The first successful resection of an intradural tumor, a fibro-myxoma, was accomplished in 1887 by Victor Horsley, and the first successful resection of an intramedullary spinal cord tumor was performed in 1907 by Anton von Eiselsberg in Austria. However, the first report of an intramedullary tumor appeared in 1911 by Charles Elsberg in New York. Elsberg described a two-stage strategy for the removal of these intramedullary tumors. At the initial operation a myelotomy would be performed. The surgeon would then return one week later to remove the intramedullary tumor. This technique allowed the neurosurgeon to remove only the extruded portion of an intramedullary tumor. Tumor within the spinal cord would not be removed for fear of neurological injury.

Following these initial reports for spinal cord tumors, other pioneering neurosurgeons attempted spinal cord surgery. However the complication rate, which included surgery at wrong levels, cerebrospinal fluid leaks, infection, paralysis and death, was quite significant. Thereafter, many neurosurgeons recommended a conservative approach with biopsy, dural grafting and radiation therapy regardless of histological diagnosis. With the advent of the operating microscope, development of microsurgical techniques, imaging technology, and intraoperative neurophysiology, the strategy for these intramedullary neoplasms has further evolved. The majority of spinal cord tumors are histologically benign and the radical or gross total removal results in long-term survival with an acceptable morbidity.

Tumors of the intramedullary spinal cord account for only 5 to 10% of all central nervous system tumors. A review of the computer surgical pathology database for intramedullary lesions at our institution between 1991 to 1998 yielded 294 cases in adults and children. The majority of these tumors were operated upon by the Dr. Fred Epstein. The 294 tumors included 117 removed from children under the age of 21 years, and 177 from patients 21 years and older. The most common single tumor type in children was the fibrillary astrocytoma which accounted for 45 (39%) tumors. There were 31 gangliogliomas which were almost as common as the low-grade fibrillary astrocytoma in the pediatric population. In our study of 164 children with intramedullary neoplasms, the majority of the tumors were located in the cervicothoracic or thoracic spinal cord. In contrast, ependymomas are the predominant tumor in adults accounting for 45% of 177 intramedullary tumors.

Intramedullary tumors may remain asymptomatic for a long time or cause nonspecific complaints which make the diagnosis difficult. The most common symptom of an intramedullary tumor in adults is pain. The pain may be diffuse or radicular in nature. There is no characteristic feature of the pain distribution in patients with intramedullary tumors, but patients with an intramedullary ependymoma tend to have dysesthetic pain as compared to astrocytomas. The diagnosis is even more difficult in children who may not complain of pain, dysesthesias or sensory loss. Other children may only complain of symptoms following a trivial fall or accident. Younger infants may even present with abdominal pain and undergo extensive gastrointestinal investigations. The onset of symptoms is often insidious and symptoms are typically present for 9 months. However, high grade or malignant neoplasms typically have a shorter presentation than indolent low-grade tumors.

Patients may also present with a motor deficit. This is the most common presentation in children with intramedullary tumors. These deficits can be seen as clumsiness, weakness or frequent falls. In children, this may manifest as motor regression such as refusal to stand or crawl after having learned to walk.
Scoliosis can also be a presenting complaint. This is seen in one third of children and young adults. The direction of the scoliosis curve is not specific. Children with scoliosis typically have paraspinal pain which is unusual for intramedullary tumors. Adult patients typically do not have scoliosis as a presenting complaint. Magnetic resonance imaging (MRI) is the imaging study of choice to identify an intradural spinal cord neoplasm. MRI scans should be performed with intravenous contrast agents (gadolinium diethylene-triamine-pentacetic acid) and in multiple planes. These images demonstrate the solid tumor component, associated cysts, and edema. Although MRI does not provide the histological diagnosis, there are some typical patterns of appearance for intramedullary tumors. Ependymomas tend to enhance brightly and homogenously with contrast. They are often associated with rostral and caudal cysts. These tumors are centrally located within the spinal cord. On the other hand, astrocytomas and gangliogliomas have a heterogeneous enhancement pattern. These tumors are often eccentrically located and produce an asymmetric enlargement of the spinal cord. Intramedullary tumors such as cavernous malformations and hemangioblastomas also have distinct imaging qualities. These lesions are typically situated near the dorsal surface of the spinal cord. Hemangioblastomas, regardless of size, have a syrinx or associated edema.

Computed tomography studies are reserved only for patients in which MRI is contraindicated or investigation of the bone anatomy is essential. This study is useful for the rare tumor which may involve bone and have extension to the spinal cord. With the advent of MRI, it is very unusual to diagnose intramedullary neoplasms with this imaging modality. Plain radiographs are mandatory for patients who present with scoliosis.

The surgical resection for intramedullary neoplasms has evolved since the initial report of Elsberg. With the advent of microsurgical technique, imaging technology and intraoperative neurophysiology, the radical resection of intramedullary neoplasms is a safe and effective treatment. In particular, the neurophysiological monitoring of motor pathways is extremely helpful to achieve a radical resection for these intramedullary tumors. The functional outcome of surgery is best correlated with the preoperative status, thus surgery should be performed early prior to onset of severe motor deficits. The present surgical adjuncts allow us to recommend radical resection for the majority of intramedullary neoplasms. This approach should be the standard for intramedullary tumors as it provides excellent progression-free survival. Adjuvant radiation and chemotherapy should only be administered for malignant gliomas.

Notes
Motor Evoked Potential (MEP) Physiology

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Throughout the phylogenetic series from the rat to humans, a brief electrical stimulus to the motor cortex may elicit a direct (D) discharge in large corticospinal tract (CT) neurons followed (under light anesthesia) by indirect (I) waves that reflect transsynaptic activation of CT neurons. While the D wave is a single synchronized discharge of CT neurons, in higher forms, especially in monkeys and humans, the I waves are multiple (3-4), highly periodic (1.4 – 2.0 ms) discharges.

Direct Activation
Conducted D discharge is usually intraoperatively recorded as a brief (- + -) wave whose amplitude depends on (1) the number of CT fibers excited, (2) the amplitude of the fiber action potentials, and (3) their synchrony because desynchronization leads to amplitude reduction by phase cancellation. Thus damage to the CT pre- or during operation could reduce the compound D wave by block in some fibers, slowing of impulse conduction in some fibers and near the site of trauma, by reducing the membrane action potential. At the site of a focal lesion, the (+ - +) complex becomes mainly monophasic (+); any effect of desynchronization on the D wave amplitude would now be reduced because (+) fiber action potentials can sum, the area under the (+) wave now reflecting the number of conducting fibers. The collision technique can also be used to detect asynchronous discharge. It should be noted that asynchronicity of CT activity sufficient to reduce CT wave amplitude will not necessarily prevent motoneuron responses, because the long duration of EPSPs reduces any effect of phase cancellation.

The older idea that CT neurons were directly activated by focal (+), but not (-) stimulation is clearly incorrect. Increasingly above threshold, both focal (+) and (-) activate CT neurons directly (and indirectly, see below). This has a serious implication for activation of CT neurons projecting to alpha motoneurons activating leg muscles, because the C1-C2 montage typically used will activate the CT bilaterally. Consequently with this montage, if an intraoperative reduction in the D wave occurs, it could be uncertain whether bilateral damage or more severe unilateral damage had occurred. Contralateral without ipsilateral leg muscle activation can be obtained with a focal anode at C2 and a larger cathode 6 cm posteriorly on the same side; it is likely that unilateral D activation occurs with this montage, because the stimulating current is directed mainly ipsilaterally.

The site of D activation with transcranial electrical stimulation in humans is most likely at low threshold points such as bends in CT fibers as they project between the paracentral lobule and the internal capsule. Unlike in the monkey, there is no evidence that with focal cathodal stimulation, D activation can occur near the initial segment – axon hillock region, where excitability is conditioned by ongoing synaptic bombardment. Theoretically, the D wave amplitude should have a sigmoid relationship to stimulus intensity (i.e. the integral of the normal distribution of thresholds around the mean). In animal models, the D wave amplitude grows
quasilinearly over a considerable range with either electrically or magnetic stimulation, yielding a very approximate measure of the number of activated fibers.

Finally, great caution should be exercised in interpreting changes in D wave amplitude with transcranial electrical stimulation during changes in anesthesia. The actual exciting transmembrane current is affected by a number of factors, including shunting of the applied current through changes in extraneural fluid compartments, such as blood vessels. The fact that D responses in animals to stimuli directly applied to motor cortex resist deep anesthesia and asphyxia makes it unlikely that human CT fibers are very different in their susceptibility to light anesthesia.

**Indirect Activation**

Although I waves are readily recorded from conducting CT fibers, their amplitude is markedly increased (by 3x) when conduction is blocked. This is important when the relative efficacy of focal (+) or (-) stimulation in generating D and I waves is compared. I waves are composed of discharges of fibers previously directly activated and of those firing only during the I waves.

I waves are generated from extrinsic and intrinsic sources.

**Extrinsic sources**

Of the numerous excitatory afferent inputs to motor cortex, the corticocortical fibers from parietal lobe and premotor cortex and supplementary motor cortex are the most likely sources of I waves. Single pulse thalamic ventralis-lateralis N powerfully excites CT neurons monosynaptically and disynaptically, but the subsequent large IPSP tends to prevent the full I wave sequence. Parietal input can excite large CT neurons monosynaptically, (I1 wave) but typically earliest excitation by premotor inputs is typically disynaptic (I2 wave).

**Intrinsic sources**

Our explanation for the I2, I3 and I4 waves is that they reflect excitation by a vertically oriented interneuron chain in motor cortex, with the more superficial interneurons contributing to the later I waves. The supporting evidence is derived from (a) the effect of pial cooling, which can cause reduction of the late I waves without affecting the I3 wave, (b) stimulation through intracortical microelectrodes preferentially elicits late I waves superficially, but a transverse electric field near lamina V elicits the I1 wave.

**Possible difficulties in the excitatory network explanation of I waves**

It has been suggested that the prolonged EPSPs with small action potentials elicited by corticocortical inputs that were recorded by Ghosh and Porter (1988) could not explain periodic I waves; a possible remedy would be activation of inhibitory neurons whose discharge is yoked to that of the CT neuron by recurrent collaterals (Ziemann and Rothwell, 2000). However, uninjured CT neurons as recorded in many laboratories show a temporary reduction of ongoing EPSPs by the fast repolarizing K+ currents, i.e. subsequent excitation may be necessary for later I waves. Furthermore, numerous laboratories have shown that single recurrent CT discharge is much less effective than a train in eliciting inhibition, rendering it unlikely that the early I wave periodicity could be explained by recurrent inhibition.

A further problem is posed by the differing synaptic delays for the earliest I activity, e.g. from parietal versus premotor stimulation. Given the “classical” distribution of corticocortical synaptic contacts throughout the cortical laminae, a similar initial I wave delay might be expected from any corticocortical input. However, the neurohistology does not define the synaptic efficacy of the contacts, i.e. the probability of transmitter release and the amount released. Clearly, some synaptic contacts may be mono- or disynaptically effective; others may preferentially activate the excitatory network or vice versa. Such details of corticocortical action require further study.

**Intrinsic membrane periodicity as another possible explanation for I waves**

A remarkable feature of I wave periodicity is that it is conserved over a wide range of intensities and sources of afferent input. While conservation of periodicity would be expected from the quantizing effect of
successive local synaptic excitations, an intrinsic membrane periodicity of 1.4 – 2.0 ms is an alternative possibility. However, intracellular injection of depolarizing current in CT neurons elicits a continuous gradation of interspike intervals rather than a preferred period reflecting an intrinsic I wave periodicity. Thus, there is no evidence in adult preparations of an intrinsic 1.4 – 2.0 ms membrane periodicity.

**Activation of the Alpha Motoneuron**

Discharge of the motoneuron by stimulated CT activity is a function of the number of activated CT fibers and the background tonic facilitatory and inhibitory inputs. The relationship between CT input and motoneuron output is inherently nonlinear. An awake, voluntarily contracting subject unlike in an anesthetized patient has many motoneurons close to firing level so that a minimal CT volley may cause muscle activation. Under anesthesia, unless background facilitation is provided by muscle stretching, motoneuron activation requires temporal summation of multiple CT volleys (Brookhart 1952; Phillip and Porter 1964). If I wave generation is depressed by anesthesia, temporal summation at the motoneuron can only be secured with multiple D waves elicited 1:1 by multiple electrical stimuli. However, because of refractoriness of CT fibers to direct stimulation, the optimal periodicity of such stimulation does not necessarily match the median I wave periodicity (1.7 ms), but is a longer period balancing escape from refractoriness against increasing decay of the previous motoneuron EPSP.

If the anesthesia is light enough, each electrical stimulus generates a D plus multiple I waves so that fewer stimuli are required for muscle activation.

**Notes**
Intraoperative Monitoring: Motor Evoked Potentials Methodology

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In order to understand the behavior of the motor evoked potentials (MEPs) recorded intraoperatively, and correctly determine their prognostic values, it is of utmost importance to understand their methodological aspects.

The methodology for eliciting MEPs intraoperatively has its origin in the early work of Patton and Amassian (1954). They discovered that direct electrical stimulation of the motor cortex in monkeys generates a series of descending volleys in the pyramidal tract. These volleys were easily recorded, in their experimental setting, over the exposed pyramids of the medulla.

It has taken almost thirty years for this discovery to be applied clinically. Merton and Morton (1980) first elicited MEPs by transcranial electrical stimulation (TES) in awake volunteers (in one of the authors). This method, aside from causing some discomfort when applied to awake patients, was used as an additional diagnostic tool for upper motor neuron lesions. More importantly, Merton and Morton’s methodology opened a new field in clinical research of the motor system.

Barker et al. (1985) discovered that electric current in the brain can be induced by a varying magnetic field and consequently activate corticospinal tract (CT) motoneurons. Since this method of transcranial magnetic stimulation (TMS) caused minimal discomfort to the patient being stimulated, it tremendously enlarged the applicability of MEPs. In fact, this method completely took over the use of TES as a diagnostic tool in awake patients.

On the contrary, eliciting MEPs by TES and TMS methods intraoperatively did not show consistent results. These methods require relatively light anesthesia, and in patients with more pronounced motor deficits, they were inefficient in eliciting MEPs. This is especially true for the TMS method since it activates the motor cortex transsynaptically and therefore is more susceptible to the effects of anesthetics. These disadvantages prevented the use of a single pulse technique for eliciting MEPs intraoperatively either with TES or TMS.

Another single electrical stimulation technique produces excellent intraoperative results. Instead of recording MEPs from limb muscles, this method records MEPs from the surface of the spinal cord (epi- or subdurally). Using this method, a consistent response (D and I waves) can be obtained. (Boyd et al., 1985, Katayama et al., 1988, Burke et al., 1993, Deletis, 1993, Morota et al., 1997). In fact, this method represents a direct clinical application of Patton and Amassian’s discoveries from the early 1950s. Thus, the knowledge they collected using this method in primates can be easily applied in intraoperative settings.

Finally, the discovery that the use of multi-pulse instead of a single pulse during TES has expanded the boundaries in the intraoperative monitoring of MEPs from limb muscles. This method overcomes the disadvantages of the single pulse technique and consistently elicits MEPs intraoperatively (Taniguchi et al., 1993, Jones et al. 1996).

In summary, there are two reliable techniques for intraoperative monitoring of the CT’s functional integrity:

1. A single-pulse stimulating technique, applied transcranially or over exposed motor cortex, while the D Wave is recorded from the spinal cord.
2. A multi-pulse stimulating technique, also applied transcranially or over exposed motor cortex, while MEPs are recorded from the limb muscles. (Fig.1)

(Note: The multi-pulse technique essentially differs from Penfield's technique in that it calls for only 5-7 stimuli with up to 2Hz of stimulating rate, while Penfield's calls for continuous stimulation during a few seconds with a frequency of 50-60Hz.)

Figure 1. **Top left:** Schematic illustration of electrode positions for transcranial electrical stimulation of the motor cortex according to the International 10-20 EEG system. The site labeled "6 cm" is 6 cm anterior to CZ. **Top right:** Illustration of grid electrode overlying the motor cortex. The size of the grid electrode relative to the brain is actually much smaller than depicted in the illustration. **Middle:** Schematic diagram of the positions of the catheter electrodes (each with three recording cylinders) placed cranial to the tumor (control electrode) and caudal to the tumor to monitor the incoming signal passing through the site of surgery (left). In the middle are D and I waves recorded rostral and caudal to the tumor site. On the right is depicted the placement of an epidural electrode through a flavectomy when the spinal cord is not exposed. **Bottom:** Recording of muscle motor evoked potentials from the thenar and tibial anterior muscles after eliciting them with a short train of electrical stimuli applied either transcranially or by stimulation of the exposed motor cortex.
For the last eight years, we have used both single and multi-pulse stimulating techniques in thousands of patients with different pathologies of the brain, brainstem and the spinal cord.

