

Intraoperative Spinal Cord Monitoring: Focusing on the Basic Knowledge of Orthopedic Spine Surgeon and Neurosurgeon as Members of a Team Performing Spine Surgery under Neuromonitoring

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Abstract:

An intraoperative functional spinal cord monitoring system is a technology used by spine and spinal cord surgeons to perform a safe surgery and to gain further surgical proficiency. However, no existing clinical neurophysiological method used in the operating room can monitor all complex spinal cord functions. Therefore, by observing the activities of certain neural action potentials transferred via limited neural tissues, surgeons need to deductively estimate the function of the whole spinal cord. Thus, as the number of spinal cord functions that need to be observed increases, spinal cord monitoring can be more reliable. However, in some situations, critical decision-making is affected by the limited capability of these methods. Nevertheless, good teamwork enables sharing of seamless information within the team composed of a surgeon, anesthesiologist, monitoring technician and nurses greatly contributes to making quick and accurate decisions. The surgeon, who is the person in charge of the team, should communicate with multidisciplinary team members using common technical terms. For this reason, spine and spinal cord surgeons must have appropriate knowledge of the methods currently used, especially of their utility and limitations. To date, at least six electrophysiological methods are available for clinical utilization: three are used to monitor sensory-related tracts, and three are used to monitor motor-related spinal cord functions. If surgeons perform electrode setting, utilizing their expertise, then the range of available methods is broadened, and more meticulous intraoperative functional spinal cord monitoring can be carried out. Furthermore, if the team members share information effectively by utilizing a clinically feasible judicious checklist or tools, then spinal cord monitoring will be more reliable.

Keywords:

orthopedic spine surgeon, neurosurgeon, intraoperative spinal cord monitoring, team approach

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1. Introduction

Recent reports from the Japanese Scoliosis Society and Scoliosis Research Society, though the distinction between spinal cord and spinal nerve root is unclear, highlighted the increasing incidence of neurological complications^{1,2)}. If spine and spinal cord surgery is performed without intraoperative spinal cord monitoring and results in any neurologi-

cal sequela, the surgeon would be extremely vulnerable to medical litigation. The spine and spinal cord surgeon will be the target of criticism as the ultimate person in charge. However, surgeons can benefit greatly from effective intraoperative spinal cord function monitoring to perform a challenging surgery safely and successfully, which increases patient satisfaction. No existing single method can reflect all complex spinal cord functions. Therefore, surgeons have to

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deductively estimate the collective function of the spinal cord by observing certain action potentials based on the activity of limited neural tissues. To increase reliability, multimodality monitoring, which involves the observation of multiple functions simultaneously, to infer as many indices as possible is used in the operating theater. However, no single method or combination of potentials has been statistically evaluated with level 1 evidence because prospective randomized controlled studies cannot be conducted to evaluate objectively the usefulness and reliability of practically utilized monitoring methods³⁾. Given these limitations, creating and managing a team that maintains close coordination to achieve the most effective intraoperative monitoring are important^{4,6)}. Moreover, the surgeon must be in charge and is responsible for the results of the surgical interventions. To this end, we believe that surgeons should have adequate basic knowledge of the methods that can be used for intraoperative monitoring of spinal cord functions, their advantages, and their disadvantages.

At least six types of electrophysiological methods are applied clinically, but the selection or combination thereof largely depends on the expertise of the monitoring technician or physician. The clinical neurophysiologist, neurologist, or monitoring technician will at times opt for a noninvasive method. However, spinal surgeons will not hesitate to utilize invasive monitoring methodologies. Thus, given a wide range of methods to select from, more spinal cord neural tissues can be observed, and intraoperative spinal cord monitoring can be as complete as possible.

Although intraoperative spinal cord and spinal nerve root monitoring is known, authors regard that they are different thesis. Intraoperative spinal nerve root monitoring still has various problems that should be solved. Therefore, this article will describe information limited to intraoperative spinal cord monitoring. This article first presents the currently available methods of intraoperative spinal cord monitoring. Then, it describes methods of managing specific problems in clinical settings.

2. Existing Intraoperative Spinal Cord Monitoring Methods

1) Methods to monitor sensory-related tracts

(1) *Somatosensory (cortical)-evoked potential after electrical stimulation of the peripheral nerve [Somatosensory-evoked potential (SEP)] (Fig. 1)*

This method of measuring evoked potential was initially evaluated in 1947 by Dawson using a low-capacity amplifier superimposing baseline potential of very low amplitude⁷⁾. In the late 1960s, the advances in electrical signal processing technology made the recording of small potentials of 2-10 μV possible even in an electrically noisy operating theater, which electrically averages more than several thousand sweeps. This method requires sufficient time to record one

sample of potentials that can be used to monitor sensory-related tracts. The development of electronic equipment such as amplifiers and data processing instruments has made recording and analyzing minute potentials possible, but this capability does not mean that the development occurred in one bound. Current intraoperative spinal cord function monitoring using various evoked potentials largely depends on the development of electronic devices that have advanced rapidly since the 1980s.

