Somatosensory-Evoked Potentials

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Key Learning Points

- The ultimate goal of intraoperative somatosensory-evoked potential (SSEP) monitoring is to ensure maintenance of neurologic integrity in a portion of the central nervous system (CNS) throughout a procedure with resultant improved outcome and decreased morbidity.
- Consensus is that standard SSEP recording monitors solely the dorsal column pathway, which mediates mechanoreception and proprioception. However, other pathways not monitored by SSEPs may contribute to somatosensory function, including the dorsal spinocerebellar tract, the anterolateral columns, the postsynaptic dorsal column pathway, and the vagus nerve.
- Stimulation and recording are the two major technical aspects of SSEP monitoring; understanding the parameters that affect each is critical to successful intraoperative SSEP monitoring. Stimulation parameters include electrode type, electrode placement, stimulus intensity, stimulus duration, stimulus rate, and unilateral versus bilateral stimulation. Recording parameters include electrode type, electrode placement (recording montage), and specific equipment parameters, which include channel availability, filters, averaging, and time base.
- Most anesthetic agents have detrimental effects on SSEPs, while a select few have beneficial effects. In general, cortical effects are more pronounced than peripheral effects.
- Several physiologic variables can affect the success or failure of SSEP monitoring, including patient temperature, blood pressure, hemoglobin levels, intracranial pressure, oxygenation, and ventilation.
- Reproducible baseline waveforms are crucial in SSEP monitoring. Evidence-based recommendations on when to intervene when SSEP monitoring is altered from baseline are difficult to provide due to the low specificity of SSEP monitoring. Classically, warning criteria that warranted intervention were a 50% amplitude reduction and/or a 10% increase in latency, not attributable to anesthetic or physiologic cause. More recent recommendations suggest that abrupt and visually obvious amplitude reductions, accounting for baseline drift, warrant intervention.

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Introduction

Intraoperative application of evoked potentials has evolved during the past 40 years, and somatosensory-evoked potential (SSEP) monitoring is the method most employed [1]. The goal of intraoperative SSEP monitoring is to ensure maintenance of neurologic integrity throughout a procedure with resultant improved outcome and decreased morbidity.

The premise of evoked potential generation is simple. When neural tissue is stimulated, either by true sensory or artificial electrical stimulation, ascending electrical impulses—or volleys—are transmitted through synapses via neural pathways. Depending on stimulation site and recording location, a characteristic waveform morphology of the ascending potential is generated. Near-field potentials result when the neural impulse passes immediately beneath the reference electrode. Far-field potentials result from impulses distant to the recording electrodes. SSEPs are, in general, mixed-field potentials [2]. The value of intraoperative SSEP monitoring is derived from consistent, reproducible, and recognizable waveforms such that meaningful conclusions can be extrapolated from data for surgical guidance. An appreciation of the anatomy and the technical aspects of SSEPs is required for this consistency and successful intraoperative employment.

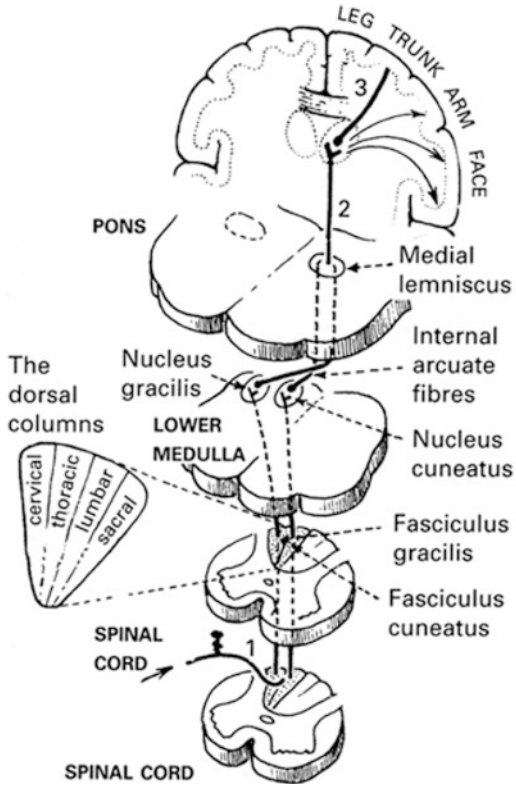
Anatomy and Vascular Supply

The somatosensory system consists of the dorsal column–lemniscal pathway (Fig. 1.1), or posterior column pathway, and the spinothalamic pathway. The former pathway mediates mechanoreception and proprioception, whereas the latter mediates thermoreception and nociception. The consensus is that standard SSEP recording monitors solely the dorsal column pathway. However, other pathways may contribute to somatosensory function, including the dorsal spinocerebellar tract, the anterolateral columns, the postsynaptic dorsal column pathway, and the vagus nerve [1, 3, 4].

The pathway of the dorsal column–lemniscal tract begins with peripheral receptor stimulation of a first-order neuron in the dorsal root ganglia. This afferent volley is transmitted via the ipsilateral posterior spinal cord in the form of the fasciculus gracilis and cuneatus to the medullary nuclei located in the cervicomedullary junction to synapse on second-order neurons. These second-order neurons decussate in the medulla as the internal arcuate fibers and ascend as the medial lemniscal pathway to third-order neurons in the ventroposterior nuclei of the thalamus, maintaining a somatotopic arrangement. Projections from the thalamus proceed to the sensorimotor cortex, where additional synapses are formed. Synapses are believed to be the site of action for inhalational anesthetics; thus, the very short-latency SSEP response is minimally affected by inhalational anesthetics. However, as the volley ascends the dorsal column–lemniscal pathway and more synapses occur en route to the cortex, cortical SSEPs are increasingly susceptible to the effects of inhalational anesthetics (see Chap. 17 for more discussion on anesthetics) [1, 3–5].

Perfusion to the dorsal column–lemniscal pathway is typically supplied by the posterior spinal arteries in the spinal cord. The posterior spinal artery originates from the vertebral arteries and travels bilaterally the length of the spinal cord in the posterior lateral sulci, supplying the posterior one-third of the spinal cord, including the posterior horns as well as the dorsal column–lemniscal pathway [6]. The anterior spinal artery, also arising from the vertebral arteries, supplies the anterior and anterolateral two-thirds of the spinal cord, including the anterior horns, spinothalamic tracts, and corticospinal tracts. However, there is a great degree of individual variability in origin of vascular supply for both the posterior and anterior spinal arteries, with each being supported by a varying number of radicular arteries, particularly in the thoracic spinal cord. Chapter 36 (“Aortic Interventions”) discusses blood supply of the spinal cord in greater detail.

