



Intraoperative Neuromonitoring for the Spine

5

Dhritiman Chakrabarti and Deepti Srinivas

5.1 Introduction

Spine surgeries are fraught with risks of inadvertent damage to neuronal structures critical for motor and sensory functions. This is especially true with regard to complex surgeries involving tumors within the spinal cord, spine deformity corrections, and multiple level fusions. The advent of intraoperative neuromonitoring (IONM) as a safeguard against such a mishap started in the late 1970s and the early 1980s for orthopedic surgeries. Earliest papers in this regard were published by Dr. Richard Brown, a neurophysiologist, in the 1970s, and there has been a gradual growth in the acceptance and utilization of these techniques, as they became more feasible in the operating room due to technological advancement [1].

This chapter will discuss the commonly used modalities in IONM for spine surgeries including somatosensory evoked potentials (SSEP), motor evoked potentials (MEP), spontaneous electromyography (EMG), and triggered EMG. In essence all these modalities rely on stimulation of a specific neural tract at one end and capturing the response of the same at the other, with appropriate impulse and response management to get a good signal to noise ratio.

D. Chakrabarti (✉) · D. Srinivas
Department of Neuroanaesthesiology and
Neurocritical Care, National Institute of Mental
Health and Neuro Sciences, Bangalore, India

5.2 Somatosensory Evoked Potentials

SSEPs are used for monitoring the integrity of the somatosensory pathway, specifically the dorsal column. The potentials are evoked by providing a train of electrical impulses on peripheral mixed nerves—commonly median and ulnar nerves in the upper limb and posterior tibial and common peroneal nerves in the lower limb. The impulse generates two responses—one orthodromic, visible as a muscle twitch in the respective hand or foot, and one antidromic, which is carried by the neural tract to the somatosensory cortex. This antidromic response in turn can be measured anywhere along the tract—usually the lumbar, thoracic or cervical spinal cord, Erb's point for brachial plexus, and scalp for cortical responses [2].

5.2.1 Relevant Anatomy

The pathway starts at the sensory receptors of the body, travels through peripheral nerves to enter the dorsal horn of the spinal cord, and ascends up the ipsilateral dorsal column to synapse at the dorsal column nuclei at the junction of spinal cord and the medulla. The fibers from the thoracic and cervical segments (upper body) terminate at the cuneate nucleus and those from the lower body at the gracile nucleus. The fibers from

these nuclei ascend up in the medial lemniscus after crossing over contralaterally to relay in the ventral-posterior-lateral nucleus of the thalamus. Third-order neurons then travel through the posterior limb of the internal capsule to the postcentral gyrus where they are distributed in a somatotopic fashion (legs in midline with the trunk and upper limb laterally) [3].

5.2.2 Stimulus Characteristics

Stimulus is provided by either subdermal electrodes or surface electrodes, in vicinity of the nerves to be stimulated. The distance between the positive and negative electrodes should be 1–2 cm, with the negative electrode being proximal. A constant current stimulator is used, with stimulus intensity kept at a level to produce noticeable twitch in the hand/foot (if not paralyzed) or if paralyzed, increased progressively from 20 to 100 mA until a good SSEP waveform is elicited. Increase in amplitude basically increases the number of nerve fibers depolarized. The stimulus is a monophasic rectangular pulse of 100–300 μ s duration. Stimulus rates govern the time in which a good waveform is produced, but high stimulus rates have been known to reduce SSEP amplitude. Optimal rate for the upper limb is approximately 10 pulses per second (pps) and for lower limb 5 pps. Stimulus rates in multiples of the electrical line frequency (50/60 Hz) should be avoided. In patients of neuropathy, lower stimulus rates produce better waveform. Also, during bilateral monitoring alternate stimulation should be used (with a delay of 100 ms), rather than simultaneous. Filter setting should be kept at 1–5 Hz for high pass and 500 or 1000 Hz for low pass [2].

5.2.3 Response Capture

Intraoperative SSEPs are usually recorded by placing needle/corkscrew electrodes on the scalp, dorsal neck (at level of C7), or Erb's point for the upper limb and scalp or lumbar/thoracic spine for

Table 5.1 Shows electrode placements for recording SSEP waveforms

	Active	Reference
<i>Upper limb</i>		
Scalp	C3'/C4' (3 cm posterior to C3/4)	Contralateral scalp electrode; dorsal neck; Fz
Dorsal neck	Seventh cervical vertebra level	Contralateral parietal scalp
Erb's point	Above mid clavicle	Contralateral parietal scalp
<i>Lower limb</i>		
Scalp	Cz' (3 cm posterior to Cz)	Fz; Fpz; Ipsilateral mastoid; dorsal neck
Spine	Lumbar or thoracic spine (rostral to surgical site)	Upper neck; scalp
Popliteal Fossa	Popliteal fossa	Upper neck

Scalp electrode nomenclature is according to the 10–20 electrode system

the lower limb. Referencing and appropriate active electrode placement is an important aspect of SSEP monitoring. Since the final waveform is simply a subtraction of reference from the active and given the time-locked nature of SSEP waveform, proper placement of reference electrode can delineate certain peaks of SSEP waves (Table 5.1) [2].