SEP is understood to demonstrate the skin sensation of the dominant region of the stimulated peripheral nerve trunk and consists of near-field potentials and far-field potentials (Fig. 1). Near-field potentials are electrical activities of the sensory cortex located near the recording electrode. These potentials are evoked by the impulses generated by the stimulation of the peripheral nerves, which are transferred to the dorsal column of the spinal cord and ascend from the medial lemniscus to the sensory cortex. These potentials are used as an index to monitor sensory tracts in the spinal cord. Far-field potentials originate from the running route of the current, although the amplitudes of the potentials are sometimes too small to be used for spinal cord monitoring.

Since 1972, SEP has been used as a method to monitor spinal cord function during surgery for spinal scoliotic deformity^{8,9)}. However, given the aforementioned reasons, recording one sample during surgery took time and determining the potential was difficult because of a poor noise-to-signal ratio. Many false-negative cases have been reported because of this difficulty^{10,11)}, and investigators could not detect the impairment of the spinal cord beyond the territory of this potential. However, whether such cases should be considered false-negatives is controversial.

Owing to the development of hardware and refined anesthetic techniques, one sweep of SEP can currently be recorded within 1.5 min with a noninvasive electrode setting. Thus, this method is routinely employed for multimodality intraoperative spinal cord monitoring, but it is not used for single use.

(a) Electrode setting and recording of potentials

Plate electrodes or needle electrodes are used for the stimulation and recording of potentials. The plate electrode is the same electrode that is used for electroencephalography, and its surface is coated with silver-silver chloride. The skin surface for electrode attachment is cleaned using a prepping paste or liquid. When the surface electrode is used for a long time, desiccation of the electrode paste should be avoided. If the paste is dry, the impedance (i.e., resistance) between the electrodes and the skin surface becomes high. As a result, heat is generated under the stimulating electrodes, which can cause burn injury and reduce the amplitude of the potential at the recording electrode. Further care must be taken to fix the electrode with EEG paste and/or with adhesive tape. Displacement of the surface electrode causes a change in the recorded potential. This concern is reduced if a needle electrode is used, but the electrode and cable should be carefully fixed with the adhesive tape.

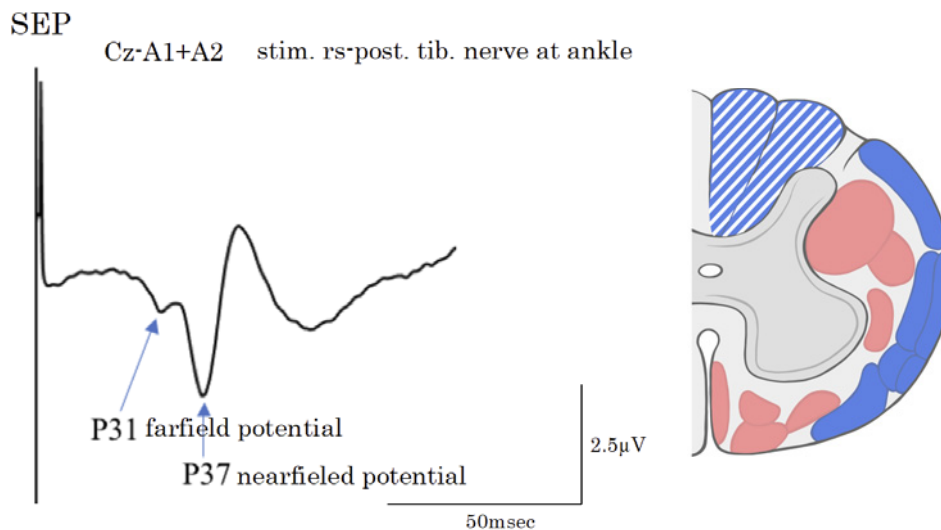


Figure 1. Sensory cortical evoked potential after electrical stimulation of the peripheral nerve.

This sensory cortical-evoked potential after electrical stimulation to the peripheral nerve was recorded with electrodes placed at Cz-A1+A2 and was evoked by the stimulation of the tibial nerve at the malleolus medialis. P31 is the far-field potential generated at the level of the brain stem, and P37 is the near-field potential recorded from the sensory cortex, which is used as the indicator of the dorsal column activity in the spinal cord.

