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INTRAOPERATIVE MONITORING USING SOMATOSENSORY EVOKED POTENTIALS

A POSITION STATEMENT BY THE AMERICAN SOCIETY OF NEUROPHYSIOLOGICAL MONITORING

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ABSTRACT. Objective: To provide an educational service to the intraoperative neurophysiologist community by publishing a position statement by the American Society of Neurophysiological Monitoring on the recommended appropriate and correct use of somatosensory evoked potentials as an intraoperative neurophysiological monitoring tool to protect patient well-being during surgery. This position statement presents the somatosensory evoked potential utilization basis, relevant anatomy, patient preparation, important systemic factors, anesthesia considerations, safety and technical considerations, documentation requirements, neurophysiologist credentials and staffing practice patterns, and monitoring applications for protecting brain, spinal nerve root, peripheral nerve, plexus and spinal cord function. In conclusion, a summary of major recommendations regarding the use of somatosensory evoked potentials in intraoperative neurophysiological monitoring is presented.

KEY WORDS. somatosensory evoked potentials, SSEP, neurophysiological monitoring, ASNM, SSEP Position Statement, intraoperative monitoring applications

1. INTRODUCTION

As early as the mid-1960's, Larson and Sances [1] reported on the utilization of somatosensory evoked potentials (SSEPs) as a monitoring tool during neurosurgical procedures. Later, McCallum and Bennett [2] and Nash et al. [3] reported on their utilization during spinal surgery. The purpose for their utilization was to act as a supplement to the use of the wake-up test and to provide warning in the case of compromised spinal cord function. Among evoked potentials, SSEPs are the most widely-utilized monitoring modality. They are routinely used during various surgical procedures when spine, brain, or peripheral nerve function is placed at risk. Several guidelines have been developed for their utilization and interpretation [4–9].

In 1987, the American Electroencephalographic Society (now the American Clinical Neurophysiology Society (ACNS)) published the first of these guidelines [4]. In 1994, these were revised [5]. Other guidelines and policy and position statements include those of the International Federation of Clinical Neurophysiology (IFCN) (1993) [9], the American Society of Electroneurodiagnostic Technologists (ASET) (1998) [6], and the International Organization of Societies for Electrophysiological Technology (OSET) (1999) [8].

This document presents the American Society of Neurophysiological Monitoring (ASNM) position statement

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regarding the utilization of SSEPs for intraoperative monitoring purposes. This statement is based on information presented at scientific meetings, published in the current scientific and clinical literature, and presented in previously-published guidelines and position statements of various clinical societies. This document may not include all possible methodologies and interpretive criteria, nor is it intended to exclude any new alternatives. Furthermore, ASNM recognizes these guidelines as an educational service.

2. SSEP ACQUISITION

2.1. *Basis for utilization*

Somatosensory evoked potentials have been utilized as an intraoperative monitoring tool for over 30 years [3]. They are currently used either to assess the functional status of somatosensory pathways during surgical procedures which may affect peripheral nerve or plexus [10–14], spinal cord (deformity correction, traumatic spinal fracture repair, tumor removal) [3, 15–17], brainstem (posterior fossa tumor removal) [18], and brain (carotid endarterectomy, aneurysm repair) [19, 20] function or to identify the sensory portion of the sensorimotor cortex (central sulcus identification or cortical mapping) [21–23].

When used to assess function, SSEP responses are typically elicited by stimulation at a peripheral site distal to the structure at risk and may be recorded at a distal site and one or more sites proximal to the structure at risk. The distal recording site is used to insure effective stimulation and the proximal recording sites are used to monitor the changes that may occur with functional compromise of the structure in question.

Several factors can affect the responses that are recorded at the proximal recording sites. These factors may be technical, physiological, anesthetic, or surgical. The basis for a surgically-related change can be either mechanical or ischemic.

2.2. *Anatomy*

SSEPs are elicited by stimulation of a peripheral nerve at a distal site; typically the median or ulnar nerves at the wrist for acquiring SSEPs from the upper extremities, and the posterior tibial nerve at the ankle or the peroneal nerve at the fibular head for acquiring lower-extremity SSEPs. The ascending sensory volley which contributes to the SSEP enters the spinal cord through dorsal nerve roots at several segmental levels and may ascend the spinal cord via multiple pathways. The general consensus is that the dorsal or posterior column spinal pathways [24–27] primarily mediate the SSEPs. Other pathways such as the dorsal spinocerebellar tracts [28, 29] and the anterolateral columns [30, 31] may contribute to the early SSEP responses that are used for monitoring purposes. No synapses are encountered between the peripheral stimulation sites and the medullary nuclei (nucleus cuneatus and nucleus gracilis) where the responses arrive after ascending the posterior column of the spinal cord. These early responses are predominantly a reflection of the integrity of spinal cord white matter and provide little direct information about the condition of spinal cord gray matter. Therefore, the ascending SSEP responses up to the level of the medullary nuclei are affected only minimally by general anesthetics. After arriving and synapsing at the medullary nuclei, the responses cross and ascend in the medial lemniscal pathways to thalamic nuclei where they once again synapse with other neurons which in turn project up to the sensorimotor cortex where additional synaptic interaction may occur. Synapses are the sites of action for inhalational anesthetic agents commonly used during surgery. Therefore, anesthetic management is a very important consideration when attempting to record cortical SSEPs.

The blood supply for nourishing the posterior column pathways which mediate SSEPs is generally thought to be the posterior spinal arteries. The anterior spinal artery is generally believed to provide the primary blood supply to the anterior and antero-lateral portions of the spinal cord which make up the remaining two-thirds of the spinal cord. Motor pathway function is mediated by spinal cord pathways which receive their blood supply from the anterior spinal artery. Therefore, loss of motor function due to compromise of the blood supply to the anterior spinal artery may be associated with little or no loss of the sensory function which is mediated by the dorsal column pathways (anterior cord syndrome) [32]. However, the degree to which this is true is uncertain and may vary between individuals. Once the responses have ascended the spinal cord, the functional status of the portions of the brain which are responsible for mediating these responses are dependent upon the blood supply to the brain and brainstem and the specific arterial branches which provide this supply. Perforating branches of the basilar artery and the vertebral artery supply the brainstem. The middle cerebral artery provides the blood supply to the area of the cortex which mediates the upper-extremity SSEPs, whereas the anterior cerebral artery provides the blood supply to the area of the brain which mediates the lower-extremity SSEPs. Decreasing blood pressure may significantly affect cerebral perfusion. In a normothermic individual, when cerebral perfusion drops to about 18 cc/min/100 grams of tissue, electrical activity of the brain decreases and SSEPs begin to diminish in amplitude. When perfusion drops to 15 cc/min/100 grams

of tissue, electrical activity of the brain drops still further and SSEPs are generally not recordable. Further drops in blood flow to the brain, particularly if they are sustained, will result in cellular damage and irreversible changes in electrical activity [33–35].

2.3. *Patient preparation*

2.3.1. Stimulation electrodes

The size, type, and location of a stimulating electrode play a role in the response that is elicited by stimulation. Optimal SSEP monitoring is dependent upon consistent and reliable stimulation at the stimulation sites throughout the surgical procedure. Several types of electrodes can be used for stimulation purposes. These include bar electrodes, EEG metal disc electrodes, adhesive surface electrodes, and subdermal needle electrodes (both disposable and non-disposable). All can be effectively used but each has its advantages and disadvantages. Bar electrodes and metal disc electrodes are used in conjunction with electrode paste and are reusable. The adhesive surface electrodes utilize a conductive gel. Although electrode pastes and adhesive gels may dry out or change their electrical conductance characteristics during lengthy surgical procedures, the use of constant current stimuli will compensate for any change in electrical conductivity as long as the electrodes remain securely in place. The non-disposable bar electrode is susceptible to being displaced and so may produce erratic responses in the OR if it is not well-secured. EEG metal disc electrodes when placed with collodion are much more stable, but are more difficult to secure than either the subdermal or adhesive surface electrodes. Stable SSEP responses are dependent on the stimulation electrodes being secured in place throughout a surgical procedure, and the responses acquired using either subdermal or adhesive surface electrodes are relatively stable when properly secured. The subdermal electrodes may or may not be reusable but because they are invasive, they are associated with concerns regarding infections and/or bleeding, and must be handled with care to avoid inadvertent needle-sticks. Despite these concerns, they are routinely used for recording purposes. The use of adhesive surface electrodes is not associated with these concerns but their use is more costly than some of the other electrode choices because these electrodes are not reusable.