After using parallel recordings of D wave and muscle MEPs, we can draw further conclusions:

A. The optimal stimulating parameters for eliciting muscle MEPs are:
The individual pulse duration should be 500 µs, the inter-stimulus interval in the train of 5-7 pulses should be 4 ms, and a stimulation rate of up to 2 Hz should be used (Deletis et al., 2000, parts 1 and 2). The stimulus intensity should be up to 200 mA. Usually, 100 mA or less is required for consistently eliciting muscle MEPs. The “corkscrew like” stimulating electrode should be placed over the C1/C2 (10-20 International EEG system). The other stimulating sites on the scalp that could be used include C3/C4, or 1-2 cm in front of C3 or C4, or Cz/6 cm in front of Cz (governed by the particulars of the case). If surgically exposed motor cortex was stimulated through the grid assembly electrode, or hand-held ball electrode, less current is required (only up to 20 mA). Other stimulating parameters are the same as for TES. In both settings the anode is the stimulating electrode. With regard to selecting muscles for stimulation, the abductor pollicis brevis muscle (APB) or forearm flexors or extensors are recommended for the upper extremities. For the lower extremities, the tibial anterior muscles (TA) and/or abductor hallucis brevis (AH) should be used. It is not necessary to average single responses.

B. For eliciting a D wave, the same stimulating sites are recommended as for muscle MEP. A single pulse of 500 µs duration and a stimulation rate up to 2 Hz should be used. Intensity of stimulation should be set up as is required for eliciting muscle MEPs.

Note: If the chosen intensity elicits muscle MEPs on one side of body, a D wave recorded epidurally represents activity of only one CT tract.

For recording a D wave, a semi-rigid epidural catheter electrode should be used. If surgery does not require laminectomy/laminotomy, a D wave recording can be achieved by placing a suitable catheter electrode percutaneously (using a Tuohy needle or through flavectomy). The averaging of 2-4 responses usually result in high quality D wave recordings.

C. General anesthetics and muscle relaxant do not influence a D wave. (Fig. 2)

Figure 2.
Recorded from an excellent motor response area for upper extremities by epidural electrode before a muscle relaxant was administered, and lower trace was recorded after administration. Note that D wave is unaffected by muscle artifact.
Figure 3. Epidurally recorded D and I waves intraoperatively showing the effect of the application of cool and warm irrigation to the exposed spinal cord. Note the increased latency of the D wave when cord is cooled.

D. A decrease in the temperature of the spinal cord temporarily prolongs the latency of D and I waves. (Fig. 3)

E. Muscle MEPs are sensitive to the use of halogenated anesthetics (isofluorane, fluorane, and enflurane). They are also sensitive to the muscle relaxants. Note: Although muscle MEPs can be elicited at the level of relaxant which gives one response out of four (train of four technique), we do not recommend the use of any relaxant during surgery except a short acting one during patient intubation.

F. The clinical correlation between the behavior of the D wave and muscle MEPs consistently show that both potentials are necessary for the prediction of postoperative motor outcome. Their importance has been shown in the case of “transient paraplegia of surgical origin” (Deletis & Kothbauer, 1998). During surgery for intramedullary spinal cord tumors in the thoracic spinal cord, the loss of muscle MEPs with preservation of the D wave always predicts postoperative paraplegia with complete recovery in a short period of time (a few hours to a few days).

G. The D wave recorded from the spinal cord exclusively represents the electrical activity of a synchronized descending volley of the fast neurons of the CT.

H. The muscle MEPs elicited in an anesthetized patient presents mixed activity of the CT and the supportive system (propriospinal system) of the spinal cord. It is likely that the supportive system is being indirectly activated from the motoneurons of the CT.

References


Notes
Somatosensory evoked potentials (SEPs) were first reported to be an effective technique for assessing spinal cord function during surgery more than 30 years ago. When elicited by peripheral stimulation of mixed nerves at the ankles and/or at the wrists, the resulting ascending volleys consist of both orthodromic ascending sensory (AS) and antidromic ascending motor (AM) components. The antidromic motor components ascend no further than the anterior horn cells in the spinal cord while the sensory volleys which primarily contribute to SEPs ascend to the cortex via the spinal cord's dorsal column pathways and more rostral medial lemniscal and thalamic pathways.

Surgical events, which cause changes in spinal function either because of ischemia or mechanical distortion, can only be detected by the use of SEPs if such events result in changes of dorsal column function. It is likely that mechanical distortion of the spinal cord will result in such changes since such anatomical distortion is likely to include the dorsal column pathways. Ischemic events are another matter. The posterior one-third of the spinal cord containing the dorsal column pathways is generally believed to receive its blood supply primarily from the posterior spinal arteries. The remaining anterior and lateral portions of the spinal cord which include those pathways which mediate motor function is thought to receive its blood supply from the anterior spinal artery. Therefore, it is questionable whether SEPs would be sensitive to changes in anterior spinal artery blood supply. Reports in the literature suggest that SEPs can indeed be insensitive to such changes that have resulted in profound loss of motor function. This limitation of SEP monitoring is well known and has resulted in the development of various techniques for directly assessing spinal cord motor function. These techniques have utilized either transcranial or spinal stimulation to elicit descending volleys of motor (DM) activity.

Transcranial stimulation techniques have been available for many years and the responses are thought to result from only motor pathway activation. However, their use, until relatively recently, had not received widespread acceptance for several reasons. These included concerns about patient safety and the fact that, until recently, the devices used to elicit motor responses were not FDA approved. In addition, commonly used inhalational anesthetic agents interfered with response acquisition as did the use of muscle relaxants.
These issues are not a concern when using spinal stimulation techniques. However, it is generally recognized that stimulation of the spinal cord via needles placed percutaneously or in decorticated spinous processes, or by epidurally placed electrodes will likely result in diffuse activation of the spinal cord including both motor and sensory pathways. However, based on the results of collision studies, it was reported that neurogenic MEPs (NMEPs) elicited by spinal stimulation and recorded from peripheral nerve were found to consist of primarily motor components which had shorter latencies and were much larger in amplitude than the small amplitude polyphasic sensory activity which they preceded. Such reports promoted the usefulness of these responses. In recent years, questions have arisen as to the accuracy or the interpretation of these findings.

In order to investigate and support the utility of neurogenic MEPs, independent investigators have performed collision studies. These studies suggest that the descending volleys of activity, known as neurogenic motor evoked potentials (NMEPs) resulting from percutaneous spinal stimulation appear to be primarily if not totally composed of descending antidromic sensory (DS) components mediated by the same dorsal column pathways as SEPs rather than motor components. Recently reported clinical findings support these collision study results. However, further studies are needed to investigate the mechanisms of peripheral muscle activation via spinal stimulation.

Notes

Anterior Spinal Cord Injury with Preserved Neurogenic “Motor” Evoked Potentials

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Introduction

SEP monitoring can detect most intraoperative spinal cord injuries but false negative results can occur due to selective injury to motor pathways. As a result, attempts have been made to introduce motor evoked potentials (MEPs) to the monitoring regimen. Initial attempts to produce a reliable measure of motor function after cranial stimulation were difficult. As an alternative, a relatively simple purported test of motor function was introduced and was termed “neurogenic motor evoked potentials (NMEPs)” (Owen, 1993). However, there is controversy regarding whether sensory, motor, or a combination of these pathways are monitored (Su et al., 1992; Toleikis et al., 2000; Leppanen et al., 1998; Owen, 1999; Péréon et al., 1998; Péréon et al., 2002). As a result of this controversy, we use the neutral term spinally elicited peripheral nerve responses (SEPNRs) in place of NMEP. We describe two cases in which intraoperative monitoring of SEPNRs persisted in the face of paraplegia and intact dorsal column function.

Methods

Stimulus and recording methods have been published (Minahan et al., 2001).

Patient #1

This 40 year-old woman with a long history of rheumatoid arthritis and kyphoscoliosis had had a prior spinal fusion which was complicated by infection and required removal of instrumentation. Subsequently she had
progressive spinal deformity and pain prompting the current surgery. Preoperative neurologic exam showed partial right L5 radicular motor and sensory deficits.

Surgery consisted of three parts. The initial portion included anterior corpectomy (T10) and fusion T4-T12 (Moss Miami system – tightened on one end only with the initial anterior approach). This was followed by a posterior-approach osteotomy (approximately T10) with segmental instrumentation T4-L1. Finally, the anterior side was reopened for tightening of the previously positioned instrumentation (slight distraction of one rod only). The surgery proceeded without apparent complication.

SEPs and spinally elicited peripheral nerve responses (SEPNRs) are shown in figure 1 with parts A, B, C corresponding to the initial three portions of the surgery described above.

Upon awakening, the patient was found to be paraplegic and immediate steps toward removal of instrumentation were taken. Both spinally elicited responses and tibial nerve sensory responses were obtained during this follow-up procedure and signals were comparable to data obtained in the primary procedure. However, all electrodes were removed after the initial procedure and then replaced for instrumentation removal with resultant alteration of signal morphology (Figure 1D). Examination of the patient 1 day after surgery showed paraplegia, loss of pin sensation bilaterally to a T12 level, normal vibratory thresholds in the toes, and intact proprioception in the great toes bilaterally (<4 mm excursions). The patient died due to a pulmonary embolus 9 days after surgery without evidence of neurologic recovery.

Patient #2

This 12 year-old girl presented with adolescent idiopathic scoliosis (77-degree right curve from T6-T12) and was otherwise healthy. The surgical procedure was a right-sided anterior spinal fusion with instrumentation from T6-T12 (Moss Miami fixation) and a posterior-approach spinal fusion from T3 to L1. The procedure proceeded without apparent complication.

SEPs and spinally elicited peripheral nerve responses (SEPNRs) were as shown in figure 2 with parts A and B corresponding to the anterior and posterior portions of the surgery respectively.

Upon awakening, the patient had no lower extremity movement and had decreased pin sensation to the mid-thoracic level. Despite this, proprioception at the great toes was intact on repeated evaluations in the immediate postoperative period. Sixteen days after the initial surgery, the patient returned for reinsertion of instrumentation. Neurologic exam at that time showed partial recovery with right lower extremity movement (2-3/5 MRC scale) and a trace right patellar reflex. However, left lower extremity monoplegia and areflexia remained. Sensory exam showed decreased pin sensation bilaterally to a T6 level with normal vibration thresholds and normal proprioception bilaterally in the toes.

Monitoring again was performed with SEPs and SEPNRs with results shown in figures 2C. SEP signals were comparable in amplitude with longer latencies due to stimulation at the ankle vs. popliteal fossae in the initial surgery. SEPNRs latencies were shorter and polyphasia was reduced due to recording at the popliteal fossae vs. ankle recording in the initial surgery. The patient began to show motor recovery on the left side 6 weeks after the initial surgery with bilateral improvement in lower extremity function thereafter. She made a complete motor and sensory recovery by 3 months postoperatively.

Discussion

Some have used SEPNRs in an attempt to address the limited scope of SEP testing however, this merits reexamination in light of theoretical, experimental, and now clinical evidence that SEPNRs and SEPs yield similar information.
The relative contribution of sensory and motor information to the SEPNR signal has been a matter of debate. SEPNRs employ nonspecific stimulation of the spinal cord so, given sufficient stimulus intensity, both motor and sensory tracts will be activated. Clearly sensory tract information will be transmitted to peripheral nerves given the absence of any intervening sensory synapse between the stimulation site and peripheral nerve. Sensory information is likely to constitute the initial portion of any response as large fiber sensory activity travels 5-10% faster than the motor activity in the peripheral nerve (Dawson, 1956) and no synaptic time delay is present.

The presence of a motor signal in the SEPNR is less certain. Motor conduction to the periphery will include synaptic activity at the anterior horn cell which is potently inhibited by standard anesthetic regimens (Deletis, 1993; Zhou and Zhu, 2000; Péréon et al., 1999). However, as traditionally described SEPNRs are not significantly affected by potent inhalational agents (Owen et al., 1991; Owen, 1999) casting doubt on a significant motor contribution to the recorded signal. Second, motor tracts have a higher threshold for activation than the sensory tracts (Haghighi et al., 1994) but as traditionally described, SEPNRs are not dependent upon any given stimulation intensity above threshold. Finally, lesioning experiments using standard elicitation methods point to transmission in the dorsal columns (Mochida et al., 1995).

Collision studies have shown that the early biphasic response is sensory in origin (Leppanen et al., 1998) or that all identified SEPNR components consist of sensory information (Toleikis et al., 2000). More recently, Péréon et al. used collision studies to show that a motor component of the SEPNR could be produced using specific stimulation and anesthesia techniques (Péréon et al., 2002). However, these techniques are not part of what has been classically called NMEPs and before this motor component can be assessed clinically, further study will be needed.

We continue to use SEPNRs as a complement to SEPs for spinal cord sensory function assessment. However, the described cases and a growing body of experimental evidence suggest that motor function is not reliably assessed by the SEPNR. Modifications to SEPNR recording methods may eventually yield a method to assess motor activity but these are not yet ready for clinical implementation. In light of this, the use of the term “neurogenic motor evoked potential” or even “neurogenic mixed evoked potential” when referring to traditional elicitation methods, can not be justified, is potentially misleading, and should be abandoned.
Figure 1: Bilateral tibial SEP and SEPNR responses for Case #1.  A. Initial anterior approach.  B. Posterior approach. Tibial SEP signals improved during this portion of the procedure after a decrease in the isoflurane from 0.7% to 0.3%. Initial SEPNR signals in this portion of the procedure were difficult to obtain due to stimulator placement and improved after proper adjustment.  C. Second anterior approach. The surgeon elected not to place spinal stimulating electrodes during this portion of the procedure.  D. The patient returned to surgery immediately after discovery of paraplegia. Robust signals persist during removal of instrumentation. For groups A, B, and C; the top traces represent initial responses while the lowest trace in each group represents the final response obtained prior to wound closure. Group D traces represent the initial data after discovery of paraplegia.
Figure 2: Bilateral tibial SEP and SEPNR responses for Case #2. A. Anterior portion of the procedure. B. Posterior portion of the procedure. C. Replacement of instrumentation 16 days after the initial procedure. During this latter procedure (group C), tibial SEP latencies are longer due to stimulation at the ankle (vs. the popliteal fossa in the original surgery) and SEPNR latencies are shorter with less polyphasia due to recording at the popliteal fossa (vs the ankle in the original surgery). For groups A and B; the top traces represent initial responses and the lowest trace in each group represents final responses obtained prior to wound closure while group C is the initial data after discovery of spinal cord injury. Time of signal acquisition is noted between left and right traces for each modality.

References


**Notes**
MEP Monitoring during Spinal Cord Surgery

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The use of the intraoperative microscope and the development of MRI and neuronavigation, represent major advances in spinal cord surgery. These tools made spinal cord and spinal cord surgical diseases more “visible” to the surgeon. A more recent breakthrough in spinal cord surgery is motor evoked potentials monitoring.

Historically, SEPs were the first to be used. SEPs provide information about stimulated peripheral nerves, cord dorsal columns, brain stem and somatosensory cortex; they do not provide information about pain and temperature, and about motor function. Nevertheless for almost 20 years they were used to get indirect informations on motor function. As a consequence, the inaccuracy of SEPs monitoring to guide the neurosurgeon during spinal cord surgery, produced a certain skepticism toward intraoperative monitoring. The possibility to have direct informations about the motor function through MEPs, has changed this attitude.

From a neurophysiological point of view, MEPs methodology is safe and reliable because of its high monitorability under general anesthesia, its high specificity and sensibility. From a neurosurgical point of view, MEPs monitoring is reliable if a clearcut relationship is evident in most of the cases between changes of the potentials and action of the surgeon, and if MEPs monitoring demonstrates a favorable impact on neurological postoperative motor outcome.

Since 1997, we introduced MEPs monitoring at the Department of Functional and Spinal Neurosurgery, Catholic University in Roma, Italy. Here we report our experience in spinal cord surgery guided by intraoperative neurophysiological monitoring. We analysed our series in order to confirm MEPs monitorability, safety, specificity and sensibility in neurosurgical spinal patients. Furthermore we will report our data demonstrating the favorable clinical impact of MEP monitoring. Finally the correlation between MEP changes during the operation and the action of the surgeon will be stressed, with the aid of a video projection of surgical cases.