5.2.4 Response Delineation

The problem with SSEP response is its extremely small magnitude—of the order of 2–4 μ V—compared to the background noise of electromyographic or EEG signals. To delineate the SSEP waveform, multiple impulses are fired (usually 500–2000) and responses captured as a time-locked electrical “snapshots” and then averaged. The background activity, due to its random nature, slowly gets canceled out to baseline, while the time-locked SSEP response adds up to a prominent waveform.

This time-locked nature of response creates a temporal dispersion of impulses when the nerves carrying the responses have differing conduction velocities (due to variation in fiber diameter)—

more commonly seen in lower limb SSEPs in old age, neuropathies, and poliomyelitic patients. This results in multiple peaks of different latencies and amplitudes, apart from those commonly described. Another implication is that due to longer fiber length, latencies of waves of the lower limb are longer than those of the upper limb and in patients with longer limbs than others [2].

5.2.5 SSEP Waveforms

The waveforms of SSEP can be defined by three characteristics—latency, amplitude, and orientation. The latency of the waveforms is defined by the time lag since impulse and is dependent on nerve length, diameter, myelination, and other factors determining conduction velocities. Amplitude is determined by the number of functional nerve fibers, their spatial orientation, temporal synchronicity of conduction, signal to noise ratio, and many other physiological factors. A 10% increase in latency or a 50% reduction in amplitude is a cause for alerting the surgeon intraoperatively. Orientation, i.e., positive or negative waves, is classically defined for SSEPs and does not vary if the test is conducted appropriately. Traditionally, positive or upright waves are named N, while negative or trough waves are named P, with the latency in milliseconds written in subscript. For example, N₂₀ wave means a positive wave at 20 ms after impulse. Table 5.2 lists the waveforms recorded from upper and lower limb SSEPs and their respective neural generators. Although many waveforms have been listed, the most common waveforms observed for intraoperative monitoring are a N₂₀ for median nerve and a P₄₀ for the posterior tibial, especially when only scalp electrodes are used (Figs. 5.1 and 5.2) [2].

Due to the high variability of latency and amplitudes in the population, population norms for the same are disregarded in favor of using the patient's own baseline as reference for intraoperative comparisons. Thus, the baseline should be acquired at physiologic and anesthetic conditions, which would be maintained constant throughout the surgery.

Table 5.2 Common SSEP waveforms and their genesis

	Waveforms	Neural generators
Upper limb (median nerve)	P9	Impulse volley from brachial plexus to spinal cord
	P14–16	Cuneate nucleus
	N18	Brainstem (superior colliculus)
	N20	Primary somatosensory cortex
	P22, N30 and P45	Unknown
Lower limb (posterior tibial nerve)	N17	At hip joint
	P24	At T12 vertebra
	P31	At foramen magnum
	N34	Brainstem (medial lemniscus)
	P40	Cortex

5.2.6 Anesthetic Considerations

SSEP monitoring requires stringent rules for the anesthesiologist:

1. Bolus dosing of hypnotics is not allowed; infusions are preferred for intravenous and constant dial setting for inhalational agents.
2. Propofol-based anesthesia is better than inhalational anesthesia; dexmedetomidine may be added as adjunct. Opioids may be used liberally.
3. N₂O is contraindicated.
4. Body temperature should be maintained constant near euthermia.
5. Hypotension, hypoxia, anemia, and dyselektrolytemia all influence SSEPs detrimentally and should be avoided.
6. Neuromuscular blocking agents are allowed and preferred as paralysis removes the EMG noise component.

Anything known to suppress cortical synaptic activity will have a detrimental effect on amplitude of SSEPs. In the event of intraoperative reduction in amplitude or increase in latency of the waveform compared to baseline, a thorough check for such factors should be carried out before reporting to the surgeon.