As the dorsal column–lemniscal pathway ascends to the medullary nuclei of the brainstem, perfusion is supplied from both the vertebral artery and perforating branches of the basilar artery. While the somatosensory cortex maintains somatotopic arrangement, blood supply is divided into the anterior and middle cerebral



DORSAL COLUMN PATHWAY

1. Fibres enter in the root entry zone and run upwards in the *dorsal columns* to the *lower medulla* where they terminate in the *nucleus gracilis* and *nucleus cuneatus*.
2. *Second order neurons* decussate as the *internal arcuate fibres* and pass upwards in the *medial lemniscus*. Maintaining a *somatotopic arrangement*, they terminate in the ventral posterolateral thalamus.
3. *Third order neurons* arise in the thalamus and project to the *parietal cortex*.

Fig. 1.1 The dorsal column pathway. (*1*) Fibers enter in the root entry zone and run upward in the dorsal columns to the lower medulla where they terminate in the nucleus gracilis and nucleus cuneatus. (*2*) Second-order neurons decussate as the internal arcuate fibers and pass upward in the medial lemniscus. Maintaining a somatotopic arrangement, they terminate in the ventral posterolateral thalamus. (*3*) Third-order neurons arise in the thalamus and project to the parietal cortex. (From Lindsay and Bone [92]; with permission)

arteries. The anterior cerebral artery supplies the cortex representing the lower extremity while the middle cerebral artery supplies the cortex supplying the face, head, neck, trunk, and upper extremity.

Venous drainage is provided by a large venous network encircling the spinal cord. This network flows to either the median posterior or anterior spinal veins. Venous blood then flows through numerous radicular veins and ultimately to the azygous and pelvic venous systems [6, 7].

Methods

As mentioned, the foremost goal of SSEP monitoring should be consistency. Achieving this consistency requires manipulation of the two major technical aspects of acquiring SSEPs: stimulation and recording. The following recommendations are based largely on published guidelines from American Society of Neurophysiological Monitoring [1] as well as more recent recommendations from the International Society of Intraoperative Neurophysiology [3].

Stimulation

To achieve consistent intraoperative SSEP monitoring, adequate stimulation must be applied. Stimulation parameters include electrode type, electrode placement, stimulus intensity, stimulus duration, stimulus rate, and unilateral versus bilateral stimulation. The specific hardware and software employed for stimulation and recording exists in a variety of commercially available units [1, 2, 8, 9].

The first step to meaningful intraoperative SSEP monitoring is stimulating appropriate nerves for a given operation. In general [1, 8], nerves chosen for intraoperative SSEP monitoring should be below, with recording sites above, the area at risk from surgery such that the monitored pathway travels through the neural area at risk. For example, during corrective thoracic scoliosis surgery, monitoring solely upper extremity SSEPs would be insufficient as the lower extremity dorsal column tract through the spinal cord would not be assayed. For this example, it would be useful to monitor the upper extremity SSEPs for position-related injury. The upper extremity SSEPs would also provide useful information for interpreting the lower extremity SSEPs. For example, a significant amplitude reduction throughout all waveforms is more likely to be related to anesthetic or physiologic parameters than if the amplitude change occurred in only the lower extremity SSEPs.

From a hardware standpoint, successful SSEP monitoring begins with proper electrode selection. Stimulation electrode options include bar electrodes, electroencephalogram (EEG) metal disk electrodes, subdermal needle electrodes, and adhesive surface electrodes. While each has advantages and disadvantages, adhesive surface electrodes are typically used intraoperatively as they are non-invasive and adhere reliably throughout the dynamic intraoperative period (including patient position changes and patient edema). Subdermal needle electrodes are also commonly used by many providers, especially when stimulation must occur within the sterile field as they can be placed intraoperatively in a sterile fashion by the surgeon. Subdermal needle electrodes are also recommended in cases where stimulation needs to occur closer to the nerve (e.g., obese or edematous patients).

Correct placement of stimulation electrodes with respect to the nerve is also critical to adequate stimulation and subsequent stable SSEPs. Placement is dependent on both the electrode being used and the nerve being stimulated (e.g., surface electrodes are generally placed 2–3 cm apart, whereas subdermal needles are placed 1 cm apart) [1, 2, 8, 9].

For upper extremity SSEPs, frequently used peripheral nerves include the median nerve (C5-T1) at the wrist and the ulnar nerve (C8-T1, ± C7) at the wrist or elbow. For median nerve stimulation, the cathode is placed over the median nerve 2–4 cm proximal to the wrist crease, and the anode is placed 2–3 cm distal over the median nerve (Note: The cathode is the proximal electrode connected to the negative pole of the stimulator; the anode is the distal electrode connected to the positive pole; this convention is used to avoid a phenomenon known as anode blocking). For ulnar stimulation at the wrist, the cathode is placed 2–4 cm proximal to the wrist crease and the anode is placed 2–3 cm distal, both over the ulnar nerve. Ulnar nerve stimulation at the elbow begins by locating the ulnar groove. The cathode is then placed 2 cm proximal to the elbow crease at the ulnar groove, while the anode is placed 2–3 cm distal over the ulnar nerve. For these mixed nerves, corresponding muscle twitch (i.e., thumb adduction) with stimulation confirms appropriate electrode placement and adequate sensory stimulation [1, 8, 9].

Lower extremity peripheral nerves commonly used for intraoperative monitoring include the posterior tibial nerve (L4–S3) at the ankle and the peroneal nerve (L4–S2) at the head of the fibula. For posterior tibial nerve stimulation, the cathode is placed between the medial malleolus and the Achilles tendon, just proximal to the malleolus; the anode is placed 2–3 cm distal over the posterior tibial nerve as it courses around the medial malleolus. For peroneal nerve stimulation, the cathode is placed just medial to the head of the fibula. The anode is placed 2–3 cm distal. For these mixed nerves, corresponding muscle twitch (i.e., plantar toe flexion with posterior tibial nerve stimulation and eversion of the foot with peroneal nerve stimulation) with stimulation confirms appropriate electrode placement and stimulus delivery [1, 8, 9].