100 patients underwent spinal cord surgery with the guide of intraoperative neurophysiological monitoring for the treatment of tumors (62 cases), of arterio-venous fistulae (13 cases), of spondylotic myelopathies (11 cases), of syringomyelies (5 cases), of spinal cervical instabilities (4 cases), for DREZ operations (4 cases), and for antero-lateral open cordotomy (1 case). Surgery was at cervical level in 49 cases, at thoracic level in 46 and at conus level in 5 cases. A total intravenous anesthesia with EV infusion of Propofol and Fentanyl or Remifentanyl was used; no muscle relaxants were administered after intubation. The monitoring protocol included motor evoked potentials and somatosensory evoked potentials. Transcranial electrical stimulation was applied to the motor cortex through scalp electrodes using the single stimulus technique (0.5ms, 1-2c/s, up to 400V) and recording the corticospinal tracts descending volley from the spinal epidural space (D-wave); and using the multiple stimuli technique (trains of 3-7 stimuli, 0.5ms, ISI = 4ms, 1-2 trains/s) and recording from limb muscles (tibialis anterior, TA, abductor hallucis, AH, and abductor pollicis brevis, APB). D-wave was updated every 10 seconds and muscle responses were periodically recorded every 1-5 minutes. D-wave amplitude and presence of muscle responses were monitored.

**MEPs monitorability**

After anesthesiological induction, D-wave was evoked in 63 patients and could be recorded in 54 of them (85.7%). Muscle MEPs at lower limbs were studied in 136 TA and were recorded in 96 cases (70.6%). The monitorability rate for lower limbs was 90%, when we combined the two techniques, D-wave plus muscle MEPs. The monitorability rate for upper extremities was 83.9% (muscle responses in APB). Only 3 patients had no motor responses both at upper and lower extremities and cortico-spinal tract activity was unmonitorable (3%). Factors affecting MEPs monitorability are the anesthesiological regimen, the degree of preoperative motor deficit, and the functional type of the lesion.
Monitorability of median nerve scalp somatosensory evoked potentials was 83.8%; monitorability of posterior tibial nerve SEPs was 63.1% after anesthesiological induction, but this rate decreased to 52.4% in cases of intramedullary tumors, after the posterior midline split necessary to reach the tumor.

**MEPs sensibility and specificity**

At the end of surgery, muscles MEPs were lost in 26 limbs; in 23 of them a postoperative paralysis was evident. In our series we had 3 false positive out of 148 limbs (2%). On the other hand, the presence of muscle MEPs at the end of the operation was always associated with no postoperative significant increase of motor deficit; no false negative.

The decrease in amplitude of muscle motor responses, or the necessity to increase stimulus intensity to obtain or to maintain the muscle response, did not correlate with a negative outcome.

**Favorable clinical impact on neurological outcome**

A - The protecting effect of MEPs monitoring is suggested by cases in whom MEPs deteriorated during the operation, the surgeon was alerted, he/she changed surgical strategy, the potentials came back to baseline, and the patient woke up from the operation with no new motor deficit. In our series, we recorded a temporary loss of muscle responses in 11 limbs (11/148, 7.4%), and a temporary loss of D wave in 4 cases (4/54, 7.4%). We can assume that MEPs monitoring saved 7.4% of patients from postoperative paralysis.

B - We compared two groups of patients operated on for the removal of intramedullary tumors. Group 1 consisted of 30 adult patients operated on with the guide of neurophysiological intraoperative monitoring. They were 15 males and 15 females. The tumor was at cervical level in 13 cases, cervico-thoracic in 4, thoracic in 12, and at conus level in 1 case. The pre-op neurological status was scored according the McCormick scale as IV in 3 cases, III in 8, II in 5, and I in 14 cases. Group 2 consisted of 15 adult patients, 9 females and 6 males, operated on without the guide of neurophysiological intraoperative monitoring. They were operated on in a period of time immediately before group 1, by the same senior surgeon. The tumor was at cervical level in 8 cases, cervico-thoracic in 3, thoracic in 3 and at conus level in 1 case. The pre-op neurological status was scored as IV in 2 cases, III in 3, II in 3, and I in 7 cases. The two groups were homogeneous as for tumor level (chi square test, p = 0.79) and pre-op neurological status (p = 1). We compared the neurological outcome at 3 months after the operation. We chose 3 months because at this follow up, neurological status can be considered stabilized, and still independent from histological diagnosis. At 3 months of follow up, the patients in group 1 did significantly better than the patients in group 2 (chi square test, p = 0.05).

**Correlation between MEPs changes and action of the surgeon**

The deterioration of MEPs during surgery could be related to a precise moment of the operation, and in most of the cases to a precise action of the surgeon. The coagulation of the tumor bed in the anterior part of the cord, the traction applied on the cord, the dissection of the tumor from the cord may induce a change in MEPs. The possibility to identify the moment and the cause of damage is extremely important in order to take a timely and adequate counteraction.

**Bibliography**

Clinical Use of Motor Evoked Potentials in Operating Room

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The employment of motor evoked potentials to monitor spinal cord functions has become commonplace during surgical treatment for spine and spinal cord diseases. The nomenclature of MEP involves two kinds of motor related potentials, one of them is the evoked spinal cord potential recorded from the spinal cord after delivering the electrical stimuli to the brain. The other is the muscle action potential recorded from the peripheral muscles after stimulating the brain or the spinal cord.

Technical terms to express these potentials are arbitrarily used by many researchers and producing some confusion. Recently, in Japan, a new nomenclature with corresponding abbreviations have been proposed to express evoked potentials employed for intra operative spinal cord monitoring:

Br(E*)-SCEP: spinal cord evoked potential after electric stimulation to the brain.
Br(E)-MsEP: muscle evoked potentials after electric stimulation to the brain.
Sp(E)-MsEP: muscle evoked potentials after electric stimulation to the spinal cord.

*When the magnetic stimulation is used (E) is converted to (M).

Sensory mediated potentials are:

Sp(E)-SCEP: spinal cord evoked potentials after electric stimulation to the spinal cord.
Pn(E)-SCEP: spinal cord evoked potentials after electric stimulation to the peripheral nerve.

Br(E)-SCEP is conducted potentials recorded from the motor related tracts of the spinal cord and Br(E)-MsEP and Sp(E)-MsEP are potentials transferred via the alpha motoneuron synapse and neuro-muscular junction. Their characteristic difference offers different attitude against the insults to the spinal cord. Typically, the amplitude of Br(E)/Sp(E)-MsEP is unstable, the pattern is variable and too sensitive during the manipulation of the spinal cord. Therefore, decrement of Br(E)/Sp(E)-MsEP amplitude does not always indicate impairment of motor function (Nakagawa et al., J. Orhtop Sci. 7:102-110, 2002). Accordingly, we are utilizing Br(E)/Sp(E)-MsEP as an adjunct to the conducted spinal cord potentials recorded from the spinal cord after stimulating the brain or the spinal cord (Br(E)/Sp(E)-SCEP. Although, in patients with spinal cord lesion graded as Frankel B, or 0 (zero) according to motor and sensory score of JOA (Japanese Orthopaedic Association) scoring system, recording of Br(E)-SCEP is barely possible.
Patients with these scores indicate the limitation of currently available monitoring methods. Furthermore, single spinal nerve root lesion and limited anterior motor neuron lesion were not well monitored by recording muscle evoked potentials. In order to carry out reliable intraoperative spinal cord monitoring, limitations of these techniques need to be adequately understood.

Potentials transferred through the tracts in the spinal cord are recorded by the flexible tube-type electrode place in the subarachnoid space near the spinal cord. We placed electrode at the lower lumbar level after performing lumbar puncture with 17-gauze Tuohy needle. Our group, and others, have used this method of electrode insertion in more than 2000 cases since 1972 without any severe complications. The placement of an additional electrodes, allowed us to record sensory mediated potentials simultaneously and to perform multimodal monitoring for successful and reliable monitoring.

Notes

Motor Evoked Potential Monitoring During Spinal Cord Surgery

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MEP monitoring is based on concepts of the motor system developed since the 1950s, when a small but essential fiber population in the corticospinal tract was described and found to give rise to a recordable traveling wave, the D-wave. After Merton’s description of transcranial electrical motor cortex stimulation in man, this knowledge was applied in the operating room.

Muscle recording techniques were introduced with magnetic and electric motor cortex stimulation. Anesthesia-induced blocking of the α-motoneurons was overcome with the development of a multipulse technique. In the 1990s MEP monitoring was established as a viable technique.

Neurophysiology
Motor potentials are evoked with transcranial electrical stimulation at C3, C4, C1, C2, Cz, and a point 6 cm in front of Cz using cork-screw electrodes.

Electrical stimulation is performed with rectangular constant current impulses of 500µs duration and intensities between 15 and 200 mA.

D-waves are elicited with single stimuli ("single pulse technique"). They are recorded as traveling waves directly from the spinal cord with an electrode inserted into the spinal epidural space by the surgeon after the laminectomy. Baseline recordings are obtained before opening of the dura. The signal does not require averaging. The stimulations are repeated at a rate of 0.5 to 2 Hz during the critical part of the procedure. This provides “real-time” feedback.

The D-wave parameter monitored is the peak-to-peak amplitude. A decrease more than 50 % of the baseline value was associated with a long term motor deficit. Latency changes of the D-wave are rare and due to non-surgical influences such as temperature.

Muscle MEPs are elicited with transcranial electrical stimulation over the same set of electrodes. A short train of five to seven stimuli with four milliseconds interstimulus intervals is used ("multipulse technique"). Compound muscle action potentials are recorded with needle electrodes from target muscles in all four extremities (thenar, anterior tibialis, abductor hallucis). Muscle MEPs also do not require averaging and can be repeated at a rate of 0.5 to 2 Hz. With the focal anode as stimulating electrode a montage of C1/2 (anode at C1, cathode at C2) or C2/1 is tried first to elicit muscle MEPs in all four extremities. In individual cases C3/4, C4/3 or Cz/6 is used as alternative stimulation points. Muscle MEPs are recorded in an alternating fashion with D-waves.

The parameter monitored is the presence or absence of muscle MEPs in the target muscles within the stimulus intensity range of 15 to 200 mA. This all-or-none concept has been adopted because of the variability of muscle MEP amplitudes and because a motor deficit occurred only when the muscle response was lost.

Clinical assessment and correlation

Our experience is based on several hundred surgeries for intra-or extramedullary spinal cord tumors. Usually pre- and postoperative motor function is classified as normal (no focal motor deficit), slightly paretic (motor deficit not exceeding 4/5 and not significantly impairing the extremity’s function, walking not impaired), severely paretic (motor deficit 3/5 or worse, significantly impaired function of extremity, or inability to walk) and plegic (0/5 or 1/5). This is consistent with the McCormick scale.

In a previously published series of 100 consecutive operations of spinal cord tumors 92 of the 100 patients had a normal or slightly impaired motor status before surgery. In all of these 92 cases muscle MEPs could be...
recorded at the beginning of surgery (“baseline”). Epidural MEPs were recordable in 59 of the 86 cases not involving the conus medullaris.

Eight patients had severe motor deficits or were paralyzed. None of them had recordable MEPs (neither epidural nor from muscle). In no preoperatively paralyzed extremity was there ever a muscle MEP recordable.

Postoperatively a short term motor status deterioration is noted in about one third of the patients (35 of 92 (38 %) patients in the above mentioned series 13). In only two a severe permanent neurological dysfunction occurred as a direct result of the operation. Therefore the risk of paraplegia following resection of a spinal cord tumor is lower than expected. These changes in clinical status are correctly reflected by the intraoperative MEP findings.

**Feasibility and practicality of monitoring**

The electrode setup is completed during the surgical and anesthesiological preparation after the patient was intubated. During the final surgical preparations and the approach baseline recordings are obtained. Additional time for monitoring preparations is minimal. Practically all patients without severe preoperative motor deficits can be monitored with either D-wave or muscle MEPs or both. The recordings are usually robust (between 10 and 70 µV amplitudes of epidural and up to 2 mV in muscle MEPs). Changes due to non-surgical influences (iv. bolus of anesthetic, temperature or blood pressure changes) can be recognized by following these parameters together with the anesthesiologist.

Intraoperatively the combined data of epidural and muscle MEPs indicate some effect of the surgical manipulation on the functional integrity of the motor pathways at some point during the procedure in almost every other patient. In about a third these changes remain until the end of the operation, and then correlate to a temporary motor deficit. In the remainder of cases the changes are reversible during surgery and this correlates to intact motor function when the patient awakes from anesthesia.

**Interpretation of D-wave data**

The pertinent parameter in D-wave interpretation is its peak-to-peak amplitude.

The monitorability of the D-wave and the intraoperative significant decline of its amplitude have been shown to be of predictive value for the motor outcome after intramedullary surgery 18. In about two-thirds of the patients with non-conus tumors a D-wave is recordable 13, 18. Since D-waves are generated by the fast-conducting corticospinal tract axons, conus tumors are not monitorable with this modality.

Patients in whom the baseline D-wave recording produces no response have a higher risk of postoperative motor deficits than those with a recordable D-wave 18. Whether this is due to an inherent subclinical damage and vulnerability of the motor tract, or to the fact that there was no monitoring support for the surgery, is not known. The explanation for the absence of a recordable D-wave in an individual with intact motor function (and recordable muscle MEPs) is believed to be due to a chronic or damage to the corticospinal tract resulting in a desynchronization of the wave 6. This appears to occur more frequently in patients with prior surgery, very extensive tumors and particularly those with prior radiation therapy.

The intraoperative amplitude decrease of the D-wave correlates with postoperative outcome. If the D-wave is unchanged, there is no postoperative deficit. If it declines more than 50 % of the baseline value or even disappears, the patients are likely to be permanently paraplegic 1, 18.

**Interpretation of muscle MEP data**
The presence of muscle MEPs indicates intact functional integrity of the corticospinal tract in all instances. Occasionally, in patients with a moderate motor deficit it may be difficult to obtain recordings from both lower extremities. If that occurs, usually responses in the weaker leg require higher stimulation intensities. Intraoperative preservation of muscle MEPs means intact motor function postoperatively in all cases.

Intraoperative loss of muscle MEPs indicates some postoperative impairment of voluntary motor control with a specificity of about 90%. For instance muscle MEPs lost in one leg during the resection means that the patient will postoperatively be unable to move this particular extremity for a limited period of time. This is called a temporary motor deficit. Loss of muscle MEPs in both legs is indicating bilateral motor deficit. Unilateral loss is of less concern as it has been shown in the past, that unilateral motor disruption always recovers with a mechanism where the intact side “takes over” control of the affected side.

**Combined interpretation of D-wave and muscle MEPs**

The D-wave amplitude is a measure of the number of fast conducting fibers in the corticospinal tract. If 50% of these fibers are damaged by the procedure, the amplitude will decrease to 50% of its baseline value. From practical experience we know that the D-wave decrease usually occurs in small increments, going down 15%, 20%, 30% and so forth. By and large D-wave amplitude decrease is associated with loss of muscle MEPs. It may be however, that muscle MEP loss occurs without D-wave amplitude decrease, or that the D-wave decreases without changes in muscle MEPs. The underlying mechanisms of these observations are not understood at this time. In any event, preservation of the D-wave above the 50% cutoff value has been found to be predictive of longterm preservation (or recovery) of voluntary motor control in the lower extremities. With loss of muscle MEPs and preserved D-wave amplitude a temporary motor deficit is expected postoperatively. In this situation it is still safe to complete a resection, or to pause and wait for recordings to improve again, which they often do. This situation is the window of warning, the window of reversible change, which allows for a change in surgical strategy _before_ irreversible injury has occurred. The interpretation of data when the high cervical cord is affected is more complicated because neural basis for motor control of
the hands and fingers is more complex than that of the more automated programs controlling lower extremity function for walking and posture.

Observations on the behavior of MEPs during intramedullary tumor surgery

Usually MEP changes occur towards the end of the resection. Since most spinal cord tumors are resected in an inside-out and piecemeal fashion (with the exception of some ependymomas) direct manipulation or vascular compromise occurs when the tumor-cord interface is reached. Often muscle MEPs disappear first. This may be preceded by an increase in threshold for this particular muscle response. Sometimes pausing the resection and irrigating the cavity with warm saline results in reappearance of the response. Similarly some D-wave amplitude decrease may also be reversible by pausing and irrigating. Sometimes dissection in a particular location results in MEP changes, and the resection can proceed at a different spot without further change. Sudden decrease in D-wave amplitude, often coinciding with sudden loss of muscle MEPs is believed to be associated with some sort of vascular injury rather than direct physical tissue manipulation. Temporary moderate elevation of mean blood pressure has been a successful means to improve the MEPs, with a satisfactory clinical result postoperatively.

The use of specific surgical instruments appears to impact on changes in MEP recordings. For instance the use of the ultrasonic aspirator (CUSA) seems to result rather frequently in an MEP deterioration. On the contrary, use of the Nd:YAG handheld microsurgical laser (SLT, Surgical Laser Technologies, Inc. Montgomeryville, PA) or the regular, or the Greenwood bipolars to vaporize tumor and mobilize small fragments seems to be less damaging. That does not mean the CUSA should not be used, but its use should be limited to removing portions of tumor already somewhat detached from the spinal cord itself, rather than to internally debulk in situ tumor mass.

