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Neurophysiological Monitoring: A Tool for Neurosurgery

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Limitations in the ability to clinically assess nervous system function during surgery have led to the development of neurophysiological intraoperative monitoring (IOM). IOM provides a real-time control loop around the surgeon and the patient. This control loop provides a dynamic assessment of the effects of surgical manipulations on the structure –function relationships of the patient's nervous system to facilitate the surgeon's decision making. Specific and sensitive measurements reflect the interactions between the surgeon's intraoperative manipulations and the functioning of the patient's nervous system.

This requires both rapid (as close as possible to real time) and multiple, simultaneous measurements of central nervous system (CNS) function. This combination allows a close and dynamic correlation with operative manipulations.

This chapter reviews our approach to IOM and summarizes pertinent literature with respect to this developing field. The emphasis is on the simultaneous acquisition of multiple neurophysiological measures. Depending on the surgical procedure, measures may be directly dependent on the functioning of the cortex [the electroencephalogram (EEG), somatosensory evoked potentials (SEPs) and visual evoked potentials (VEPs), direct cortical stimulation], the brain stem [brain stem auditory evoked potentials (BAEPs) and brain stem somatosensory evoked potentials (BSEPs)], and cranial nerves (CN) II, III, IV, V, VI, VII, VIII, IX, X, XI, and XII spontaneous and evoked electromyography (EMG), the spinal cord (sensory and motor potentials), and peripheral nerves (evoked EMG and compound action potentials).

Neuroanesthetic Considerations

It is well known that the type of anesthesia, the patient's blood pressure, cerebral blood flow, body temperature, hematocrit, and blood gas tensions all affect the patient's CNS function and thus the observed intraoperative neurophysiological measures.[39] Many of the monitoring techniques place competing and complex demands on anesthetic management, with a variety of techniques being used at different times during a single operative procedure to enable the appropriate neurophysiological measures.[96]

Halogenated inhalational agents are favored by anesthesiologists for many procedures; however, they tend to significantly reduce the amplitude and shift the frequency components of the EEG, reduce the amplitude and increase the latencies of somatosensory and motor evoked potentials,[91] eliminate visual responses, and confound evoked EMGs.[104] We have found the optimal anesthetic technique to be a balanced narcotic technique, usually fentanyl, nitrous oxide ($< 50\%$), a low level of isoflurane ($< 0.5\%$), and a short-acting muscle relaxant that can be rapidly reversed

when it is necessary to observe evoked EMGs. This technique may need to be modified if motor potentials are recorded to predominantly total intravenous anesthesia.

In many situations, halogenated hydrocarbon inhalation agents are desired to help control blood pressure. In our experience this problem is best approached by beginning the operative procedure under balanced narcotic technique, and then once baseline responses have been obtained and compared with the preoperative responses, introducing inhalation agents in a controlled fashion. It has also been our experience, particularly in children, that responses can be maintained at an isoflurane level of ~0.3 minimum alveolar concentration (MAC), whereas many adults can maintain their responses at 0.5 MAC.

Of the inhalation agents, isoflurane produces the weakest effects on cortical activity. Thus, in those cases where a balanced narcotic technique can not be used, isoflurane is recommended as the anesthetic from a monitoring perspective. These effects are very individualized, and even low levels of inhalation agents may reduce the amplitudes of cortically generated activity in some patients (**Fig. 3–1**).[92] The somatosensory short latency potentials (BSEPs) behave similarly to those from the auditory system (BAEPs) and are unaffected by most anesthetic manipulation.[29,40,65]

◆ Monitoring Systems

The presently available systems supporting IOM allow the simultaneous acquisition of evoked potentials, EEGs, and EMGs along with data from the anesthesiology monitoring unit,[95] and have significantly increased the utility and sensitivity of IOM (**Fig. 3–2**).

Neurophysiological signals are amplified using differential amplifiers[36] in which two input channels to the amplifier are differenced. This differencing has the effect of eliminating identical (in-phase) signal components that might be present at each recording electrode (presumably noise), and retaining the signals that are different (out-of-phase) and presumably produced by physiological generators. The effectiveness with which a differential amplifier rejects in-phase signals compared with its ability to amplify out-of-phase signals is called the common mode rejection ratio (CMRR). Differential amplifiers typically have CMRRs of greater that 10,000:1 (80 dB). For efficient rejection of in-phase signals, it is extremely important that the electrode impedances of each electrode of a pair not only be as low as possible but as similar as possible because any inequality in electrode impedance will produce amplitude differences in the in-phase activity that will be amplified along with the desired signal.

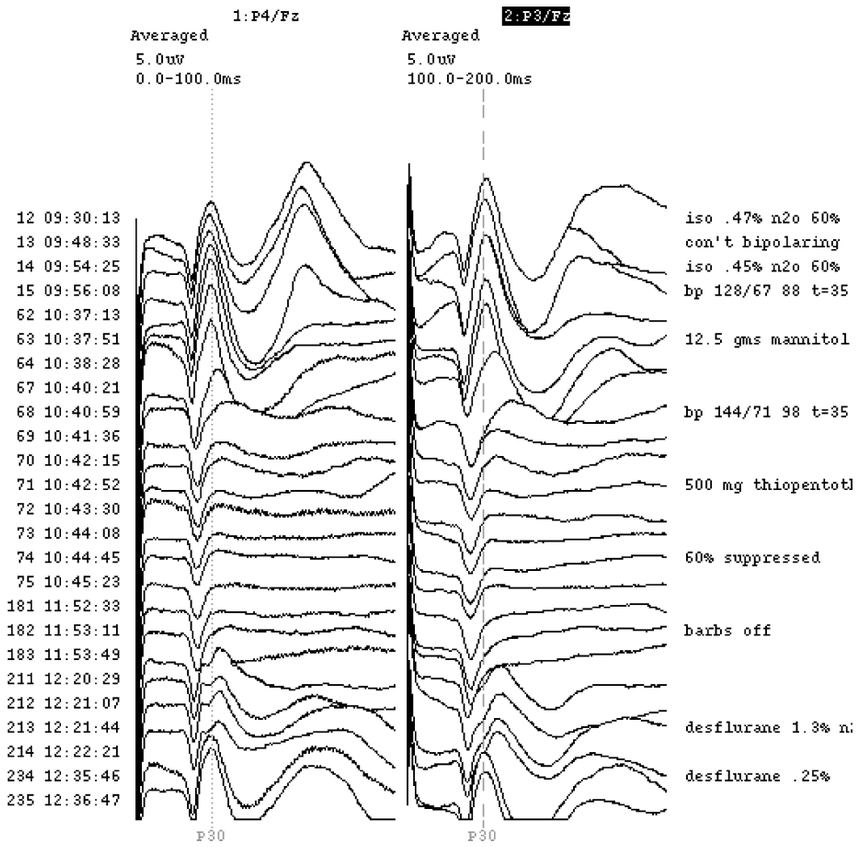

Figure 3–1 Bilateral median nerve evoked potentials demonstrating effects of multiple anesthetic agents during carotid endarterectomy. Sequential recordings start at the top of the figure. Initial responses are within normal limits. Recordings start to deteriorate, and thiopental is given, reducing P30. When thiopental is turned off, recordings return rapidly, but the effect of desflurane can be seen. As desflurane levels are decreased, recordings return to baseline at the bottom of the figure.

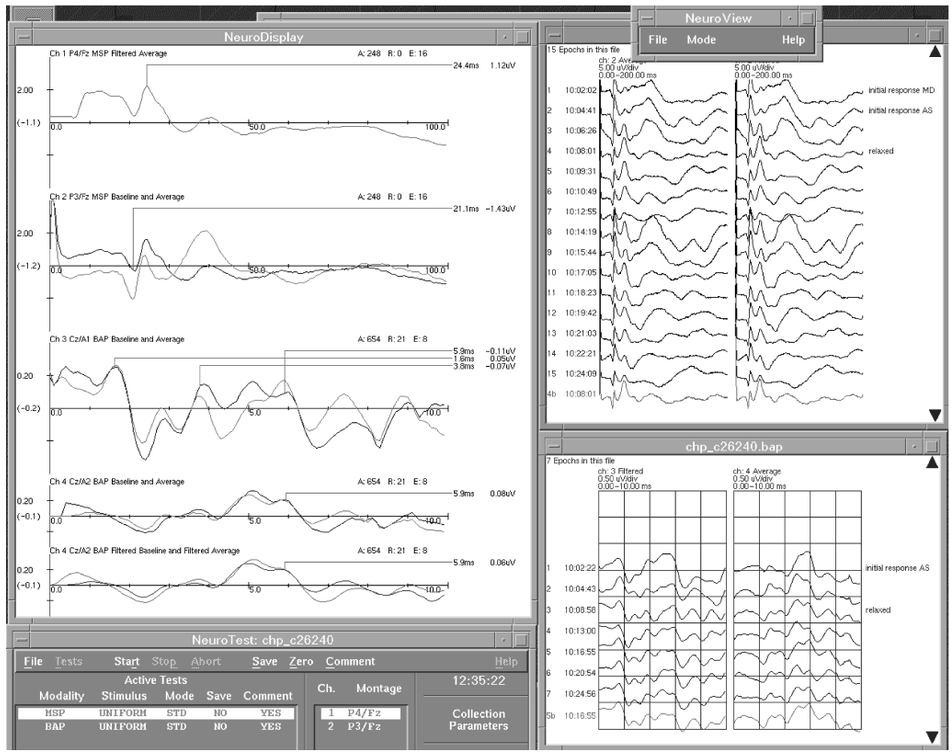

Figure 3–2 Example of median nerve evoked potentials (MSPs) and BAEPs being acquired simultaneously with the second channel (ch 4) of BAEPs being digitally filtered. Channels 2, 3, and 4 are also being compared against baseline data. Waterfall displays of both modalities are also shown with baseline responses at the bottom of each waterfall, and annotating comments are attached to the appropriate recording.

In evoked potential recording, the observed neuroelectric activity, either from the scalp or propagating activity from the cord, is assumed to consist of a signal component representative of underlying activity evoked by the stimulus and random noise consisting of both physiological signals not relevant to the study and environmental noise generated by ubiquitous sources of electrical signals. Evoked potentials are typically a fraction of the size of the spontaneous brain activity appearing in the background EEG, and about one thousandth the size of the other physiological and extraneous potentials with which they are intermixed. The aim of evoked potential recording is to acquire a large, clear response with the least possible noise contamination (i.e., the best signal to noise ratio possible); thus the elimination of unwanted signal components is essential. This elimination is accomplished through the use of both analog and digital filtering techniques and signal averaging.

After signal amplification, the most effective method for extracting a signal of interest from background noise is signal averaging. Signal averaging is in effect a cross-correlation between a point-process defined by the occurrence of the stimuli and the recorded evoked activity (i.e., an optimal filter).[58] In averaging, the signal component at each point is coherent and adds directly, whereas the background and noise components tend to be statistically independent and summate in a more or less root-mean-square (RMS) fashion.