The electrical stimulus applied during SSEP monitoring is a series of square-wave pulses, with durations of 0.1–0.3 ms, at a given intensity [1, 3, 8]. When stimulating mixed sensory and motor nerves, the stimulus intensity is adjusted to elicit a minimal twitch of the distal muscles

innervated by the peripheral nerves. In purely sensory nerves, stimulation intensity two to three times the sensory threshold is recommended [2]. Typical intraoperative stimulation intensity ranges from 10 to 50 mA. However, stimulation intensity up to 100 mA may be required intraoperatively to elicit a reproducible, recognizable waveform, as there may be underlying pathology in addition to the deleterious effects of anesthetics on SSEPs [1].

Possible tissue damage from repeated high current at the stimulation sites warrants consideration, but the literature contains no evidence to support this concern if stimulation is within parameters on commercially available instruments for SSEP monitoring [1]. Use of constant current stimulation is recommended to compensate for any change in contact resistance. This compensation is limited by the maximum output voltage of the stimulator. With constant current stimulation, the output of the stimulator is current-limited when contact resistance is excessive. Most instruments designed for SSEP monitoring have a built-in warning for this [1, 8].

The frequency of stimulation generally ranges from 2 to 5 Hz [1, 3, 8, 9]. To decrease noise with averaging, the rate of stimulation should not be an integer multiple of the line power supply frequency (50 or 60 Hz), the most common noise frequency. When excessive noise occurs, small changes in the stimulus rate may improve the SSEP quality [1, 3, 10].

Stimulation can be unilateral or bilateral. Simultaneous bilateral stimulation can enhance SSEPs, while potentially masking unilateral changes. To effectively and simultaneously monitor both sides of an extremity pair, interleaved unilateral (alternating left and right) stimulation is recommended [1, 3]. A four-limb interleaving may show some benefit in enhancement of cortical SSEP amplitudes [3].

Recording

In conjunction with adequate stimulation, appropriate recording techniques must be employed to achieve consistent intraoperative SSEP monitoring. Recording parameters include electrode type, electrode placement (recording montage), and specific equipment parameters, which include channel availability, filters, averaging, and time base.

As with stimulating electrodes, a variety of recording electrodes are available, each with attendant advantages and disadvantages. For intraoperative SSEP recording, subdermal needles and metal disk electrodes are used most frequently. Subdermal needles are placed quickly and have minimal impedance, though they must be secured with tape or surgical staples to prevent dislodging. Metal cup electrodes take longer to secure and require conductive gel or paste. Corkscrew electrodes, like subdermal needles, are quickly placed and have the advantage of being secure. For direct cortical recording, as employed during corticography, strip or grid array electrodes are used [1, 9, 11, 12]. A ground electrode is placed between the stimulation sites and recording electrodes, usually on the shoulder [4].

As mentioned previously, recording sites for intraoperative monitoring should be proximal to the surgical area at risk, with stimulation sites distal. As the neural volley ascends the dorsal column–lemniscal pathway, different generators of the potential are recorded by various recording electrodes.

Recording electrical activity requires measurement of voltage between two electrode sites, an active electrode and a reference electrode. These electrode pairs are called recording montages, denoted by active electrode–reference electrode. In general, one cortical montage and one subcortical montage are used to record the ascending neural volley for intraoperative SSEPs. Scalp electrode locations for recording are based on the 10–20 International System of EEG electrode placement (Fig. 1.2). An additional recording site, distal to the stimulation site but proximal to the surgical site, is often used to verify peripheral conduction [1].

A recording from a given montage for a specific stimulated peripheral nerve has a characteristic waveform distribution measured in amplitude (microvolts) and latency (milliseconds). This is recorded on a graph of voltage (microvolts) versus