2.3.2. Stimulation sites

Although SSEPs can be elicited by any tactile stimulus, they are normally elicited by an electrical stimulus presented to either major nerve trunks or dermatomes. The responses that are elicited when a major nerve trunk is stimulated are normally called mixed-nerve or major-nerve SSEPs or simply SSEPs, whereas the responses elicited by dermatomal stimulation are referred to as dermatomal SSEPs (DSSEPs).

Dermatomal responses (DSSEPs) should be elicited by using surface rather than subdermal needle electrodes [36, 37]. Surface electrodes should primarily stimulate the sensory fibers innervating the skin surface, whereas needle electrodes will largely stimulate the underlying muscle tissue. In theory, proper placement of the stimulating electrodes will result in responses which are mediated by only a single nerve root. However, as a result of dermatomal overlap and individual variability, the responses that are elicited may be mediated by more than one nerve root or an unanticipated nerve root. As a result, the utility of these responses may be compromised. Dermatomal maps and optimal locations for eliciting dermatomal responses have been published [36, 37]. Other factors such as side-to-side relative stimulation intensity can also compromise their utility [36].

Mixed- or major-nerve SSEPs are typically elicited by stimulating either the median or ulnar nerves in the upper extremities or the posterior tibial or peroneal nerves in the lower extremities. Stimulation sites are normally chosen because of easily-identifiable anatomical landmarks and the ease with which a stimulating electrode can be placed near the nerve to be stimulated. Unless the sites are unavailable, upper-extremity stimulation electrodes are normally placed near the wrist. To stimulate the median nerve, the cathode of the stimulating pair of electrodes should be placed about 2–4 cm proximal to the wrist crease between the tendons of the palmaris longus and flexor carpi radialis muscles. The anode electrode should be placed 2–3 cm distal to the cathode to avoid what is known as anodal block. Similarly, for ulnar nerve stimulation, the cathodal electrode should be placed 2–4 cm proximal to the wrist crease on either side of the tendon of the flexor carpi ulnaris muscle, and the anode should be placed 2–3 cm distal to the cathode [4, 5, 8]. Other effective sites of stimulation in the upper extremity are the superficial radial nerve at the wrist and the ulnar nerve at the elbow.

In order to acquire SSEP responses from the lower extremities, stimulation of the posterior tibial nerve is normally done near the ankle and stimulation of the peroneal nerve is normally done slightly distal to the knee near the head of the fibula. To stimulate the posterior tibial nerve, the cathode should be placed between the medial malleolus of the ankle and the Achilles tendon, just proximal to the malleolus. The anode electrode should be placed 2–3 cm distal to the cathode. This placement overlies the nerve as it follows a path around the malleolus. To stimulate the peroneal nerve, the cathode should be placed distal to the lateral aspect of the knee and slightly medial to the head of the fibula, and the anode

electrode should be placed 2–3 cm distal to the cathode [4, 5, 8].

2.3.3. Stimulation technique

Because a dermatome is defined as an area of skin innervated by a single nerve root, surface rather than needle electrodes should be used to elicit the DSSEP responses [36, 37]. Surface electrodes may consist of either EEG-type disc electrodes, or adhesive electrodes. However, in order to elicit SSEP responses, either surface or subdermal needle electrodes can be used to present the stimuli. Although each of the means for presenting stimuli has its own advantages, none appears significant and all are generally equally effective. Current spread to the underlying nerves is the effective stimulus, and the use of a constant-current stimulus is meant to compensate for any changes in contact resistance. However, the intensity of the constant-current stimulus and the ability to compensate for contact resistance changes are limited by the maximum output voltage of the stimulator. When the contact resistance is excessive, the current output of the stimulator will be current-limited. Most machines designed for the purposes of acquiring evoked potentials will indicate a warning when this is the case. Use of a constant-voltage stimulus provides a constant stimulus intensity only if the contact resistance does not change. For this reason, the use of constant-current stimulation is recommended [4, 5].

An electrical stimulus is typically presented as a series of rectangular pulses with a certain pulse duration and frequency of presentation. The intensity of the stimulus is dependent on its amplitude, pulse duration and frequency. An increase in any of these parameters will normally cause an increase in stimulus intensity because the amount of current flow will increase. However, the way the underlying nerves or tissue reacts to the stimulus is not solely dependent on the stimulus intensity, but is also dependent upon the placement of the stimulation electrodes in relation to the intended neural structures to be stimulated. For some patients with large or edematous extremities, the current spread resulting from the use of surface electrodes may be ineffectual for exciting the intended underlying neural structures. In such cases, the use of subdermal needle electrodes may be more effective. Subdermal needle electrodes can be placed closer to underlying nerves than surface electrodes. As a result, the stimulation intensities needed to stimulate underlying nerves will be less when using subdermal needle electrodes rather than surface electrodes. It is suggested that a pulse duration of 200–300 microseconds be used for eliciting both SSEPs and DSSEPs [4, 5]. Controlling the stimulus rate is essential in obtaining high-quality evoked responses. The critical factor in obtaining evoked responses is the assumption that the response and the underlying noise are not synchronized. Thus, in order to have the noise decrease in amplitude with averaging, the stimulus rate should not be a submultiple of any noise frequency. As the most common noise frequency is 60 Hz, it is important that stimulation rates such as 5.0, 4.0, or 10.0 Hz not be used [4, 5, 8]. Often, there are other sources of noise in the evoked response, and sometimes minimally changing the stimulus rate (for example from 4.7 to 4.9 Hz) may change the quality of the recorded evoked potentials in the setting of high-amplitude rhythmic noise [38]. Stimulation rates between 2 and 5 Hz are recommended [4, 5, 8]. However, lower stimulation rates (between 1.5 and 3 Hz) can sometimes improve lower-extremity responses, particularly when compromise of neurological function is present; whereas upper-extremity SSEPs may demonstrate little or no change at stimulation rates as high as 9 Hz. Increasing the stimulus rate beyond 9 Hz for the upper-extremity SSEPs, and beyond 5 Hz for the lower-extremity SSEPs typically results in a substantial degradation of the SSEPs, particularly the cortical responses [4, 5, 8].

Supramaximal stimulation intensities should be utilized, which produce repeatable responses and ensure that variations in response amplitudes are not a result of variations in effective stimulation intensities. Generally, it should not be necessary to utilize stimulation intensities which exceed 50 mA in order to elicit repeatable SSEPs or DSSEPs and to provide effective monitoring [8]. Although commercial stimulators can generally provide stimulation intensities greater than 50 mA, it is unusual for a stimulus of this intensity to be ineffective for eliciting SSEP responses, unless pathology is present or the current spread from the stimulating electrode is not reaching the underlying neural tissue at a sufficient intensity to cause excitation, such as in patients with large or edematous extremities. The effectiveness of the stimulus for eliciting well-defined repeatable responses will vary between patients, and will depend on several factors including: (a) the type of stimulation electrodes being used; (b) the proximity of the electrodes to the underlying neural structures; (c) the anesthetic management; and (d) the conduction status of the neural pathways being monitored. In such cases, increasing stimulus intensities to as high as 100 mA may be necessary to produce an effective stimulus, but the monitorist should consider other options as well, such as repositioning the stimulation electrodes, changing to needle rather than surface stimulation electrodes, or selecting an alternate stimulation site. Although concerns may exist regarding the possibility of tissue damage resulting from high current-densities at the stimulation sites, these concerns appear to be unfounded and there is no evidence in the literature or otherwise to support them, if the stimulus parameters available on commercially-available devices are utilized.