Neurophysiological Measures

Neurophysiological measures are available that provide a functional map of nearly the entire neuroaxis. These measures include the EEG, an unstimulated measure of cortical function suitable for providing information concerning the degree of cortical activation related to either metabolic processes (e.g., hypoxia) or pharmacological manipulation (e.g., pentobarbital-induced burst suppression to protect the patient's cortical function)[75]; the somatosensory and visual cortical potentials (SEPs and VEPs), which provide additional measures of cortical function specific to certain pathways and vasculature; the auditory and somatosensory brain stem potentials (BAEPs and BSEPs), which provide information about the brain stem function specific to certain pathways[86]; compound nerve action potentials (CNAPs) providing information from both the spinal cord (SCAPs) and the peripheral nerves; and, finally, both continuous and evoked EMGs recorded from muscles [compound muscle action potentials (CMAPs)] innervated by the various cranial and peripheral nerves, which provide direct information about the integrity of the cranial nerves, their underlying brain stem nuclei,[51] the spinal cord, and peripheral nerves.

All measured potentials may be characterized as either near-field or far-field potentials (NFPs or FFPs). These concepts express observed differences between types of potentials

and are meant to distinguish between two different manifestations of volume-conducted fields.[54]

FFPs are recorded at some distance from the presumed generator, however, and the point at which a "near field" becomes a "far field" has never been clearly defined. A useful definition for the FFP is one that fails to decay in proportion to the square of the distance from the generator.

Electroencephalogram

The EEG is a valuable monitoring tool in almost all cerebrovascular procedures or tumor resections where significant risk for interruption of blood flow to the brain occurs.

Cerebral blood flow alterations may occur during carotid endarterectomy, clipping or coiling of cerebral aneurysms, or repair of the internal carotid artery associated with tumor removal from the cavernous sinus. In most open cases, proximal and distal control of the feeding artery is required, potentially reducing blood flow to the brain. Associated with this decreased availability of blood may be hypoxia caused by an inability of the collateral circulation to adequately supply blood to the brain (**Fig. 3–3**).

The second most useful application of EEG monitoring has been to help define the occurrence of embolic phenomena during these same procedures, which results in decreased blood flow and a potentially ischemic event, but which may be treated intraoperatively if recognized.[12]

In all of these situations EEG monitoring can help identify the presence of an insult, define the possibility for immediate therapy, and define the degree of burst suppression if barbiturate brain protection is instituted.

The typical pattern seen in the EEG during cerebral hypoperfusion is a reduction or loss in high-frequency activity and the appearance of large-amplitude slow waves in the range of 1 to 4 Hz. There are situations where the EEG may be acutely depressed upon injection of an anesthetic that rapidly passes the blood–brain barrier. Such situations may be found in high-dose opioid anesthesia, where fentanyl induces an immediate and marked reduction of fast frequency activity in the EEG, with an increase in low-frequency, high-amplitude activity.[33]

A simple but useful summary of possible changes is that decreased frequency with increased amplitude implies an ischemic event to the cortex,[106] widespread frequency slowing and decreased amplitude usually imply brain stem ischemia,[87] whereas ischemic events affecting the thalamus and the internal capsule produce unremarkable changes in the EEG[106] but possibly significant changes in the SEPs.

Somatosensory Evoked Potentials (Ascending Spinal Cord Activity)

SEPs are used during spinal surgery, vascular procedures, and cranial base procedures. For most cases we simultaneously stimulate the median or ulnar nerve at the wrist, and the common peroneal nerve as it passes under the head of the fibula, or the posterior tibial nerve at the medial malleolus.

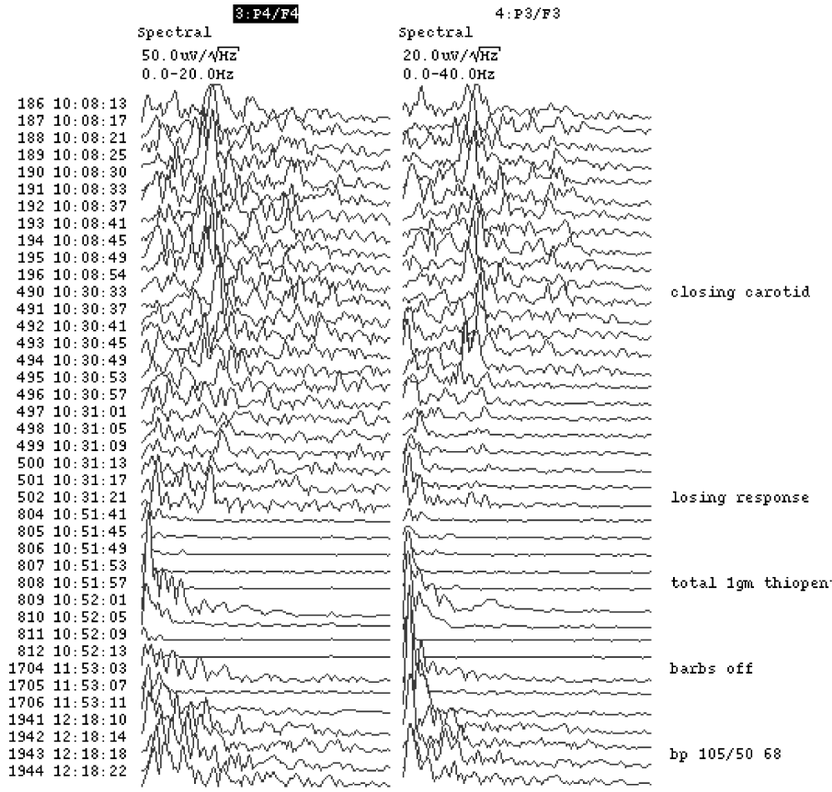

Figure 3–3 Power spectrum of two channels of electroencephalography recorded during temporary clipping of the left middle cerebral artery. Data are sequentially presented starting at the top of the figure. The spectra in column 2 demonstrate changes associated with cross-clamping and recovery after removal of the clip. Both channels of data reflect the generalized effect of thiopental on cortical activity and its underlying metabolic demand.

In addition, dermatomal SEPs are of use in selected cases where concern exists about protecting particular nerve roots, such as during tethered cord release.

SEPs are dependent on the stimulation of large afferent fibers of peripheral nerves. Following stimulation of peripheral nerves in the arms or the legs, SEPs can be reproducibly recorded over the spine and scalp. In the spinal cord, the SEPs are conducted primarily through the dorsal columns; however, extensive work has been done to clarify the generators for the various components of the SEPs.[24,25] In humans, loss of posterior column function is associated with abnormality of the SEPs; however, extralemniscal pathways may also mediate some mid- and long-latency scalp SEP components.

In our experience, SEPs are extremely sensitive and specific to spinal cord injury whether it occurs in the dorsal or in the ventral pathways. This is confirmed in the literature,[76] where a false-negative rate of 0.063% was found for 51,263 spinal cases in which SEPs were the only modality monitored. Furthermore, the negative predictive value (i.e., the likelihood of normal spinal cord function in the presence of stable SEPs) was 99.93%. This is a significant improvement over the 0.72 to 1.4% incidence of spinal cord injury reported for unmonitored cases.[62]

Temperature changes significantly influence the SEP latency. For each degree Celsius of local cooling, the nerve conduction velocity decreases by ~2.5 msec. During long operations, a drop in temperature around the nerve being stimulated can result in a progressive increase in latencies unrelated to surgical manipulation. Also, latencies may be transiently affected when the surgeon irrigates with physiological solution at cooler temperatures. Significant changes are also seen related to hypotension. Attention must be paid to these changes because spinal cord hypotension in patients with myelopathy may lead to an extension of the myelopathic lesion.

Upper Extremity (Median and Ulnar Nerve) Evoked Potentials

Median and ulnar nerve evoked potentials (MSPs and USPs) are both useful in assessing the brachial plexus, cervical spinal cord, brain stem, and telencephalon. These potentials are useful in preventing and reducing surgical morbidity during procedures that pose potential harm to the cervical cord and in assessing the level of hypoxia in cortical and spinal tissue.[35] Only the MSPs are described in detail here because the USPs are usually identical except for their level of entry into the spinal cord.

Stereotypical MSPs are simultaneously recorded from the ipsilateral Erb's point referenced to the contralateral Erb's point, the neck (cervical CV_7) and parietal (P_3 or P_4) (electrode locations are given in the International 10/20 system[49]) scalp with a reference to a frontal electrode (**Fig. 3–4**).

At Erb's point, the response is an NFP consisting of an apparently triphasic (positive-negative-positive) nerve action potential, reflecting the passage of a mixed nerve volley passing the brachial plexus. This component is usually labeled N_{11} for the large negative-going component generated at 11 msec (all waves will be identified as N or P for their polarity subscripted by the latency of the wave). At the cervical C_7 recording site, the NFP consists of an N14 wave with an associated complex waveform. It has been postulated that these waves are generated in the dorsal roots, dorsal horn, posterior columns, and structures of the lower brain stem.[27,28] The response recorded from scalp electrodes placed (roughly over the hand area of the sensory cortex) contralateral to the stimulated arm consists of a P_{15}, N_{20}, P_{30} complex. Some data suggest that P_{15} is thalamic in origin,[93] whereas N_{20} is generated in thalamocortical pathways, and P_{30} is generated in parietal cortex.[2,37] After this wave, there is considerable disagreement as to the identity of the cortical underlying generators; however, it is clear that the parietal cortex is involved in the generation of the N_{20}/P_{30} complex and that the parietal association areas are involved in the generation of the later waves.

Lower Extremity (Common Peroneal and Tibial Nerve) Evoked Potentials

In the lower limbs, nerves used to elicit SEPs include the tibial and peroneal nerves. Occasionally the femoral nerve is also used. Spinal potentials are most consistently obtained by stimulation of the tibial nerve at the medial malleolus or peroneal nerve in the popliteal fossa.

Recordings are made routinely at the lumbar spine and the cerebral cortex (Pz/Fz). SEPs also can be recorded along the thoracic or cervical spine as clinically indicated. Stimulation of the posterior tibial nerve at the ankle evokes P_{32} and N_{42} potentials in the younger population,[24] which gradually increases in latency until adult values of 40 and 48 msec, respectively, are obtained.[108] Stimulation of the common peroneal nerve at the popliteal fossa produces waves that are slightly shorter in latency.[25] The first useful component is an N_{20} wave, which is usually maximal over the T12 or L1 vertebra. At more rostral and caudal levels it may be possible to record small "traveling" waves, representing the envelope of action potentials in the dorsal roots and sensory tracts of the spinal cord.

Spinal SEPs are relatively easy to obtain in children, with the amplitude and definition of the waves decreasing with increasing age such that by the midteenage years these responses are more difficult to obtain. The response over the mid and lower lumbar spine consists of an initially positive triphasic potential. This reflects the NFP produced by a volley of action potentials ascending through the cauda equina (**Fig. 3–5**).

Dermatomal Responses

A disadvantage of SEPs produced by stimulation of large nerve trunks is that input to the spinal cord usually occurs over more than one level. This problem can be addressed by delivering the stimulus to small cutaneous nerves that are derived from a single dorsal root and which innervate the "signature area" of a particular dermatome.