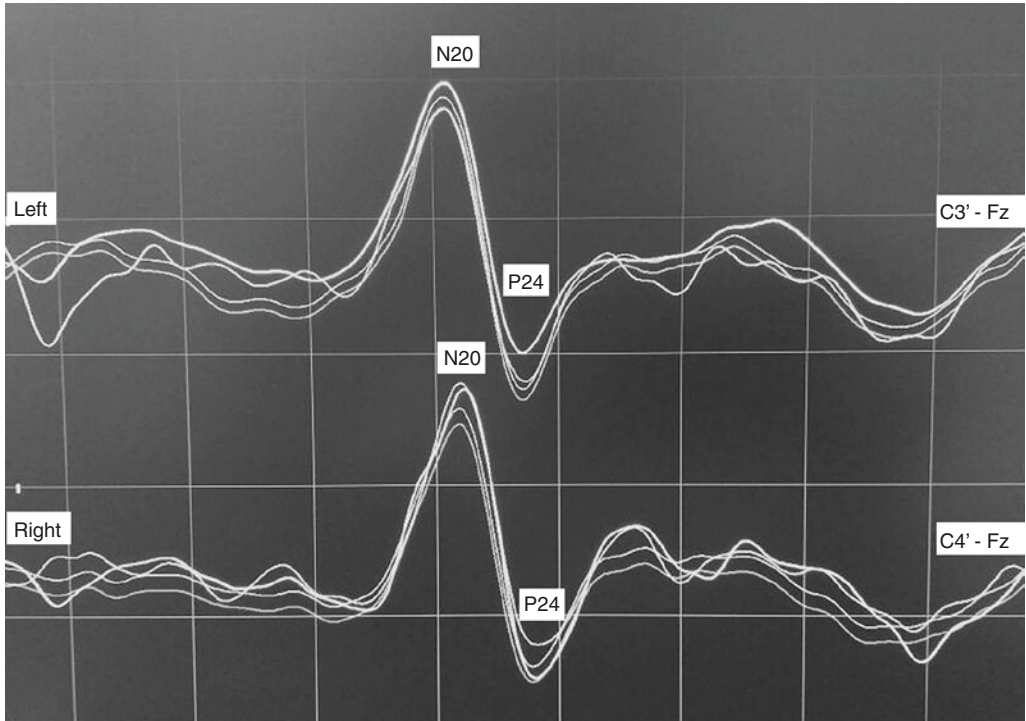


Fig. 5.1 Representative image of median nerve SSEP

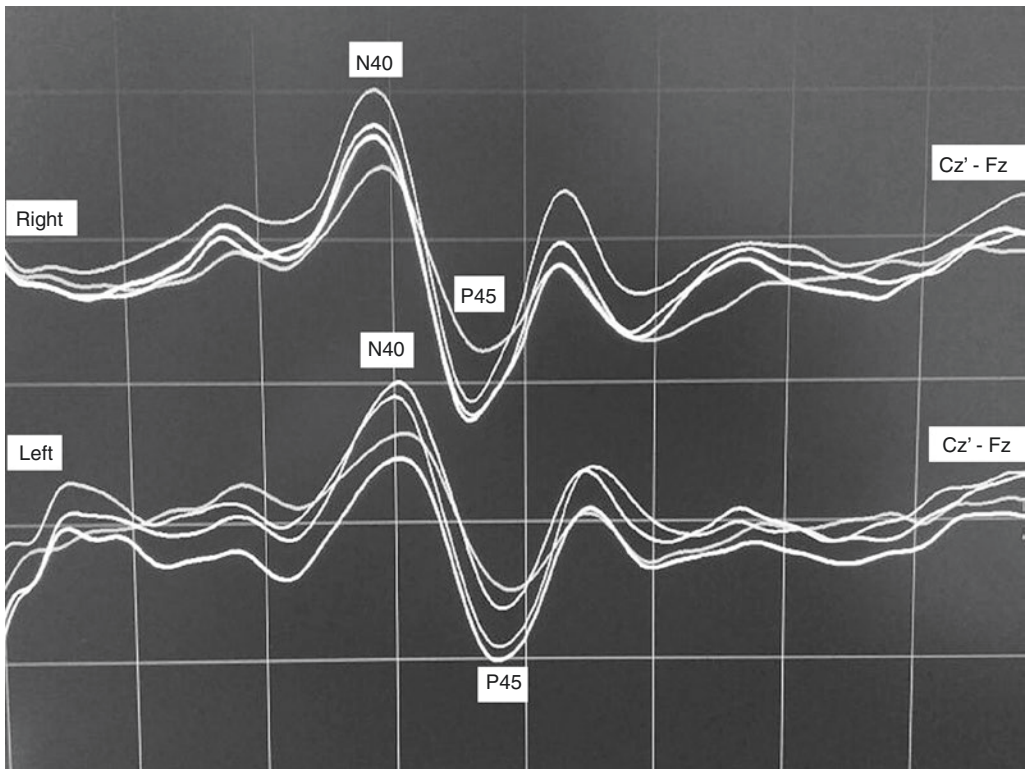


Fig. 5.2 Representative image of posterior tibial nerve SSEP

5.2.7 Uses of SSEP

1. Spinal cord monitoring for intraoperative injuries: SSEP is used for spinal cord monitoring in cases of spinal tumors, scoliosis, spinal canal stenosis, trauma surgery, as well as abdominal aortic aneurysm surgeries. Upper limb SSEP is used for cervical spinal cord monitoring, while surgeries around the thoracolumbar spine require lower limb SSEP. Standard criteria of 50% reduction in amplitude and 10% increase in latency are used for warning surgeon, after ruling out physiological, anesthetic, and technical causes.