Different concerns apply to the acquisition of DSSEP responses. For these responses, high stimulation intensities may result in current spread and the contamination of the desired DSSEP responses from a single dermatome with the responses from adjacent dermatomes or from neural structures located beneath the skin surface such as muscle-stretch receptors. In addition, the latencies of DSSEP responses have been shown to be related to stimulus intensities [36]. For these reasons, attention must be paid to stimulation intensities. Minimally-effective stimulation intensities should be utilized to elicit DSSEP responses and elevated stimulation intensities should be avoided.

There are various ways of presenting the electrical stimuli in order to elicit SSEPs. The earliest versions of monitoring equipment only allowed the responses to be recorded from stimulation of a single site. For validation purposes, this acquisition process was then repeated to insure that the responses replicated. A similar set of responses were then acquired from the opposite extremity, and it would typically be several minutes before a new set of responses could be acquired from the first stimulation site. This format for data acquisition could significantly delay the detection of a unilateral SSEP change. As a result, improvements in the data acquisition equipment occurred which made it possible for stimuli to be interleaved between a pair of extremities such that the responses from each extremity were essentially being recorded simultaneously. This improvement has been widely adopted, has resulted in faster data acquisition, and has permitted the rapid determination of SSEP changes and side-to-side asymmetries [4, 5, 8, 39]. Another method for eliciting SSEPs is to simultaneously present stimuli to a pair of extremities. Historically, this methodology has been discouraged because it was felt that the resulting responses could mask significant unilateral functional changes. For patients with little or no neurological deficits and well-defined responses, bilateral stimulation appears to provide no significant advantages over interleaved unilateral stimulation. There is no published evidence which indicates that the usage of the bilateral stimulation technique is better able to detect functional changes than interleaved unilateral stimulation. However, bilateral stimulation may be of value when the responses that result from the stimulation of a single extremity are too small and/or variable to use for monitoring purposes. As a result, unless otherwise indicated, it is recommended that the presentation of interleaved unilateral stimulation be used for monitoring purposes rather than simultaneous bilateral stimulation.

The choice of what nerves to stimulate will largely be dictated by the location of the surgical site. For monitoring purposes, it is extremely important to select nerves whose responses are mediated by neural tissue at risk during surgery. Therefore, when the thoracic region of the spinal cord is at risk, monitoring median nerve responses to detect a spinal cord insult would be useless, whereas monitoring posterior tibial nerve responses would not. When the neural tissues at risk are nerve roots, DSSEPs have been shown to be sensitive to changes in nerve root function [37]. Occasionally, a nerve's responses may be partially mediated by tissue above and below the site at risk. In such cases, it is possible that the response mediated by tissue above the site at risk can mask an abnormal response mediated by tissue at the site of risk. The result is that the recorded responses may demonstrate little or no changes despite the production of a neurological deficit. It is best to choose to monitor the responses of nerves which are entirely mediated by tissue located below the area at risk [4, 5]. In addition, the choice of what nerves to stimulate may also result from other factors such as what neurological structures are at risk as a result of positioning, which nerves are accessible or which nerves, when stimulated, will simply provide the best responses. For example, changes in brachial plexus function due to positioning are generally best detected by monitoring ulnar rather than median nerve function. In patients with large edematous legs, peroneal nerve stimulation may provide better responses than posterior tibial nerve stimulation.

2.3.4. Recording electrodes

Just as it was important that the stimulation electrodes be associated with a consistent and reliable stimulus presented in a safe manner, it is also important that the recording electrodes provide consistent, reliable, and good-quality recordings in a safe manner as well.

Subdermal needle or metal surface "cup" electrodes (gold, silver, or tin) are typically used for recording from the body surface [8]. The subdermal needle electrodes are convenient to use because they can be quickly and easily placed. However, if they are not taped or fastened down, they can be easily displaced as well; usually by the anesthetist reaching under the surgical drapes or while preparing to take an x-ray. Therefore, if subdermal needles are utilized, they should be positioned to avoid being displaced. Otherwise, a corkscrew version of the straight subdermal needles or surface electrodes can be used instead. Corkscrew electrodes are literally screwed into the scalp and are difficult to displace, whereas surface electrodes are filled with conductive gel or paste and are secured to the recording sites using collodion or tape.

A "strip" or grid electrode array can be used for direct cortical recordings of SSEPs. These type of recordings are used for correlating the anatomy of the cortical surface with anatomical function (corticography) [21, 22].

2.3.5. Recording sites

Because the questions or concerns are different, the recording montage that is used for intraoperative monitoring purposes may be different from one that would be used for diagnostic purposes. The recording montage will depend upon the number of recording channels available. It may also depend upon whether responses can be simultaneously recorded from both sides of the body and whether replication is desired. The basic principle of mixed-nerve SSEP monitoring is to stimulate distal to the surgical site at risk and to record at a sites(s) proximal to the surgical site. In most cases, these recording sites should include at least one cortical and one subcortical recording site. An additional recording site can be placed proximal to the stimulating site but distal to the surgical site. This site is typically used to verify the status of the peripheral stimulus. For upper-extremity stimulation, this site is usually the ipsilateral Erb's point; for lower-extremity stimulation, it is the ipsilateral popliteal fossa. It is of value to record cortical responses in all cases since they provide an indication of anesthetic management and are readily recognized. However, reliance only on the cortical responses can result in false-positive changes because they are significantly affected by general anesthesia and blood pressure. Because far fewer synapses are associated with mediating the subcortical response, anesthetic effects are far less pronounced than on the cortical responses. However, reliance only on subcortical responses can also result in false-positive findings due to the quality of the subcortical responses, their generator sites, and other factors. As a result, it is advisable to utilize both cortical and subcortical recording sites. When the spinal recording site is not available, such as during a posterior cervical procedure, the subcortical response can be recorded from one earlobe or linked earlobes.

The cortical recording site is used to record the SSEP as it arrives at its endpoint in the post-central gyrus of the contralateral somatosensory cortex. The location of these electrodes for upper-extremity stimulation is at CP3 or CP4, contralateral to the side of stimulation and 2 cm posterior to the C3 and C4 positions of the 10–20 International System of EEG electrode placement. For lower-extremity stimulation, the cortical recording site is at CPz, on the midline and 2 cm posterior to the Cz position of the 10–20 system.

The nomenclature that is used to designate the peaks and valleys of SSEP waveforms uses N and P, respectively, to designate the polarity of the recorded signal (negative is up and positive is down) and an integer to denote the nominal post-stimulus latency of the signal in normal adults. Illustrations of sample SSEP waveforms with the requisite peaks and valleys marked using this nomenclature appear in previously-published guidelines [5]. There are a number of different ways to record the important cortical and subcortical responses. Two peaks are generally used to define the amplitude of the cortical SSEP responses. These two peaks, labeled N20 and P22, which result from median nerve stimulation, are considered to be waves of thalamic and cortical origin. Two derivations have been suggested for recording these waves. One is CPc (cortex contralateral to the stimulus – i.e. CP3 if the right arm is stimulated and CP4 if the left arm is stimulated) −Fz (midline frontal electrode).