Pudendal nerve responses are a special case of dermatomal responses, particularly useful in patients with spina bifida or tethered cords. The pudendal nerve carries sensory fibers from the penis, urethra, anus, and pelvic floor muscles, and supplies motor innervation to the bulbocavernosus and pelvic floor muscles, the external urethral sphincter, and the external anal sphincter. Cortical responses to

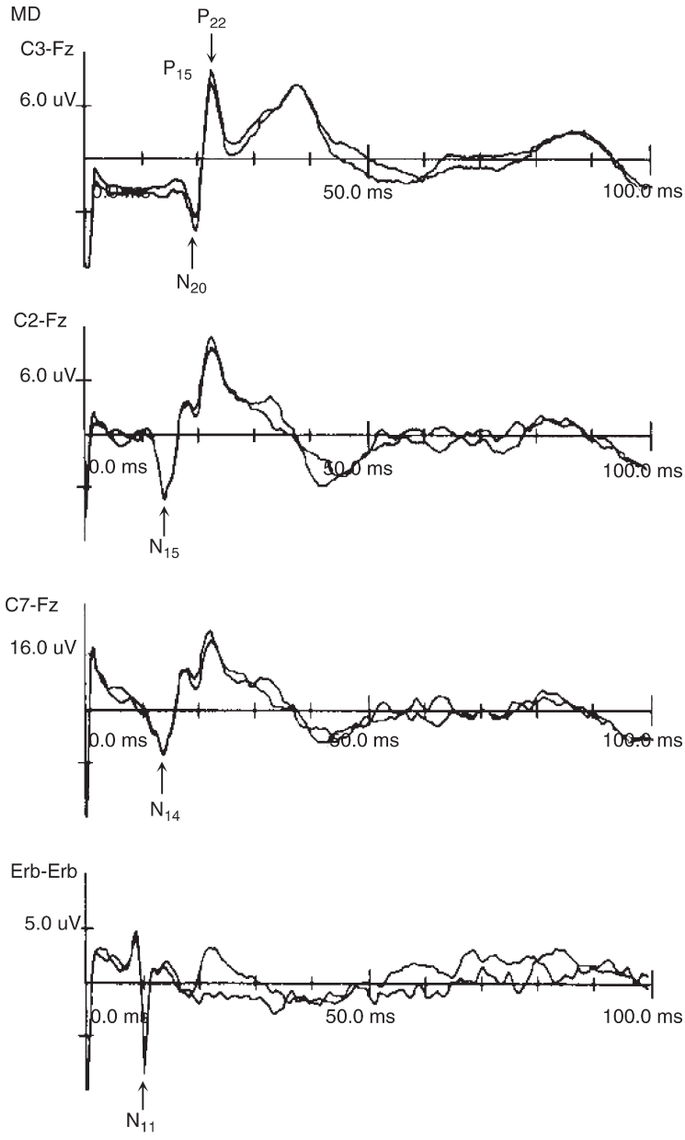

Figure 3–4 Median nerve evoked potentials (MSPs) demonstrating the significant waves at different levels along the neuraxis from Erb's point (ch 4) to the contralateral scalp (ch 1).

electrical stimulation of the dorsal nerve of the penis, the urethra,[41] and the urinary bladder[4] have all been described. Pudendal nerve responses are similar in morphology to the tibial nerve SEP and are best recorded from the same area of the scalp.[42]

Brain Stem Evoked Responses

BSEPs are monitored routinely during all procedures in which SEPs are recorded. We routinely record between electrode locations M_1 (left mastoid) and Fz, similar to the recording locations for BAEPs. The waves and their generators[27] are (1) P_{10}, the brachial plexus; (2) P_{12}, dorsal column nuclei; (3) P_{15} medial lemniscus; (4) N_{16}, thalamus; and (5) later peaks representing the thalamocortical projections. It is believed that multiple parallel spinal cord pathways are activated by suprathreshold stimulus intensities and that they contribute differentially to the various BSEP peaks.[85]

Ventral Cord Monitoring

Even though the results of SEP monitoring in preventing both motor and sensory iatrogenic injury during spinal surgery have been excellent, they cannot provide complete coverage of the spinal cord, and several cases have been reported of spinal injury going undetected using only SEP monitoring.[19,59]

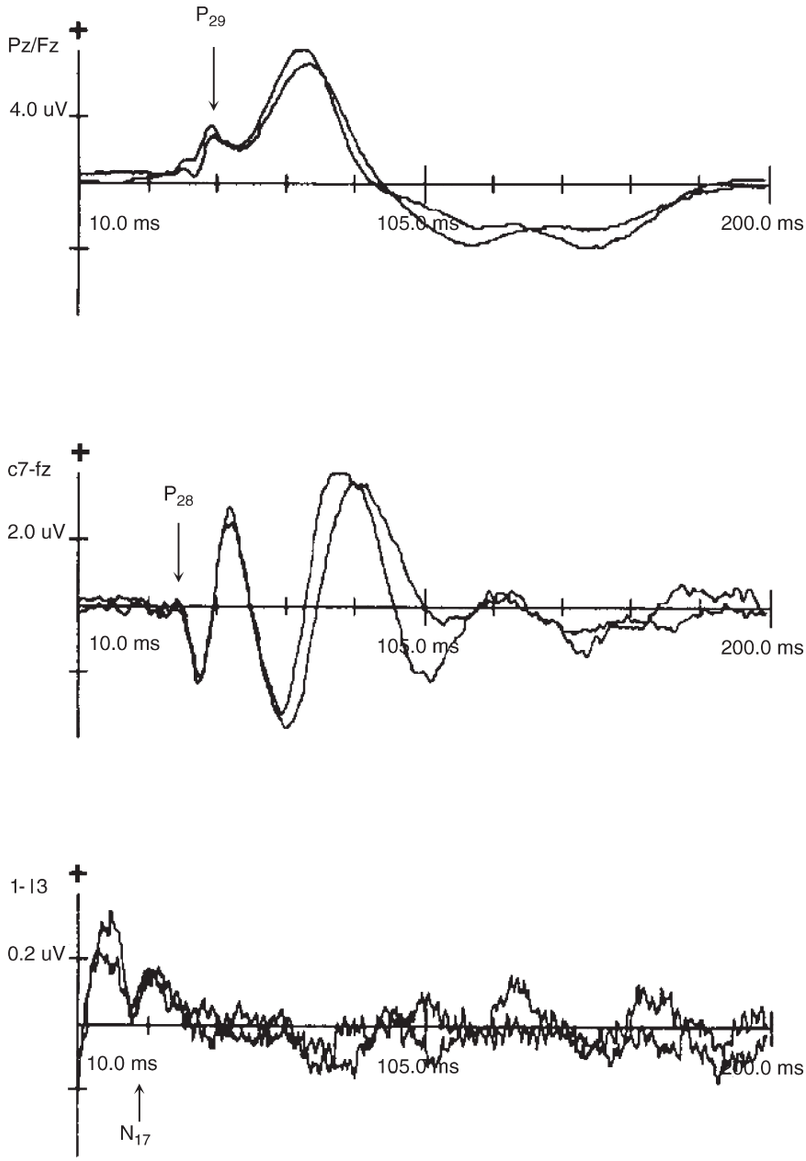

Figure 3–5 Posterior tibial nerve evoked potentials demonstrating components at different levels of the neuroaxis from the lumbar region bottom to the scalp top.

Thus considerable attention has been paid to developing robust and reliable methods for monitoring the more ventral corticospinal tracts.[47] Two methods briefly reviewed here are cerebellar and motor potentials (evoked EMGs).

Cerebellar Potentials (Ascending Activity)

In addition to the ascending dorsal columns and spinothalamic tracts and descending ventral motor tracts, several other ascending long tracts exist and are useful for IOM purposes. These pathways include the ventral and lateral spinocerebellar and cuneocerebellar tracts, which provide dense input to the cerebellum. Several studies have demonstrated that stimulation of the peripheral nerves commonly utilized to generate SEPs also generates a cerebellar evoked potential (CEP).[45] Moreover, animal models have demonstrated that the evoked potential recorded from the cerebellum is generated via ascending ventral spinal cord tracts.[44] Thus this stimulation and recording technique provides an assay of the ventral spinal cord utilizing conventional techniques developed for SEP monitoring. These responses may be obtained reliably and are reproducible from an additional electrode placed over the occiput and require the same anesthetic technique used to record SEPs.

Motor Evoked Potentials (Descending Activity)

Motor evoked potentials (MEP) have been under serious investigation in the IOM field for ~20 years.[47,66] In general, stimulation has involved either cortical or spinal cord sites. Noninvasive stimulation has been investigated using either electrical[63] or magnetic[9] stimulation of the motor cortex,[89]

indirect stimulation of the spinal cord via spinous processes,[79] or direct stimulation of the spinal cord[100] by placing subdural or epidural stimulation electrodes. Various responses are recorded distal to the operative site for these assorted stimulation techniques. **Fig. 3–6** summarizes both the stimulating and the recording techniques currently available.[105] Recording sites include (1) spinal cord evoked potentials (SCEPs) using transcutaneous or direct (epidural or subdural) recording electrodes; (2) direct (D) and indirect (I) waves from the spinal cord using epidural recording sites; (3) CNAPs, referred to as NMEPs in **Fig. 3–6** recorded from peripheral nerves using transcutaneous or subdermal needle electrodes; and (4) CMAPs from muscle groups of the upper and lower extremities using transcutaneous or subdermal needle electrodes. CMAPs are referred to as myogenic potentials, whereas CNAPS have been termed neurogenic responses (**Fig. 3–6**).

Transcranial Stimulation

The motor cerebral cortex or brain stem can be activated by either electrical or magnetic stimulation; however, only electrical stimulators are currently approved by the Food and Drug Administration (FDA) for transcranial stimulation. Scalp electrodes or electrode plates placed adjacent to the scalp or hard palate can be used to stimulate the cortex and underlying tissues. Stimulation voltages are typically in the range of 100 to 250 V. SCEPs have been observed with between 100 and 4000 stimuli being averaged. CMAPs obtained following transcranial stimulation do not require averaging and provide a rapid assessment of motor pathway function; however, these responses are very susceptible to anesthetic influence and have considerable intrinsic variability, making their interpretation difficult. CNAPs have been extremely unreliable, again due to anesthetic effects.

Transcranial electrical stimulation through the intact scalp has been shown to result in a charge density that might result in neuronal damage if applied directly to the cortex.[78] However, electrical stimuli are attenuated by a factor of 30 due to the high resistance of the intervening muscle, skull, and meninges. Thus the charge density at the surface of the brain with electrical stimulation is estimated to fall well within acceptable safe limits.[3] One of the most important stimulation parameters for eliciting reliable transcranial Motor evoked potentials (MEPs) is the interstimulus interval (ISI) of a burst of stimuli, applied at the above-referenced rate.[101] It has been found that bursts of stimuli with an ISI between 2 and 5 msec produce a maximal response by overcoming the depressant effects of general anesthesia.[50,52] The significant parameters and morphological fea- tures of CMAPs generated via transcranial stimulation are response threshold, onset latency, central conduction time, and response size[48] (**Fig. 3–7**).