One important limitation of SSEP is that it provides monitoring for the dorsal column of spinal cord which is supplied by posterior spinal artery as opposed to the motor tracts being supplied by anterior spinal artery. Thus, a normal intraoperative SSEP may rarely conclude with the patient having a motor deficit postoperatively [4].

Another important consideration for SSEP in this regard is the time delay in acquiring waveforms. In comparison with MEPs, SSEPs lag behind by a mean of 16 min in detection of changes [5]. Since reversibility of injury in neuronal structures is time dependent, MEP supersedes SSEP as the modality of choice in this regard. The guidelines for intraoperative neurophysiological monitoring attest to the same as a level I recommendation [6]. To circumvent this problem, SSEP is set up for continuous stimulation (and thus updating the waveform as a moving average) throughout the surgery.

2. Dorsal column mapping: During an intramedullary spinal tumor resection, the surgeon utilizes anatomical landmarks such as dorsal median sulcus and the median dorsal sulcal vein to identify the anatomical cord midline. The “functional” or “physiological” midline can be identified using SSEP monitoring, in case of anatomical distortion due to the tumor. A multielectrode grid is placed over the dorsal column for response capture and the posterior tibial nerve stimulated. Due to somatotopic distribution of nerve fibers in the dorsal column, the highest amplitude of SSEP is recorded nearest to the midline. After bilateral

confirmation of the same, the cord midline is identified [7].

3. Cortical surgeries near the somatosensory cortex.
4. Cortical ischemia monitoring during temporary vessel occlusion in intracranial aneurysm surgeries: Upper limb SSEP for middle cerebral artery and lower limb SSEP for anterior cerebral artery territory.
5. Central sulcus mapping: Utilizes change in phase of SSEP waveform across a strip of six electrodes lain directly over the brain surface to locate the central sulcus.

5.3 Motor Evoked Potentials

Initial history of MEP was plagued by its sensitivity to anesthetic agents belying its practical intraoperative utility. With the advent of high-frequency multi-pulse stimulation by Taniguchi in 1993, this shortcoming was addressed, and its role in intraoperative corticospinal tract monitoring has been on the rise [8]. As opposed to SSEPs, MEPs are conducted in an anterograde fashion, with stimulation being provided at the cortex and signal being captured at level of spinal cord and muscles. It monitors the corticospinal tract, and thus intraoperative deficits in this modality correlate directly with postoperative motor deficits. This modality has come into vogue recently, mainly as a supplement to SSEPs for functional monitoring of the spinal cord. Higher sensitivity of MEPs to anesthetic agents hampered its initial popularity, although it is fairly commonly used nowadays in neurosurgery.

MEPs are generated by transcranial electrical or magnetic stimulation of the cortex, which produces signals captured at the spinal cord level—“D” and “I” waves, and at the muscle level—compound muscle action potentials (CMAP).

5.3.1 Relevant Anatomy

The motor system of the humans can be divided into two parts—upper (comprising cerebral cortex, basal ganglia, and cerebellum) and lower (spinal cord pathways). The motor pathway starts

at the primary motor cortex (precentral gyrus) in the posterior part of the frontal lobe, which is somatotopically organized similar to the sensory cortex. This area receives afferent connections from the premotor cortex, supplementary motor area, brainstem, cerebellum, and basal ganglia, which provide inputs and feedback and modify the output of the motor cortex. The lower part of the motor system is the continuation of the upper part (corticospinal tract) or helps modifying the motor output by providing inputs to interneurons in the spinal cord, which in turn synapse with the corticospinal tract neurons. It is divided into the lateral system (corticospinal and rubrospinal tracts) and medial system (tectospinal, vestibulospinal, and reticulospinal tracts). Of importance in the monitoring context are the corticospinal tract, which carries the action potential of the impulse to the alpha motor neurons, and the reticulospinal tract, repeated stimulation of which helps facilitate the impulse conduction from corticospinal tract to alpha motor neurons under anesthesia. The final common pathway of the motor system starts at the alpha motor neurons, the axons of which travel through peripheral nerves to supply skeletal muscles [9].

5.3.2 Stimulus Characteristics

Stimulus is usually provided transcranially via corkscrew electrodes with electrical field supplied using a constant voltage or constant current stimulator. Constant voltage stimulators have been found to have higher success rates [10]. Voltage requirement should be titrated to achieve a good baseline MEP and should be maintained the same throughout surgery. Usual starting voltage is 150–250 V and can be increased up to 500–600 V. For upper limb monitoring, C3–C4 electrode placement (10–20 system) is used, while for lower limbs, Cz-Fz/Fpz is preferred. The side being stimulated should be the anode, while the other is cathode (only for upper limb MEP)—anodal stimulation has higher success rates of producing D-waves and CMAPs. A train of 3–6 pulses with pulse width of 50–75 μ s and pulse interval of 2–4 ms is used [11–13].