The use of bipolar coagulation always disrupts all electrophysiological recordings for the time the current is active. One of the distinct advantages of the microsurgical laser beyond its advantages as a microsurgical instrument with powerful cutting capability is that its use does not produce an electrical artifact, therefore monitoring continues undisturbed.

References

Anesthesia and Motor Evoked Potential Monitoring

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The anesthesia that is used during surgery where motor evoked potential (MEP) monitoring is used can markedly affect the ability to record some types of responses. This review will focus on both the theory and practical aspects of these anesthetic agents. In theory, the type of interaction between the anesthesia and the motor responses should be predictable from knowledge of the mechanism of action of the anesthetic drugs involved. Unfortunately, we do not have a thorough understanding of the mechanism of anesthesia, but the major target for anesthetic action appears to be at neural synapses (especially the GABA and NMDA receptors which mediate electrolyte channels (Na⁺, Cl⁻, Ca²⁺)).

Hence synaptic transmission is hampered. In addition, ketamine appears to hinder axonal conduction. As a result, these two effects suggest that the major anesthetic impact on neurological pathways will be at synaptic connections with an additional minor component based on the length of the pathway [1]. This is consistent with the observed effects (below) and corroborated by the observation that muscle recorded responses from transcranial magnetic stimulation are altered by anticonvulsant medications which do not produce anesthesia [2] but produce post-synaptic enhancement of GABA receptors. Different anesthetic agents produce unique effects depending on the specific locations of anesthetic action, drug type, and it's potency. Finally, the presence of neurological disease may enhance the effects of anesthesia drugs as well as changing the relative effects on different pathways. As discussed below, providing anesthesia during monitoring of the motor
pathway can pose a very significant challenge for the anesthesiologist in the very patients where it may be most important.

Overview
For motor cortex stimulation (transcranial or direct) two basic mechanisms produce a descending electrical volley. First, they produce a direct activation of the pyramidal cells producing a D (direct) wave. Second, activation of internuncial pathways produce a series of I waves that follow the D waves down the descending motor pathways in 0.3-0.5 millisecond intervals after the D wave. D waves appear to originate from the trigger zone of the motor cortex pyramidal cells by direct stimulation whereas I waves appear to be produced by transsynaptic activation of tangentially oriented corticocortical interconnections of lamina V as well as corticocortical projections from precentral and premotor cortex. Since magnetic stimulation induces a tangentially oriented electric current in the brain, weaker magnetic stimulation may preferentially produce I waves. Hence, although electrical and high magnetic field impulses directly stimulate the pyramidal cells, weaker magnetic impulses appear to depend on synaptic activation for production of a response.

Since no synapses are involved, the production of D waves will be relatively immune to anesthetic effects on the motor cortex. However, since the production of I waves involves synapses, the production of these waves will be reduced with anesthetic agents which depress synaptic function. The situation may be a bit more complex since synaptic function (and the ability to activate I waves via synaptic stimulation) is likely the result of a delicate balance of inhibitory and excitatory influences from adjacent neural pathways. Therefore, it is possible that anesthetic agents which block inhibitory influences may lessen the anesthetic impact by making internuncial synapses more easily activated. Likewise, anesthetics, which block excitatory influences, may worsen the anesthetic impact at the internuncial synapses.

Once activated, the electrical responses that travel down the spinal cord reaches the a-motoneuron where, after sufficient stimulation has occurred, a peripheral nerve response results. For a single stimulation of the motor cortex, D and I waves both appear necessary for bringing the a-motoneuron to firing threshold for production of a peripheral nerve response. Likewise, techniques that involve stimulation of the spinal cord or sensory reflex arcs will also traverse the a-motoneuron. Methods that involve stimulation of the nerve root or motor component of the peripheral nerve will not involve this synapse. As the second synaptic system in the motor pathway, corticospinal tract (CT) a-motoneurons synapse in a location potentially susceptible to anesthetic effects. Anesthetic action here may have two effects. First, partial synaptic blockade may compound a loss of I waves making it more difficult for cortical stimulation to bring the a-motoneuron to firing threshold. This may explain why cortical stimulation with weak magnetic fields (tcMMEP) is more susceptible to inhalational anesthesia than with electrical stimulation (tcEMEP). At higher anesthetic doses, synaptic blockade may inhibit synaptic transmission regardless of the composition of the descending spinal cord volley of activity.

Of note is that stimulation of the pathways that lead to peripheral motor response (peripheral sensory stimulation or stimulation of the sensory pathways of the spinal cord that result in descending, antidromic, volleys), may pass through other synapses such that the anesthetic effects may be more complex. Likewise, anesthetic effects that alter the excitatory or inhibitory influences on the a-motoneuron may also alter the anesthetic effect on the a-motoneuron.

One method that has somewhat overcome the anesthetic effect at the a-motoneuron is multipulse stimulation of the motor cortex. In this case, multiple D waves are produced such that anesthetic depression of the internuncial pathways in the cortex has little effect. Thus, for this technique, the major anesthetic effect may be at the a-motoneuron. This may allow better myogenic responses at low anesthetic doses. However, at higher doses of anesthetics, these multiple D waves may be insufficient to overcome the depression effectively blocking the response. Clearly, the interstimulus interval of the multipulse stimulation will also interact with the effectiveness of the technique. With widely spaced stimuli, decay of the effect at the a-motoneuron may prevent effective summation. With closely spaced stimuli, the cortical neurons may not
have recovered effectively from the previous response to produce an adequate response to subsequent stimuli. Hence an optimal interstimulus interval (ISI) should be found. It is possible that anesthetic influences may alter the optimal ISI if it alters the recovery characteristics of the motor cortex or spinal cord for the production of spinal cord responses. The same is true if anesthetic influences alter the decay characteristics of the a-motoneuron that effect summation.

The third major synaptic location for anesthetic effect in the motor pathway is at the neuromuscular junction. Fortunately, with the exception of neuromuscular blocking agents and drugs which alter acetylcholine transmission, anesthetic drugs have little effect at the neuromuscular junction. The converse is also true as neuromuscular blocking agents have little effect in synaptic transmission and axonal conduction in motor pathways other than the neuromuscular junction. This means that neuromuscular blockade will need to be carefully controlled when myogenic responses are monitored.

Finally, it should be noted that anesthetic drugs might have an indirect effect on motor evoked responses by virtue of alterations in the physiological factors that provide nutrient supply to the neural tracts. For example, anesthetic agents typically lower blood pressure which have the potential to contribute to neural ischemia and alteration in motor responses. Similarly, anesthesia or anesthetic management can cause changes in cerebral or spinal cord blood flow through changes in vascular tone mediated by the anesthetic directly or through carbon dioxide and tissue pH. Of interest is that synaptic function may be the most highly vulnerable region of the neural tracts to ischemia and physiological changes because of its high dependence on energy metabolism.

Effects of Specific Anesthetic Agents
Since agents may differ as to which synaptic transmitter they interact with, the actual effect on the evoked responses may also differ. Further, as above, if they interact primarily at excitatory or inhibitory responses they may produce a spectrum of effects at different concentrations due to changes in the balance of excitatory and inhibitory contributions to the motor pathway. Since the electroencephalogram (EEG) is produced by synaptic activity, anesthetic drugs on MEP effect often parallels the effects on the EEG [6,7].

Halogenated Inhalational Agents
The most common anesthetics in use today, the halogenated inhalational agents (desflurane, enflurane, halothane, isoflurane, sevoflurane), have been extensively studied with motor evoked responses [8-17]. These agents produce synaptic inhibition as revealed by reduction in frequency and amplitude in the EEG until electrocerebral silence occurs. As such, one would predict anesthetic depression at the a-motoneuron as well as in the internuncial neurons of the motor pathway. Depression of the neuromuscular junction does not appear to be a major effect on the MEP.

These agents depress the EEG to different degrees at equipotent anesthetic concentrations. The relative order seen is isoflurane (most potent), enflurane, and halothane (least potent) [10]. Studies with the newer
agents sevoflurane and desflurane suggest that these agents are similar to isoflurane at steady state. However, due to their more rapid onset and offset of effect (because of their relative insolubility), they may appear to be more potent during periods when concentrations are increasing. Also because of their lower solubility, their use allows a more rapid adjustment during anesthesia (i.e. the concentration can be raised or lowered more rapidly if needed).

Single pulse transcranial stimulation with MEP recorded in muscle appear to be so easily abolished by inhalational agents that they are often unrecordable in the presence of these agents [9,14,18,19]. When recordable, the major effect appears to occur at low concentrations (e.g. less than 0.2-0.5% isoflurane) [12,16,20,21]. This effect is likely due to depression of the a-motoneuron synapse as well as loss of I waves due to anesthetic effects in the internuncial synapses [15,22]. Changes in the H reflex confirm an effect of halogenated inhalational agents at the spinal level [23]. Figure 1 shows the loss of amplitude of the tcEMEP CMAP as isoflurane concentration is increased in the ketamine anesthetized baboon.

![Figure 1. The effect of increasing isoflurane concentrations on the compound muscle action potential (CMAP) response to transcranial electrical motor cortex stimulation (tcEMEP) in a ketamine anesthetized baboon. As can be seen, the amplitude decreases progressively with increasing concentrations.](image)

In contrast to myogenic responses, the D response seen in the epidural space is highly resistant to the effects of these agents and is easily recordable at high concentrations [19,20,24,25] and can be used for monitoring. This has suggested that the most prominent anesthetic effect on tcMEP is at the a-motoneuron level [11,13]. However, the loss of I waves from a cortical effect may be sufficient to block myogenic responses, even in the absence of anesthetic effects at the a-motoneuron. This is because repetitive I waves appear to be necessary for producing myogenic responses in the unanesthetized state [26]. Figure 2 shows the tcEMEP epidural response in a baboon as isoflurane concentration is increased from 0.3% to 2.1%. Note that although the D wave is maintained, the I waves are lost.
Studies comparing tcMMEP and tcEMEP suggest that the magnetic technique can be more sensitive to the inhalational agents [10] probably because magnetic stimulation (especially weaker field strengths) rely more on transsynaptic activation of the CT. High magnetic strength tcMMEP (which produces D waves) appears to overcome this cortical difference. The difference between tcEMEP and tcMMEP likely also relates to the type of current pulse driving the magnetic coil. Since biphasic or rapidly attenuated sine wave pulses may be more effective than monophasic pulses, anesthetic effect may be more pronounced in the latter technique [27,28].

Because the D wave is resistant to anesthetic depression, the anesthetic effect at the a-motoneuron can be partially overcome at low concentrations by multiple pulse transcranial stimulation [33,34]. In this circumstance the multiple D waves formed (and I waves if produced) summate at the a-motoneuron resulting in a peripheral nerve and motor response when cortical stimuli are placed at an ISI interval of 1-2 ms optimally, but can be effective to 10 ms [33]. Alternatively, the anesthetic effect can also be partially overcome by activation of the H reflex by peripheral nerve stimulation combined with transcranial stimulation [35]. Hence, low concentrations of inhalational agents appear acceptable when high frequency transcranial stimulation is used (trains of stimuli with ISI of 2-5 milliseconds [29,30]). As predicted, higher concentrations of these agents eliminated the myogenic responses from this stimulation. Clinical experience (noted below) suggests that avoiding the inhalational agents may still be desirable for monitoring during high frequency stimulation [30]. It appears that the total intravenous anesthesia (TIVA) technique also may produce superior responses with high frequency stimulation [30-32].

As indicated above, the optimal interstimulus interval may vary with the anesthetic effect [36]. This has been noted with isoflurane and is depicted in Figure 3. Shown is that a relatively broad ISI (1-5 ms) is effective at low concentrations (0.2% isoflurane), however, a wider interval appears better at higher concentrations (e.g. 4-5 milliseconds at 0.4-0.6 % isoflurane). At even higher concentrations (1% isoflurane), the most effective ISI was 1 millisecond. These suggest that if inhalational agents are used with the multipulse technique, a “tuning” of the stimulation ISI may improve the effectiveness of the monitoring.
Studies with spinal or epidural stimulation show minimal effects of anesthesia on neurogenic or myogenic responses suggesting the neurophysiology of the electrical activity arriving at the α-motoneuron is different than from cortical stimulation [3,37]. However, the anesthetic effects in the spinal cord at all of the synapses involved (sensory and motor pathways) may change the mixture of orthodromic motor and antidromic sensory contributions to the recorded responses. Machida studied the responses in the peripheral nerve and muscle following epidural stimulation in the cat [34]. He noticed that single pulse stimulation produced a response that was eliminated by pentobarbital, by low dose isoflurane and by posterior column transection (but not lateral column transection). When a pair of stimuli was used (ISI 1-5 milliseconds), a new complex in the peripheral nerve response was seen. This complex and the CMAP were eliminated only by high dose isoflurane or by lateral spinal cord transection. Machida’s study suggests that the type of spinal cord stimulation and the anesthetic used may alter the balance of sensory and motor contributions to the peripheral nerve and muscle response of spinal stimulation. Of interest is that the sensory tracts were more easily stimulated than motor tracts. Recent studies suggest that with isoflurane anesthesia, the motor component is preferentially blocked, perhaps by interaction at the synapses at the α-motoneuron or by differential effects on conduction in the spinal tracts in humans [20]. Based on these studies, it is conceivable that spinal stimulation techniques may monitor a mixture of sensory and motor pathways that may change with the type and dosage of the anesthetic agents used.

Nitrous Oxide

Despite its weak anesthetic profile, studies with tcMMEP [8] and tcEMEP [38] show that nitrous oxide produces depression of myogenic tcMEP. When compared at equipotent anesthetic concentrations, nitrous oxide produces more profound changes in myogenic tcMEP than any other inhalational anesthetic agent [1]. Like halogenated agents, the effects on the epidurally recorded MEP are minimal.

Figure 4. The effect of increasing nitrous oxide concentrations on the compound muscle action potential (CMAP) response to transcranial electrical motor cortex stimulation (tcEMEP) in a ketamine anesthetized baboon. As can be seen, the amplitude is progressively decreased with increasing concentrations similar to isoflurane.

Despite the depressant effect of nitrous oxide, it has been used with recording of myogenic responses, particularly when combined with opioids (“nitrous-narcotic” anesthetic technique). It has also been used to
supplement intravenous based anesthetics with opioids combined with propofol [30,32] or etomidate [32,39-42]. It has been used in concentrations of <52% [42-43], 50-60% [30,44-47], 60-65% [48], 65-66% [39,40], and 70-75% [18,25,32]. Since nitrous oxide is rather insoluble in tissues, its concentration and the depressant effect can be titrated rather quickly so that if chosen for an anesthetic technique it could be reversed rapidly [41].

Figure 4 (CMAP responses) and 5 (epidural responses) show the effect of increasing inspired nitrous oxide from 0 to 79% on tcEMEP. The effects appear to mimic the effects of isoflurane (i.e., loss of CMAP and I waves at higher concentrations).

Studies suggest that nitrous oxide may actually be “context sensitive” in its effects, similar to its effects on the EEG (i.e., the actual effect may vary depending on the other anesthetics already present). Studies of equianesthetic mixtures of isoflurane and nitrous oxide have demonstrated that the mixture has a more potent effect on cortical SSEP than would be predicted by adding the effects of each agent [49]. This suggests that the mechanism of action of nitrous oxide may be different from isoflurane.

**Intravenous Analgesic Agents**

Since the inhalational agents and nitrous oxide are poor choices for anesthesia when myogenic responses of tcMEP are desired, anesthetic techniques have focused on intravenous anesthetic agents for clinical monitoring. If the inhalational agents need to be completely avoided, then intravenous agents can be combined to produce a total intravenous anesthetic (TIVA). Fortunately, because the mechanism of action of intravenous agents appear to be different that inhalational agents, these agents differ in their effects on MEP such that they can be more favorable for clinical monitoring.

**Opioid agents**

Since analgesia (pain relief) is a primary component of anesthesia, the opioids (fentanyl, alfentanil, sufentanil, and remifentanil) are the intravenous agents most frequently chosen to accomplish this when inhalational agents must be avoided or used in low concentrations. As with minimal depression of the EEG (a dose related decline in frequency of the EEG in the delta range while maintaining amplitude), opioid effects on MEP are less than inhalational agents. Studies with myogenic responses from tcMEP from electrical and magnetic stimulation show only mild amplitude decreases and latency increases which usually permit recording [21,50-52]. The observed effects are reversed with naloxone, suggesting that this effect is related to mu receptor activity [53-55].