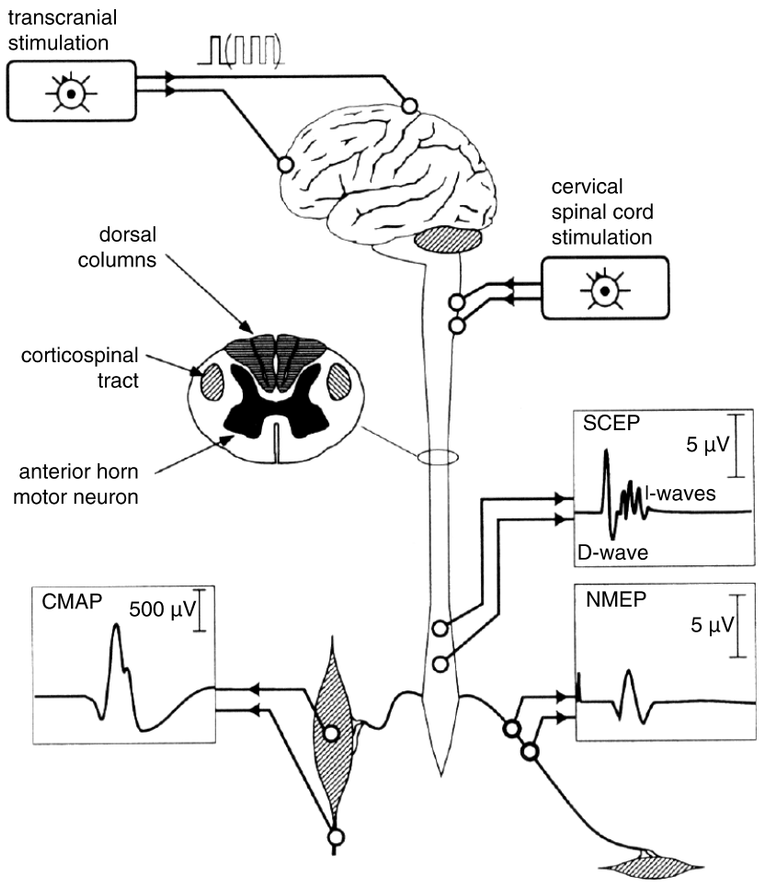

Figure 3–6 Various stimulating and recording sites for intraoperative motor evoked potential (MEP) monitoring. SCEPs are spinal cord evoked potentials. NMEPs are neurogenic motor evoked potentials, which are also referred to as compound nerve action potentials (CNAPs). CMAPs are compound muscle action potentials. (Printed with permission from Kalkman CJ, Ubags LH. Motor evoked potential monitoring. Current Opinion in Anaesthesiology 1997; 10:327–332.)

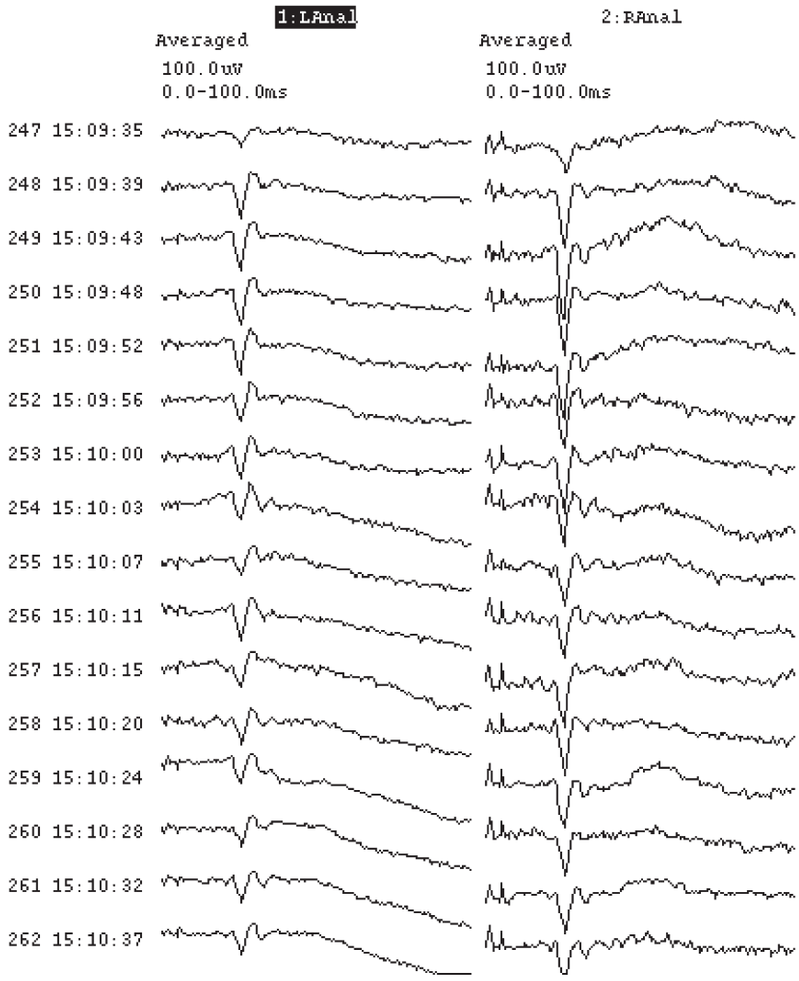

Figure 3–7 Compound muscle action potentials obtained by transcranial electrical stimulation during lumbosacral instrumentation from the external anal sphincter muscle.

Epidural spinal recordings of corticospinal tract activity following transcranial stimulation produce a complex of positive and negative components composed of I and D waves[48,,84] **(Fig. 3–8).**

Indirect Spinal Cord Stimulation

Indirect stimulation of the spinal cord through vertebral bone has been used to produce descending neural activity recorded peripherally from mixed nerves (CNAP).[80] The CNAPs are typically recorded at the popliteal fossa, with stimulation provided through a pair of electrodes positioned at adjacent spinal processes in the cervical region. Considerable controversy exists over the relative contribution of the sensory and motor pathways to these neurogenic spinal evoked potentials. Thus the term *descending neurogenic evoked potential (DNEP),* which describes the stimulation method and the direction of the neural volley along the spinal cord, but not necessarily its composition, has been adopted. Collision studies[56] have raised serious doubts about the independent utility of this method because both modalities (SEPs and DNEPs) appear to be primarily mediated by the same neural pathways, namely, the dorsal columns.[103] The consensus, based on these experiments, is that these responses are not a pure motor response but are largely composed of antidromic sensory activity and minimal orthodromic motor activity.[82]

Direct Cord Stimulation

Considerable work has been done with direct stimulation over the midline of the posterior, rostral spinal cord and recordings made either with epidural or subdural[30] strip electrodes or peripheral CMAPs.[74] Epidural SCEPs recorded from the midline of the posterior spinal cord produced by a descending spinal cord volley of action potentials can vary in morphology depending on both the stimulating and the recording sites. The dominant waves seem to be an initial negative spike (N_1) followed by a slow negative component (N_2). The conduction velocity of the N_1 component has varied greatly, ranging from 47 to 90 m/s, whereas the average conduction velocity of the N_2 component has ranged from 46 to 53 m/s.[56,63]

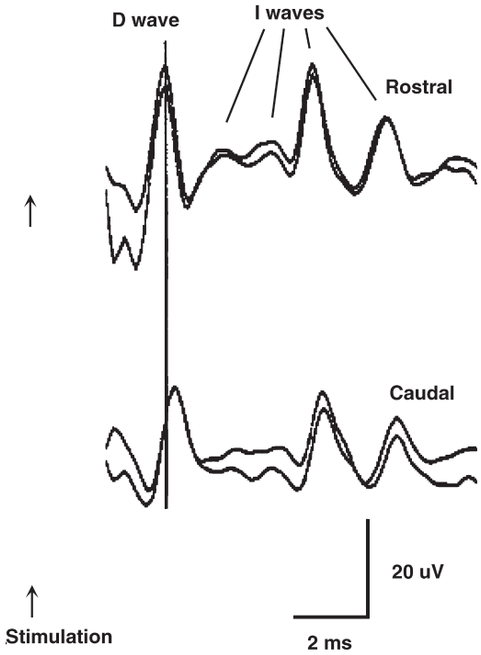

Figure 3–8 Typical direct (D) and indirect (I) waves recorded from the epidural space.

Spinal Cord and Peripheral Nerve Electromyography

The EMG, a useful indicator of the integrity of descending activity in the spinal cord, is electrical activity produced in muscle fibers below the skin and has a frequency content ranging from 15 to 150 Hz.[26] The EMG is either spontaneous (e.g., anal sphincter activity produced by irritation of the S_3 to S_5 roots during an untethering procedure involving the lower portion of the cauda equina) or evoked, of the type produced in selective rhyzotomy for the treatment of spasticity, for pedicle screw placement, or as already discussed for spinal cord evaluation. Evoked EMGs have a considerably larger amplitude ($\geq$ 100 μV) than sensory evoked potential data ($\geq$ 0.2 μV), and therefore these signals do not require averaging to extract them from the background noise.

Cranial Nerve Electromyography

Cranial nerve function is monitored continuously during many cases for two reasons: first, to identify the location and orientation of the cranial nerves in the operative field; and second, to preserve functioning in the cranial nerves and their related brain stem nuclei.[70]

The major observed variables are the EMGs recorded from the appropriate muscle group innervated by the cranial nerves of interest. The cranial nerves, along with the associated muscle groups, which are usually monitored using EMG techniques, are the facial nerve (VII) through the orbicularis oculi, orbicularis oris, and the mentalis muscles innervated by the zygomatic branch, the buccal branch, and the mandibular branch, respectively; the abducens nerve (VI) through the lateral rectus muscle; the trigeminal nerve (V) through the masseter muscle; the trochlear nerve (IV) from the superior oblique muscle; and the oculomotor nerve (III) through the medial and inferior rectus and the inferior oblique muscles of the eye. When appropriate, the functioning of the glossopharyngeal (IX), vagus (X), spinal accessory (XI), and hypoglossal (XII) cranial nerves is monitored by placing electrodes in the stylopharyngeus, cricothyroid, trapezius, and intrinsic muscles of the tongue, respectively. In general, the cranial nerves ipsilateral to the operative side are monitored; however, bilateral activity is monitored as necessary.

The amplifier band pass is set from 10 to 1000 Hz. The unstimulated EMG activity from multiple channels is monitored continuously throughout the case. Most importantly, the activity from all recorded muscle groups is made continuously audible. The audio system is of paramount importance in identifying the level of activity in the muscle groups. These signals are listened to continuously for evaluation of nerve function by both the neurophysiologists and the surgeons.

Four categories of EMG activity are observed: (1) no activity, which in an intact nerve is the best situation, but which also may be the case in a sharply dissected nerve; (2) irritation activity, which sounds like soft intermittent flutter and is consistent with working near the nerve; (3) injury activity, which sounds like a continuous, nonaccelerating tapping and can indicate permanent injury to the cranial nerve; and (4) a "killed-end" response, which sounds like an accelerating firing pattern and is an unequivocal indicator of nerve injury.[83] It is important to note that a sharply cut nerve may produce only a brief burst of activity; thus monitoring cannot be expected to replace extreme caution when working near the cranial nerves (**Fig. 3–9**).