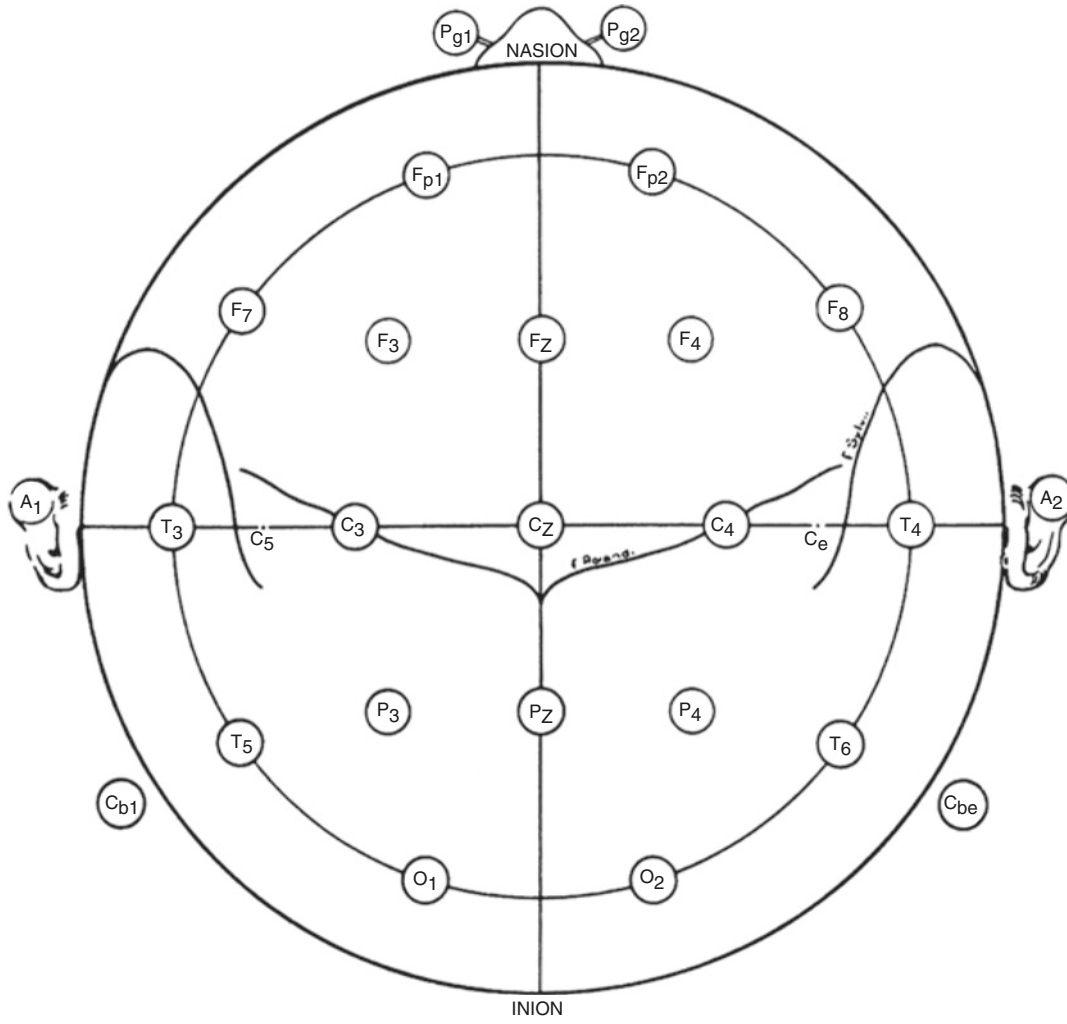


Fig. 1.2 10–20 International System of Electrode Placement. A single plane projection of the head, showing all standard positions and locations of the Rolandic and Sylvian fissures. The outer circle was drawn at the level of the nasion and inion. The inner circle represents the temporal line of electrodes. This diagram provides a useful stamp for the indication of electrode placements in routine recording. "CP" and "FP" locations are midway between the designated "C" and "P" and "C" and "F" locations, respectively; "c" and "i" indicate respective locations contralateral and ipsilateral to the side of stimulation, respectively. (From Klem et al. [93]; with permission)

time (milliseconds) and represents the SSEP. In general, this characteristic morphology is from potential changes between the electrodes of the montage as the volley of the SSEP passes beneath. These sites are referred to as the generators of the waveform. Waveforms are labeled "N" and "P" to represent the polarities of the signal (generally, negative is up and positive is down, although the specific convention used may vary by individual) followed by an integer to represent the post-stimulus latency of the wave in normal adults. For example, for cortical recording from median nerve stimulation, characteristic peaks N20 (a negative, or upward, deflection at about 20 ms) and P22 (a positive, or downward, deflection at about 22 ms) define the amplitude of the waveform (Figs. 1.3 and 1.4). The generators of these peaks are thought to be the thalamus and somatosensory cortex [1, 8].

For upper extremity peripheral nerve stimulation, there are several montages commonly used

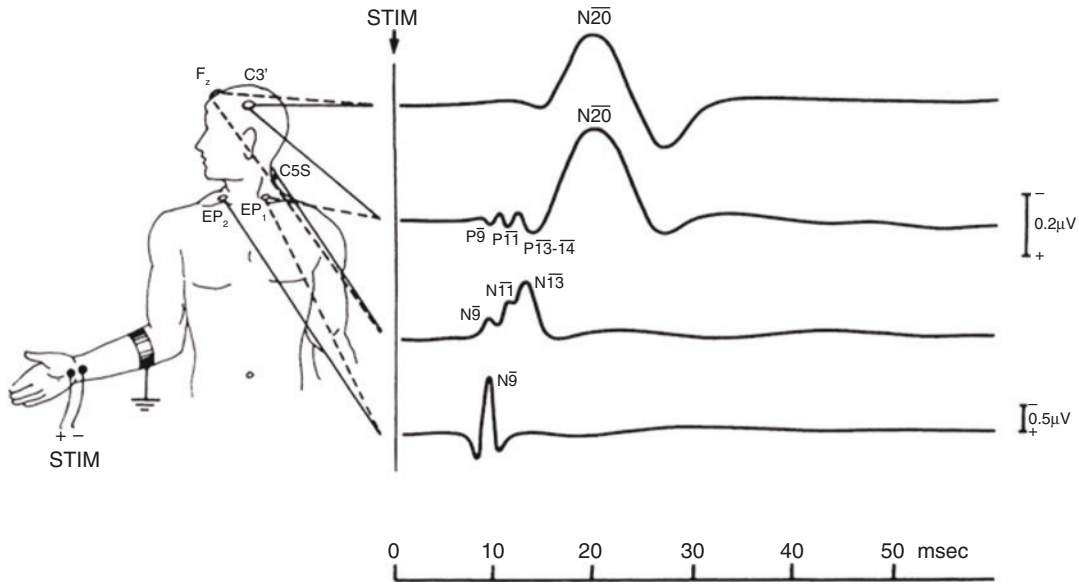


Fig. 1.3 Schematic diagram of normal SSEPs to arm stimulation. Tracings are obtained from the regions identified on the anatomic model. (From Misulis and Fakhoury [2]; with permission)

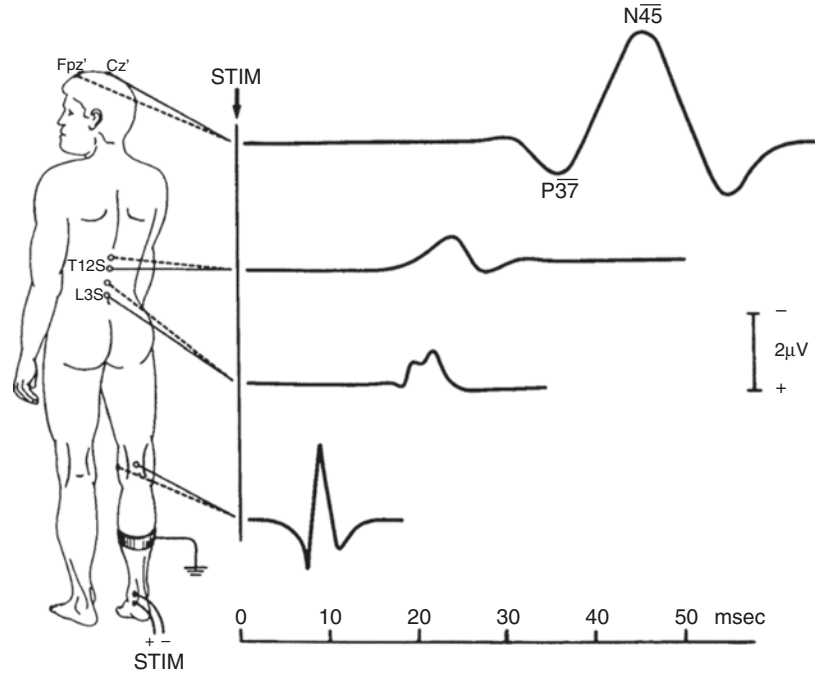


Fig. 1.4 Normal posterior tibial nerve SSEPs. Traces from bottom to top show popliteal fossa potential, lumbar potential, low thoracic potential, and scalp potential. (From Misulis and Fakhoury [2]; with permission)

for cortical recording. The responses recorded are most likely generated by the thalamus and somatosensory cortex. Since cortical responses are characteristically sensitive to general anesthetics, and because patients in the operating room may have underlying neurologic injury, different montages may be used to enhance cortical response amplitude. Montages include CP3-Fz or CP3-CP4 for right arm stimulation, and CP4-Fz or CP4-CP3 for left arm stimulation. [1, 3, 4, 9].