Transcranial magnetic stimulation has advantage over electrical with regard to exemption of stimulation of pain fibers in the scalp and dura and thus is a practical technique in awake patients [14]. However, anesthetic-induced suppression makes it impractical for intraoperative use.

5.3.3 Signal Capture

D-waves are captured at the spinal level using epidural or subdural electrodes implanted on a catheter at 2–3 cm distances, which is placed either percutaneously using a Tuohy needle or intraoperatively at the site by the surgeon [11, 12].

CMAPs are recorded using pairs of needle electrodes inserted into the appropriate muscle belly. Distal muscles used for fine movement are more sensitive to damage to corticospinal tract (lateral motor system) per se, while proximal and trunk muscles are supplied by the medial motor system (reticulospinal, tectospinal, and vestibulospinal tracts) and thus not so sensitive. For upper limb monitoring, thenar and abductor digiti minimi are preferred, and for lower limb tibialis, anterior and abductor hallucis are preferred. For gross spinal cord monitoring though, proximal muscles can also be used, and theoretically any limb muscle can be used [11, 12].

5.3.4 MEP Waveforms and Their Genesis

MEPs are generated by electrical stimulation of axons of the motor tract neurons rather than the cell bodies. The initial stimulation produces an action potential which is captured as a negative deflection at the spinal cord level (D-wave), and its importance in monitoring is only up to the alpha motor neuron. This wave is unaffected by anesthesia due to purely axonal conduction without any synaptic activity. If used, a criterion of 50% reduction of its amplitude is used for prediction of neurological deficit.

After the initial stimulus, the signal is propagated to neighboring motor cortical neurons via

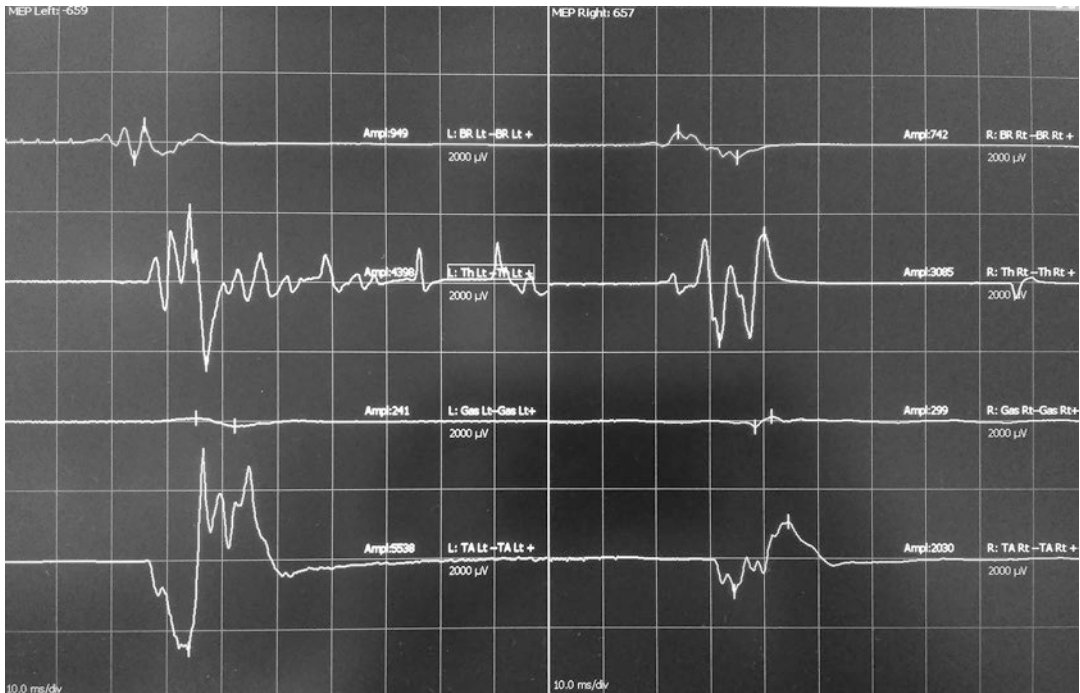


Fig. 5.3 Representative image of MEP monitoring of brachioradialis, thenar muscles (superior 2 waveforms) and gastrocnemius, tibialis anterior muscles (inferior 2

waveforms). Left and right panels are two sides being monitored, respectively

synaptic connections, and these produce multiple small waves (I waves), also captured at the spinal cord level. The “I” waves follow the “D” waves with a latency of 1.5 ms. These waves are affected by anesthetic agents due to predominant reliance on synaptic activity for their genesis. The signal then propagates to individual muscles, and EMG of the muscle twitch is captured as polyphasic CMAPs (Fig. 5.3). The CMAPs demonstrate a run-to-run variability even in individual patients, and thus the waveform acquired after the end of a train of impulses is displayed, rather than averaging approach as in SSEP. Due to reliance on muscle end plate for their genesis, CMAPs are severely affected by neuromuscular blocking agents and to a lesser extent by inhalational anesthetic agents (which in turn affect excitability of alpha motor neurons).