In addition to monitoring the ongoing EMG activity, the various cranial nerves may be electrically stimulated. This is usually done to determine the location of the nerve in the operative field because many times the nerve is encased by tumor and may not be directly observable, or to determine the functional integrity of the nerve.[83] The most common example of this procedure is the direct stimulation of the seventh nerve. The stimulus utilized is a constant voltage, with a pulse frequency of 10 Hz and a pulse width of 100 µsecs. The voltage amplitude is typically varied between 0.1 and 1 V. In some situations, where very precise localization of the nerve is required, bipolar stimulating electrodes are utilized.[43]

Auditory Evoked Potentials (Brain Stem) and Direct Recording

Monitoring the function of the eighth cranial nerve is used to preserve hearing, locate the eighth nerve, and determine if the overall function of the brain stem is altered.

Brain Stem Auditory Evoked Potentials (BAEPs)

The classic BAEP consists of a minimum of five and a maximum of seven peaks. The first five peaks, Jewett waves I through V, are the principal peaks used in clinical practice. All occur within 10 msec of a brief click or tone presentation.

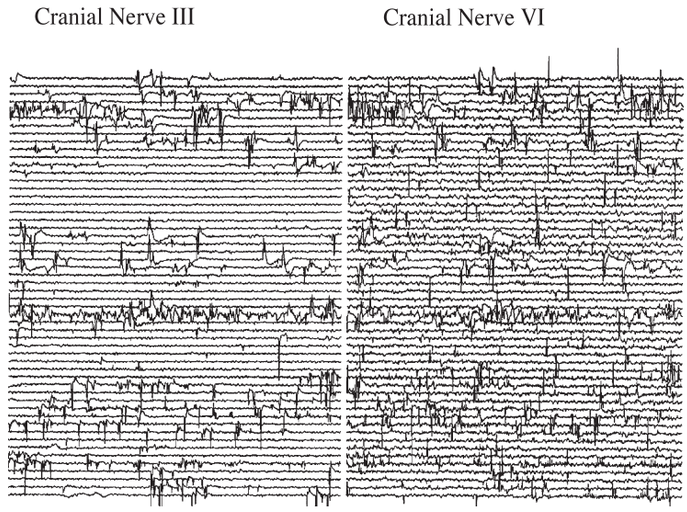

Figure 3–9 Spontaneous electromyographic recorded from the medial rectus and lateral rectus muscles of the eye, innervated by cranial nerves III and VI during resection of a cranial base tumor.

Wave I is generated in the cochlear portion of the eighth nerve. Its latency is ~1.5 to 2.1 msec in a normal adult. Wave I is present in recordings made on the ipsilateral side to the stimulus but is not usually seen on contralateral-side recordings. Wave II is generated bilaterally at or in the proximity of the cochlear nucleus. The latency between waves I and II is ~0.8 to 1.0 msec. The amplitude of wave II on the contralateral side may be greater than on the ipsilateral side. Wave III is generated bilaterally from the lower pons near the superior olive and trapezoid body. The latency between waves I and III is ~2.0 to 2.3 msec in a normal adult. Wave III may be smaller on the contralateral side than on the ipsilateral side. Waves IV and V are probably generated in the upper pons or lower midbrain, near the lateral lemniscus or possibly near the inferior colliculus.[17] In ipsilateral recordings waves IV and V may fuse into a complex that can vary between two identifiable components with a common base to a single wave with a tall, wide peak. On the contralateral side the peaks tend to be more easily identified. Wave V tends to be the most robust peak and is typically the last to disappear when stimulus intensity is reduced. In addition, there tends to be a large negative-going wave following wave V, which aids in its identification. Wave V, being the most robust is most closely followed during intraoperative procedures (**Fig. 3–10**).

The intensity level of the click is set to ~90 dB sound pressure level SPL. However, when the patient is known to have a hearing loss or a given patient's responses are not well

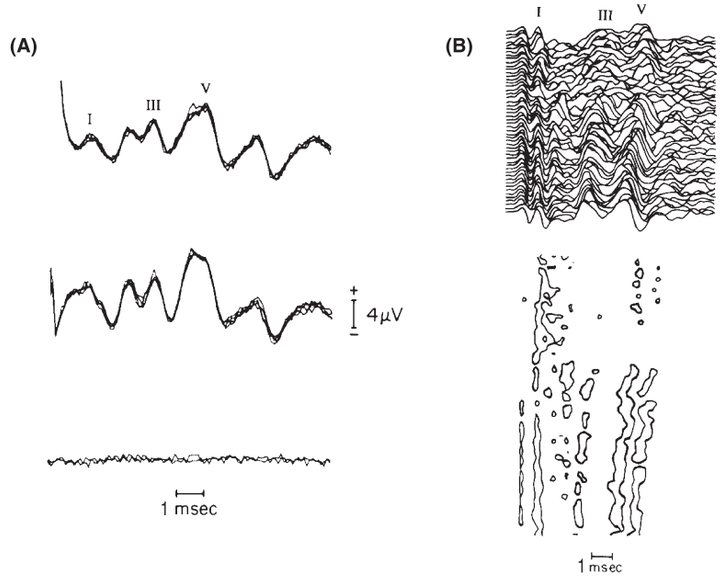

Figure 3–10 **(A)** Normal BAEPs and **(B)** BAEPs recorded during microvascular decompression for trigeminal neuralgia showing increase in latency as a function of retraction.

defined, higher intensity levels may be required. In such cases an intensity level of 95 dB SPL is typical. Rarefaction and compression clicks are applied in an alternating fashion to minimize apparent stimulus artifact. The stimulus rate is usually set between 9.3 and 19.3 Hz because of the well-known effects of higher stimulus rates on response latencies.[107]

Baseline responses for each ear are acquired prior to the beginning of surgery. These data are compared with the preoperative evaluation and used as baselines throughout the case.

Waves I to V are relatively resistant to sedative medication and general anesthetics. Thus BAEP recording places no constraints on the anesthesiologist. However, they are sensitive to temperature changes, with absolute and interpeak latencies increasing by ~0.20 msec/°C.

The latency of wave V is the primary concern in IOM of the BAPs because this is the most robust and easily identifiable of the waves. Latency shifts of greater than 0.3 msec are reported to the surgeon. However, clear changes in the wave morphology, even with latency shifts less than 0.3 msec, are reported. The next average is recorded as soon as possible to confirm the presence of a significant change. In cases where potentials are completely lost, the neurophysiologist reports the loss and then immediately checks to ensure that both the stimulating system and the recording electrodes are functioning properly.

Auditory Nerve Compound Action Potentials (Direct Recording)

CNAPs may be recorded directly from the cochlear portion of the eighth cranial nerve ($CNAP_a$).[72] To accomplish this recording, the intracranial portion of the eighth nerve must be exposed during the operation. The eighth nerve is composed of the vestibular and cochlear divisions. Near the brain stem the cochlear division is located on the caudal side of the eighth nerve and is anterioventral to the eighth nerve near the porus acusticus. Moller and Jannetta[68] reported a technique for recording the $CNAP_a$ by placing a recording electrode on the exposed eighth nerve. They recommended that the electrode be made of fine, malleable, multistrand, Teflon-insulated silver wire with a cotton wick sutured to the wire.

The recording electrode need not be placed directly on the cochlear portion of the nerve to record $CNAP_a$. The amplitude of the recorded potentials is largest, however, when the recording electrode is placed on the cochlear division. Even when placed on the vestibular portion of the eighth nerve the amplitude of the potentials is normally several microvolts. The $CNAP_a$ recorded in a patient with normal hearing appears as the triphasic waveform previously described. This recording technique provides the capability to detect changes in neural conduction almost instantaneously on the basis of recording click-evoked CNAP and can be valuable in patients with preexisting hearing loss and, as a consequence, poor BAP recordings.

Visual Evoked Potentials

VEPs are used to aid in determining the functional integrity of the visual system, primarily in the region of the optic nerves, chiasm, and optic radiations.[1] The recorded activity is generated either at the retina (electroretinogram) or at the occipital cortex.

Except in selected situations, stimulation of the visual system using a bright flash is not recommended for diagnostic purposes due to intersubject variability;[22] however, in the operating room this is a very helpful and effective technique. Four waves are typically seen in the VEP: P_{60}, which is thought to be generated in subcortical structures; and N_{70}, P_{100}, and N_{120}, which are all thought to be generated in the primary visual cortex.[55]

Peripheral Nerve Compound Action Potentials

The recording of CNAPs from the peripheral nerve, evoked by supramaximal stimulation, provides a measure of the functional integrity of the nerve and may be thought of as a physiological biopsy of the nerve. Pathophysiological mechanisms produce reductions in conduction velocities, desynchronization of CNAPs and CMAPs, and complete conduction block.

Measurements of this type are used to protect a particular peripheral nerve from damage during surgical repair of some other structure and to aid the surgeon in determining the correct approach to repairing a damaged peripheral nerve[34] (e.g., repair of a neuroma-in-continuity by neurolysis or anastomosis). CNAP recording is useful because the amplitude of the CNAP is approximately correlated with the number of moderately sized early myelinating fibers present in the recovering nerve. The presence of these fibers in a recovering nerve indicates that neurolysis alone will be effective, as opposed to resection and repair, in reestablishing useful distal function.[102] The appearance of a CNAP in a damaged nerve precedes the reinnervation of the muscle and is therefore detectable considerably earlier than EMG evidence of reinnervation and even longer before clinical recovery. The absence of a CNAP 3 to 4 months after injury demonstrates failed regeneration and allows for repair to be undertaken at a time when denervated muscle is still receptive to returning axons.

The major focus of CNAP recording is the presence or absence of a CNAP across a segment of the damaged nerve. When a CNAP is present, the surgeon may stop with neurolysis and be assured that the damaged nerve will likely recover to a reasonable degree. When the CNAP is absent, the surgeon must be prepared to resect and repair the damaged section of peripheral nerve (**Fig. 3–11**).