For subcortical recording of upper extremity peripheral nerve stimulation, response generators vary with the montage used and include the spinal cord, the cervicomedullary junction, higher parts of the brainstem, and the thalamus. Common montages include CPi–Erbc (Erb's point contralateral to the stimulus), CvN–Fz (posterior spinal cervical electrode over the Nth cervical spinous process, typically C6 or C7), Fz–A1/A2 (linked ear electrodes), Cz–A1/A2, and FPz–A1/A2 [2, 3, 4, 9].

Cortical recording of stimulation of lower extremity peripheral nerves represents generators of the neural volley in the somatosensory cortex. Recording montages used include CPz–2 cm posterior to Cz, CPz–Fz, CPz–CPc, and FPz–Cz [2, 3, 4, 9].

The generator source(s) of far-field subcortical potentials from lower extremity peripheral nerve stimulation are thought to lie in the brainstem. Recording montages to acquire these potentials include CPi–A1/A2, CvN–Fz, and FPz–A1/A2 [2, 3, 4, 9].

Peripheral recording of the nerve volley distal to the stimulation site but proximal to the surgical site can confirm the conduction of the peripheral stimulus. For lower extremity SSEPs, this site is the ipsilateral popliteal fossa—one electrode at the popliteal fossa (4–6 cm above crease) and the other placed 2–4 cm proximal. For upper extremity SSEPs, this site is the ipsilateral Erb's point (2 cm above the midpoint of the clavicle and at the posterior border of the head of the sternocleidomastoid muscle) referenced to the contralateral Erb's point or a scalp electrode, often Fz [1, 4, 9].

After acquisition of the evoked potential, some signal manipulation is required to distinguish the evoked potential from background noise such as spontaneous EEG activity, electrocardiogram (ECG) activity, muscle activity, or 60 Hz noise. Amplifiers are used to increase the size of the biologic signal, while filters are used to reduce noise. The signal is averaged over repeated stimuli to increase the signal-to-noise ratio [1, 3].

Filters should be set to provide quality potentials with the least amount of averaging. Low-frequency (high pass) and high-frequency (low pass) filter settings are combined to eliminate non-physiological components of the acquired potential being studied. For most instruments, the standard settings are 20 Hz for the low-frequency filter and 3000 Hz for the high-frequency filter. Maintaining standard settings allows a laboratory to make meaningful comparisons for any given patient to laboratory normal value [1, 3].

However, since intraoperative potentials are also compared to a patient's baseline recorded earlier in the case, other suggested settings specific to either cortical or subcortical potentials have been suggested. For cortical potentials, these suggested filter settings are 1–30 Hz for the low-frequency filter and 250–1000 Hz for the high-frequency filter. For subcortical potentials, 30–100 Hz and 1000–3000 Hz are suggested, respectively. To improve cortical SSEPs, setting the high-frequency filter as low as 300–500 Hz may help decrease artifact as the relative frequency content of cortical potentials is lower than subcortical potentials. The 60-Hz rejection filter should be reserved as a last resort to improve SSEPs as it can cause "ringing artifact" [1, 3, 8, 9].

Recorded potentials are averaged over repeated stimuli to increase the signal-to-noise ratio. Guidelines have suggested acquiring 500–2000 trials per averaged response [1, 3, 8, 9]. However, the signal-to-noise ratio and need for prompt intraoperative reporting may dictate the number of trials averaged. The optimal choice of montage allows the largest signal-to-noise ratio, which minimizes the number of averages needed and the acquisition time of a response [11–14]. In addition, in a rare patient, the somatosensory fibers are uncrossed such that the ipsilateral and contralateral cortices need to be evaluated for the maximal amplitude [15].

The time base (milliseconds) for waveform display also needs to be appropriate for the given potential. Generally, this means 50 ms for upper extremity potentials and 100 ms for lower extremity potentials [1]. Also, in the presence of underlying abnormal neurologic function and subsequent increased latency of SSEPs, the time base may need to be increased to adequately acquire and display the evoked potential.

Intraoperative Variables Affecting SSEPS: Pharmacology and Physiology

In addition to the stimulation and recording parameters discussed earlier, pharmacologic and physiologic variables can also significantly affect the reliable recording of evoked potentials. Understanding how these variables influence the process is essential to successful intraoperative SSEP monitoring.

Anesthetic drugs have various effects on SSEP amplitude and latency. While the mechanisms of action for specific anesthetic drugs differ along with each drug's effect on SSEPs (i.e., some drugs enhance SSEPs, while most decrease SSEPs), all anesthetics share a general mechanism of action by altering either the function of synapses or axonal conduction to change neuronal excitability (see Chap. 17) [5, 16]. As the number of synapses in a pathway increases, the effect of a given anesthetic drug on the SSEP is more pronounced. Therefore, cortical potentials are more sensitive than subcortical, spinal, or peripheral nerve recordings to anesthetic effects [1, 5, 17]. This includes both deleterious and augmentative effects on SSEPs.

Inhalational Anesthetics

Halogenated inhalational agents produce a dose-related reduction in amplitude and increase in latency of SSEPs. This SSEP decrement is more pronounced for cortical recordings than subcortical, spinal, or peripheral recordings [1, 5, 17]. Some limited studies espouse the ability to effectively monitor SSEPs using a mixed intravenous-volatile anesthetic [18]; however, this remains controversial.

Nitrous oxide decreases cortical SSEP amplitude and increases latency [19, 20]. This effect is synergistic with halogenated inhalational agents and most intravenous anesthetics [1, 5, 17, 20, 21]. For example, with equipotent doses, nitrous oxide combined with halogenated agents produces a greater decrease in amplitude and increase in latency of the cortical SSEP [14, 20]. As with halogenated agents, the effect on subcortical and peripheral SSEPs is minimal [1, 5, 17, 20]. In small studies the noble gas Xenon, when used as an anesthetic, has been shown to reduce amplitude but not latency in SSEPs [22].