The other is CPc-CPi (contralateral to ipsilateral – i.e. CP3-CP4 or CP4-CP3 depending upon which arm is being stimulated). Each of these is acceptable and each laboratory should choose what is appropriate. It is, however, critical to be able to record in either way. In some patients with neurologic injury, the cortical responses may be of extremely-low amplitude and hence a cortical response may be recorded using one derivation and not the other. The other key element in choosing the appropriate recording derivation is that the responses obtained must be easily interpretable if interleaved left- and right-sided stimulation is employed. For example, in this case it would not be sufficient to use CP3-Fz, since this best yields the N20-P22 response only when the right arm is stimulated. Thus, it would be either appropriate to record from the single derivation CP3-CP4 or from both CP3-Fz and CP4-Fz. There are many ways in which to record the far-field subcortical potentials. The P14 and N18 far-field potentials are most-likely generated in the caudal medial lemniscus and multiple generator sources in brainstem and thalamus, respectively, and are best recorded by using a derivation that includes ipsilateral (to the side of stimulation) centro-parietal cortex to a non-cephalic reference such as CP3-right Erb's point for left median nerve stimulation [5, 40]. Another subcortical response which is typically recorded is known as the cervical or N13 response. There is more than one method to record this response. One method is to use a cervical-to-Fz recording derivation. However, since the N13 has two components, one at the cervico-medullary junction and one generated in the cord [41, 42], the placement of the cervical electrode could be critical depending on the surgical procedure being monitored. Another method to record this response is to use Fz or Cz to linked ears. This recording montage has the advantage of recording responses with components from generators in the medulla or higher [43]. The peripheral potentials at the brachial plexus are best recorded with electrodes over Erb's point, which is just 2 cm above the midpoint of the clavicle, and at the angle between the clavicle and the posterior border of the head of the sternocleidomastoid muscle. The responses ipsilateral to the stimulation site are referenced to the opposite Erb's point.

After stimulation of the posterior tibial nerve or the peroneal nerve, because of the anatomy of the somatosensory cortex, the major positive and negative peaks of the cortical responses (P37 and N45) are often of highest amplitude at CPz, so that one derivation for recording the cortical responses is CPz-Fz (frontopolar electrode). However, because of "paradoxical lateralization" resulting from the lateral orientation of the dipole generator of the P37 peak, high-quality cortical responses can also be recorded using CP3-CP4 or a CPz-CPc derivation. As in the case of the upper-extremity SSEPs, the ability to record other derivations decreases the chance that a low-amplitude cortical response will be overlooked. Subcortical responses consisting of P31 andN34 waves originating from the brainstem (and analogous to the upper-extremity N13 peaks) can be recorded either from CPi (ipsilateral with respect to the side of stimulation)-linked ears, or a cervical-Fz derivation [44]. Peripheral responses can be recorded using two electrodes on each leg; one placed at the popliteal fossa and the other placed three to four centimeters proximal to the popliteal fossa electrode.

Although a ground electrode can be placed anywhere on the body, to reduce the amount of noise pickup it is best to place it nearer rather than farther from the other recording electrodes. Placing it on a shoulder is generally a good site. Multiple reference grounds are never used because they introduce ground loops which may introduce excess noise in the recordings, and an earth ground should never be used for safety reasons because it provides an alternate path for the bovie current. Keeping the recording input leads short and the electrode impedance values at 5k ohms or lower for gold disc or subdermal electrodes will help to minimize the amount of stimulus artifact and other electrical noise that is recorded. However, the acquisition of some stimulus artifact can be useful because it demonstrates that the stimulators are functional when troubleshooting is necessary.

2.3.6. Recording technique

The subcortical responses are affected only minimally by general anesthetics, whereas the cortical responses are very much affected by commonly-used general anesthetics. As a result, when inhalational anesthetic agents are utilized, it is not unusual during a surgical procedure to observe a marked amplitude depression of the cortical responses, with little change in the subcortical responses. However, although the subcortical SSEP response is normally very well defined for upper-extremity stimulation, it is often poorly defined for lower-extremity stimulation. Therefore, if lower-extremity cortical SSEP responses are important for monitoring purposes, it is important to pay attention to measures which may improve the ability to record these responses. These measures include changing the anesthetic management, improving or using alternate recording sites, and increasing the intensity or decreasing the frequency of stimulation. However, these changes should be made early in the surgical procedure and prior to the time when any neurological function is placed at risk, in order to avoid any erroneous interpretation of the acquired data. The same is true regarding changing any of the stimulation or recording parameters.

Number of channels. Previous guidelines have already been established which address the technical requirements needed for an evoked potential machine in order to provide safe and effective monitoring capabilities [4, 5, 8]. Based on the requisite number of recording sites needed for monitoring the responses from each stimulation site, and the need to interleave stimuli between multiple stimulation sites, it is recommended that machines have at least eight display channels for each monitoring modality (upper- or lower-extremity SSEPs or DSSEPs). Eight channels will allow for simultaneous display of four channels of the cortical and subcortical responses from a pair of extremities. If the responses from more than one monitoring modality are simultaneously acquired (i.e. SSEPs and spontaneous EMG), additional recording channels may be necessary and equipment requirements must be adjusted accordingly.

Filters. The choice of optimal filter settings is important for intraoperative neuromonitoring. The purpose of filtering is to optimize response acquisition. The goal in choosing filters for intraoperative monitoring is always to provide the most easily interpretable response with the least averaging. For most laboratory diagnostic studies, the typical filters are set at 20–3 k Hz and are not changed from patient to patient. The reason for this is that, in routine laboratory testing, comparisons are made between the given patient and a set of normals. Any differences in technique will make comparisons difficult. It is likely that the precedence for those filter settings that have been recommended as intraoperative signal acquisition parameters have evolved from their use in a diagnostic setting. However, the various waveform morphology subtleties for which these filter settings are important in a diagnostic setting are far less important in the intraoperative monitoring setting. In addition, the intraoperative setting is associated with significantly more environmental noise which complicates the acquisition of useful monitoring data. In monitoring, results obtained during a surgical procedure are compared to the same patient's results at an earlier point in that procedure. Thus, different filter settings may be chosen for different patients as long as they are not changed (unless absolutely necessary) during the course of the surgery. Although it is important to begin with standardized

high- and low-frequency filter settings, they can be changed at the beginning of a case in order to optimize recordings. It has been suggested that the system bandpass for the cortical responses be initially set to 1–30 to 250–1000 Hz [4, 5, 8] and for the subcortical responses, the system bandpass should be 30–100 to 1000–3000 Hz [4, 5, 8]. The relative frequency content of the cortical responses is much lower than that of the subcortical responses. The majority of the energy contained in cortical SSEP responses is present in the frequency pass band above 30 Hz and below 500 Hz. Therefore, to record these responses, it is often useful to set the high-frequency filter to as low as 300–500 Hz in order to eliminate high-frequency artifact. For peripheral and subcortical responses, because of the higher-frequency content of physiological activity, the high setting of the pass band window can be set as high as 1000 Hz. Increasing the high-frequency filter settings to greater than these will have very little effect on the physiological frequency content of the intraoperative evoked responses, and will just increase the amount of high-frequency environmental noise that is recorded. In an electrically-hostile environment like the operating room, where many of the pieces of equipment that are used during surgery produce electrical signals which can contaminate the neurophysiological responses with signals both in the low- and high-frequency ranges, it is not unusual to set narrow recording bandpasses to avoid the acquisition of excess artifact from these sources. Widening the pass band so that it includes more high- and low-frequency activity is likely to result in the acquisition of less-than-optimal responses. Despite the fact that 60 Hz artifact is common in this environment, the 60 Hz rejection filter is not recommended because of the "ringing artifact" it can cause in the recorded responses, and should only be used as a last resort when useful responses cannot be acquired without its utilization.