Other Monitoring Modalities

Oximetry

The use of near infrared spectroscopy (NIRS) to measure cerebral oxygenation is a developing field.[18] The systems that are currently available are based on reflectance spectrophotometry.[6] These devices provide a very localized regional oxygen saturation index (rSO_2) or relative hemoglobin oxygen, deoxyhemoglobin, total hemoglobin, and cytochrome oxidase, and a total oxygen index. The difficulties with this technique pertain to the fact that the distance between where the light enters the tissue and the point of detection is unknown and variable depending on the degree

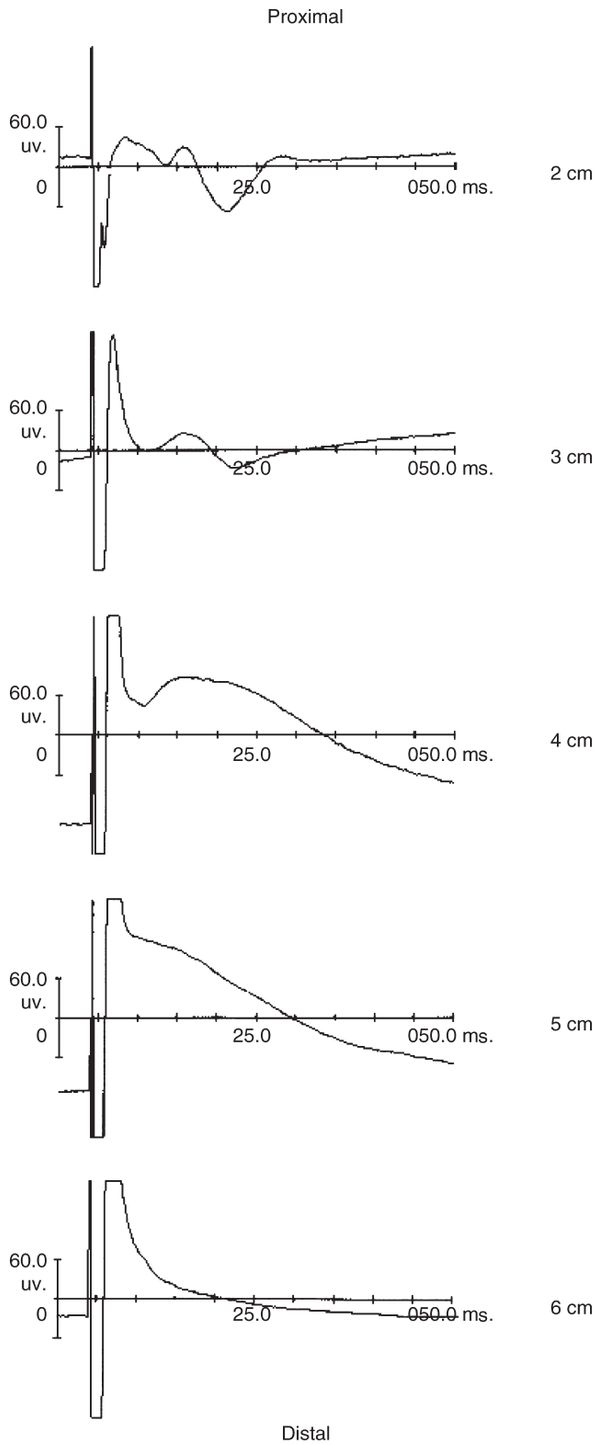

Figure 3–11 Compound nerve action potentials recorded above and below a neuroma-in-continuity, suggesting that an anastomosis was the appropriate treatment.

of light scattering and on the amount of absorbing material in the tissue.

All calibrations must be tested on the basis of jugular venous and arterial blood oxygen saturation. Studies have examined the relationship between regional oxygen saturation of hemoglobin and jugular venous saturation.[16] The cerebral oximeter was less accurate and precise and also demonstrated a systematic error in bias unrelated to cerebral perfusion pressure. Comparisons have been made between MSPs and cerebral oximetry during carotid endartectomy.[21] This technology will play an important role in IOM as it develops further.

Transcranial Doppler

Transcranial Doppler (TCD) sonography has proven to be a safe and reliable intraoperative tool for measuring blood flow velocities within the major vessels of the cerebrovasculature. Pulses of ultrasound, delivered at frequencies of 2 MHz, are directed using a probe that can either be handheld or fastened securely with a head holder. The pulses are directed toward the major vessels at the base of the skull through various bony windows located on the skull.

The frequency shift, or Doppler effect, in the reflected sound indicates the velocity of the reflecting substance within the artery. Images can then be rendered from the time-dependent intensity of the reflected sound.

TCD sonography has been used extensively during carotid endarterectomy for both the detection of changes in blood flow velocity during cross-clamping of the internal carotid artery and detection of embolus during dissection, shunt placement, and reopening of the carotid artery. Blood flow velocities can also be useful as a measure of a lack of autoregulation after the artery has been cleared of debris. The lack of autoregulation is revealed as a sustained increase in velocity, which presumably is an indication of a hyperemic blood flow state.

Microvasculature Doppler

Microvasculature Doppler sonography has also proven to be an invaluable tool during various neurosurgical procedures. A sterile handheld 20 mHz, 1 mm pulsed Doppler may be employed to insonate arterial vasculature directly within the surgical site. The Doppler is placed either directly on the vessel or on a vessel that may be encased in either bone or tumor. The Doppler probe is able to insonate at various depths beginning at 1 mm. The depth of insonation can be advanced in 1 mm steps up to 10 mm.

Microvasculature Doppler sonography has been used extensively during aneurysm surgery, providing real-time assessment of vasculature patency after aneurysm clipping[5,57,97] and thus preventing permanent ischemic damage. Microvasculature Doppler sonography during aneurysm surgery utilizes direct insonation of exposed vasculature and feedback concerning patency of parent and daughter vessels as well as information regarding the successful obliteration of the aneurysm itself. Several reports have demonstrated either or both the readjustment and the replacement of aneurysm clips based on feedback provided by the handheld Doppler.[5]

Microvasculature Doppler sonography can also be utilized during skull base procedures for the identification of critical vasculature in either tumor or bony dissection. In contrast to aneurysm surgery, microvascular Doppler sonography during skull base procedures utilizes insonation of vasculature through bony structures or intracerebral masses, that is, when the vessels are not visible to the surgeon. It has been reported that intraoperative Doppler sonography is an effective means by which to locate and identify critical vascular structures during skull base tumor resection.[7] The identification of this vasculature allows for the successful approach and resection of intracerebral masses in a situation where simple visual identification is not possible. Doppler sonography also allows for confirmation of vascular patency after exposure of the vasculature in question and serves as a valuable adjuvant to other forms of IOM known to improve outcome during skull base procedures.

◆ Neurosurgical Procedures

Cortical Localization

The surgical resection of cerebral cortex is often limited by neighboring regions of essential functional cortex. There is a high degree of individual variability with respect to cortical topography and functional localization.[77] Intraoperative brain-mapping techniques have been used to localize language cortex, sensorimotor pathways, and seizure foci. Methods of direct cortical recording and stimulation as well as subcortical stimulation enable maximum tumor resection and minimal morbidity.

Phase Reversal

MSPs recorded from the cortex are similar in appearance to the data previously presented. P_{15} is approximately equally distributed over the entire scalp because it is generated in the subcortical structure. N_{20} and P_{30} have extensive distribution over the scalp with a maximum over the parietal area contralateral to the stimulus and phase reversal across the central sulcus. MSPs are easily recorded directly from the human cortex, using surface point contact electrodes due to their large amplitude, and in contrast to their widespread scalp distribution, N_{20} and P_{30} are highly localized to the immediate rolandic-perirolandic area in direct recordings. Thus three characteristics make MSPs ideally suitable for functional localization studies: (1) localization close to the rolandic fissure, (2) their large amplitude in this location, and (3) the amplitude reversal of N_{20} and P_{30} across the rolandic fissure (**Fig. 3–12**).

Evoked potentials from the scalp either from a parietal electrode or from an electrode placed between the contralateral parietal and central position and are used to compare the polarity of corresponding peaks recorded from scalp and subdural electrodes. The cortical electrodes are positoned prerolandic when the peaks recorded from the cortex are phase reversed with respect to the parietal scalp electrodes. If the peaks are in phase, the electrodes are postrolandic.[61] All somatosensory evoked responses produce results; however, the best results are obtained with the MSPs.

Cortical Stimulation

We have found the techniques described by Berger at al,[15] with slight modification, to be very effective. Simultaneous electrocorticography (ECoG) is performed to monitor for after-potential discharge indicating that the direct stimulation is too intense and should be reduced to avoid the induction of seizure activity. Patients under general anesthesia remain unparalyzed until the motor mapping is completed.

Direct application of current to the sensory cortex may elicit paresthesias in the appropriate somatic area in awake patients, especially when the face and hand areas are

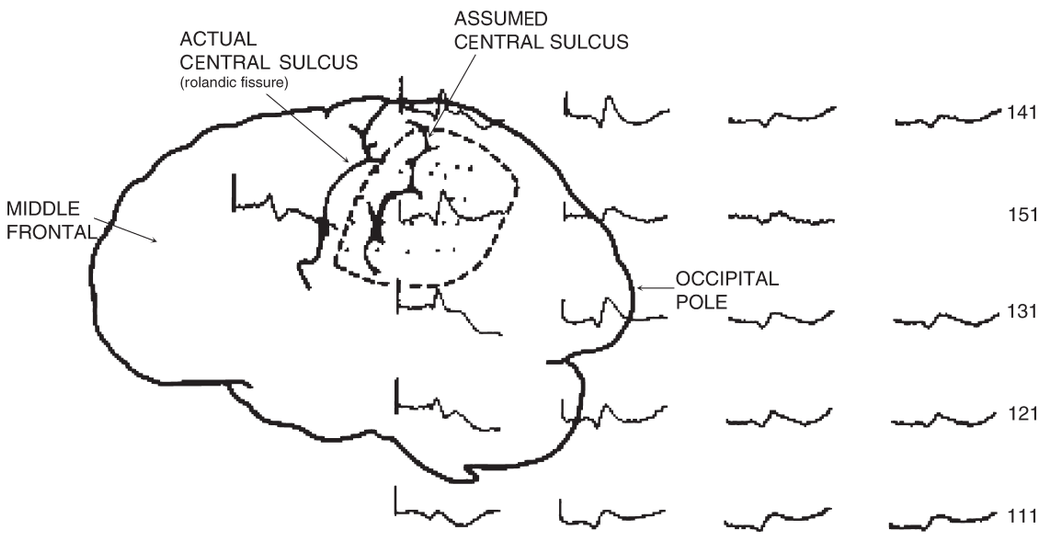

Figure 3–12 Median nerve evoked potentials phase reversal across the central sulcus allowing localization of motor and sensory strips.

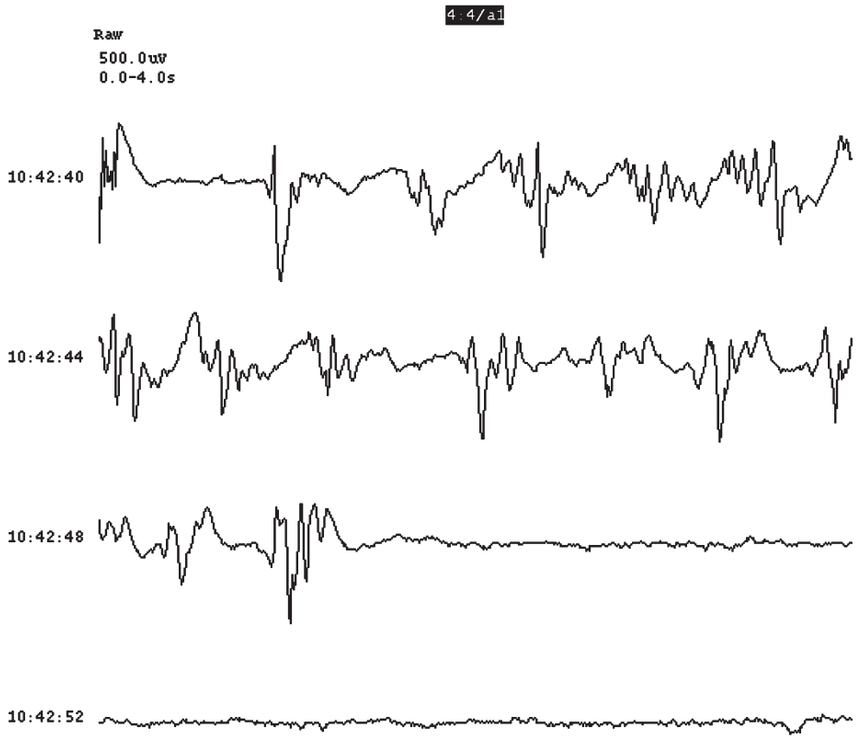

Figure 3–13 Seizure activity induced by prior direct cortical stimulation, which is turned off at the beginning of the top trace. In this situation the afterdischarge lasted for ~10 seconds.

stimulated. Language mapping is performed using the maximal current that does not evoke afterdischarges yet is effective in altering language function. Patients are asked to repeat standard phrases and name standard objects during the stimulation. Repeated instances of speech arrest or anomia accompanying stimulation are the end points used to determine language localization.