Intravenous Anesthetics

In general, the intravenous drug effects on SSEPs are less than those from inhalational agents. With the exceptions of etomidate and ketamine, minimal effects on cortical SSEPs are seen with low doses of intravenous anesthetics, although this is dependent on the route of administration (bolus versus infusion, for example). Moderate reduction in amplitude and increase in latency are seen with higher doses, again with the exceptions of etomidate and ketamine. Most intravenous agents have negligible effects on subcortical SSEPs. The following provides details for specific intravenous anesthetic effects on SSEPs.

Barbiturates produce a short-term dose-dependent reduction in amplitude and increase in latency of cortical SSEPs, with little effect on subcortical and peripheral SSEPs [1, 5, 17, 23]. Specifically, the SSEP decrement for induction doses of thiopental lasts less than 10 min [19, 23–25]. Infusion of methohexital as part of a total intravenous general anesthetic has been shown to provide excellent conditions for SSEP monitoring [26]. Even at doses causing EEG suppression, barbiturates allow the monitoring of cortical SSEPs [1, 5, 23, 27–30].

Propofol influences SSEPs in a similar manner to that of barbiturates but with desirable rapid emergence after prolonged infusion. As a one-time induction dose, there is no change in amplitude for cortical and subcortical SSEPs from median nerve stimulation, but there is a mild increase in cortical latency [23, 31]. Propofol induction and infusion causes cortical amplitude reduction with recovery after infusion termination [5, 32]. Propofol has no effect on

epidural-evoked potentials [5, 33]. Combined with opioids, propofol produces less cortical amplitude depression than nitrous oxide or midazolam [1, 23, 34–37]. Compared to equipotent doses of halogenated agents [1, 4] or nitrous oxide [1, 38], the amplitude decrement is less with propofol. As part of a balanced total intravenous anesthetic, propofol is compatible with intraoperative monitoring of SSEPs [1, 5, 23, 35, 39, 40].

Etomidate and ketamine are unique in that they increase cortical SSEP amplitude. Etomidate produces a marked increase in cortical amplitude and a mild increase in cortical latency [1, 5, 17, 19–21, 23, 24, 39]. Etomidate's effects on subcortical amplitude vary from no change to mild reduction [1, 5, 17, 21, 23, 24, 39, 40]. Despite this potential for subcortical SSEP amplitude reduction and variable peak specific effects on latency, infusion of etomidate as part of a total intravenous general anesthetic has been used to improve cortical SSEPs [5, 41, 42], even when intraoperative monitoring was otherwise unobtainable [5, 41]. Etomidate has the drawback of adrenal suppression.

Ketamine increases cortical SSEP amplitudes with no change in cortical latency or subcortical potentials [1, 5, 23, 43, 44]. The addition of nitrous oxide [5, 43] or enflurane 1.0 MAC [5, 45] to a ketamine anesthetic decreases SSEP amplitude by approximately 50%. However, ketamine has been used successfully as part of a balanced anesthetic with midazolam and nitrous oxide for intraoperative SSEP monitoring during spine surgery [23, 46] and is an acceptable component of total intravenous anesthesia (TIVA) for SSEPs [1, 4]. Drawbacks to ketamine include hallucinations, long half-life with subsequent prolonged emergence, sympathomimetic effects, and increased intracranial pressure in the setting of intracranial pathology.

The alpha-2 agonists clonidine and dexmedetomidine are anesthetic agents with a broad spectrum of applications. Adjuvant clonidine [23] and dexmedetomidine [23, 47–50] use is compatible with intraoperative SSEP monitoring.

In general, systemic opioids mildly decrease cortical SSEP amplitude and mildly increase latency with minimal effect on subcortical and peripheral potentials [1, 5, 20, 23, 51]. Bolus dosing of opioids has a greater impact on SSEP changes than continuous infusion [1]. Therefore, opioid infusions are an important component of anesthesia for intraoperative SSEP monitoring. Remifentanil is often used as it has a short context sensitive half-time and promotes rapid emergence. Neuraxial opioids, excluding meperidine, have minimal or no effect on SSEPs [5, 17, 23, 52–55]. The decreased cortical amplitude and increased cortical latency seen with subarachnoid meperidine [23, 52] are likely secondary to its local anesthetic-like qualities. Neuraxial opioid-only techniques can augment analgesia without affecting intraoperative SSEP monitoring.

Benzodiazepines have mild depressant effects on cortical SSEPs [1, 5, 23]. In the absence of other agents, midazolam causes mild to no depression of cortical SSEPs, a moderate increase in N20 latency, and minimal to no effects on subcortical and peripheral potentials [1, 5, 21, 56]. Used as an intermittent bolus or continuous infusion (50–90 μg/kg/h) to promote intraoperative SSEP monitoring [1], midazolam is useful to promote amnesia with TIVA and to ameliorate hallucinations with ketamine [17].

Droperidol, a sedative-hypnotic used in neuroanesthesia, has minimal effects on SSEPs [1, 5, 17]. Concern for QT prolongation is a consideration.

Neuromuscular blocking agents commonly used during general anesthesia do not directly affect SSEPs. However, by decreasing electromyographic artifact and/or interference from muscle groups near recording electrodes, neuromuscular blockers may increase the signal-to-noise ratio and improve the quality of SSEP waveforms [5, 23, 57].

Perioperative infusion of systemic lidocaine is used to decrease postoperative pain. Infusion of relatively high-dose lidocaine has been shown to decrease cortical SSEP amplitude and increase latency [58], while lower infusion rates have been shown to have no effect [59].

Summarizing pharmacologic effects, intravenous anesthetic agents are more compatible with intraoperative monitoring of SSEPs than inhala-

tional agents. While inhalational agents have been used in low dose combined with other intravenous agents, TIVA is preferred for consistent intraoperative SSEP monitoring in patients with small-amplitude SSEPs. Also, motor-evoked potentials (MEPs) are frequently paired with intraoperative SSEP monitoring and are extremely sensitive to inhalational agents, often requiring TIVA. TIVA can be any combination of intravenous drugs for end-effects of hypnosis, amnesia, analgesia, optimal surgical conditions (i.e., an immobile patient), and quick metabolism for an immediate postoperative neurologic examination. A typical infusion combination is propofol and remifentanil with intermittent midazolam, with or without muscle relaxant. However, as mentioned previously, various other hypnotic and opioid drugs may be used. To help ensure amnesia, a monitor of anesthetic depth may be useful (see Chaps. 10 and 17 for additional information about anesthesia considerations).