One important consideration is that, laterality of D and I waves cannot be determined. Since it is impossible to determine how much of

contralateral corticospinal tract has been stimulated, reduction of amplitude of D-waves does not help in determining the laterality and extent of damage. Hence, CMAPs are used much more commonly than D-waves during MEP monitoring [11].

5.3.5 Neurogenic MEPs (NMEP)

A version of MEP stimulation involves direct stimulation of the spinal cord using epidural electrodes, with signal capture on the spinal cord distally. However, it has been revealed through collision studies that this stimulation produces a mix of sensory and motor pathway action potentials and thus lacks specificity. The contribution of the sensory pathways provides the main component of the NMEP wave, and thus it truly cannot be called an MEP. This approach has thus been aborted in favor of traditional MEPs [11, 15].

5.3.6 Anesthetic Considerations

Since cortical synaptic activity is required for acquiring MEPs, anesthetics have a detrimental effect on this modality. The basic rules stay similar to SSEP, except that MEPs are more sensitive to anesthetic agents than SSEPs and the requirement of exclusion of neuromuscular blocking agents from the anesthesia protocol. Although certain researchers have proven that partial neuromuscular blockade may allow MEP monitoring, this practice is not widely followed, and muscle relaxant usage is eschewed [16, 17].

Due to the lack of muscle relaxation and non-specific activation of the motor cortex, MEP stimulation cannot be continued throughout the surgery akin to SSEP. It has to be done in an on-demand fashion, with the surgeon forewarned, due to physical movement of the patient's whole body during the stimulation. Also a bite block needs to be placed imperatively to prevent tongue bites and lip lacerations.

5.3.7 Uses of MEP

Uses of MEP for monitoring of the spine are similar to those of SSEP, though it is rarely used as a standalone monitor (due to technical difficulty of obtaining it intraoperatively). Usually it is used as a supplement to SSEP for monitoring cortico-spinal tract, which gets excluded with SSEP. Due to the extreme variability in MEP waveforms in the same patient, criteria for warning are not consistent (30–100% amplitude reduction in literature) [18]. It would be safe to say that clinical judgment should be used after taking into account SSEP waveforms, with 50% reduction as a threshold for suspicion. The threshold criteria for brain surgery should be less than that of spinal cord surgeries [19].

5.4 Spontaneous Electromyography

Spontaneous EMG, as opposed to SSEP and MEP, does not rely on specific stimulation of a neural tract to observe changes. In essence it may

be compared with electroencephalography, such that spontaneous background activity of muscles gets monitored and any changes point to mechanical, thermal, or metabolic irritation of the neural tract in real time. Better temporal resolution of this technique compared to evoked potentials makes it an invaluable adjunct to neurosurgical tract monitoring techniques.

5.4.1 Stimulus Characteristics and Response Capture

Stimulus for this technique is physiological or iatrogenic perturbation of neural tracts at the operative site. Without stimulation, no activity will be recorded from the muscle, but during surgical manipulation such as stretching or compression of nerves, spontaneous discharges are observed. However, false-positive discharges occur frequently during cauterization and cold saline irrigation since electrical discharges and temperature changes can stimulate neuronal activity [20].

The response capture is done using bipolar needle electrodes (≥ 5 mm apart) inserted into specific muscles following the motor distribution of specific parts of the spinal cord (Table 5.3). The same electrodes used for MEP monitoring may be repurposed for this when MEP is not being conducted.

The recordings are done with a gain of 50–500 μV and filters of low pass at 10 KHz and

Table 5.3 List of muscle targets for electrode insertion for spontaneous EMG monitoring of spinal cord levels [20]

Spinal cord level	Target muscle
C4	Supraspinatus
C5	Deltoid/biceps
C6	Biceps/wrist extensors
C7	Triceps/wrist flexors
C8/T1	Intrinsic muscles of hand
T6–T12	Rectus abdominis
L1	Iliopsoas
L2	Adductor longus
L3	Vastus medialis
L4	Vastus lateralis
L5	Tibialis anterior/extensor hallucis longus
S1	Medial gastrocnemius
S2–5	Perianal muscles

high pass at 20–30 Hz. For cautery artifact removal, a switch may be provided directly connected to the amplifier, albeit with the knowledge of inability of obtaining recordings during cauterization.

5.4.2 Waveform Characteristics

The discharges may be visualized on screen and more often be linked to an audio output, which provides a real-time feedback to the neurosurgeon. The semiology of waveform is extremely variable; thus, the presence of the wave or duration and frequency of discharges is more important clinically. A single burst of discharge maybe ascribed to a specific maneuver on part of the neurosurgeon or nearness to a nerve root, but trains of neurotonic discharges imply constant irritation and maybe indicative of nerve root damage [20].