Averaging. For monitoring purposes, well-defined responses should be acquired as quickly as possible. Some guidelines [4, 5] have suggested acquiring 500–2000 trials per averaged response. If a typical stimulus rate of 4.7 stimuli per second were used to acquire these responses, then acquiring responses consisting of 500–2000 trials would take anywhere from 1.75 to 7 min to acquire a response, while acquiring 300 trials per response would take only about a minute! Although these responses will contain some noise, if the bandpass is well-selected and the noise level is not too high, the response will be quite reproducible and the overall amount of noise content will be very small. By increasing the number of trials from 300 to 1000, the response acquisition time will increase over threefold, while the noise will decrease by a factor of 1.83 (the square root of the factor by which the number of sweeps increased). If 3000 trials were used to acquire the responses, they would take 10 times the amount of time to acquire, and the noise would decrease only by a factor of 3.16. In general, most of the systems that are currently used to acquire SSEPs require the acquisition of between 300 and 500 samples for both upper- and lower-extremity somatosensory evoked responses. However, the actual number of samples depends on the signal-to-noise ratio and the urgency of reporting a result to the surgeon. In some cases, such as during temporary occlusion of an intracranial vessel, the surgeon may wish to be informed of changes in the evoked responses more quickly than every 2–5 min. In this case, if signal quality is sufficient, adequate upper-extremity SSEPs can sometimes be obtained with as little as 100 samples. If the number of samples is reduced, the monitorist needs to be sure that the responses obtained are indeed real and not artifact. Usual techniques for verifying the responses include repetition or the use of the "odd-even" averaging feature available in many evoked potential devices which allows separate display of the mean of the even-numbered and odd-numbered traces. In other situations, the number of samples is determined by the signal-to-noise ratio, since the level of unsynchronized noise in the evoked response decreases with the square root of the number of samples.

Timebase. The timebase that should be utilized to acquire and display the acquired responses from the upper and lower extremities should take into account the normal conduction time between the stimulation and recording sites. This of course will depend upon factors such as the age and size of the individual. However, the latency of the peak of the upper-extremity response which is typically used for monitoring purposes normally appears about 20 ms after the stimulus onset. For the lower extremities, the peak-of-interest normally appears at twice this latency or at 40 ms after the stimulus onset. Therefore, the timebases for upper- and lower-extremity responses are generally set at about 50 and 100 ms, respectively.

2.4. *Anesthesia*

Although the monitoring of evoked potentials can be beneficial during many surgical procedures, the anesthesia used to facilitate these procedures produces effects which alter the evoked responses. The effects are most prominent on the cortically-generated responses (which may demonstrate no repeatability) and less so on the subcortical and peripheral responses (which may demonstrate little or no apparent change) and is variable between individuals. The effects are generally dose-related and the effects on cortical SSEPs tend to parallel the effects on EEG. Most of the commonly-used anesthetic drugs produce dose-related SSEP changes; amplitude decreases and latency increases.

The relative degree of change differs between anesthetic agents. The drug dosage that causes a 50% decrease of cortical SSEP amplitude correlates with the lipid solubility of the agent and therefore its anesthetic potency [45, 46]. Therefore, when anesthetic techniques are being considered, the effect of each anesthetic agent on specific monitoring modalities must be considered.

2.4.1. Halogenated inhalational agents

Probably the most commonly used anesthetics are the halogenated inhalational agents (desflurane, enflurane, halothane, isoflurane, sevoflurane). All these agents produce a dose-related increase in latency and reduction in amplitude of the cortically-recorded SSEP responses, which can be extremely deleterious and result in unstable responses over time. The effects are less on the subcortical SSEP responses recorded over cervical spine, and are minimal on spinal responses recorded epidurally or on peripherally-recorded responses. Several studies have demonstrated that halogenated agents differ in their potency of effect on cortical SSEPs. Isoflurane has been reported to be the most potent with enflurane and halothane the least potent [47]. At steady state, the potency of sevoflurane and desflurane appear to be similar to that of isoflurane. If it is essential to monitor cortical SSEPs (particularly if this monitoring modality is used in conjunction with any type of motor responses elicited by transcranial stimulation), the use of halogenated inhalational agents may need to be restricted or eliminated entirely. This may be particularly important when monitoring patients with spinal cord compression or other pre-existing conditions such as cerebral palsy. However, if the recording of subcortical responses is adequate for monitoring purposes, low doses ($<$0.5 MAC) of halogenated agents may be acceptable anesthetic choices. It is also important to note that all of these agents have complex pharmacokinetics so that it may take 10–20 min or longer for equilibration of concentrations in the brain and lung to occur. Thus, the changes in the evoked potentials may lag substantially behind changes in the end-tidal inhalational agent monitor.

2.4.2. Nitrous oxide

If monitoring cortical SSEPs is essential, the use of nitrous oxide should be avoided. It is not a reliable amnestic and can be replaced with Versed. Nitrous oxide produces decreases in cortical SSEP amplitude and increases in cortical SSEP latencies when used alone or in conjunction with halogenated inhalational agents or opioid anesthetics. When compared to other inhalational anesthetic agents at equipotent anesthetic concentrations, nitrous oxide produces the most profound cortical SSEP changes [34]. Because nitrous oxide is relatively insoluble, its effects can rapidly change when its concentration is varied. As a result, the cortical SSEP amplitude increases and latency decreases associated with a decrease in nitrous oxide concentration may mask the opposite changes coincident with a neural compromise. Therefore, if nitrous oxide is used, it is important that significant changes not be made during the critical times in the procedure. Nitrous oxide has been reported to have a synergistic effect on cortical SSEPs when used in conjunction with other inhalational agents. Like halogenated agents, nitrous oxide produces less effects on subcortical and peripheral sensory responses. Therefore, if monitoring can adequately be done using only subcortical and/or peripheral recordings, the use of nitrous oxide may be acceptable.

2.4.3. Intravenous analgesic agents

The depressant effects of inhalational agents may be inconsistent with the utilization of cortical SSEPs or the acquisition of motor responses for monitoring purposes. In such cases, intravenous agents can be combined and utilized to produce a total intravenous anesthetic (TIVA). The use of TIVA is the best choice for monitoring purposes. The common intravenous agents include analgesics (opioids or ketamine) and sedative agents (barbiturates, benzodiazepines, etomidate, propofol or droperidol).

Opioid analgesics generally produce only mild effects on evoked potentials [46]. The effects consist of minimal changes in spinal or subcortical responses whereas they produce some amplitude depression and latency increases in cortical responses. These effects appear to be related to drug concentrations with maximal changes occurring at the same time that drug concentrations peak after a bolus drug-delivery. Because the effects of opioid administration are less than those of inhalational agents, opioid-based anesthesia has been frequently used when cortical responses are utilized for monitoring purposes. However, because opioid anesthesia is often insufficient to produce sedation and lack of awareness, they have been used in conjunction with an inhalational agent (halogenated or N_2O). However, the use of an inhalational agent may be unnecessary if a sedative drug, such as Versed, can be utilized.

Ketamine also produces effects on evoked potentials which differ from those of inhalational agents. These primarily consist of an increase in cortical SSEP amplitudes [48] with minimal effects on subcortical and peripheral responses. Ketamine provides excellent analgesia and hypnosis but its use can be associated with post-operative hallucinations in adults and increases in intracranial pressure

in patients with intracranial abnormalities. The possibility of post-operative hallucinations can be minimized by the administration of a benzodiazepine (such as Versed) pre-operatively and intra-operatively; particularly during closing. However, Ketamine has other cardiac side-effects which may make its use undesirable and its half life is too long for cases where rapid/early neurologic assessment is needed and where it may cloud the issue immediately post-op.