The physiologic milieu of an intraoperative patient is very dynamic and can affect SSEP amplitude and/or latency.

Temperature

Changes in body temperature can affect SSEPs. Mild hypothermia increases cortical SSEP latency but has little effect on cortical amplitude and subcortical or peripheral responses [1]. Mild hypothermia (down to 32 °C) may even be associated with increased cortical amplitudes [60–62]. With profound hypothermia, cortical SSEPs disappear. Subcortical, spinal, and peripheral responses may remain with increased latency, but they also disappear at lower temperatures [1, 63]. Rewarming improves the latencies but not in the reverse trajectory as cooling [1, 23]. Mild hyperthermia (39 °C) is associated with a decrease in cortical and subcortical latencies with no change in amplitudes [23, 64].

Like core temperature, local temperature changes at anatomic sites can affect SSEPs. For example, temperature changes at the surgical site from surgical exposure or cold irrigation in the surgical field can affect SSEPs. Also, stimulating an extremity exposed to cold intraoperative temperatures, with or without cold intravenous fluid infusing, may affect SSEPs [5].

Tissue Perfusion

Changes in blood pressure can affect tissue perfusion and thus can affect SSEPs. If cerebral perfusion is insufficient to meet basic metabolic demand, cortical SSEP amplitude begins to diminish. With normothermia, this occurs when cerebral perfusion decreases to about 18 cm^3/min/100 g of tissue [1, 5, 17, 65–67]. Further reductions in perfusion below approximately 15 cm^3/min/100 g of tissue can cause loss of cortical SSEPs [1, 5, 55, 57, 65–67]. Subcortical responses are less sensitive to reductions in tissue perfusion.

Regional ischemia, with or without any degree of systemic hypotension, can be caused by local factors that can affect SSEPs. Examples include spinal distraction, surgical retractor-induced ischemia, position ischemia, tourniquet-induced ischemia, ischemia from vascular injury, and vascular clips (either temporary or permanent) [5, 68–70].

Oxygen delivery is affected by changes in hematocrit, which alters oxygen-carrying capacity and blood viscosity. Primate data reveal that in general, mild anemia produces an increase in SSEP amplitude. Primate data also reveal that reductions in hematocrit beyond mild anemia cause further SSEP amplitude reduction and increase in SSEP latency [5, 23, 71, 72].

Oxygenation/Ventilation

Variations in both oxygen and carbon dioxide levels can affect SSEPs. Mild hypoxemia does not affect SSEPs [5, 73]. A decrease in SSEP amplitude was reported as a manifestation of intraoperative hypoxemia [74]. Up to a $PaCO_2$ of 50 mmHg, hypercarbia has no effect on human SSEPs [23, 75]. Cortical amplitude augmentation and a mild decrease in latency occur with hyperventilation in awake volunteers [23, 73].

However, in isoflurane-anesthetized patients, hypocapnia to 20–25 mmHg caused no change in amplitude and a mild decrease in latency [23, 76].

Intracranial Pressure

Increased intracranial pressure decreases amplitude and increases latency of cortical SSEPs [5, 63]. As intracranial pressure increases, there are pressure-related cortical SSEP decrements and concurrent loss of subcortical responses with uncal herniation [5].

Other Physiologic Variables

A multitude of other physiologic factors may affect SSEPs, including fluctuations in electrolytes and glucose, total blood volume, and central venous pressure [5].

Criteria for Intervention During Intraoperative SSEP Monitoring

Reproducible, recognizable baseline waveforms are the foundation of successful intraoperative SSEP monitoring. It is from these baselines that intraoperative changes are based. The dynamic intraoperative milieu, including surgical and anesthetic influences, can make the process of SSEP monitoring challenging and complicate the interpretation of the significance of changes from baseline. Providing evidence-based alarm criteria for intraoperative changes in amplitude and latency is difficult. Intraoperative SSEP changes of 45–50% amplitude reduction and 7–10% latency increases can occur without changes in postoperative neurologic function [23, 77–79]. However, empirically, an amplitude reduction of 50% or greater and/or a latency increase of 10% or more, not attributable to anesthetic or physiologic causes, are considered significant changes warranting intervention [1, 3, 23, 80, 81]. The validity of these alarm criteria has been studied [1, 82, 83]. In addition to the degree, the duration of monitoring abnormalities also matters; postoperative patient deficits are more likely when intraoperative monitoring decrements exceed 40–60 min [84].

Dorsal Column Mapping

SSEPs have utility in intraoperative mapping during intermedullary spine surgery, providing surgeons with a path to enter the cord where a tumor might obscure the anatomy in a process called dorsal column mapping. Tumor distortion of anatomic landmarks of the spinal cord can make surgical dissection challenging; misidentification of midline may lead to dorsal column injury during myelotomy and tumor resection. Dorsal column mapping is a relatively new technique to help identify structures in the spinal cord during intramedullary tumor resection to decrease morbidity during these procedures [85]. MEPs are considered the gold standard for monitoring the motor pathways; however, SEPs can provide further specificity for assessing the integrity of the dorsal column. Typically, dorsal column sensory mapping is used in combination with MEPs [86].

Three methods for dorsal column sensory mapping have been described. SSEPs can be both evoked and recorded directly on the exposed spinal cord with direct electrical stimulation and recording with the use of a miniature epidural multielectrode [87]. The spinal cord evoked potentials (SCEPs) correspond to summation of neural activities that originate from both ascending and descending tracts near the recording electrode. As SCEP ascending sensory-related dorsal column potentials are very large in size, they potentially mask the activity of the corticospinal and other descending tracts. Thus, SCEP alone cannot provide sufficient information about motor-related function [86, 88].