As with systemic opioids, the spinal application of morphine or fentanyl for postoperative pain management produces minimal changes in the H-reflex [56,57] suggesting effects on motor evoked responses should be minimal. In addition to minimal effects on the motor pathways, fentanyl has been suggested to be useful in reducing background spontaneous muscle contractions and associated motor unit potentials, which may improve CMAP recordings.
The effects of opioids appear to be related to drug concentration, since maximal changes occur at the same time drug concentrations peak, after bolus drug delivery. One study of fentanyl suggests that the effect on sensory evoked responses may be minimized by using a drug infusion to avoid transient bolus effects [58]. Remifentanil, a rapidly metabolized opioid, may be well suited for use by infusion since its concentration and effect can be rapidly changed.

Because the effects of opioids are less than inhalational agents, opioid-based anesthesia has usually been used when myogenic tcMEP are monitored [18,24,25,30-32,39,40,42,44-48,59-68].

**Ketamine**

Ketamine is a less frequently utilized analgesic in anesthesia but a valuable component of anesthetic techniques for recording responses that are easily depressed by anesthesia. This is because ketamine is an excitatory agent (probably through its interaction at the NMDA receptor) that may heighten synaptic function rather than depress it. For example, ketamine produces high-amplitude theta activity in the EEG, with an accompanying increase in beta activity that appears to represent activation of thalamic and limbic structures. It has been reported to provoke seizure activity in individuals with epilepsy but not in normal individuals. In addition, ketamine has been reported to increase cortical SSEP amplitude [56], and increase the amplitude of muscle and spinal recorded responses following spinal stimulation [21,69]. This latter effect on muscle responses may be mediated by the same mechanism which potentiates the H reflex [70].

Minimal effects were observed in myogenic tcMEP with ketamine [21,71,72]. Muscle responses and spinal recorded responses to spinal stimulation are also enhanced at doses that do not produce spike and wave activity in the EEG [65,69]. As such, ketamine has become a valuable adjunct during some TIVA techniques for recording muscle responses. In these techniques it has been combined with opioids [42,59,66,67] or methohexitol [66]. High dosages, however, produce depression of the myogenic response consistent with its known property of spinal axonal conduction block [73]. These effects have made ketamine a valuable adjunct to anesthesia with tcMEP, however, its hallucinatory potential and known increase in intracranial pressure with intracranial pathology have led to a reluctance to utilize it in anesthesia.

**Sedative-Hypnotic Drugs**

Intravenous sedative agents are frequently used to induce or supplement general anesthesia, particularly with opioids or ketamine, when inhalational agents are not utilized. This is because fentanyl is primarily an analgesic and, even with high doses, sedation, anxiolysis or amnesia cannot be assured (i.e. intraoperative awareness may be present). Although ketamine doses produce some dissociative effects in addition to analgesia, supplementation of ketamine with sedative drugs can reduce the risk of excitatory events including hallucinations. Hence, a total intravenous anesthetic usually includes an opioid or ketamine for analgesia combined with a sedative-hypnotic agent. Like opioids and ketamine, the sedative-hypnotic agents (except droperidol) can be used by infusion to reduce transient changes in the monitored responses.

In studies where the different drugs have been compared, marked differences in recording myogenic tcMEP have been observed [18,21,65]. In general, thiopental, midazolam and propofol produced marked depression in bolus doses. Because of the slower metabolism of these drugs the authors concluded that thiopental and midazolam were poor drugs for induction of anesthesia as their effects may linger into the surgical procedure.

**Barbiturates**

Popular drugs for induction of general anesthesia, barbiturates are similar to inhalational agents in their effect on the EEG, producing mild activation (fast activity) at low doses, and a depressant effect leading to burst suppression and electrical silence at higher doses. Not surprisingly, myogenic responses of tcMEP are unusually sensitive to barbiturates. Further, the effect appears quite prolonged; in one study, induction eliminated the tcMMEP response for a period of 45-60 minutes [21], suggesting that barbiturates may be a poor induction choice when monitoring with this modality. For this reason most anesthetic protocols do not use thiopental for induction of anesthesia. However, it has been successfully used in some anesthetic regimes.
and given as intermittent boluses during the anesthetic [68]. Given newer, better agents (e.g. propofol and etomidate), the use of barbiturates has largely been eliminated during tcMEP monitoring.

One exception, methohexitol, has different characteristics from thiopental. It is rapidly metabolized so that it is short acting and rapidly titratable. In addition it is known to enhance seizure activity at low doses so that it may reduce the inhibitory influences on the motor pathway. Although not commonly used, one TIVA protocol for myogenic tcMEP successfully utilized methohexitol infusions with opioids and ketamine [66]. Fortunately this drug is more rapidly metabolized and appears to have excitatory properties (low doses can be used to identify seizure foci during cortical mapping of epilepsy).

**Benzodiazepines**

The benzodiazepines, notably midazolam, have been advocated as supplements to TIVA in routine surgery because of excellent sedation and amnestic qualities (particularly to reduce the chance of hallucinogenic activity with ketamine). However, at higher doses they produce generalized slowing of the EEG into the theta and delta range without burst suppression suggesting marked synaptic inhibition via GABA channel action. It has been used as intermittent boluses during recording of myogenic tcMEP [68], but as with thiopental, midazolam produces prolonged marked depression of myogenic tcMEP [51,65,75,76]. This has been interpreted as inhibition of cortical pyramidal cell neurons. Like barbiturates, the benzodiazepines have not gained favor for induction or as a component of TIVA during myogenic tcMEP recordings.

**Etomidate**

As opposed to the barbiturates and benzodiazepines, etomidate can enhance synaptic activity at low doses, possibly by changing the balance of inhibitory and excitatory influences on motor pathways. At low doses (0.1 mg/kg) etomidate may produce seizures in-patients with epilepsy [77] and marked myoclonic activity is often seen with anesthesia induction. However, at higher doses it can produce a flat EEG. Since etomidate is rapidly metabolized, its concentration can be rapidly adjusted to take advantage of the enhancing activity or reduce the depressant effects seen at high concentrations. This effect has been used to enhance amplitude in both sensory and motor evoked responses [78,79]. Fortunately the enhancing activity occurs at doses that are consistent with the desired degree of sedation and amnesia needed for TIVA.

![Figure 6](image)

**Figure 6.** The effect of increasing doses of etomidate on the compound muscle action potential (CMAP) response to transcranial electrical motor cortex stimulation (tcEMEP) in a ketamine anesthetized baboon. As can be seen, the amplitude is progressively decreased with increasing concentrations similar to isoflurane. Note an initial increase in CMAP amplitude at low doses.
Studies with tcMEP have suggested that etomidate is an excellent agent for induction and monitoring of these modalities [21,51,65,67,80,81]. Of several intravenous agents studied, etomidate had the least degree of amplitude depression after induction doses or continual intravenous infusion [21]. Latency (onset) changes were not observed and amplitude enhancement of muscle responses was not observed except at high dosages [80]. Because of the prolonged effect of thiopental, etomidate has been used for induction of anesthesia during monitoring [41,42,45,59,67]. As a component of TIVA, infusions of etomidate have been combined with opioids [40,41,60,67].

Figure 6 (CMAP) and 7 (epidural) showing recordings from tcEMEP with increasing concentrations of etomidate, demonstrate that etomidate behaves differently than inhalational agents or propofol (below). Note an initial increase in CMAP amplitude at low doses (an effect more prominent in tcMMEP than tcEMEP) and an increase in I waves rather than a loss.

Propofol
As the newest sedative-hypnotic agent, propofol has been extensively studied. It produces dose dependent depression of the EEG reminiscent of the barbiturates and can produce burst suppression and electrical silence at high doses. This is consistent with the postulated site of anesthetic action of propofol on the cerebral cortex [82]. However, the drug is very rapidly metabolized such that the drug concentration can be titrated down to levels compatible with adequate TIVA and MEP recording.

Studies with tcMEP have demonstrated a depressant effect on myogenic response amplitude, also consistent with a cortical effect [51,65,83]. As a component of TIVA, induction of anesthesia can include propofol [30] and infusions of propofol have been combined with opioids [30-32,48]. Not unexpectedly, propofol has been used in tcEMEP when the recordings are epidural [13].

Figure 8 (CMAP) and 9 (epidural) show recordings from tcEMEP with increasing concentrations of propofol. Note the pattern is similar to inhalational agents with loss of CMAP and I waves at higher concentrations.

Figure 7. The effect of increasing doses of etomidate on the epidural response to transcranial electrical motor cortex stimulation (tcEMEP) in a ketamine anesthetized baboon. Note that although the D wave is maintained, the I waves are lost (similar to isoflurane.

Figure 8. The effect of increasing doses of propofol on the compound muscle action potential (CMAP) response to transcranial electrical motor cortex stimulation (tcEMEP) in a ketamine anesthetized baboon. As can be seen, the amplitude decreases
progressively with increasing concentrations (similar to isoflurane). Note the pattern is similar to inhalational agents with loss of CMAP at higher concentrations.

**Figure 9.** The effect of increasing doses of propofol on the epidural response to transcranial electrical motor cortex stimulation (tcEMEP) in a ketamine anesthetized baboon. Note the pattern is similar to inhalational agents with loss I waves at higher concentrations.

**Droperidol**

Droperidol has little effect on the EEG when used alone. However, it is known to lower seizure threshold, probably by dopamine antagonism. It does not appear to produce neuroexcitatory phenomena or induce seizures in epileptic patients. When combined with fentanyl (“neurolept anesthesia”), it increases EEG alpha activity at low doses. At higher doses, it produces high amplitude beta and delta activity. It appears to have minimal effects on myogenic tcMMEP when combined with opioids [60,65]. However, since its effect is long lasting, it is not suitable for use by infusion and many anesthesiologists would prefer to utilize a more rapidly metabolized sedative hypnotic for TIVA.

**Muscle Relaxants**

Since muscle relaxants have their major site of action at the neuromuscular junction they have little effect on electrophysiologic recordings that do not derive from muscle activity. In fact, they may improve or be essential for some types of recordings where the muscle activity near the recording electrode may be unwanted noise. This is true for epidural or peripheral nerve recordings where the activity of overlying muscle obscures the response from transcranial or spinal stimulation. For recording of epidural or neurogenic responses, complete or near complete neuromuscular blockade is highly desirable [25,61,84]. Figure 10 shows recording from the epidural space from tcEMEP with (below) and without (top) muscle relaxation. Note the muscle artifact obscures the identification of I waves.

**Figure 10.** Recordings from the epidural space from tcEMEP with (below) and without (top) muscle relaxation. Note the muscle artifact obscures the identification of I waves.

Certainly, complete neuromuscular blockade will prevent recording of muscle responses (CMAP) during MEP. However, partial neuromuscular blockade has the
benefit of reducing a substantial portion of the movement which accompanies the testing and may facilitate some surgical procedures where muscle relaxation is needed for retraction of tissues. In these cases, careful monitoring of the blockade of the neuromuscular junction is critical.

Two methods are customarily utilized to assess the degree of neuromuscular blockade [85]. The method that best quantitates the blockade involves measuring the amplitude of the CMAP (T1) produced by supramaximal stimulation of a peripheral motor nerve (M response). When neuromuscular monitoring is conducted this way, successful monitoring of myogenic responses have been accomplished at 5-15% [61], 10% [63], 10-25% [64], 10-25% [47], 20% [40,41,45,59,60], 25% [42], and 30-50% [24,43,67] of T1 compared to baseline. Clinically, anesthesiologists often assess neuromuscular blockade by counting the number of twitches resulting from four motor nerve stimuli delivered at a rate of 2 Hertz (called a train of four response). Measured this way, acceptable CMAP monitoring has been conducted with only 2 of 4 responses remaining [31,48]. For comparison of the two techniques, only one response of four is present when T1 is less than 10%, two twitches at 10-20%, and 3 twitches at 20-25% of the baseline T1 response [85]. When intense neuromuscular blockade is required (e.g. recording of epidural or neurogenic responses), T1 response less than 10% [86] or no more than 2 of 4 twitches [37] has been recommended.

Many clinicians use closed loop control systems to monitor the twitch and control the infusion so that excessive blockade does not eliminate the ability to record or mimic loss of the response with neural injury [40,43,60,64,87,88]. Because of varying muscle sensitivity to muscle relaxants, the neuromuscular blockade may need to be evaluated continuously in the same muscle groups used for monitoring. It is important to note that the use of neuromuscular blockade is controversial during monitoring of muscle responses from mechanical stimulation of nerves and partial paralysis may reduce the ability to record these responses (e.g. facial nerve monitoring or monitoring for pedicle screw placement).

Although recording of myogenic responses is possible with partial neuromuscular blockade, the amplitude of the CMAP will be reduced by the blockade. Studies suggest the actual reduction varies from a linear reduction paralleling the % T1 effect to a slightly decreased rate of reduction [89,90]. As a consequence of the amplitude reduction, the ability to record with partial neuromuscular blockade will be dependant on other factors which reduce the myogenic response amplitude such as anesthesia or neurologic disease. Hence, amplitude reduction with initially small responses or with anesthetic choices that markedly reduce amplitude may make the use of blockade more difficult. Fortunately the CMAP amplitude is usually quite large. It is also important to recognize that the use of amplitude criteria for warning of impending neurological injury may not be possible as inevitable fluctuations in the degree of blockade may obscure the application of strict criteria.

Conclusion - Anesthetic choice for motor tract monitoring

These studies suggest that for monitoring of epidural D responses from transcranial stimulation the sole anesthetic consideration is the use of adequate muscle relaxation to prevent paraspinal muscles from obscuring the epidural recordings. Because of its resistance to anesthesia, the D wave response should be remarkably stable if the anesthetic state fluctuates such that both amplitude and latency criteria should be usable for determining neurophysiological change. If maintenance of I waves is desired then the anesthetic choices are limited as discussed below for recording of myogenic responses. To date, the use of I waves have not been described although their loss might be indicative of ischemia in the motor cortex.
Anesthesia for monitoring of peripheral muscle responses to spinal cord nerve root stimulation should also be unaffected by anesthetic choice with the sole exception of neuromuscular blockade. If the responses are dependant on sensory tract stimulation (e.g. monitoring of reflex activity through the spinal cord), then anesthetic choice must consider the effects on the α-motoneuron and the synapses involved in the pathway.

Anesthesia choice for recording of neurogenic or myogenic responses from spinal stimulation has been described clinically. Neuromuscular blockade is clearly important (as with epidural recording) to reduce the influence of overlying muscle. The studies presented here, particularly those of Machida [34], suggest that anesthesia may play a very important role in determining the contributions of sensory and motor pathways to monitoring responses following spinal stimulation. Since the type and intensity of stimulation may vary between different clinically used protocols, it is difficult to make anesthetic recommendations that would allow preferential recording of motor tract responses.

Clearly, the choice of anesthesia makes a marked difference in the ability to record myogenic (and presumably neurogenic) responses following transcranial stimulation of the motor tracts. Because these responses are exquisitely sensitive to a large variety of anesthetic agents, it appears that the best technique for monitoring is a total intravenous technique. Current drug combinations usually include opioids with ketamine, etomidate or closely titrated propofol infusions [30,31,66,40-42,59]. Although neuromuscular blockade reduces the amplitude of the muscle response, a controlled degree of blockade (10-20% of single twitch remaining, or 2 of 4 twitches remaining in a train of four response), is highly desirable to reduce patient motion and facilitate some procedures. A tightly controlled muscle relaxant infusion is needed to accomplish this to avoid excessive blockade which would hamper monitoring. In the circumstances of anesthetic and neuromuscular blockade reduction in amplitude, the amplitude of the myogenic response will inevitably fluctuate during the procedure. Hence warning criteria may need to be less dependent on amplitude and more dependant on onset-latency or the simple presence or absence of the response.

Perhaps newer transcranial stimulation or response facilitation techniques will allow a more liberal anesthesia utilization. Although high frequency stimulation would appear to allow the use of depressant agents (notably, low dose inhalational agents), the authors of clinical studies using this technique recommend TIVA. Clearly this is an area of anesthesia and monitoring that awaits advances to allow a wider application of this monitoring technique.

References


Interventional Neuroradiology is nowadays playing a leading role in the treatment of several brain and spinal cord vascular diseases. Spinal cord arteriovenous malformations (SCAVMs) represent one of the most challenging vascular lesions faced by interventional neuroradiologists. This is due to the intimate relationship between the pathological angioarchitecture of the SCAVM and the physiological vascularization of the surrounding normal spinal cord. In addition, due to the hemodynamic changes produced by the SCAVM, the normal vascular spinal cord supply may not be predicted based solely on angiographic findings. Accordingly, although embolization is now the first choice of treatment for SCAVMs, it is still considered as potentially a high risk procedure because of the risk of spinal cord ischemia.

In addition to the careful angiographical analysis, clinical provocative testing is a method used to identify the functional eloquence of the territory of a catheterized vessel. It is performed by clinically assessing neurological changes after injection of a short acting anesthetic agent from a microcatheter placed in a feeding artery for the AVM. However, when the embolization is performed under general anesthesia, clinical evaluation has to be replaced by either a so-called “wake-up test” or by intraoperative neurophysiological monitoring (INM).

