation with pairs of pulse trains (Journee et al., 2007) can facilitate the recording of myogenic MEPs, as can electrical stimulation of the foot before recording of lower-limb MEPs (Frei et al., 2007). As these techniques are relatively new, parameters for them are not included in this guideline.

Recording Electrodes and Recording Sites

D-waves are recorded between paired electrodes placed near the spinal cord, either epidural or subdural. They may be placed percutaneously using a Touhy needle or placed by the surgeons within the surgical field. Where there is a discrete spinal cord lesion, such as a tumor, recording D-waves both rostral and caudal to the lesion may be useful. Long distances between the recording electrodes minimize in-phase cancellation and produce larger D-wave amplitudes but admit more noise; a spacing of 2 to 3 cm is adequate (Deletis and Sala, 2008).

Myogenic MEPs should be recorded from limb muscles on both sides of the body. Needle and surface electrodes are both effective in recording these signals. Either type and their leadwires should be securely fastened to the skin to prevent dislodgement during surgery.

In the upper limb, myogenic MEPs are optimally recorded from hand muscles (thenar, abductor digiti minimi, or first dorsal
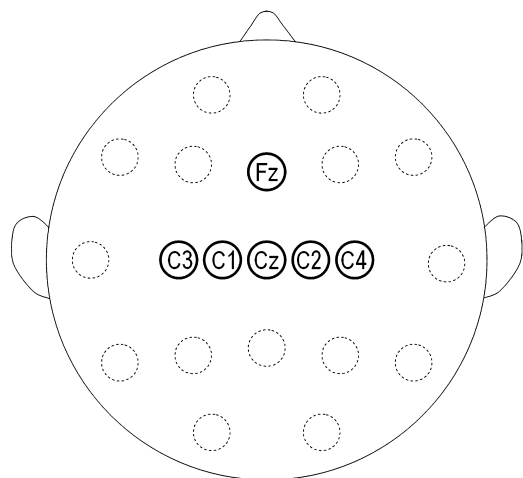
FIG. 7. Stimulating electrode positions for transcranial electrical stimulation. The dashed circles represent other electrode positions within the international 10-20 system.

interosseous muscles) because of their being predominantly under corticospinal tract control. More proximal muscles, especially forearm muscles, can be used as well. Upper-limb MEPs are useful for monitoring the neuraxis when the region at risk is above the lower cervical spinal cord, that is, the rostral cervical spinal cord, the brainstem, or the corticospinal tracts within the cerebrum. When the thoracic and lumbar spinal cord are at risk, upper limb MEPs may be used as a control recording to identify systemic effects, such as anesthesia, that might be affecting the MEPs recorded from lower limb muscles. They may also be used to monitor for brachial plexus compromise because of positioning of the patient's arms.

In the lower limb, the tibialis anterior and abductor hallucis are the muscles most commonly used for myogenic MEP monitoring. More proximal muscles may be used as well, but tend to give less reliable MEPs. Myogenic MEP recording sites should include leg muscles when the thoracic spinal cord is at risk. Myogenic MEPs can also be recorded from the anal sphincter; this is most often used during surgery on the lower spinal cord and in the region of the cauda equina.

Measurements and Alarm Criteria

Alarm criteria based on latency are in general not useful during MEP monitoring (Deletis and Sala, 2008). Amplitude measurements are used to assess both D-waves and myogenic MEPs.

The amplitude of the D-wave is measured from its peak to the following peak of the opposite polarity. As is the case for IONM of sensory evoked potentials, the most common alarm criterion is a 50% drop in the signal amplitude.

The amplitude of the myogenic MEP is measured between the most positive and the most negative points of the response waveform. Owing to the intrinsic variability of myogenic MEPs in the absence of spinal cord compromise (Fig. 4), a 50% amplitude decrease is usually not an appropriate alarm criterion for spinal cord monitoring with myogenic MEPs, as it would cause too many false alarms. Currently, there is no consensus as to what constitutes an appropriate alarm criterion for myogenic MEP monitoring of the spinal cord; the criteria are still evolving. One alarm criterion that is

widely used during spinal cord tumor surgery is complete disappearance of the myogenic MEP in the lowest threshold muscle(s). However, it may be preferable to notify the rest of the surgical team if the myogenic MEP decreases by a threshold percentage larger than 50% (e.g., 75%, 80%, or 90%) rather than waiting until it disappears completely. Such marked amplitude decrements can precede complete disappearance, but an 80% criterion still produces a number of false positives during spine surgery (Langeloo et al., 2007). Other alarm criteria have been used during myogenic MEP monitoring, including an increase in the threshold stimulus intensity required to elicit an MEP (Calancie et al., 1998) and a decrease in the duration and complexity of the myogenic MEP (Quinones et al., 2005); see Langeloo et al. (2007) for a review of MEP alarm criteria.

Anesthetic Considerations

D-waves are relatively unaffected by anesthesia. However, owing to anesthetic effects at the synapse between the corticospinal tract axon and the anterior horn cell, myogenic MEPs are markedly affected by anesthesia, to a greater extent than most other electrophysiologic tests used for IONM (Fig. 5). Therefore, the choice of the anesthetic regimen is particularly critical when myogenic MEPs are being monitored. Halogenated inhalational agents are suboptimal because they prominently suppress myogenic MEPs, especially at high concentrations. Intravenous anesthetics such as propofol and dexmetatomidine also affect myogenic MEPs, but to a lesser extent. Total intravenous anesthesia using propofol and opioid infusions appears to be optimal and is the preferred anesthetic regimen for monitoring of myogenic MEPs at many institutions, but MEPs can be monitored successfully in most patients when limited concentrations (typically <0.5 MAC) of halogenated inhalational agents are used. Opioids have only minor effects on myogenic MEPs. Nitrous oxide produces marked changes in myogenic MEPs, but they can be successfully recorded using a "nitrous-narcotic" technique. Effects of specific anesthetic agents on MEPs are described in greater detail in Sloan and Jäntti (2008). The use of neuromuscular blocking drugs during MEP monitoring was addressed above.