A second method is the anterograde bipolar stimulation of the spinal cord with phase-reversal SSEPs recorded from C3' and C4 on the scalp. Stimulation can be performed on the dorsal column with a current kept constant at 2 mA at 2.1 Hz for a duration of 100 ms. The probe is

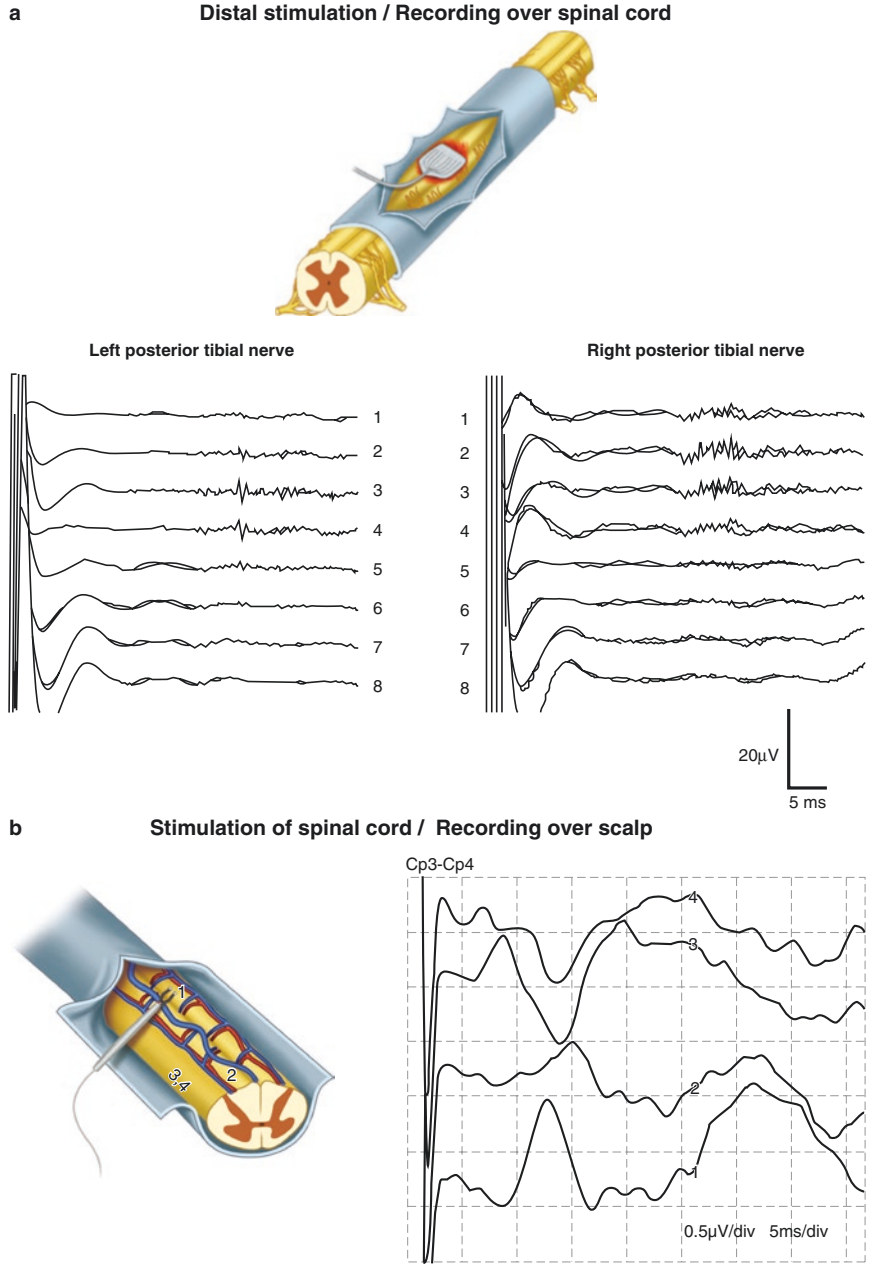


Fig. 1.5 Two methods of dorsal column mapping. (**a**) Posterior tibial nerves are stimulated in sequence and recordings of the resultant volley of action potentials are performed from the surgical field with a custom electrode placed, so that its contacts extend in a transverse orientation across the median raphe of the spinal cord. About 100–200 sweeps are averaged. In the example, the median raphe of the spinal cord lies between contacts 2 and 3. Two drawbacks of the technique are the need of a custom electrode and potential difficulties with good electrode contact across the entire exposed spinal cord. (**b**) Stimulation is applied with a bipolar stimulator at various locations that traverse the presumed median raphe. The contacts of the stimulator are aligned along the long axis of the spinal cord and stimulating current is adjusted to minimize current spread, while retaining a reproducible SSEP signal (typically 0.3–0.5 mA). Recording is performed from scalp electrodes in a transverse orientation, with additional channels required for interpretation. In the example, the median raphe is close to stimulation site 2 (trace 2), with a distinct "phase reversal" between traces 1 and 3

first placed lateral on the dorsal column and moved in steps toward the suspected midline. Once past midline, the polarity of the response will reverse. The area of the spinal cord that is not activated by stimulation is located between the reverse polarities and represents the physiological midline and safest place to perform the myelotomy [85, 89, 90].

Finally, SSEP stimulation from a peripheral nerve (usually the posterior tibial nerve), followed by recording over the dorsal column with the use of a multielectrode grid placed transversely over the dorsal surface of the cord can provide information of spinal cord anatomy. The multielectrode grid can selectively record the traveling SSEP waves from the dorsal surface of the exposed spinal cord. Due to the somatotopic distribution of ascending fibers in the dorsal column (see Fig. 1.1), the highest amplitude recorded responses represent the closest proximity to the midline. Stimulation and recording is then repeated on the contralateral side, allowing for "physiological midline" to be identified between the two amplitude peaks (Fig. 1.5) [88, 91].

Other Intraoperative Applications for SSEPs

Intraoperative SSEPs are employed for a wide range of surgeries. The common goal is to ensure maintenance of neurologic integrity throughout a procedure with resultant improved outcome and decreased morbidity. Peripheral nerves and brachial plexus monitoring can be used for surgical guidance as well as for avoidance of position-related neurapraxia during surgeries such as total hip arthroplasty and shoulder arthroscopy. Spinal cord function can be monitored during spine fusions, spinal cord tumor removal, arteriovenous malformation repair, and abdominal and thoracic aortic aneurysm repair. The brainstem and cortical structures can be monitored during tumor resection, carotid endarterectomy, and cerebral aneurysm clipping. Lastly, SSEPs can be employed intracranially to localize the border of the motor cortex during brain surgery [2] (see Chap. 9, "Brain and Spinal Cord Mapping").

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