Through the years, INM has been proposed as a better alternative to the wake-up test to assess the functional integrity of neural pathways during endovascular procedures. Somatosensory evoked potentials (SEPs) have been used since the mid-1980s based on the clinical evidence that SEPs were sensitive to compromises in anterior and posterior spinal artery circulation, but their reliability in evaluating the integrity of descending motor tracts was not ideal. In the last decade, the advent of a reliable technique to record muscle motor evoked potentials elicited by a transcranial multipulse electrical stimulation has further improved the specificity and sensitivity of INM.
We perform endovascular procedures with the assistance of both INM and provocative tests with sodium amytal and lidocaine, which is now a critical step in the decision making whether or not to proceed with embolization. We routinely perform provocative tests once the catheter has reached the point in the feeder to the SCAVM where embolization is contemplated. Sodium amytal and lidocaine selectively block the gray and white matter of the spinal cord, respectively. If the provocative test is positive (loss of MEPs or drop of SEPs’ amplitude) liquid embolization from that specific catheter position should not be performed because this would risk the patient to post-operative motor or sensory deficits.

We have so far combined provocative tests with INM in 84 procedures performed in 52 patients, including 47 Amytal and 56 Lidocaine tests. Nineteen positive tests were documented, 4 after Amytal and 15 after Lidocaine injection. Positive tests occurred after injection of the drug either in the posterior (PSA) or the anterior spinal artery (ASA) territory. Although one might expect a correlation between the vascular territory where the drug is injected and the INM modality that is affected (MEPs for ASA and SEPs for PSA), this was not true in 100% of the cases. The pathophysiology of this observation will be discussed.

We had one false negative result (increased spasticity after embolization) in this series. While the negative predictive value of provocative tests was very high (97.6%), we couldn’t test the positive predictive value of this technique because we usually do not embolize if a test is repeatedly positive. It should be emphasized that a non-selective catheterisation of the vessel feeding the SCAVM could induce spreading of the drug to the normal spinal cord and, therefore, a false positive result, so that the possibility that provocative tests may overestimate the effects of embolization exist.

This method of monitoring is also useful for the embolization of spine tumors and dural / extradural fistulas. Although spinal cord arteries do not supply these lesions, spinal cord ischemia can occur during embolization when embolic materials inadvertently go into the spinal cord artery. This complication usually occurs when a spinal cord artery is not well visualized by angiography due to overlapping abnormal vascularity of the lesion or metallic instrumentation, or distortion of the spinal cord by the lesion itself or previous surgical intervention. Therefore, the purpose of monitoring during embolization for these diseases is early detection of spinal cord ischemia. Provocative test can also be performed if the existence of spinal cord artery is suspected but not well demonstrated by angiography.

Overall, the combination of provocative tests with INM has proven very useful in enhancing the safety of endovascular procedures and we recommend their use whenever embolization of a spine or spinal cord vascular lesion is performed under general anesthesia.

Notes

Neurophysiological Assessment and Monitoring Techniques of Facial Nerve During Percutaneous Embolization of Vascularized Lesions of the Face

Adauri Bueno De Camargo, MD
Introduction

Facial paresis has been described as a complication of vascular malformation treatment immediately post-embolization or as a late onset within first 24 hours after the procedure.

The exact mechanism of the nerve injury has not been known. It might be caused by single or a combination of factors: direct puncture of the nerve branches by the injection needle, direct alcohol toxicity to the nerve fibers after injection, or pressure to the nerve branches by mass effect caused by the injected volume.

To understand the mechanism of facial nerve injury involved it is first necessary to determine the anatomy of facial nerve branches before the procedure and to test the facial nerve functional integrity, both during the entire procedure and the 24-hour follow up.

Objectives

We reviewed existing intraoperative facial nerve monitoring and mapping techniques developed to cope with different needs. None of them continuously monitor facial nerve functional integrity. For our specific needs, during facial vascular anomaly treatment, we developed methods of facial nerve monitoring and mapping based on existing ones in order to:
1- prevent direct injury to the facial nerve during face skin puncture.
2- prevent direct injury to the facial nerve during ethanol injections
3- to follow up development of late injury (post-interventional) of facial nerve

Methodology

We studied 42 patients undergoing 69 procedures of angiogram and treatment of facial vascular malformation (VMF) or vascularized lesions of the face by direct puncture for ethanol sclerotherapy and/or embolization. Facial motor deficits were already present in 24 patients. These patients had previously been treated before, either with ethanol sclerotherapy or with other invasive procedures for their facial lesions. Those figures
suggest the high rate of complications involving treatment of this pathology, showing how sensitive facial nerve is for currently available invasive procedures.

Patients were under general anesthesia. Intubation was performed with, if any, low dosage of short-acting muscle relaxant. Total intravenous anesthesia was used. Train of four muscle twitches was monitored (Median nerve stimulation/recordings from APB muscle) and mapping of the facial nerve branches started after patient was out of relaxation.

**Percutaneous mapping of facial nerve branches**

Percutaneous mapping of facial nerve branches was performed with a handheld pen-like probe (cathode) referenced to anode (stick pad electrode) placed on the pre-auricular area. Visual target muscle twitches (VTMT) were observed using/with threshold electrical stimulation of Facial nerve branches.

The anatomy of the facial nerve branches was determined with the probe stimulation. The nerve branches paths were drawn on the skin with a surgical marking pen, making them visible.

**Continuous monitoring of VTMT**

Motor threshold for VTMT was tested during the entire procedure as well as at post-interventional follow-up, up to three times within 24 hours. Intensity of stimulation was adjusted whenever necessary to maintain VTMT. Correlation of VTMT with each procedure step was made: puncture of VMF, injection of contrast, injection of ethanol and/or other substance.

Surgeons / Interventional radiologists were warned (warning was given) whenever changes in VTMT threshold were observed and procedures were eventually interrupted.

Physical examination of facial muscle function and face asymmetry was performed before the procedure and up to three times during the 24-hour follow-up testing.

**Results**

Percutaneous mapping was feasible in XY (%) procedures and monitoring with VTMT was possible in XY (%).

Changes in VTMT thresholds happened during XY (%) procedures. Changes varied from 3 mA to higher than 30 mA.

XY (%) procedures were interrupted because of increase in VTMT threshold.
**TABLE**
XY patients had previous facial functional impairment.

XY showed worsening of facial paresis.

XY patients presented new deficits either when they woke up or early (3 to 6 hours after the procedure) during the 24-hour follow-up.

XY patients recovered within 24 hours and XY patients presented long-lasting deficits. All patients showed recovered within 6 month-follow-up. (*full recovery of pre-procedure facial nerve functional status*)

**Discussion**

Mapping was not possible in those procedures where the patient already presented with severe facial paresis, probably due to muscle atrophy. Neither was it possible when the lesion was too big, too bulging or hardened. We believe these factors would prevent electrical stimulus to reach the nerve and elicit VTMT.

Patients presenting lesions extending too proximal to the facial nerve trunk exit at (*from*) the stylomastoid foramen can not be adequately monitored.

These patients are prone to false negative results (unchanged VTMT threshold with facial paresis when patient wakes up) when the site of the facial nerve lesion might be proximal to the site of the electrical stimulation. Only one patient who was recently treated (01/XY or XY%) presented a false negative result for this reason.

All other patients who presented with deficits had their procedures (XY/XY) interrupted because of the monitoring warning.

Whenever neurophysiological monitoring showed increase of VTMT threshold of more than 6 mA - XY procedures - patients presented with paresis lasting up to 6 month.

When increase of VTMT threshold was from 3 to 5 mA, only XY% of them showed paresis. These deficits were minor – affecting partially the territory of one facial nerve branch, lasted shorter or had no deficit at the end of the 24 hour follow up.

**Conclusions**

Data analysis suggested that changes in VTMT threshold correlate with facial nerve functional outcome. Changes in VTMT threshold in between 3 and 5 mA show probability of or mild facial nerve functional impairment. Changes of 6 mA or higher correlate with marked facial paresis.

Intraoperative neurophysiological monitoring, as well as neurophysiological testing during 24-hour follow-up helped detecting *risks possibility* of facial nerve functional impairment. Whether ethanol toxicity and/or mass effect over a nerve branch plays the main role is still to be clarified.
Evoked Potential Mapping and Monitoring for Intracranial Vascular Surgery

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Surgery of intracranial vascular lesions harbors a significant risk for new neurological deficit. Ischemia from deliberate or inadvertent occlusion of large, or small perforating vessels, vasospasm, or brain retraction is the major cause of postoperative deterioration, permanent severe paresis belonging to the most devastating deficits. Intraoperative evoked potential mapping and monitoring provides information about the location, and the functional state of the sensorimotor areas and pathways. A close correlation between central cortical perfusion and SEP responses has been established, which becomes less significant in subcortical regions. SEP monitoring has become a routine in aneurysm surgery at many centers. We have been able to demonstrate that MEP recordings reveal subcortical ischemia which goes undetected by SEPs. Here, we report on our mapping and monitoring experience in over 700 cases of intracranial vascular surgery.

Vascular Malformations
With pericentrally located AVMs and cavernomas, functional mapping by means of SEP phase reversal and/or MEP stimulation mapping is used in our institution to reveal the topographic relation of the lesion with the sensorimotor cortex [1]. Anatomical criteria alone may fail, even if computerized neuronavigation is used, due to the often limited intraoperative view, and the functional reorganization possibly induced by the vascular lesion. In a series of 67 cases from our department, the lesions were intraoperatively found to be located differently as suggested by preoperative imaging in 12%. The usefulness of SEP phase reversal to identify the sensorimotor cortex has been confirmed in over 500 cases in our institution. It helps to plan the resection strategy including retractor placement, and allows to determine the optimum stimulation site for continuous MEP recording. With deeply seated lesions adjacent to, e.g., brainstem motor pathways, MEPs are elicited by transcerebral stimulation.

MEP monitoring is highly sensitive to ischemia of the motor pathways. It helps to assess the risk of postoperative motor impairment when applying a test clip to a feeding artery, and indicates possible deterioration with other intraoperative maneuvers and events, like retractor placement, electrocoagulation, vasospasm, or low systemic blood pressure. Early surgical intervention can be triggered to prevent permanent new deficit. However, with a bleeding AVM, the scope of surgical measures is limited, and MEP results may only allow to predict, not to influence postoperative outcome. Stable MEP recordings will allow the surgeon to proceed safely with a possibly dangerous maneuver. In our experience, irreversible MEP loss, mostly occurring with bleeding AVMs, predicted long-lasting new paresis in all 7 out of 21 monitored cases. If MEP deterioration was reversible after surgical intervention, there was only minor transient, or no new motor deficit in all 5 cases of this series. Stable MEPs indicated unimpaired postoperative movement in all cases.

On the contrary, stable SEP recordings missed new paresis in 3 out of 6 cases. SEPs may be monitored in combination with MEPs to provide complementary information about somatosensory areas and pathways. SEP monitoring alone is not advisable due to the high rate of false negative results with regard to motor outcome.

Aneurysms
Evoked potential monitoring is performed in our institution with all incidental and symptomatic aneurysms of the anterior, and proximal posterior circulation including infratentorial locations. With aneurysms of the
distal posterior circulation the vascularization of the sensorimotor patheways is not affected, such that SEP and MEP monitoring would not provide any useful information. VEP recordings have been shown not to correlate reliably with occipital cortex and visual pathway perfusion, and is no longer used for monitoring purposes. SEP recording has become the standard monitoring procedure for intracranial aneurysm surgery in many institutions. In a series of surgical treatment of 282 aneurysms in 226 patients in our institution, significant SEP changes occurred in 11.3%, mainly from accidental or intentional vessel occlusion, triggering reapplication of aneurysm clips, repositioning of retractors, or removal of temporary clips in 8.1% of cases[3]. SEP monitoring has proven a useful adjunct in almost 700 cases of aneurysm surgery at our institution. However, corresponding to what has been reported throughout the literature[2], there is a significant rate of false negative intraoperative SEP responses with regard to new postoperative deficits including pareses. It has been argued that this may arise from subcortical ischemic lesions going undetected by SEP recording, since the vascularization of somatosensory and motor pathways diverges at this level much more than cortically. In order to overcome this flaw of the established method, we introduced MEP monitoring after transcranial stimulation in combination with SEP recording on a routine base for aneurysm surgery. For about the same time, evoked potential monitoring results have been supplemented by intraoperative microdoppler recordings. Monitoring results and perioperative as well as intraoperative data have been documented prospectively for 100 operations of 130 aneurysms in 95 patients. SEPs reflected new postoperative paresis in 1 case of cortical infarction from internal carotid occlusion, but missed new motor deficit in 11 other cases, which was mainly light and transient from subcortical ischemia, and was reflected by MEPs in cases except for one late edema case. The high rate of light new paresis in this series may be due to its prospective nature, and corresponds to other prospective studies. MEPs triggered clip replacement, readjustment of retractors, or application of papaverine with spastic vessels in 14 cases, SEPs in 4 cases. Stable EP recordings allowed to proceed in 9/14 cases of temporary vessel occlusion. Microdoppler recordings revealed, or confirmed inadvertent vessel occlusion in 7/9 cases, but could not reflect impending new motor deficit from subcortical ischemia in any case. While continuous MEP monitoring was not always possible during microsurgical dissection, frequently due to strong muscle twitching artifacts, SEP recording proved feasible under most conditions. Thus at this point it can be concluded that MEP monitoring during aneurysm surgery is superior to SEP and microdoppler in detecting impending motor impairment, particularly from subcortical stroke, while SEPs may provide valuable information if MEP recording is not feasible. Microdoppler recording seems superior to evoked potentials in early detection of inadvertent vessel occlusion, if applied immediately after clipping.

References

Notes

Neurosurgical Management of Neuropathic Pain
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Neuropathic pain is a very difficult problem that the neurosurgeon has frequently to deal with. “Neuropathic pain is the pain associated with primary injury of neural tissues - peripheral or central”- according to the definition given by J.M. Gybels and W.H. Sweet in their book: “Neurosurgical treatment of persistent pain”.
The authors will present—though schematic views—the guidelines that they advocate to use according to the various types of neuropathic pain that one may encounter.

The first step management is to verify that all “anatomical” cause(s) likely to be responsible for the pain has (have) been eliminated, corrected or repaired. In the peripheral nerves one can mention: neurolysis, nerve relocation-transposition, neuroma excision, fascicular repair,…, for the spinal roots or spinal cord: decompression, fixation of the spine.

If any anatomical correction can be done, and after all physical therapies and all medical treatments known to be active on neurogenic mechanisms (anticonvulsivants, tricyclic antidepressants,…) have been tried, neurosurgical treatments can be considered.

The available techniques are:

1. **Modulative**, by using neurostimulation directed to the peripheral nerves, the spinal cord, the thalamus or the precentral cortex, or by implanting delivery systems (namely programmable pumps) to infuse analgesic drugs intrathecally
2. **Ablative**, by making selective therapeutic lesions in well-defined targets proved to sustain pain mechanisms (especially DREZotomy at the Dorsal Root Entry Zone level).

**Indications**

We have learnt from our thirty-year experience that for neuropathic pain treatment, consideration of the topographical level of the responsible lesion is of prime importance for determining the type of neurosurgical method to use and the target to choose (fig.1 and fig.2).

1. **When pain is due to peripheral nerve lesions**, if there is no evidence to indicate an “anatomical” treatment (freeing of the nerve, resection of a neuroma, etc), neuro-stimulation has to be tried first. This can be done by external Transcutaneous Nerve Stimulation (TNS) by direct Peripheral Nerve Stimulation (PNS) if the nerve(s) is (are) deeply situated, or the more commonly used Dorsal Column Stimulation (DCS) method. If DCS fails, Lesioning surgery in the main components of pain are of the paroxysmal and/or the allodynic types.
2. When pain is related to plexus and/or root lesions, it is of prime importance to determine the exact location of the lesion, i.e., distal or central to the dorsal root ganglion (DRG), as well as the completeness of the anatomical-functional interruption of the radicular fibers (especially the large caliber primary afferents). This can be assessed by studying the nerve conduction velocity and the somatosensory evoked potentials. If interruption is central and total, DCS cannot be effective, because of degeneration of DRG axons all along the spinal cord, up to their brain stem relay nuclei. If neurostimulation is applied, the target should be the contralateral thalamic somatosensory nucleus (ventro-postero-lateral nucleus) using stereotactic deep Brain Stimulation (DSB). An alternative solution may be Precentral Cortical Stimulation (PCS).

In true “deafferentation” pain syndromes, known to be accompanied by hyperactivity of the dorsal horn cells (like after brachial plexus or lumbosacral avulsion or after cauda aquina injury), therapeutic lesioning of the DREZ may be particularly effective.

