American Clinical Neurophysiology Society

Guideline on Transcranial Electrical Stimulation Motor Evoked Potential (TES-MEP) Monitoring

**Introduction**

Motor evoked potentials (MEPs) are electrical signals recorded from neural tissue or muscle following 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). SEPs directly assess only a part of the spinal cord, the dorsal columns (Emerson, 1988). 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; 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 in order 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 (Taniguchi et al., 1993, Szelényi et al., 2007b). 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 (TMS) 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, TMS is not the optimal MEP technique for IONM due to the anesthetic suppression of TMS-MEPs which are generated mainly by eliciting I waves (see 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 TMS 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 a muscle contraction, the compound muscle action potential is called the “M-wave” or the myogenic MEP. M-waves can be recorded from multiple muscles simultaneously following a single train of transcranial stimuli. Train stimulation is needed to reliably elicit M-waves under anesthesia. The excitatory postsynaptic potentials in the anterior horn cells summate to bring them to threshold and fire them. Both D-waves and M-waves can be used for IONM (Fig. 2).

TES predominantly generates D-waves under the stimulating anode, and therefore predominantly generates M-waves in muscles contralateral to the stimulating anode (Fig. 3). However, in rare patients with congenital motor non-decussation TES produces predominantly anode-ipsilateral M-waves (MacDonald et al., 2004). M-waves 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, due to changes in cortical excitability related to anesthetic effects (Legatt, 2006).

Mention should be made of a technique utilizing 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, M-waves following 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 M-wave 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. Since there are no synapses between the stimulated cortical pyramidal neurons and the MEP recording site, multi-pulse stimulation is not required, though 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-wave 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.

M-waves 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 an M-wave 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 M-waves highly sensitive to anesthetic effects 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 different 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, M-waves, 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 M-wave MEP monitoring.

- **Anesthesia:** D-waves are relatively insensitive to anesthesia. M-waves are easily suppressed by anesthesia, especially by inhalational anesthetics, which sets limits on the anesthetic regimen that can be used during MEP monitoring of M-waves (Sloan and Heyer, 2002).

- **Neuromuscular blockade (NMB):** Neuromuscular blockade does not affect D-waves, but total NMB eliminates M-waves. Omitting NMB permits straightforward M-wave 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 M-wave interpretation. Some centers generally omit NMB, while others tend to employ 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:** M-wave monitoring 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; M-wave monitoring 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. M-waves 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. M-waves adequate for monitoring may be present in such patients (Fig. 5).

- **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. M-wave monitoring records from muscles on each side separately.

- **Timing of alarm:** Because M-waves 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 M-wave loss, 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 M-wave loss generally predicts cord infarction and permanent motor deficits. In contrast, during surgery for intramedullary spinal cord tumors, patients in whom M-waves are lost but D-waves persist generally have transient post-operative weakness or paralysis; the M-wave 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- and M-wave 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 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, including the influence of stimulus and recording parameters, anesthesia, neuromuscular blocking agents, and other factors that may affect the MEPs during IONM; knowledge of anatomical structures, neurophysiological events and other factors involved in the generation of MEPs, the clinical significance and pathophysiological 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 inter-pulse 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 stimulators of either type can also be effective. 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 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, though surface electrodes can also be employed. Low impedances, which correlate with a larger contact area between electrode and tissue, help to prevent tissue injury from the high stimulus currents employed 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 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. 6). 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 non-decussation). An anode at Cz can be paired with a cathode at Fz (Fig. 6). 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 M-waves are monitored, multi-pulse 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. Multi-pulse stimulation elicits a train of D-waves, and often some I-waves as well, and the excitatory post-synaptic potentials that they produce in the anterior horn cell summate to above threshold, thus firing the lower motor neuron and generating the M-wave (Legatt 2004). If the inter-pulse interval (interval between stimulus pulses in the train) is too long, the post-synaptic potentials don't 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 due to their refractory periods (Deletis et al., 2001a). Inter-pulse intervals between 2 and 4 ms (i.e., intra-train pulse repetition rates of 250 to 500 Hz) are typically optimal for M-wave monitoring. A train of 3 pulses will suffice in some patients; others will require more. It is best to have a starting set of stimulus parameters (stimulus intensity, number of pulses per train, and inter-pulse interval/pulse rate) for the initial recordings under anesthesia, and then to adjust the parameters as necessary to obtain MEPs adequate for IONM in each individual patient.