5.4.3 Anesthetic Considerations

Physiological variables (temperature and blood pressure) and choice of hypnotic agents have no effect on spontaneous EMG recordings. However, neuromuscular blocking agents need to be excluded from the protocol. As with MEPs, the discharges may be recorded at partial neuromuscular blockade (up to 75%); however due to uncertainty over interindividual variability, it is preferred they be excluded [21].

5.4.4 Limitations and Pitfalls

1. False negatives: Although this modality tests the integrity of the nerve, it is possible for the nerve to be stimulated, even after transaction, if the stimulation occurs on the distal part of the transected nerve, thus providing a false impression of continuity [20].
2. False positives: Trains of neurotonic discharges can be elicited by irritation of the nerve root with sudden temperature changes (warm or cold saline) or with mechanical irritation due to irrigation, which in themselves are benign. Overall this modality has a high sensitivity for nerve root damage but low specificity [21].

5.4.5 Uses

Any surgery with a risk of damage to a known motor nerve can be monitored using this technique. Cranial nerve monitoring also comes under the ambit of this monitoring modality, but will not be discussed in this chapter. In the spinal surgery context, any of the spinal nerve roots from cranial to sacral may be monitored for a variety of surgeries such as decompression, deformity correction, fusion, pedicle screw placement, or tumor resection [20].

5.5 Triggered EMG

Triggered EMG will be discussed here in the context of pedicle screw monitoring. The monitoring is based on the electrical insulating ability of the pedicle bone, which requires a higher current for stimulation of the underlying nerve root compared to when it is breached. This technique was initially demonstrated by Calancie in porcine model for accuracy of screw placement [22].

5.5.1 Stimulation Characteristics

The stimulation is conducted using a handheld probe by the surgeon, with stimulator being anodal and cathode being placed in the nearby surgical tissue. The stimulation may be either a constant current type or constant voltage type. Although theoretically a constant voltage has advantage over constant current, due to the latter one being susceptible to current shunting in variable intraoperative conditions, usually a constant current stimulation is done, with thresholds for medial pedicle breach being set in mA. The stimulation current of 5–30 mA is used, with threshold for suspicion of pedicle breach ranging from 5 to 10 mA. The variability in this threshold is due to interindividual variability in bone thickness, due to variability in bone thickness in lumbar and thoracic vertebrae, and due to the inherent weakness of constant current stimulators of current shunting, which leads to high false-positive and false-negative rates and unnecessary surgical delays. The stimulator may be used on the pedicle screw head itself or as exploratory probing of the pedicle screw tract [11, 20, 21].

5.5.2 Response Capture

The response is captured at the muscle level using similar electrode configuration for free-running EMGs. Bipolar electrodes may be placed directly in the muscle belly (higher specificity but smaller waveform amplitude), or monopolar electrode with subdermal reference (higher amplitude, lower specificity) may be used. The waveform acquired is a CMAP, and criterion for suspicion is the current threshold at which it is acquired. Usually <6 mA gives high probability of medial breach, and >8 mA provides a low likelihood of breach [23–25].

5.5.3 Anesthetic Considerations

The same protocol as free-running EMGs is followed and neuromuscular block is prohibited.

Key Points

- The neural tracts in danger of damage during surgical procedures of the spine can be monitored using a variety of modalities specific for various tracts and can be either spontaneous or evoked.
- Somatosensory-evoked potentials (dorsal column), motor-evoked potentials (corticospinal tract), spontaneous electromyography (EMG), and triggered EMG (nerve root monitoring) are the various modalities commonly in use for this purpose.
- SSEP is based on retrograde conduction of impulses from peripheral nerve stimulation, which are recorded at somatosensory cortex on the scalp. MEP is based on orthodromic conduction of impulses from stimulation of the motor cortex and recording the same from the spinal cord (D and I waves) and muscles (compound muscle action potentials).
- Spontaneous EMG is usually used as an adjunctive monitoring and helps recognize nonspecific neural tract irritation with excellent temporal resolution.