In post-herpetic pain, (which corresponds to lesions both of the DRG cells (and related axons going to and running through the spinal cord) and of the dorsal horn), DCS can be tried if sufficient corresponding dorsal column fibers are still functional. Surgery in the DREZ may be especially indicated when the main components of pain are of the paroxysmal and/or allodynic types.

3. When pain is due to Spinal cord lesions, if pain is in the territory below the lesion, DCS can only be effective if the corresponding dorsal columns retain sufficient function. In cases in which the territory below the lesion is totally anesthetic, DCS will not work. Imaging and measurements of SSEPs may be useful to check integrity of the dorsal columns. When pain is in the territory corresponding to the (injured) lesioned segments of the spinal cord, DCS may be effective on that pain, but only if the segmental primary afferents of large caliber (i.e., the lemniscal fibers) are still – at least partially-functional.

The same differentiation of pain between its segmental and its infralesional components is of paramount importance when considering indication for DREZ surgery. According to our experience, surgery in the DREZ is only effective on the pain corresponding to the lesioned segments, i.e., the so-called segmental pain, probably because generators are located in the dorsal horn of the concerned segments. Conversely, DREZ surgical lesions do not influence pain in the territory below the lesion, even if performed at the corresponding cord levels.

4. When pain is due to Brain lesions, which was –until recently- classically not accessible to neurosurgical procedures, the newly introduced precentral (motor) cortex stimulation can be tried. PCS seems to be especially promising in post-stroke (hyperpathic) pain and also in trigeminal neuropathic pain.

Conclusion

All procedures for neuropathic pain are limited by the tendency to lose effectiveness over time. Success varies with patient selection and procedure used. Following rigorously guidelines based on anatomy and physiology significantly decreases the risk of failure.
Spasticity is one of the most common sequelae of neurologic diseases. In most patients spasticity is useful in compensating for lost motor strength. Nevertheless in a significant number of patients it may become excessive and harmful leading to further functional losses. Excess of spasticity may affect adult patients, and have its origin in spinal cord or cerebral lesions. It may also impair the development of children, especially those affected with cerebral palsy. When not controllable by physical therapy, medications and/or botulinum toxin injections, spasticity can benefit from, intrathecal pharmacotherapy or selective ablative procedures. Because excessive hypertonia has to be reduced without suppression of the useful muscular tone or impairment of the residual motor and sensory functions, neuro-ablative procedures must be as selective as possible. These selective lesions can be performed at the level of peripheral nerves, spinal roots, spinal cord, or the Dorsal Root Entry Zone (DREZ-lesions). The authors will present – in a simplified form – the algorithms for management of harmful spasticity, first in adults and second in children with cerebral palsy.

**Indications for Surgery in Adults**

Intrathecal Baclofen administration is indicated for para- or tetraplegic patients with severe and diffuse spasticity especially when from spinal origin. Because of its reversibility, this method has to be considered...
prior to considering an ablative procedure. But range between excess of hypotonia with loss of strength and
an insufficient effect is very narrow. An intrathecal test through a temporary access port can be useful before
indicating permanent implantation.

**Neuro-ablative techniques** are indicated for severe focalized spasticity in the limbs of paraplegic, tetraplegic
or hemiplegic patients.

Neurotomies are preferred when spasticity is localized to muscle groups innervated by a small number of, or
a single, peripheral nerve (or nerves). When spasticity affects an entire limb, microsurgical DREZotomy is
preferred. Several types of neuroablative procedures can be combined in the treatment of one patient, when
needed.

Whatever the situation and the etiology may be, orthopedic surgery must be considered only after spasticity
has been reduced by physical and pharmacological treatments first and, when necessary, by neurosurgical
procedures.

The general rule is to **tailor individual treatments** as much adapted as possible to the particular problems of
the hemiplegic or the paraplegic patients (fig. 1).

**Indications for Surgery in Children with Cerebral Palsy:**
In children surgical indications depend on preoperative abilities and disabilities and the eventual functional
goals. For guiding indications we have adopted the following classification in six groups.

1 - **In independent ambulatory patients**, the goal is to improve efficiency and cosmesis in walking by
eliminating as many abnormally responsive neural circuits as can be identified through functional posterior
rhizotomy. Surgery is best performed as soon as possible after the child has demonstrated the ability to work
with a therapist, usually between ages 3 and 7 years, and frequently must be done in conjunction with
operations on tendons because of concomitant shortened muscles.

2 - For **ambulatory patients dependent on assistance devices** (canes, crutches, rollators, walkers), the goal is
to lessen that dependence. A child with poor trunk control or lack of protective reaction but with good
underlying strength in the antigravity muscles can safely undergo a functional posterior rhizotomy. In children
dependent on hypertonicity in the quadriceps to bear weight, a limited sectorial rhizotomy is preferable. For
children who are in the process of developing ambulatory skill and need an assistance device only temporarily,
it is important to delay surgery until they have perfected these skills.

3 - For **quadruped crawlers** (or bunny hoppers) the goal is to achieve assisted ambulation during
midchildhood to early adolescence. A functional posterior rhizotomy will decrease hypertonicity in the leg
musculature and allow better limb alignment in the standing position for a child with adequate muscular
strength. However, a child who exhibits quadriceps weakness can be considered for a sectorial posterior
rhizotomy. Children in this group can present at a young age with progressive hip dislocation. The goal is to
stop the progressive orthopedic deformity by using obturator neurotomy with adductor tenotomies or
functional posterior rhizotomy.

4 - For **commando (or belly) crawlers** disabled by severe deficiencies in the postural control, the goal of
posterior rhizotomy is only to improve functioning in the sitting position by increasing stability.

5 - In **totally dependent children, with no locomotive abilities**, the goals are simply to improve comfort and
facilitate care. As with group 4, the preferred treatment is posterior rhizotomy, but there is also a need for
exploring the efficacy of intrathecal baclofen.
6 - **For asymmetrical spasticity**, selective peripheral neurotomies must be considered, especially obturator and tibial for the spastic hip and foot, respectively. For upper limb spasticity, the microsurgical DREZotomy procedure and/or selective neurotomies of the flexor muscles of wrist and fingers can be considered.

* In summary, for children, the main goal is to stop and prevent progressive and irreversible orthopedic deformities (fig.2). Lumbo-sacral posterior rhizotomies can be indicated for reducing the excessive general level of spasticity in diplegic (and even quadriplegic thanks to distant effects in upper limbs) patients. ITB is an alternative, but the range between an insufficient effect and an excessive effect responsible for a global decrease in tone impairing gait and reducing muscular strength, is often very narrow. In cases with localized hyperspasticity threatening a joint, peripheral neurotomy (ies) can be the solution, as for instance obturator neurotomy for hip spasticity. Frequently orthopedic surgery can be usefully performed in conjunction with neurological surgery to lengthen tendons.

**Conclusion**

By suppressing excessive spasticity, correcting abnormal postures, and relieving the frequently associated pain, surgery for spasticity allows physiotherapy to be resumed and sometimes results in the reappearance of, or improvement in, useful voluntary motility. When dealing with these patients, the surgeon must know the risks of the available treatments. To minimize those risks, the surgeon needs a strong anatomic, physiological, and chemical background, rigorous methods to assess and quantify the disorders; and the ability to work in a multidisciplinary team.

**NOTES**

Operative Recordings from Peripheral Nerve

Leo T. Happel, PhD
The science of EMG and nerve conduction studies has long provided clinicians with essential information relating to nerve and muscle function. Using this information, clinicians have been able to diagnose nerve injuries and follow their recovery. Recently, with the addition of operative nerve conduction studies, important information relating to nerve injury and to nerve regeneration can be added. While in the past the difficult decisions that confronted the surgeon faced with a severe nerve injury had to be made intuitively, now functional testing of peripheral nerve can be performed in the operating room and these decisions can be based on hard information.

Operative peripheral nerve electrical studies can provide a more accurate localization of a peripheral nerve injury. By placing stimulating and recording electrodes on a segment of nerve the presence of significant numbers of larger axons can easily be determined. As one slides these stimulating and recording electrodes along the length of nerve the point at which axons are no longer viable, the exact point of severe injury, can be accurately assessed. This technique is superior to the method of sectioning the nerve from distal to proximal until normal fasicular anatomy can be seen.

Operative recordings can also detect the early stages of nerve regeneration long before conventional EMG techniques. This permits a recovering nerve injury to be evaluated at the operating table at a time when surgical repair would be optimal. Based on the findings, the surgeon can determine the best way to deal with this particular injury. He may be able to discriminate between injuries that would best respond to resection and repair as opposed to injuries that would best respond to more conservative treatment such as neurolysis.

Recording peripheral nerve action potentials in the operating room is relatively easy and requires little time. The instrumentation necessary is usually available at most hospitals and could range from EMG equipment to evoked potential machines. Both of these instruments could record the compound nerve action potential (CNAP). The electrodes necessary to make contact with performed nerve can be easily made though there are some commercial vendors for these. Often, the requirements of specific cases give rise to improvisation. For example, when only a very short segment of nerve can be accessed it is possible to stimulate or record from a site outside of the operative field. However, I would caution against using muscle responses to nerve stimulation as an indicator of function. In this case, the artificial synchronization of small, pathological motor units by nerve stimulation may deceive the observer into thinking there is good function.

One begins recordings by placing both stimulating and recording electrodes on nerve which is known to be normal. Stimulus rates of 1 to 3 per second are generally used. At stimulus intensities of 3 to 5 volts (0.5 to 2 milliamperes) and recording sensitivities of 100 Micro volts per cm a response can usually be seen. Filter settings should be approximately 10 hertz to 3 kHz. Then, the electrodes can be moved to a section of nerve whose function is unknown. If a response is seen it proves the presence of viable axons. Then, an appropriate decision in the treatment of the nerve can be made. A flowchart is included in this handout to facilitate the procedure.

The technical problems most frequently encountered include excessive stimulus artifact, 60 cycle noise, and movement artifact. The problem of excessive stimulus artifact is not one that can be completely eliminated since there are many causes. Loss of stimulus isolation due to capacitive currents (improper draping of wires) can be corrected if recognized. Artifact can also be minimized by insuring adequate distance between stimulating and recording electrodes (at least 2 cm), by separating the wires from stimulating and recording electrodes as much as possible, and by using a tripolar stimulating electrode.

Movement artifact can be eliminated with the help of the anesthesiologist. Neuromuscular blocking agents can be used successfully during operative peripheral nerve recordings and this prevents muscle activation with electrical stimulation of nerve. Thus, the absence of a compound muscle action potential prevents its confusion with the CMAP.
If no response is seen from a section of injured nerve the electrodes can be moved, sliding along the length of
the nerve, from distal to proximal. In this way, one can discern the level at which viable axons can be found.
This is accomplished without cutting the nerve which risks damage to regenerating axons. I have found many
examples of nerve lesions that appear to be profound but, upon testing, are proven to have axonal continuity.
Similarly, I have seen lesions which appear mild but can be demonstrated, functionally, to be much more
severe. The physical appearance of a lesion in continuity may be misleading.

In conclusion, operative recordings of peripheral nerve activity furnish important information to the surgeon
that may facilitate difficult decision making. Previously surgeons were required to look at anatomy and infer
function though now this function can be determined directly. This assures that decisions are based on good
information and the outcome of repair to an injured nerve will be optimal.

Notes

Neurophysiological Implementation during Surgery on the Sacral Nervous System

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A relatively high percentage of pediatric surgical pathology is of the lumbosacral (LS) spinal cord and sacral
roots within the cauda equina, where the LS nervous system could be damaged. In the last few years,
effective methods for the intraoperative testing of the LS nervous system have been developed. We have had
much success with these and will describe each in detail. From a didactic standpoint, we have categorized
these methods based on recordings of neurophysiological signals of sensory systems (afferent events) and
recordings of signals from motor systems (efferent events). In intraoperative monitoring practice, they have
been incorporated in one set of monitoring protocols (fig. 1).

**Figure 1:** Neurophysiological events used to intraoperatively monitor the sacral nervous system. To the left are afferent events after stimulation of the dorsal penile/clitoral nerves and recording over the spinal cord: (1) Pudendal SEPs, travelling waves, (2) Pudendal DRAP and (3) Pudendal SEPs, stationary waves recorded over the conus. To the right are efferent events: (4) anal M-wave recorded from the anal sphincter after stimulation of the S1-S3 ventral roots, (5) anal MEPs recorded from the anal sphincter after transcranial electrical stimulation of the motor cortex, and (6) bulbocavernosus reflex obtained from the anal sphincter muscle after electrical stimulation of the dorsal penile/clitoral nerves. (Reprinted from Deletis, V. (2001). Neuromonitoring. In APediatric Neurosurgery (D. MacLeone, Ed.) Fourth Edition, pgs 1204-1213. W.B. Saunders Co., Philadelphia.)

We will briefly mention some other beneficial methods used in the neurophysiological testing of awake patients with a pathology of the sacral nervous system, although it cannot be used intraoperatively, in order to give an integrative view of sacral nervous system neurophysiology.

**Afferent events**

After electrical stimulation of the dorsal penile or clitoral nerves, a variety of neurophysiological signals can be recorded along the sensory pathways conveying this information to the brain. Recording of cerebral somatosensory evoked potentials from the scalp after such stimulation has been shown to be very useful in the testing of patients with sacral involvement (Vodušek et al. 1996). Unfortunately, due to its high sensitivity to anesthetics, it cannot be used intraoperatively.

**DRAP (dorsal root action potentials)** (see fig. 1, inset 2)

Recording of the DRAP of pudendal nerve afferent fibers, or the Pudendal neurogram is the mapping method most frequently used for selective dorsal rhizotomy (SDR) to relieve spasticity in children with cerebral palsy.

In this surgery, the DRAP is used to quantify the amount of pudendal afferent fibers coming from dorsal penile or clitoral nerves and entering the spinal cord via each of the S1, S2 and S3 dorsal roots. The DRAP is evoked by electrical stimulation of the penis or clitoris via two cup electrodes fixed on the dorsal surface of the penis or one on the clitoris and another on the adjacent labia majora. For recording DRAP, the surgeon frees a dorsal root and isolates it from its neighbors by lifting it outside the spinal canal using a hand-held bipolar hook electrode (Deletis et al. 1992; Huang et al. 1997).

For the purpose of SDR, an S2 root is spared if it carries pudendal afferents. If it is essential to cut the S2 root it can be avoided by dividing it into rootlets and cutting only those that do not carry pudendal afferent fibers.

In the study performed in 105 CP children, (Huang et al. 1997) it was shown that the distribution of pudendal afferents in individual patients was highly asymmetrical (with respect both to side and sacral roots). One of the most striking aspects of this asymmetry was that 7.6% of patients in this series had all pudendal afferent fibers (from the right and left pudendal nerves) entering the spinal cord via only the S2 roots (Fig 2 C and F). Recently we find out that similar phenomenon exist for the pudendal afferents from the anal mucosa entering to the spinal cord via single sacral root (Deletis et al. 2000) (Fig. 3). These data could explain the significant urogenital and sexual dysfunction after relatively restrained injury to the sacral roots. We suggest that mapping the DRAP during SDR be mandatory if S2 roots are considered for lesioning (Lang et al. 1994). Furthermore, we suggest that this method should be used in any surgery where S2 and S3 roots could be damaged.

**Pudendal somatosensory evoked potential (SEPs)- Stationary wave** (see fig. 1, inset 3)

This potential obtained by electrical stimulation of dorsal penis/clitoris nerves, sometimes called spinal segmental response, could be very easily recorded when the conus region and root entry zone from S2 to S4 roots is exposed. If an electrode is placed precisely over this anatomical structure, high amplitude potential
could be recorded, representing activity of the interneurons of the gray matter of the S2 to S4 spinal cord segment generated by sensory afferents form bilateral pudendal nerves.

**Pudendal somatosensory evoked potential (SEPs) - traveling waves** (see fig. 1, inset 1)
This potential is very rarely recordable from the dorsal column of the spinal cord, and has a rather low amplitude (1-2 µV). Due to the rare recordability and low amplitude we did not find this potential suitable for intraoperative monitoring of the sacral nervous system integrity.

**Efferent events**
Three kinds of motor events can be recorded intraoperatively from the motor part of the sacral nervous system: motor evoked potentials from the anal sphincter (anal MEP), the M-wave after direct stimulation of motor roots of the cauda equina, and the bulbocavernous reflex. Each of these events represents a different kind of activity that belongs to the motor part of the sacral nervous system.