Intravenous sedative agents are often combined with opioids or ketamine in order to produce a completely intravenous anesthetic. Like the opioids and ketamine, these agents can be slowly infused so as to reduce transient changes in the monitored responses. Droperidol is one of these agents which appear to have minimal effects on cortical SSEPs [49]. Other sedative agents are the barbiturates. One of those frequently used for induction is thiopental. However, use of this agent produces transient decreases in cortical response amplitudes and increases in response latencies. Longer-latency cortical response components are most affected, whereas effects on subcortical and peripheral responses are minimal. In general, induction with barbiturates is compatible with SSEP monitoring because redistribution of these drugs allows resumption of monitoring after a short time. Another barbiturate frequently used to produce barbiturate-induced coma is phenobarbital. Doses of this agent which produce a silent EEG do not affect the acquisition of SSEPs. Therefore, SSEPs can be successfully used to monitor neurologic function during barbiturate-induced coma.

Among the benzodiazepines, midazolam, in doses consistent with induction of anesthesia (0.2 mg/kg) and in the absence of other agents, produces mild depression of cortical SSEPs [50] and minimal effects on subcortical and peripheral sensory evoked responses. Because of midazolam's excellent amnestic qualities, an infusion (50–90 micrograms/kg/hr started after a 0.1 milligram/kg load) can be used to maintain a steady level of supplemental hypnosis during opioid analgesia. This combination is usually supportive of the acquisition of cortical SSEPs. In addition, midazolam is an excellent supplemental hypnotic when ketamine is utilized and may be helpful in reducing the hallucinations associated with ketamine usage.

The use of etomidate has been reported to cause an amplitude increase in cortical sensory components after injection [51] with no changes in subcortical or peripheral components. A sustained amplitude increase with constant drug infusion has been used to enhance SSEP cortical recordings that were otherwise unsuitable for monitoring purposes [52].

Propofol has great appeal for intravenous-based techniques during evoked potential monitoring. Unlike etomidate, propofol does not appear to enhance cortical responses. Instead, propofol induction produces amplitude depression of cortical SSEPs with a rapid recovery after the termination of infusion. The changes in evoked potential amplitude with propofol are substantially smaller than with equipotent doses of halogenated agents [46] so that propofol is the preferred agent to use during the recording of SSEPs. This is especially true for the lower-extremity SSEPs, which are much more sensitive than the upper-extremity SSEPs to the effects of the halogenated agents. The rapid metabolism of propofol makes it an excellent drug for tightly-controlled infusion anesthesia. Its rapid metabolism allows the depth-of-anesthesia and effects on evoked responses to be adjusted rapidly.

For monitoring purposes, TIVA is clearly the best choice but practically, its widespread adoption may occur slowly since many anesthesiologists are not trained and/or comfortable with its usage. In this case, when only SSEPs and no motor evoked potentials (MEPs) are being acquired, a reasonable substitute might be to maintain inhalational agents at less than 0.5 MAC with no nitrous oxide and to rely primarily on narcotics. If the SSEPs are too poor to monitor or if MEPs are being acquired, then Versed should be substituted for the inhalational agents.

2.4.4. Muscle relaxants

Muscle relaxants are generally believed to have no effect on SSEPs. However, they will improve SSEP quality by reducing the amount of electromyographic noise or interference from muscle groups near the SSEP recording electrodes. This effect may be responsible for the SSEP enhancement noted with low doses of propofol and meperidine. The presence of excessive myogenic artifact (particularly from recording electrodes placed on the back of the neck) may indicate the need for additional relaxant.

2.4.5. Choice of anesthetic agents

A number of factors determine the choice of anesthetic agents when monitoring is to be performed. These include (1) how anesthetic agents may interact with a patient's pathophysiology, (2) surgical requirements (i.e., performance of a Stagnara wake-up test, awake during a carotid endarterectomy procedure), and (3) the specific monitoring modalities to be utilized.

In general, anesthetic agents produce an alteration in the evoked responses consistent with their clinical effects on the CNS. Several important generalizations can be made regarding the effects of anesthetic agents on SSEPs. First, most anesthetic agents tend to decrease neural conduction and synaptic transmission. As a result, they tend to decrease

the amplitude and increase the latency of SSEPs. Second, the effects of anesthetics on SSEPs appear to be most pronounced in regions where synaptic transmission is prominent. Therefore, the effects of anesthetics are most pronounced on cortically-generated peaks, and least effective on brainstem, spinal cord, and peripheral responses. Third, anesthetic effects appear to be dose-related although many agents have a disproportionate effect at low dosages in the range where major clinical anesthetic effects are occurring. Fourth, just as patients react differently to the same dose of an anesthetic drug, so also their SSEPs are affected differently. Finally, during periods when neurological function is acutely at risk, it is important to maintain a steady-state of anesthesia. Taking into consideration all these factors, an anesthetic regimen can usually be chosen which will permit effective monitoring to occur.

2.5. *Systemic factors*

2.5.1. Temperature

Operating room temperatures are generally well below body temperature. As a result, it is not unusual for a patient's temperature to drop during surgery. The temperature of the room, the length of the surgery, and the amount of surgical exposure will all contribute to the patient's heat loss and resulting body temperature. Diminished body temperature will affect the metabolism of the drugs that an anesthesiologist uses. To counteract this effect, anesthesia personnel often use heating-blanket-type devices to maintain the patient's body temperature. Another effect of diminished body temperature is a decrease in neural conduction velocity, with a resulting increase in SSEP peak latencies. SSEP changes with minor variations in temperature are gradual (roughly 0.75–1.0 ms increase in latency of the N20 for every 1 °C decrease in nasopharyngeal temperature) and occur without significant amplitude changes [39]. However, with very low temperatures the cortical evoked responses disappear (roughly 22 °C) [53] and subcortical, spinal, and peripheral SSEP responses with elevated peak latencies may be relied upon for the monitoring of somatosensory function. However, subcortical responses also disappear at even lower temperatures.

2.5.2 Blood pressure

Blood pressure affects the perfusion of neural tissue. A certain amount of neural perfusion is necessary to meet the metabolic demands of the tissue. If these demands are not met, the electrical activity of the tissue will begin to shut down. Cortical SSEPs begin to change when cortical blood flow drops below 18 ml/100 g/min [33–35]. The amplitudes drop and the response latencies systematically lengthen. Further ischemia causes a loss of cortical SSEPs when the cortical blood flow drops below approximately 15 ml/100 g/min [33–35]. This rate of flow is not sufficient to maintain cortical electrical activity, but is just above the critical threshold for permanent neurological damage. Therefore, loss of electrical activity is an early-warning sign and the degree and duration of low flow below this warning threshold appears to correlate with the degree of permanent neurological damage.

In general, cortical evoked potentials appear to be minimally attenuated when systolic blood pressure is kept stable at 80 mm Hg [39]. However, the degree of degradation of cortical SSEPs with decreases in blood pressure varies between individuals. Pressures which produce no SSEP changes in one patient may produce significant changes in another. Cortical SSEP changes which cannot be otherwise explained may result from hypotension. Because of autoregulation, the critical threshold at which ischemic changes in the SSEP responses occurs is dependent upon the patient's "normal" outpatient blood pressure. It is also dependent upon the presence of cerebrovascular disease. Subcortical and spinal SSEP recordings are more resistant to ischemia and may continue to demonstrate measurable electrical signals even after blood flow to the generator sites has ceased for several minutes.

2.6. *Safety and technical considerations*

2.6.1. Electrical safety and maintenance

(See Electroencephalography Position Statement)

2.6.2. General infection control guidelines

(See Electroencephalography Position Statement)

3. DOCUMENTATION

3.1. *Report*

A report should be generated for the patient's medical record indicating that monitoring was performed during the surgical procedure. The report should describe what function was monitored, how the monitoring was performed, what information the monitoring provided, and should also include any other information that was relevant to the medical status of the patient. Any information relevant to the well-being of the patient must be shared

with other healthcare professionals for continuing-care reasons. Therefore, the report should be completed as soon as possible. Even if this report is not completed prior to the patient leaving the operating room, the monitorist should be certain that all relevant monitoring data has been communicated to the physicians caring for the patient. Specifically, aside from information conveyed during the surgical procedure, this should include the status of the monitored responses relative to the baseline responses obtained during the surgical procedure.