Because changes in the anesthetic regimen may alter myogenic MEPs, when myogenic MEPs are to be monitored, the anesthetic regimen should be kept as steady as possible. This is especially important around the time of critical maneuvers such as aneurysm clipping, alteration of the spinal alignment during spinal deformity surgery, or positioning of a patient with cervical spinal stenosis or a mechanically unstable spine. Therefore, bolus doses of anesthetic agents should be avoided around those times.

Concurrent Monitoring of SEPs

The use of MEP monitoring does not obviate the need for SEP monitoring of the spinal cord and brain. The dorsal columns of the spinal cord and the somatosensory pathways in the brain may be compromised during surgery without concurrent compromise of the corticospinal tracts (e.g., by a posterior spinal artery territory infarction or by a thalamic lesion) and thus without MEP changes. Therefore, when MEPs are used for intraoperative monitoring, SEPs should be monitored as well. Concurrent monitoring of SEPs and MEPs can detect compromise of either sensory or motor tracts and also provides a measure of redundancy, so that at least one method for monitoring the integrity of the nervous system is usable if the other one is, or becomes, unusable due to preexisting neurologic

compromise, anesthetic effects, NMB, excessively noisy data, or other technical problems (Legatt and Emerson, 2002).

Safety Considerations

Current densities in the brain with TES are far lower than levels that have been demonstrated to be safe (MacDonald, 2002) during direct brain stimulation, but the high extracranial current densities can cause contraction of the temporalis muscles and forceful jaw closure, which in turn can cause mouth injury. In MacDonald's series of over 15,000 operations with TES-MEP monitoring (2002), there were 29 tongue or lip injuries and one mandibular fracture. Endotracheal tube rupture has also been reported (MacDonald and Deletis, 2008). Padding or soft bite blocks should be used to prevent or mitigate mouth injury or endotracheal tube damage during TES.

Patient movement due to contraction of axial and limb musculature could also pose risks to the patient. Partial NMB may mitigate this, but may also complicate interpretation of the MEPs in some situations. As noted above, if used, partial NMB should be done with a continuous infusion of the paralytic drug, using EMG measures such as the assessment of the responses to train-of-four stimulation (Sloan and Jäntti, 2008) to assess the degree of NMB and titrate the infusion rate. If movement in the area of the surgical field is large enough to interfere with the surgery, the timing of TES should be coordinated with surgical maneuvers to avoid producing movement at times when this would be hazardous.

Electrical stimulation of the brain can trigger seizures. This is a well-known possibility with direct cortical stimulation, especially with prolonged trains of repetitive pulses (the "Penfield technique"), but also can occur with TES. This incidence of clinical seizures during TES is low—five seizures in one series of over 15,000 operations during which TES-MEP monitoring was performed (MacDonald, 2002). The incidence of electrographic but clinically silent seizure activity (similar to the after–discharges encountered during direct cortical stimulation studies) is unknown, as is their clinical significance. It has not been shown that a history of epilepsy predisposes a patient to seizures during TES, and such a history should not be viewed as a contraindication to TES. The role of concurrent EEG monitoring during TES-MEP recordings is unclear; it is used in some centers but not in all. Those who administer anesthesia during TES should be prepared to treat seizures should they occur. If a seizure occurs, the risk of a seizure must be balanced against the benefits of TES-MEP monitoring in preventing injury to the central motor pathways in deciding whether to discontinue TES-MEP monitoring.

In the early years of MEP monitoring, a variety of conditions were considered to be relative contraindication to TES, including epilepsy, a cerebral lesion, elevated intracranial pressure, implanted devices such as a cardiac pacemaker or a cochlear prosthesis, and convexity skull defects or metal skull plates under or close to the stimulating electrodes (Legatt, 2002; MacDonald, 2002). However, in many centers, some or all of these conditions are currently not regarded as barring TES, and patients with these conditions have had uneventful TES-MEP monitoring (MacDonald and Deletis, 2008). The benefits of MEP monitoring must be weighed against the potential risks in each patient.

Communication With the Rest of the Surgical Team

Significant changes in the IONM data should be communicated rapidly to the rest of the surgical team. If the MEPs are not obtainable (due to preexisting neurologic compromise in the patient,

anesthesia, NMB, or technical factors), this should also be communicated to the surgeons, lest they proceed with surgical procedures in the mistaken belief that the MEP data are demonstrating that the motor pathways are intact.

DISCLAIMER

This guideline is provided as an educational service of the American Clinical Neurophysiology Society (ACNS). It is based on an assessment of current scientific and clinical information. It is not intended to include all possible proper methods of care for a particular problem or all legitimate criteria for choosing to use a specific procedure. Neither is it intended to exclude any reasonable alternative methodologies. ACNS recognizes that specific patient care decisions are the prerogative of the patient and the physician caring for the patient, based on all circumstances involved. The clinical context section is made available to place the evidence-based guidelines into perspective with current practice habits and challenges. Formal practice recommendations are not intended to replace clinical judgment.

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