TES with pairs of pulse trains (Journee et al., 2007) can facilitate the recording of myogenic MEPs, as can electrical stimulation of the foot prior to 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 in close proximity to the spinal cord, either epidural or subdural. They may be placed percutaneously via 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 2–3 cm is adequate (Deletis and Sala, 2008).

Myogenic MEPs should be recorded from limb muscles on both sides of the body. Needle electrodes typically record larger signals than do surface electrodes. Either type and their leadwires should be securely fastened to the skin to prevent dislodgement during surgery.

In the upper limb, M-waves are optimally recorded from hand muscles (thenar, abductor digiti minimi, or first dorsal interosseus muscles) due to 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, i.e., 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 due to positioning of the patient's arms.

In the lower limb, the tibialis anterior and abductor hallucis are the muscles most commonly used for M-wave monitoring. More proximal muscles may be used as well, but tend to give less reliable MEPs. M-wave recording sites should include leg muscles when the thoracic spinal cord is at risk. M-waves 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 M-waves.

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. An alarm criterion of a 30% drop may be more appropriate when D-waves are used to monitor surgery for cerebral lesions near the central sulcus (Yamamoto et al., 2004).
The amplitude of the M-wave is measured between the most positive and the most negative points of the response waveform. Due to the intrinsic variability of M-waves 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 M-waves, as it would cause too many false alarms. Currently, there is no consensus as to what constitutes an appropriate alarm criterion for M-wave 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 M-wave in the lowest threshold muscle(s). However, it may be preferable to notify the rest of the surgical team if the M-wave 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 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 M-wave 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 M-wave (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, due to anesthetic effects at the synapse between the corticospinal tract axon and the anterior horn cell, M-waves are markedly affected by anesthesia, to a greater extent than most other electrophysiologic tests used for IONM. Therefore, the choice of the anesthetic regimen is particularly critical when M-waves are being monitored. Halogenated inhalational agents are suboptimal because they prominently suppress M-waves, especially at high concentrations. Intravenous anesthetics such as propofol and dexmetatominidine also affect M-waves, 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 M-waves at many institutions, but MEPs can be monitored successfully in most but not all patients when limited concentrations of halogenated inhalational agents are used. Opioids have only minor effects on M-waves. Nitrous oxide produces marked changes in M-waves; but myogenic MEPs 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).

Since changes in the anesthetic regimen may alter myogenic MEPs, when M-waves 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, neuromuscular blockade, 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 neuromuscular blockade 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 – 5 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 afterdischarges 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 again 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 cochlear prosthesis, and convexity skull defects 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, 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 is demonstrating that the motor pathways are intact.

(ADD PRACTICE AND LIABILITY DISCLAIMER AS PER NEW GUIDELINES FORMAT)

References


Legatt AD. MEPs elicited by cathodal stimulation during transcranial electrical stimulation-MEP monitoring. Neurology 2006; 66(Suppl. 2):A68.


**Figure Captions**

**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 and Amassian VE. Single- and multiple-unit analysis of cortical stage of pyramidal tract activation. J Neurophysiol 17:345-363, 1954)

**Fig. 2.** Concurrent monitoring of M-waves (left) and D-waves (right) during surgery for a spinal cord tumor. The M-waves 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; p.421-444)

**Fig. 3.** MEPs to TES between electrodes at positions C1 and C2, recorded bilaterally from thenar and tibialis anterior muscles during an occipito-cervical fusion. (from Legatt AD. MEPs elicited by cathodal stimulation during transcranial electrical stimulation-MEP monitoring. Neurology, 2006; 66(Suppl. 2):A68)

**Fig. 4.** M-waves recorded from the left tibialis anterior and thenar muscles following multipulse TES with the anode over the right hemisphere, over a three-hour period during an occipito-cervical fusion. Note the large run-to-run variability of the MEP amplitudes and waveshapes. The numbers in the middle are the clock times of each run. (from Legatt AD. Ellen R. Grass
Fig. 5. No clear D-wave is present in epidural recordings caudal to an intramedullary tumor of the cervical spinal cord (left), but TES with brief stimulus trains elicits clear myogenic MEPs (right). (from Deletis V, Kothbauer K. Intraoperative neurophysiology of the corticospinal tract. In: Stålberg E, et al., eds. Spinal Cord Monitoring. Wien: Springer, 1998; p. 421-444)

Fig. 6. Stimulating electrode positions for TES. The dashed circles represent other electrode positions within the International 10-20 System.