3.2. *Monitoring data*

All the SSEP data traces and other information that are acquired during monitoring should be saved electronically and/or printed for possible later review. The monitoring records should include detailed information such as demographic data, diagnosis and type of surgery, equipment and neuromonitoring procedures, neuromonitoring personnel, intraoperative events, and clinical outcome, if available. When possible, great care should be taken to acquire artifact-free SSEP responses prior to, during, and after various routine and critical surgical events. In addition, relevant physiological variables (e.g. blood pressure, temperature), anesthetic agents and levels, significant SSEP changes, any critical alerts or alarms to the surgeon and anesthesiologist, the responses of the surgeon to any data supplied, and any interventions or changes in surgical or anesthetic care based on intraoperative neuromonitoring should all be appropriately documented on the hardcopy of the SSEP response traces and/or the log of the neuromonitoring remarks for each patient [4, 5, 8, 54]. The requirements of what data needs to be saved, where it is to be saved, and for how long is dictated by state law, but some hospitals' policies regarding medical record storage exceed state requirements.

3.3. *Alarm criteria*

It has been advocated on empirical grounds that a 10% increase in latency of the primary SSEP cortical response (i.e., N20 or P37), or a decrease or more than 50% in cortical peak-to-peak amplitude is indicative of a significant surgical event and therefore are criteria for intervention [55, 56]. Significant response changes are a cause for concern and heightened vigilance. Reproducibility of any such changes is critical before an alarm is given. Studies have been performed to assess the validity of these criteria for intervention [57, 58]. These alarm criteria are dependent upon a number of factors. These include (1) response variability, (2) anesthetic usage, (3) the presence or absence of pre-existing neurologic injury, (4) the rate of response change, and (5) surgical events at the time of change. These criteria must be taken into account when intervention is a consideration.

4. CREDENTIALS AND STAFFING PRACTICE PATTERNS

Staffing models for intraoperative neurophysiological monitoring (IOM) vary greatly across institutions. The ASNM recognizes the importance of appropriately-qualified IOM personnel and refers the reader to a separate position statement regarding this sensitive issue. However, prior to finalizing our positions on staffing, the ASNM believes that the following statements may assist institutions and individuals in evaluating IOM personnel qualifications. IOM may be divided into two levels of service delivery: professional and technical. Individuals performing or supervising IOM services should have gained appropriate education, training, and experience prior to practicing in a clinical setting.

The ASNM recommends certification by the American Board of Neurophysiologic Monitoring (ABNM), or its equivalent, as a measure of professional level qualification. Criteria for ABNM certification includes: (1) an advanced degree: Masters, Ph.D., M.D., or D.O.; (2) documented clinical experience with the requirement of at least 300 monitored cases over a minimum of three years; (3) surgeon attestations regarding monitoring experience; (4) the passing of two examinations, one written and the other oral.

The ASNM recommends the Certification in Intraoperative Monitoring (CNIM) sponsored by the American Board of Registry for Electroneurodiagnostic Technologists (ABRET®) as a measure of technical-level qualification. Criteria for ABRET certification includes: (1) a high school degree and healthcare credential or bachelor's degree; (2) documented clinical experience with the requirement of at least 100 cases; (3) the passing of a written examination; (4) attestation by a supervising physician as to eligibility.

In addition to appropriate credentials, the ASNM recognizes the value of continuing education, as well as the development of institutional policies and procedures including scope-of-practice, duties related to both technical and professional aspects of practice, and interpersonal communications.

5. MONITORING APPLICATIONS

5.1. *Nerve root function*

Nerve root function can be assessed using monitoring techniques of sensory and/or motor function [36, 37, 59, 60].

The monitoring techniques assessing motor function will be discussed in another section of the standards. The SSEPs that are elicited by mixed-nerve stimulation are mediated by several cervical or lumbo-sacral nerve roots as they enter and ascend the spinal cord. These responses may appear normal despite the presence of a nerve root whose function is abnormal [37]. This is thought to result from the abnormal function being masked by the responses mediated by other nerve roots whose function is normal [37]. Therefore, in order to test the function of individual nerve roots, body surface areas innervated by a single nerve root (known as dermatomes) can be electrically stimulated. The responses that result from this form of stimulation are called dermatomal somatosensory evoked potentials (DSSEPs). These responses are elicited using surface electrodes and the same stimulation parameters as are used to acquire SSEPs. In addition, the recording techniques and parameters used to acquire DSSEPs are the same as those used to acquire SSEPs as well. The size and latency of these responses are dependent upon the size of the stimulation electrodes and the stimulation intensity [36] and although subcortical responses may be recorded, the largest-amplitude responses are generally recorded from the scalp. Although the responses are not sensitive to muscle-relaxant levels, as are the responses associated with assessing motor pathway function, DSSEPs, like mixed-nerve SSEPs, are affected by many of the anesthetic drugs commonly used during surgery. DSSEPs are sensitive to nerve-root compression and mechanical manipulation [37]. It is questionable as to whether they are sensitive to nerve-root decompression. In addition, they can detect a misplaced pedicle screw only when the screw contacts and mechanically irritates a nerve root, but are ineffective when no contact occurs [37]. In addition, DSSEPs are an averaged response and would require at least a few minutes to detect and confirm a mechanical insult. The major shortcomings of the DSSEP technique have been addressed by the use of motor pathway assessment techniques.

Surgical application examples include the following: placement of pedicle screw instrumentation, cauda equina tumor removal, release of tethered cord, and treatment for spina bifida.

5.2. *Peripheral nerve and plexus*

SSEPs can be used to assess the functional status of peripheral nerves and plexuses [10–14]. They are also useful for identification purposes and for assessing functional continuity. These anatomical structures consist of both sensory and motor nerve fibers. The responses recorded directly from these structures as a result of distal peripheral nerve stimulation are compound nerve action potentials (CNAPs) and consist of both orthodromic and antidromic sensory and motor activity. It is not until the ascending responses are recorded from more proximal sites over the spinal cord or higher that they represent true somatosensory (SSEP) responses.

Even when nerves are not surgically exposed, their function can still be placed at risk. This can be the result of a surgical maneuver or of positioning. Peripheral stimulation can be used to elicit SSEP responses from these nerves and the resulting responses are typically recorded from the scalp or over the spine; sites proximal to where their function has been placed at risk.

Surgical application examples include the following: peripheral nerve repair, position-related ulnar nerve and brachial plexus dysfunction, avoidance of neuropraxia during shoulder arthroscopy, and protection of sciatic nerve function during total hip arthroplasty.

5.3. *Spinal cord*

5.3.1. Cervical

SSEPs are now widely used to assess spinal cord function [3, 15–17, 23, 27, 28, 42, 56, 61–72]. In order to accurately do so, the elicited responses must be completely rather than partially conducted through the surgical site or sites at risk. Therefore, care must be taken when selecting stimulation sites. Peripheral nerve responses are mediated by more than one spinal nerve root as they enter the spinal cord. The responses elicited by median nerve stimulation are mediated by several nerve roots, but primarily the C6 nerve root. Although these responses are easy to elicit and are normally quite large in amplitude, they may not be an effective monitoring tool if the surgical site at risk is located distal to C6. Ulnar nerve responses which are mediated primarily by the C8 nerve root, and/or the responses elicited by lower-extremity stimulation may be more effective monitoring tools in this case. The choice of stimulation sites for eliciting lower-extremity SSEPS is generally the posterior tibial nerve at the ankle. However, when this site is not available or is considered unreliable due to unusually large ankles or edema, stimulation of the peroneal nerve at the fibular head may be the stimulation site of choice.