Focal seizure activity may occur with increasing current intensity during any of these testing procedures and is detected by the simultaneous ECoG. If this activity does not cease spontaneously within 10 to 30 seconds, intravenous Valium or a short-acting barbiturate should be given. Cold saline applied to the cortex will also suppress seizure activity and has the advantage of not interfering with further recording (**Fig. 3–13**).

◆ Vascular Procedures

The functioning of the cerebral cortex is extremely sensitive to changes in arterial oxygenation, cerebral blood flow, or partial pressure of oxygen. This sensitivity is rapidly reflected by changes in EEG,[67] SEPs, and cerebral oximetry. Some factors that may contribute to ischemic events are decreased oxygen-carrying capacity due to hypovolemia or decreased cerebral perfusion pressure due to factors associated with decreased systemic arterial pressure, increased intracranial pressure, or mechanical obstruction of cerebral vessels.[33]

Critical information is gained from monitoring the EEG and SEPs (both median nerve and tibial or peroneal nerve). Changes in observed activity may be due to retraction, brain stem compression, or impairment of blood flow to cortical and subcortical structures. Cortical activity also guides the surgeon regarding the adequacy of collateral flow when hypotension, intentional temporary occlusion, or cerebrovascular bypass is necessary for treatment of vascular anomalies. In addition, functional information may be obtained prior to the removal of cortical tumors.

For cortical responses, the amplitude and latency of the N_{20}/P_{30} complex are of primary concern. In general, a decrease of more than 50% in amplitude or an increase of more than 10% in latency is communicated to the surgeon. Another average is obtained as soon as possible to confirm the stability or persistence of the response change. The neurophysiologist consults with the anesthesiologist to determine if a change in blood pressure, level of anesthesia, or type of anesthesia could have contributed to the observed variations in either or both the amplitude and the latency of the evoked potential.

Intracranial Aneurysms

Cerebral aneurysm obliteration carries risks associated with cerebral ischemia secondary to occlusion of parent and perforating arteries, cerebral vasospasm, as well as embolic events associated with vessel manipulation and clip application.

To reduce ischemic insult, multimodality IOM has been successfully implemented and shown to be a useful adjunct during these procedures.[60] The evoked potential modalities recorded during aneurysm clipping will be dictated by the location of the lesion. For posterior circulation aneurysms, both BAPs and SEPs should be recorded simultaneously. These modalities will provide physiological feedback concerning the integrity of several different brain stem pathways as well as provide information concerning the integrity of the somatosensory cerebral cortices. For anterior circulation aneurysms, SEP recording in response to median nerve and tibial nerve stimulation is essential. These modalities provide information about the normal functioning of both midline and lateral somatosensory cortical function secondary to potential disruptions in blood flow during the procedure. In addition to evoked potential monitoring, bihemispheric EEG should be recorded during these procedures.[81]

Endovascular Treatment of Intracranial Aneurysms

IOM has been useful in the surgical treatment of intracranial aneurysms, and this usefulness has carried over to the endovascular treatment of intracranial aneurysms.[8] MSPs, tibial nerve evoked potentials (TSPs), BAPs, and EEGs have been recorded in 43 consecutive patients undergoing Guglielmi detachable coiling (GDC) of anterior and posterior circulation cerebral aneurysms using methods already described. Thirty-one procedures (72.1%) had no neurophysiological changes during the procedure. Twelve procedures (27.9%) were observed to have significant alterations in monitored parameters. All 12 of these procedures involved coiling of the anterior circulation aneurysms. No posterior circulation aneurysm embolizations ($N = 14$) have been associated with BAP changes. Of those with significant changes, nine (20.9%) were transient, whereas three (7.0%) persisted throughout the procedure. No significant change in baseline neurological status was observed in 39 (90.6%) patients. Transient neurological change, as defined by a return to baseline within 2 months of the procedure, was observed in three (6.9%), and one (2.3%) patient experienced a persistent neurological deficit (**Fig. 3–14**).

Carotid Endarterectomies

The majority of patients with either asymptomatic or symptomatic carotid artery stenosis undergo carotid endarterectomy (CEA) under general anesthesia with and without mandatory intraluminal bypass shunting of carotid artery blood flow and using IOM to determine the need for selective use of intraluminal carotid shunts. The latter option makes no assumption of the patient's ability to tolerate cerebral hypoperfusion. Instead, IOM can be used to evaluate the patient for cerebral ischemia and to identify those patients that do not have adequate collateral cerebral perfusion and require supplemental perfusion through use of a carotid artery shunt. Using IOM in carotid endarterectomy

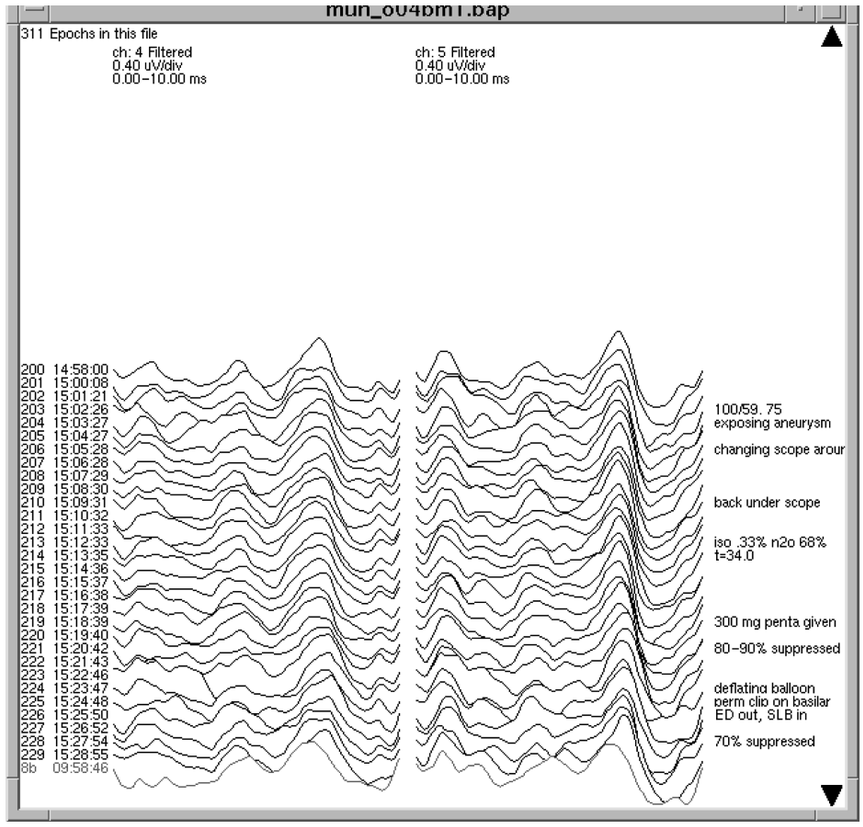

Figure 3–14 Bilateral BAEPs during clipping of basilar tip aneurysm.

reduces the frequency of shunt placement, which has been associated with iatrogenic injury.[46,99] In addition, IOM allows the blood flow through carotid shunts to be evaluated for adequacy during carotid endarterectomy and is also sensitive to intraoperative thromboembolic events.[12]

Pallidotomy and Deep Brain Stimulation

In pallidotomy, the goal is to place large, destructive radiofrequency, thermal lesions within as much of the internal segment of the globus pallidus as possible without causing iatrogenic injury to adjacent structures, specifically the internal capsule and the optic tract. Although the lesion-making electrode is placed under stereotactic guidance, even small deviations in the final electrode tip position can result in misplaced lesions with devastating consequences to the patient. Because of this, small, reversible test lesions are made that are evaluated in two ways. Because the patient is awake, the integrity of the internal capsule can be continuously examined by having the patient follow commands to make arm, leg, or facial movements. Having the patient repeat complex sentences can assess dysarthric speech. The optic tract can be continuously evaluated electrophysiologically with use of flash visual evoked potentials (FEP). Typically the large P100 cortical response is monitored before, during, and after test lesions, and changes in either or both the FVP and voluntary motor commands are used to change the electrode tip location until there is a return to baseline behavioral and electrophysiological values. A permanent lesion is then placed.

IOM would be an important adjunct to the procedure to confirm the electrode tip has not strayed off target. To ensure proper electrode placement and to minimize morbidity, MSP, MEP, and FVP tests may be utilized. In addition, more advanced IOM methods such as recording from single neurons to identify gross firing patterns of cell groups may be necessary to determine where the electrode tip is, given the small cell volume of structures such as the subthalamic nucleus.

◆ Microvascular Decompression Procedures

IOM has been a significant factor in reducing the incidence of hearing loss in microvascular decompression (MVD) operations.[69] In neurovascular compression syndromes (of cranial nerves V, VII, VIII, IX, X, and XI and the lateral medulla), we routinely monitor BAEPs and appropriate cranial nerve EMGs. The eighth cranial nerve is more sensitive to mechanical manipulation than other cranial nerves of the cerebellopontine angle, and monitoring BAPs has proven to be important in reducing risks of hearing loss by detecting changes in neural conduction in the auditory nerve. It has been shown that changes in the BAP caused by retraction could be reversed by releasing the retraction, resulting in preservation of hearing. It has been our experience in MVD procedures that an increase in the wave V latency of greater than 1.5 msec and a decrease in wave V amplitude of greater than 50% at least three times in a single operation significantly increases the risk of ipsilateral hearing loss to greater than 10%.[53]

Trigeminal Neuralgia

Trigeminal neuralgia (TN) is thought to be due to ephaptic transmission in the trigeminal nerve between large-diameter myelinated A-fibers and poorly myelinated A-delta and C (nociceptive) fibers. Vascular compression of the trigeminal nerve occurs most commonly at the root entry zone by the superior cerebellar artery. Monitoring a CN V MVD procedure requires only the use of BAPs, although monitoring fifth nerve EMG during reexploration procedures is worthwhile using subdermal electrodes over the masseter muscle. Via the retromastoid approach, cerebellar retraction is adjusted or eliminated if the latency of wave V changes more than 1.0 msec[32]; however, latency shifts greater than 0.3 msec are noted. Failure to respond to such changes could result in iatrogenic injury, causing, for example, loss of hearing. In one series of over 3000 patients, 75% were pain free at 15 years with an incidence of hearing loss of just over 0.5%[11] (**Fig. 3–10**).