References

1. Møller AR. Introduction. In: *Intraoperative neurophysiological monitoring*. 2nd ed. New York: Springer; 2011. p. 1–6.
2. Møller AR. Monitoring somatosensory evoked potentials. In: *Intraoperative neurophysiological monitoring*. New York: Springer; 2011. p. 93–122.
3. Møller AR. Anatomy and physiology of sensory systems. In: *Intraoperative neurophysiological monitoring*. New York: Springer; 2011. p. 57–92.
4. Nuwer MR, Dawson EG, Carlson LG, Kanim LE, Sherman JE. Somatosensory evoked potential spinal cord monitoring reduces neurologic deficits after scoliosis surgery: results of a large multicenter survey. *Electroencephalogr Clin Neurophysiol*. 1995;96:6–11.
5. Hilibrand AS, Schwartz DM, Sethuraman V, Vaccaro AR, Albert TJ. Comparison of transcranial electric motor and somatosensory evoked potential monitoring during cervical spine surgery. *J Bone Joint Surg Am*. 2004;86-A:1248–53.
6. Hadley MN, Shank CD, Rozzelle CJ, Walters BC. Guidelines for the use of electrophysiological monitoring for surgery of the human spinal column and spinal cord. *Neurosurgery*. 2017;81:713–32.
7. Mehta AI, Mohrhaus CA, Husain AM, Karikari IO, Hughes B, Hodges T, Gottfried O, Bagley CA. Dorsal column mapping for intramedullary spinal cord tumor resection decreases dorsal column dysfunction. *J Spinal Disord Tech*. 2012;25:205–9.
8. Taniguchi M, Cedzich C, Schramm J. Modification of cortical stimulation for motor evoked potentials under general anesthesia: technical description. *Neurosurgery*. 1993;32:219–26.
9. Møller AR. Anatomy and physiology of motor systems. In: *Intraoperative neurophysiological monitoring*. New York: Springer; 2011. p. 169–205.
10. Shigematsu H, Kawaguchi M, Hayashi H, et al. Higher success rate with transcranial electrical stimulation of motor-evoked potentials using constant-voltage stimulation compared with constant-current stimulation in patients undergoing spinal surgery. *Spine J*. 2017;17:1472–9.
11. Møller AR. Practical aspects of monitoring spinal motor systems. In: *Intraoperative neurophysiological monitoring*. 2nd ed. New York: Springer; 2011. p. 207–34.
12. Legatt AD, Emerson RG, Epstein CM, MacDonald DB, Deletis V, Bravo RJ, López JR. ACNS Guideline. *J Clin Neurophysiol*. 2016;33:42–50.
13. Lee JJ, Il KY, Hong JT, Sung JH, Lee SW, Yang SH. Intraoperative monitoring of motor-evoked potentials for supratentorial tumor surgery. *J Korean Neurosurg Soc*. 2014;56:98–102.
14. Chen R, Cros D, Curra A, et al. The clinical diagnostic utility of transcranial magnetic stimulation: report of an IFCN committee. *Clin Neurophysiol*. 2008;119:504–32.

15. Péréon Y, Tich SNT, Delécrin J, Dang CP, Bodin J, Drouet JC, Passuti N. Combined spinal cord monitoring using neurogenic mixed evoked potentials and collision techniques. *Spine (Phila Pa 1976)*. 2002;27(14):1571–6.
16. Sloan TB, Erian R. Effect of vecuronium-induced neuromuscular blockade on cortical motor evoked potentials. *Anesthesiology*. 1993;78:966–73.
17. Kim S-H, Jin S-J, Karm M-H, Moon Y-J, Jeong H-W, Kim J-W, Ha S-I, Kim J-U. Comparison of false-negative/positive results of intraoperative evoked potential monitoring between no and partial neuromuscular blockade in patients receiving propofol/remifentanyl-based anesthesia during cerebral aneurysm clipping surgery. *Medicine (Baltimore)*. 2016;95:e4725.
18. Journée HL, Berends HI, Kruyt MC. The percentage of amplitude decrease warning criteria for Transcranial MEP monitoring. *J Clin Neurophysiol*. 2017;34:22–31.
19. MacDonald DB. Overview on criteria for MEP monitoring. *J Clin Neurophysiol*. 2017;34:4–11.
20. Park J-H, Hyun S-J. Intraoperative neurophysiological monitoring in spinal surgery. *World J Clin Cases*. 2015;3:765–73.
21. Lall RR, Lall RR, Hauptman JS, Munoz C, Cybulski GR, Koski T, Ganju A, Fessler RG, Smith ZA. Intraoperative neurophysiological monitoring in spine surgery: indications, efficacy, and role of the preoperative checklist. *Neurosurg Focus*. 2012;33:E10.
22. Calancie B, Lebowitz N, Madsen P, Klose KJ. Intraoperative evoked EMG monitoring in an animal model. A new technique for evaluating pedicle screw placement. *Spine (Phila Pa 1976)*. 1992;17:1229–35.
23. Raynor BL, Lenke LG, Bridwell KH, Taylor BA, Padberg AM. Correlation between low triggered electromyographic thresholds and lumbar pedicle screw malposition. *Spine (Phila Pa 1976)*. 2007;32:2673–8.
24. Bosnjak R, Dolenc VV. Electrical thresholds for biomechanical response in the ankle to direct stimulation of spinal roots L4, L5, and S1. Implications for intraoperative pedicle screw testing. *Spine (Phila Pa 1976)*. 2000;25:703–8.
25. Parker SL, Amin AG, Farber SH, McGirt MJ, Sciubba DM, Wolinsky J-P, Bydon A, Gokaslan ZL, Witham TF. Ability of electromyographic monitoring to determine the presence of malpositioned pedicle screws in the lumbosacral spine: analysis of 2450 consecutively placed screws. *J Neurosurg Spine*. 2011;15:130–5.