Several recording sites can be used to monitor upper-extremity SSEP activity. These include sites on the extremities, over the brachial plexus, over the cervical spine, and one or more sites on the scalp. The primary purpose of the recording sites on the extremities and over the plexus is to verify the presentation of a peripheral stimulus that is adequate to elicit recordable SSEPs. A technical problem such as a stimulator malfunction or a displaced stimulation electrode may be easily diagnosed using either of these

recording sites. The recording site over the cervical spine may be the most important SSEP recording site because the responses are usually from a location(s) above the sites at risk and are generally unaffected by the anesthetic drugs used for patient management. When the recording site over cervical spine is not available (such as when it is in the surgical field), these responses may be recorded from one earlobe or linked earlobes. These responses have several peaks as a result of multiple generator sites. The N13 peak has multiple generators, some of which are below the medulla and some at the cervico-medullary junction. The P14 which is better-recorded in the Cz-linked ears reference is clearly generated above the level of the spine. When the cervical responses are adequate for monitoring purposes, the cortical responses serve as a backup, but are very susceptible to the effects of the anesthetic drugs commonly used for patient management. Therefore, these responses may exhibit significant changes during surgery that are not a result of the surgeon's activities. Therefore, attention must be paid to the drugs being used. Good communication is therefore necessary between the anesthesia and monitoring teams; particularly if the cortical responses become important for monitoring purposes. It must also be remembered that SSEPs assess sensory function mediated only by the dorsal column pathways, and not motor function. Therefore, surgical insults to the anterior spinal cord or blood supply to the anterior spinal cord may not be detected by SSEPs.

Surgical application examples include the following: anterior and posterior cervical spinal fusions.

5.3.2. Thoraco-lumbar

Upper-extremity SSEPs, although insensitive to changes in thoraco-lumbar spine function, can be useful for detecting functional changes associated with arm positioning during thoraco-lumbar surgical procedures. In addition, when changes in lower-extremity SSEPs occur, the status of upper-extremity SSEPs can provide important information regarding the effects of the anesthetic drug management for interpreting these changes.

Surgical application examples include the following: scoliosis/kyphosis correction and repair, abdominal aortic aneurysm repair (AAA), removal of spinal cord tumor, spinal fracture repair, and arteriovenous malformation repair.

5.4. *Thalamus and brainstem*

SSEP pathways traverse the brainstem as they project up to the thalamus. Occasionally, tumor-removal may risk damage to these pathways and the acquisition of SSEPs are a useful monitoring modality [18, 73]. However, in most cases, monitoring of SSEPs is of secondary importance to the monitoring of the function of various cranial nerves. SSEPs can be used to determine the location for making a thalamic lesion or implanting a deep brain stimulator in the thalamus for alleviating tremor in patients with Parkinson's disease[74].

Surgical application examples include the following: craniotomy for removal of C-P angle tumor, and thalamotomy for decrease of Parkinsonian tremor.

5.5. *Brain*

During various surgical procedures when brain function is at risk, it is common to monitor these procedures using SSEPs alone or in conjunction with recordings of EEG activity [19–22, 33, 35, 75–81]. Loss of function can result from surgical removal or manipulation of neural tissue or tissue ischemia. Occasionally, the location of a tumor is near the sensory-motor area of the brain. When removing the tumor, a surgeon would prefer to spare the motor area. However, it is often difficult to delineate these areas based on visual inspection of the cortical surface. However, it is known that recordings of upper-extremity SSEPs will demonstrate polarity inversion as the responses are recorded from sensory and then motor cortex. Using a technique known as electrocorticography, SSEP responses are recorded from the brain surface using a grid of recording electrodes. By recording the SSEP responses from each grid electrode, the locations where polarity inversion occurs can be mapped and the location of the sensory and motor areas can be determined.

Some surgical procedures can place brain function at risk as the result of an ischemic event. These procedures include craniotomies for aneurysm clipping or arteriovenous malformation, and carotid endarterectomies. For both types of procedures, SSEPs are often recorded in conjunction with processed or unprocessed EEG activity. The location of an aneurysm will generally define what areas of the brain are at risk for an ischemic event and what SSEPs may be helpful for monitoring purposes. For instance, the middle cerebral artery (MCA) provides blood to the sensory area for the hand, whereas the anterior cerebral artery (ACA) provides the blood supply to the sensory area for the leg. Clipping of a middle cerebral artery aneurysm could result in a misplaced clip and compromised blood flow within the MCA, or within lenticulostriate perforating vessels from the MCA that supply the thalamus and the white matter. As a result, the misplaced clip could result in a loss of the contralateral upper-extremity SSEPs, but could also result in a loss of the lower-extremity SSEPs if blood flow in the perforating vessels is compromised. On the other hand, when clipping an ACA aneurysm, a misplaced clip may result in

a significant change in the contralateral lower-extremity SSEPs, with no change in the upper-extremity SSEPs. Such changes may or may not occur in conjunction with similar EEG changes. Carotid occlusion may affect both upper- and lower-extremity SSEPs. However, it should be pointed out that there are limitations to the use of SSEPs for vascular procedures. Their use is only sensitive to ischemic events which affect the SSEP-generator sites. SSEPs may therefore be insensitive to ischemic events in other areas of the brain which receive their vascular supply from branches of the above-mentioned arteries.

Surgical application examples include the following: craniotomy for tumor removal, craniotomy for aneurysm repair, carotid endarterectomy, and localization of motor cortex during craniotomy (corticography).

6. MAJOR RECOMMENDATIONS SUMMARY

A. The ASNM strongly supports the position that the acquisition and interpretation of intraoperative SSEPs be done by qualified individuals. It agrees with the guidelines of other professional societies regarding the technical and professional qualifications of individuals responsible for SSEP acquisition and interpretation. It supports the use of the ABRET® certification examination as a means for assessing the technical qualifications of individuals responsible for intraoperative SSEP acquisition, and the use of the ABNM certification examination as a means for assessing the qualifications of individuals responsible for intraoperative SSEP interpretation and professional oversight of intraoperative monitoring activities. (Class III evidence, strong Type C recommendation.)

B. On the basis of current clinical literature and clinical and scientific evidence, somatosensory evoked potentials (SSEPs) are an established intraoperative monitoring modality for either localizing the human sensorimotor cortex or assessing the function of the somatosensory pathways during surgical procedures in the spinal cord and cerebrum. (Class II and III evidence, Type A recommendation)

C. On the basis of current clinical literature and the opinions of most experts, SSEPs have limitations as an intraoperative monitoring tool. These include the following:

   1. SSEPs are an effective means of monitoring cortical function during various cerebrovascular surgical procedures (i.e., carotid endarterectomies, clipping of intracranial aneurysms of the anterior vessels of the circle of Willis). Other monitoring techniques such as analog and computer-processed electroencephalography and/or transcranial doppler techniques may provide additional information in the appropriate clinical situation (Class II and III evidence, Type B recommendation)
   2. SSEPs may provide indirect information about motor pathway function. Other techniques that directly monitor motor pathway function may provide additional information in the appropriate clinical situation. (Class II and III evidence, Type B recommendation)
   3. SSEPs are affected by commonly-used anesthetic drugs and physiological parameters. This is particularly true for cortical SSEP responses and less so for subcortical responses. Monitoring of spinal cord and cerebral function should include:

      a. the use of cortical and subcortical recording sites. (Class II evidence, Strong Type B recommendation)
      b. documentation of anesthetic dosages and physiological parameters. (Class II evidence, Strong Type B recommendation)

   4. The sensitivities of mixed-nerve SSEPs and dermatomal SSEPs (DSSEPs) for assessing spinal nerve root function are controversial. Other techniques which utilize spontaneous and triggered myogenic activity may be more efficacious in the appropriate clinical situation. (Class III evidence, Type E recommendation)

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