**Anal sphincter M-wave** (see 1, inset 4)
Mapping of the S1, S2 and S3 motor roots that contribute to the motor part of the pudendal nerves can be easily performed by directly stimulating the exposed cauda equina by a hand-held probe and recording the electrical activity from the anal sphincter muscle (anal M-wave) through tiny wire hook electrodes inserted preoperatively in the right and left hemisphincter muscles. The mapping motor sacral roots within the cauda equina can be very useful in detecting a “hidden” root within the tumor or testing the phylum terminale for adherent sacral roots during untethering of a tethered spinal cord.

**Anal MEP (Anal sphincter muscle-MEP)** (see fig.1, inset 5)
This efferent response from the anal sphincter can be elicited and monitored by transcranial electrical stimulation over C1/C2 scalp points, in the similar fashion as for eliciting MEPs from the limb muscles. The recorded response indicates the functional integrity of the descending pathways for suprasegmental volitional control to the anal sphincter, as well as the motor part of the pudendal nerves, from anterior horn to anal muscle. Sometimes deep anesthesia can be an obstacle for eliciting anal MEP.

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**Mapping of Pudendal Afferents**

![Mapping of Pudendal Afferents](image-url)
Figure 2: Six characteristic examples of DRAP showing the entry of a variety of Pudendal Nerve fibers to the spinal cord via S1-S3 sacral roots. A) Symmetrical distribution of DRAPs confined to one level (S2) or three levels (D). Asymmetrical distribution of DRAPS confined to the side (B), only one root (C or F), or all roots except right S1. Recordings were obtained after electrical stimulation of bilateral penile/clitoral nerves. (Reproduced from: Vodusek D.B., Deletis V.: Intraoperative neurophysiological monitoring of the sacral nervous system. In: Neurophysiology in Neurosurgery: A Modern Intraoperative Approach. V Deletis and Shils J. (Eds.). Academic Press. 2002, pp197-212)

Figure 3: To the right: Example of extreme asymmetry of pudendal afferents from dorsal penile nerves. All afferents from right and left penile nerves in this 4-year-old cerebral palsy patient enter to the spinal cord via a single left S2 root. Each trace is an average of 100 responses twice recorded to show reproducibility. To the left: Example of extreme asymmetry of pudendal afferents from anal mucosa. All afferents from anal mucosa in this 4-year-old cerebral palsy patient enter to the spinal cord via a single left S3 root. Each trace is an average of 100 responses twice recorded to show

**Bulbocavernosus reflex (BCR)** (see fig. 1, inset 6)
The BCR is an oligosynaptic reflex mediated through the S2- S4 spinal cord segments, elicited by electrical stimulation of the dorsal penis/clitoris nerves with the reflex response recorded from any pelvic floor muscle. The afferent paths of the BCR are the sensory fibers of the pudendal nerves, its reflex center is the S2-S4 spinal segment, and the efferent paths are the motor fibers of the pudendal nerves and anal sphincter muscles. In neurophysiological labs, the BCR is usually recorded from the bulbocavernosus muscles, and this is where it gets its name. We have described an intraoperative method for recording the BCR from the anal sphincter muscle (Deletis and Vodušek 1997). Recently it has been shown that use of short train of stimuli can further improve elicitability of BCR (Rodi et al.). The advantage of BCR monitoring is that it tests the functional integrity of three different anatomical structures: sensory and motor fibers of the pudendal nerves, and gray matter of the S2-S4 sacral segments. A preserved reflex should indicate the preserved integrity of all of these structures. Also, this reflex can be recorded in babies as young as 24 days.

**Mapping and monitoring other sensory and motor roots within cauda equina**
Other motor roots of the cauda equina (L1 to S1) can be mapped by recording the M-wave after electrical stimulation of the exposed cauda in a similar fashion as for the anal M-wave. The electrical activity from the appropriate myotomes should be recorded. Motor evoked potentials from the quadriceps femoris, tibial anterior, and abductor hallucis muscles are easily obtainable after transcranial electrical stimulation of the motor cortex.
By electrical stimulation of the tibial nerves at the ankle or popliteal fossa, recording of the stationary wave over conus can be achieved. Furthermore, the traveling waves can be recorded more proximal over the spinal cord. This can be done with the identical electrodes as for pudendal SEPs. By using these methods, monitoring of the sensory roots of the cauda equina, dorsal horns, and dorsal columns can be achieved.

**References**

Notes

Brainstem Surgery

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During the decade of the brain, a more rational and constructive approach to the surgical management of neoplastic and vascular brainstem lesions has emerged. The surrendering attitude which still characterizes part of the neurosurgical community when dealing with the “untouchable” brainstem, has been progressively counterbalanced by increasing evidence that surgical “violation” of the brainstem is safely feasible in subgroups of patients. The extraordinary multiplanar capabilities of MRI allow to accurately distinct different patterns of brainstem mass lesions. MRI data together with a refined neurological evaluation support the decision-making process in selecting those patients amenable of surgical treatment, and in planning the optimal surgical strategy. Surgery of the brainstem, yet, remains a challenging task which require deep knowledge of the microsurgical and functional correlative anatomy of the brainstem.
This presentation, accordingly, will revisit those aspects of functional neuroanatomy relevant to modern neurosurgical approaches to the brainstem. This latter is characterized by an extremely dense, although phylogenetically ordered, concentration of functionally relevant structures like cranial nerve nuclei, motor and sensory pathways, crossing bundles and the reticular formation. Reviewing the modern neurosurgical approaches to the brainstem, from the midbrain to the cervico-medullary junction and the fourth ventricle, we will then attempt to individualize a map of safe “entry zones” which may guide the surgeon in the choice of the least dangerous approach to this critical area of the central nervous system.

A multimodality intraoperative neurophysiological monitoring (INM) has introduced in our Department in September 2000. Since then, 30 patients with brainstem tumors have been operated with the assistance of INM. The role of brainstem mapping in assisting the surgeon while entering the brainstem, as much as the invaluable help provided by the continuous monitoring of corticospinal and corticobulbar pathways during tumor removal will be discussed.

Finally, results from a personal experience with over 300 brainstem gliomas and vascular lesions (cavernomas, hemangioblastomas) surgically treated at the Department of Neurosurgery of Verona in the last 17 years will be reviewed.

**Brainstem mapping**

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Brainstem mapping (BSM) is an emerging new neurophysiological procedure which enables to locate cranial motor nuclei (CMNs) during brainstem surgery. BSM is regarded as an indispensable tool to avoid direct damage to the CMN when the lesion locates inside the brainstem and the normal anatomical landmarks are lost by distortion caused by the tumor compression.
BSM on the floor of the fourth ventricle using a hand held monopolar probe. The medullary tumor is partly observed in the dorsal aspect of the brainstem.

In general, BSM is performed through the floor of the fourth ventricle. Electrical stimulation is delivered to the floor of the fourth ventricle and the EMG response is recorded from the needle inserted in the muscle.

Standard parameters for BSM is shown below:

**Stimulation**
- Cathode: hand-held monopolar probe (diameter of the tip: 0.75mm)
- Anode: cervical muscles in the operative field,
- Wave form: square wave, single pulse
- Duration of stimulation: 0.2 msec
- Frequency: 1.0 - 4.0 Hz
- Intensity: 2.0 mA for screening, then squeeze intensity to detect threshold.
  - Use supra threshold intensity for the mapping

**Recording**
- Epoch time: 20 msec
- Amplification: 10,000 times
- Muscles for EMG recording:
  - CMN VII: orbicularis oculi & oris
  - CMN IX/X: posterior pharyngeal wall
  - CMN XII: lateral wall of the intrinsic tongue muscle
BSM usually starts with the stimulation intensity of 2.0mA for searching the CMNs. Once the response is obtained, the stimulation intensity is squeezed to the thresholdal level so that exact location of the CMN is identified.

With the BSM experience accumulated, there seemed to be repetitive patterns in terms of tumor displacement of the CMNs. In pontine tumors, the facial nucleus are likely to be displaced at the edge of the tumor exposed on the floor of the fourth ventricle. Localization of the facial nucleus is mandate to avoid its damage by compression or myelotomy during tumor resection. In Medullary tumors, one or several lower CMNs are located on the ventral side of the tumor. Unmapped CMN before tumor resection could be mapped near the bottom of tumor cavity as the tumor resection advanced. Attention should be focused on the bottom of tumor cavity to avoid damaging the lower CMNs. In cervicomedullary junction spinal cord tumors, the tumor extend into the fourth ventricle while compressing the caudal part of the floor of the fourth ventricle up to rostral side, if the tumor is low grade one. Rostral end of the tumor tends to situate ventral to the displaced lower CMNs. Undermining the tumor below the caudal end of the floor of the fourth ventricle is required during tumor resection.

Understanding surgical (or “functional”) anatomy revealed by BSM will help perform brainstem surgery safer.
During the session of BSM in the symposium, video-taped actual BSM of the medullary tumor shown above is to be demonstrated.

References:

Notes

Mapping and Monitoring of Cranial Nerves

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Intraoperative neurophysiologic monitoring of cranial motor nerves III, IV, VI, VII, IX, XI, XII\(^{18,13,17,22,20}\) has evolved during the past 2 decades and is now in routine use in connection with many forms of neurosurgical operation. Monitoring of the motor portions of CNV, and CNX\(^{17,25,20}\) and CNXII\(^{17,20}\) has also proven to be beneficial in many skull base operations. Here an overview is presented of the basis for intraoperative mapping and monitoring of cranial nerves.
The auditory nerve was the first sensory cranial nerve to be monitored systematically either through the use of farfield potentials (BAEP), or by recordings directly from the exposed nerve reducing the incidence of postoperative hearing deficits after operations in the cerebello pontine angle. Techniques for mapping of cranial nerves V and VIII and of the brainstem, which evolved later, have proven effective in aiding the surgeon in selective sectioning of these nerves. Mapping of the floor of the fourth ventricle has made it possible to find safe entries to deep brainstem structures and thereby reducing postoperative morbidity.

The facial nerve was the first cranial motor nerve to be monitored routinely. The technique for monitoring the facial nerve has improved since then and the function of the facial nerve is now monitored routinely by recording electromyographic potentials from facial muscles while the surgical field is probed using a hand held monopolar stimulator. In operations of large acoustic tumors it is beneficial to probe the tumor for the purpose of finding regions of the tumor where there is no part of the facial nerve present to make it possible to remove large portions of a tumor with minimal risk of injuring the facial nerve. This procedure also reduces the operating time. At later stages of operation on large acoustic tumors the facial nerve can be located by the same monopolar stimulating electrode, although a bipolar stimulating electrode would be preferential because of its greater spatial selectivity. EMG potentials recorded from facial muscles in the absence of electrical stimulation of the facial nerve provide information about surgically induced irritation and injuries to the facial nerve. Making EMG potentials audible provides the surgeon with important information about surgical manipulations that may cause injury to the facial nerve.

Similar techniques as used for monitoring of the facial nerve can be used for monitoring of other cranial motor nerve such as CNIII, CNIV, CNVI, CNVII, CNIX, CNX and CNXI and CNXII which are often at risk of being injured in skull base operations. Monitoring of the nerves that innervate the extraocular muscles is particularly important in operations at or close to the cavernous sinus and it has been shown to reduce the risks of serious postoperative neural deficits. Monitoring of CNXII is essential because of its small size and the fact that it is often displaced by tumors. Monitoring of the motor portions of CNV is less frequently done but it is useful in many operations including operations for large acoustic tumors.

Monitoring of sensory cranial nerves can be done by recording far field evoked potentials such as the BAEP, VEP and TEP, and by the direct recording of the compound action potentials (CAP) from the respective nerves when they are surgically exposed. Recording directly from a sensory cranial nerve is most frequently done for the auditory nerve but has also been done from CNV, intracranially, and from the optic nerve. Recordings of the CAP from an exposed sensory nerve such as the auditory nerve provide faster and more precise information than can be gained from recording of far field potentials such as the BAEP.

Personal experience from monitoring a large number of patients undergoing microvascular decompression operations for cranial nerve (VII, V, and VIII) disorders have indicated that hearing loss can be reduced to very low numbers if the surgeon responds promptly to any detectable change in auditory evoked potentials. If intervention is not taken, even in response to small changes, it inevitably will result in postoperative permanent deficits in a certain number of patients.

Recording from the surface of the cochlear nucleus is also effective in direct monitoring of the auditory nerve. The surface of the cochlear nucleus forms the floor of the lateral recess for the fourth ventricle. Evoked responses from the cochlear nucleus can be recorded by placing an electrode into the lateral recess of the fourth ventricle, which can be reached through the foramen of Luschka. Such recordings are more stable than recordings from the exposed auditory nerve because the electrode that record, from the cochlear nucleus can be better secured in place. This is especially important when monitoring of auditory evoked potentials is done to aid in hearing preservation in operations for acoustic tumors.

Monitoring of the optic nerve and optic tract has not won general use, mainly because it is not possible to focus a checkerboard pattern of changing contrasts on the retina of an anesthetized individual. It has been shown recently that changes in potentials evoked by high intensity flash may be better related to injuries of
the optic nerve or optic tract than that of potentials that are evoked by flashes of lower intensity\textsuperscript{20}. This may eventually lead to better protocols for monitoring the visual system.

Microvascular decompression (MVD) is an effective treatment of hemifacial spasm (HFS) and intraoperative monitoring of the abnormal muscle response can help to identify the offending blood vessel\textsuperscript{12,14,17}. Such monitoring can also confirm that the facial nerve has been adequately decompressed before the end of the operation, decreasing the necessity of re-operations and increasing the success rate\textsuperscript{14}. Similar monitoring for microvascular decompression of the trigeminal nerve has not been developed, but intraoperative mapping of the trigeminal nerve is beneficial in operations where selective sectioning of the trigeminal nerve is to be made\textsuperscript{26}.

Monitoring of BAEP is also valuable in operations where the brainstem may be compressed or surgically manipulated because BAEP monitors the general function of the brainstem\textsuperscript{1,17}. Changes in the BAEP can often be detected before changes in cardiovascular function become apparent.

The postoperative permanent deficits of concern have usually been limited to those that give clear clinical signs or symptoms. However, recent studies have shown that many patients experienced a change in life quality after operations for acoustic tumors even if they had no postoperative symptoms or signs of specific deficits that could be related to the operation\textsuperscript{18}. This does not prove that the intraoperative events that caused the impairment of the quality of life of these patients could have been detected by electrophysiologic means. However, these findings may indicate that might be beneficial that the surgeon reacted to very small intraoperative changes in function as indicated by (small) changes in recorded electrical potentials.

While intraoperative monitoring is usually regarded to be a technique that can help reduce the risks of postoperative permanent neurological deficits, electrophysiologic recordings can also provide help and guidance to the surgeon in certain kinds of operations. One example of the use of electrophysiologic methods to guide the surgeon is intraoperative mapping of neural structures. Mapping of the eighth nerve to find the cleavage plane between the vestibular nerve and the auditory nerve is one such example of intraoperative mapping\textsuperscript{3,21}. Mapping of the trigeminal nerve to identify its three branches is another example\textsuperscript{26}. Mapping of the trigeminal nerve is important in operations where partial section of the trigeminal nerve is to be done close to the brainstem. Normal variation in the anatomy implies uncertainty in determining the anatomical location of each of the three portions of the trigeminal nerve. Such mappings are done for the purpose of achieving the best possible therapeutic results and at the same time reducing the risks of injuring structures the function of which should be preserved. Mapping of the intracranial portion of the trigeminal nerve is best done by electrical stimulation of the nerve at the location where sectioning is to be performed, while recording antidromic compound action potentials (CAP) from the individual branches of the nerve where they emerge from their respective foramina in the face, using subdermal needle electrode. The electrical stimulation of the nerve intracranially should be done by a handheld bipolar stimulating electrode. Mapping of the intracranial portion of the auditory-vestibular nerves\textsuperscript{3,21} in operations when the vestibular part is severed while preserving the auditory nerve can be done by recording the CAP from the nerve using a handheld bipolar electrode while applying clicks to the ear. The auditory nerve is best identified when clicks of low intensity (approximately 25 dB above threshold) are used\textsuperscript{21}.

Mapping of the floor of the fourth ventricle for the purpose of finding a safe entry to the interior of the brainstem\textsuperscript{27,28} is an example of mapping that can help a surgeon to carry out an operation with the smallest possible risk. Such mapping is done by identifying cranial nerves that travel close to the surface of the floor of the fourth ventricle\textsuperscript{28} by probing of the region with a handheld bipolar stimulating electrode while recording electromyographic potentials from muscles that are innervated by these nerves, the location of which are to be determined. The locations of such nerves is then used as individual references for anatomical maps of the brainstem that makes it possible to decide where the floor of the fourth ventricle can be opened with the least risk. It is mainly CNVII that is available for such identification but also CNXII can be identified.
Mapping and monitoring of the cranial nerves have helped reduce the risks of permanent postoperative deficits in the past encouraging an increased use of such intraoperative monitoring and further developments of the methods that are used.

References


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