Two patients of 300 having an MVD for TN over a recent 12-month period have had their BAPs disappear completely during dural closure. The CP angle was immediately reexplored, and a prominent vascular compression of the cochlear nerve was observed. MVD of this nerve was then performed with an immediate restoration of the BAPs.[109]

Hemifacial Spasm

Hemifacial spasm (HFS) is thought to be due to either ephaptic transmission[90] or hypersensitization of the facial nucleus.[31] The pathogenesis is from vascular compression of the facial nerve at the root entry zone most commonly by the posterior inferior cerebellar artery. Facial nerve EMGs in patients with HFS are notable for "lateral spread," or the abnormal dispersion of action potentials through branches of CN VII. Successful treatment of HFS may depend on the elimination of lateral spread with removal of an offending vessel from the root entry zone of CN VII.[10] This is confirmed intraoperatively with facial nerve EMG produced by stimulating the zygomatic branch of CN VII and recording a direct evoked EMG from the orbicularis oculi and an abnormal indirect evoked EMG from the mentalis muscle.[71] In this operation the disappearance of the abnormal indirect evoked EMG is used to determine the end point of the decompression, as opposed to its use in other operative procedures where the EMG activity serves either a warning or identifying function. In a series of 684 patients, 84% were spasm free after 10 years.[10] In this series 2.6% had an ipsilateral deaf ear, and 0.9% had severe facial weakness (**Fig. 3–15**).

We have also noticed in a series of 67 patients having MVD for HFS that, of 46 (69%) who had multiple previous Botox injections, six (13%) were surgical failures, whereas all 21 Botox-naive patients had complete or dramatic improvement. All the failed Botox patients had a nonclassical lateral spread (indirect response).[53]

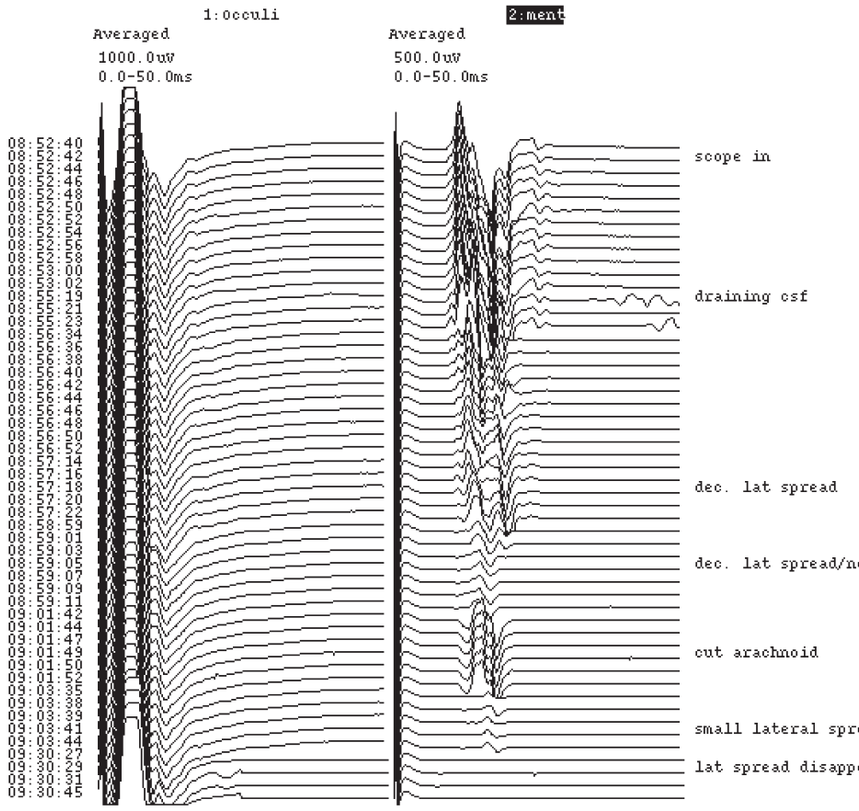

Figure 3–15 Lateral spread serving as an end point for surgical decompression. These data were recorded from a 59-year-old female with left hemifacial spasm. The direct responses are shown in the left column, and the indirect responses are shown in the right column.

Cranial Base Procedures

Neurophysiological monitoring during cranial base procedures can rapidly become quite complex. It is not unusual to monitor as many as nine different neurophysiological variables simultaneously; for example, EEG, BAPs and BSEP, SEPs, and EMGs relating to five cranial nerves (III, IV, V, VI, and VII). The major risks in these procedures are due to problems associated with maintaining adequate blood supply to the brain stem and cerebral hemispheres and to the effect of various operative manipulations aimed at adequately exposing the tumor and removing it.

In removing tumors from the cavernous sinus, clival region, fourth ventricle, or posterior fossa or within the cerebellopontine angle, appropriate cranial nerve EMG recording is critical.[94]

Acoustic Neuromas

From an IOM perspective, one must first determine whether the patient has useful hearing prior to surgery. This is best accomplished via an audiogram and baseline BAEP testing. If the patient does have useful hearing and a reasonable BAEP tracing is obtained, then a hearing preservation approach to the tumor may be chosen (middle fossa, retrosigmoid).[13] As with other IOM strategies employed with procedures involving masses of the posterior fossa, a multimodality approach is utilized. BAEPs should be recorded in response to auditory stimulation delivered to the ipsilateral ear. It has also been shown that compound nerve action potentials recorded directly from the eighth nerve can assist in hearing preservation during these procedures.[23] Additionally, facial nerve free-running EMG should be continuously recorded from the orbicularis oculi, orbicularis oris, and mentalis muscle groups and made audible to the surgeon.[88]

Evoked facial nerve EMG activity should also be elicited via monopolar stimulation to map the course of the seventh nerve through the cerebellopontine angle. This is vital in attaining a favorable outcome with regard to facial nerve function.[38] In larger tumors (and in those patients without useful hearing), it is useful to record BAPs in response to stimulation of the contralateral ear as a measure of brain stem function. It is also essential to measure brain stem function via MSP recordings in response to median nerve stimulation in cases where large tumors cause significant brain stem displacement. Additional cranial nerves should also be monitored in larger lesions. The fifth cranial nerve, which is usually adjacent to the rostral border of the tumor, can be monitored via EMG recording from the messeter muscle and the ninth and tenth cranial nerves, which are usually adjacent to the caudal tumor edge and can be monitored via recording from the soft palate and vocal cords. Overall, IOM techniques for acoustic neuroma surgery can be very challenging and complicated; constant vigilance on the part of the neurophysiologist and interaction with the surgeon are necessary (**Fig. 3–16**).

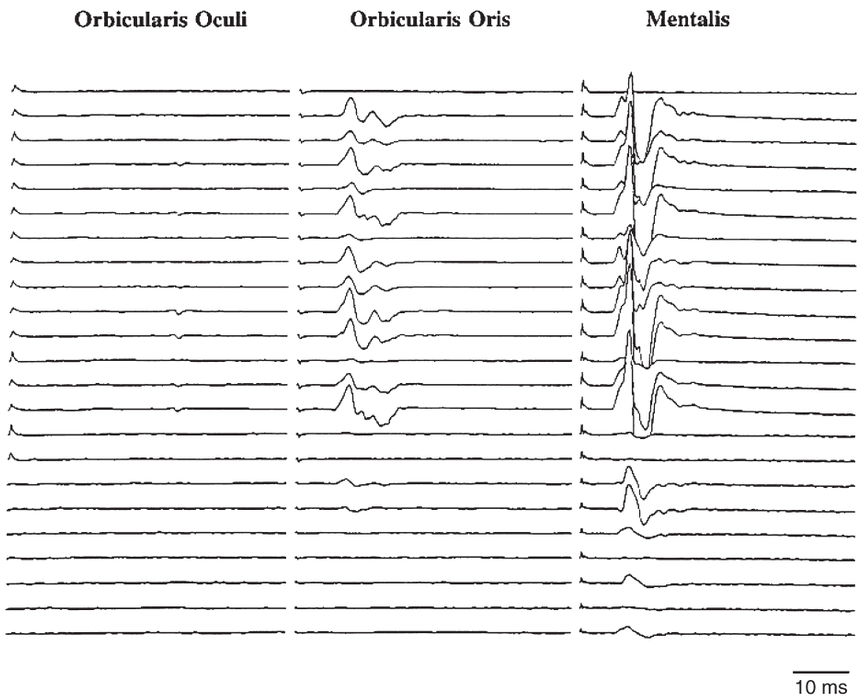

Figure 3–16 Compound muscle action potentials obtained from stimulation of CN VII during removal of an acoustic neuroma.

Mapping the Floor of the IV Ventricles

In the normal posterior fossa, the motor nuclei of the cranial nerves are located on the floor of the fourth ventricle relative to various anatomical landmarks. In cases where pathology is present, these normal landmarks can be distorted and, as a consequence, may not be identified. In persons with fourth ventricular brain stem masses that are adherent to or growing from the floor of the fourth ventricle or in pathologies that are intrinsic to the brain stem (e.g., cavernoma), techniques have been developed that allow identification of motor nuclei using direct electrical stimulation. The facial colliculus and the motor nuclei of CN IX/X and XII can be located,[73,98] and decisions concerning further tumor dissection or brain stem myelotomy can be made. Procedurally, different points along the floor of the fourth ventricle are stimulated with a monopolar or bipolar probe, and EMG responses are recorded from various muscle groups, including the orbicularis oculi, orbicularis oris, mentalis, soft palate, and intrinsic muscles of the tongue. Once the extent and borders of the nuclei have been identified, the surgeon can proceed.

Posterior Fossa Procedures

Intra-axial posterior fossa tumors can be of a wide variety, occurring in both adults and children. Whatever the age or tumor type, a multimodality approach to IOM is preferred when the surgical procedure involves the posterior fossa.[20] Specifically, with tumors filling the fourth ventricle, BAEP and SEP recordings are essential. SEP recordings should be made in response to at least median nerve stimulation, and care should be taken to record a subcortical brain stem potential in addition to cortical recordings during these procedures. The BAEP should be recorded in response to either right or left ear stimulation, although if the tumor is eccentric to one side, the ipsilateral ear should be stimulated. In addition to evoked potential monitoring, multiple bilateral cranial nerve EMG recordings should be obtained during these procedures.[64]

◆ Discussion

The commonly accepted goal of IOM is to prevent morbidity; however, the more fundamental goal is to provide information that allows the surgeon to accomplish the desired operative objective with as little morbidity as possible. This requires rapid and reliable interpretation of the data under sometimes suboptimal circumstances, and excellent communication between the surgeon and the neurophysiologist.

Several general rules have been found to be useful in our experience. We consider all increases in latency from baseline, for early and middle latency components ($<$ 50 msec), of 10% to be significant. We also consider all amplitude reductions greater than 50% from baseline to be significant, requiring the immediate attention of the surgical team. Finally, we consider the degree of variability in the responses to be highly correlated with the degree of pathology. For example, a normal spinal cord will produce very consistent and nonvariable responses, but a spinal cord with a significant lesion will produce highly variable responses. And most importantly, responses that are highly stable at the beginning of a

case but start to demonstrate increasing variability in either amplitude or latency are indicative of a potentially developing lesion.

The issue of cost benefits of monitoring has only been addressed partially and incompletely in the literature. In one paper[14] the financial records of 193 patients were evaluated for monitoring during cranial base surgery. In this series, the average cost of monitoring was $555 per case, whereas the estimated cost of the additional hospital stay for a patient with a major preventable deficit was $52,500. In this series there were 47 patients with significant monitoring changes that were acted on and who demonstrated no postoperative deficits. If deficits were prevented in only three of these patients because of monitoring, then IOM is cost-effective.

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