Schematic drawings attached to each potential are used to roughly indicate neural tissues represented by the potential. Potentials, which are delivered through the neural tissues shown as diagonal lines and large-diameter nerve fiber as dot, are regarded to compose evoked potentials. Blue indicates sensory-related tract, and red indicates motor-related neural tissue.

To monitor spinal cord functions at the cervical and thoracic levels, the tibial nerve at the popliteal fossa or just behind the medial malleolus of the ankle is stimulated. The polarity of the stimulating current should be proximal-site negative. The recording electrodes are placed based on the international 10-20 system at a site 2 cm outside (i.e., C1 and C2) of the median central portion Cz (i.e., vertex) or 2 cm behind (i.e., C1' and C2') that position. Another electrode is placed at a site 2 cm behind the Cz (i.e., CPz). The reference electrode is placed on the bilateral earlobes or at a site 2 cm forward of the Fz (i.e., FPz). A differential amplifier amplifies the potential between C1' or C2' and CPz using the bilateral earlobe electrodes or FPz as the indifferent electrode.

When monitoring only the cervical spinal cord, SEPs generated by upper limb stimulation may be observed. In this situation, the recording electrode is placed at a site 2 cm behind the point of 7 cm outside the Cz. The recording and reference electrodes are different from those for lower limb stimulation. Please refer to other documents for further details of electrode placement¹²⁾.

The frequency of stimulation applied to the nerve trunk is 2-5 per second (Hz), and several hundred sweeps are averaged using a signal averager to record an extremely low potential. Recording one sample potential requires approximately 1.5 min with the currently available instruments.

(b) Effect of anesthesia and other factors

All inhalation anesthetics influence the cortical-evoked potential (i.e., near-field potential: P37) by diminishing its amplitude. Halogenated anesthetics such as desflurane and sevoflurane produce a dose-related reduction in the amplitude of the near-field component of SEP^{12,13)}. Therefore, administering propofol with ketamine intravenously is recommended. On the contrary, anesthesia-resistant far-field potential (P31) can be utilized as the indicator of spinal cord function under inhalational anesthesia despite being technically demanding. Neuromuscular blocking agents do not affect the SEP, whereas some reports indicate that changes in body temperature, blood pressure, circulating blood volume, arterial blood oxygen saturation, and intracranial pressure influence the SEP^{13,14)}.

(c) Recorded potential and its analysis

The recorded potential is generally expressed as a negative value for upward potentials and as a positive value for downward potentials, with the latency from the stimulus to potentials added as a numerical value (Fig. 1). Critical points are a 10 ms delay in latency and 50% decrement in amplitude¹²⁾.

(d) Strengths and weaknesses

Strengths:

- It is a noninvasive method.
- A medical license is not required to set up electrodes

and record.

- It can be performed on an alert patient, and preoperative and postoperative recordings are possible.

Weaknesses:

- The potential amplitude is so small that it necessitates the averaging of several hundreds of sweeps.
- Obtaining one sample potential is time-consuming, and real-time monitoring cannot be performed.
- In general, indexed cortical potentials (i.e., near-field potentials) are affected by the depth of anesthesia and by changes in body temperature, blood pressure, circulating blood volume, arterial blood oxygen saturation, and intracranial pressure.

(2) Spinal cord-evoked potential after electrical stimulation of the spinal cord [Sp(E)-SCEP] (Fig. 2)

This spinal cord-evoked potential is a method developed by Japanese orthopedic surgeons in 1972^{15,16}. Basic research, including wave pattern analysis, has been conducted intensively by many Japanese orthopedic researchers¹⁵⁻²⁰. This method has been criticized for the invasiveness of the electrode setting, although the spine and spinal cord surgeon can perform it without difficulty as described later. Once the stimulating and recording electrodes are placed close to the spinal cord, multimodal spinal cord monitoring utilizing these electrodes can be easily conducted. The clinical relevance and feasibilities of this potential have been reported primarily by Japanese orthopedic surgeons^{21,22}.

(a) Electrode setting and recording of potential

Tamaki developed a fine tube-type electrode that could be introduced into the subarachnoid space after lumbar puncture with a 17-gage Tuohy needle²². The electrode made from polyethylene tube, which has sufficient flexibility and stiffness to prevent injury to the spinal cord, is attached with two fine platinum wire coils at the tip and can be advanced to a preferred level in the subarachnoid space, even to the level of the craniocervical junction, if no obstruction exists. The same electrode is used to deliver stimulation at the rostral site from the epidural space. If the electrode is not deployed in the subarachnoid space, the potential can be recorded using the electrode placed in the epidural space.

The original type of this electrode is unfortunately not available in the market, but several companies provide an electrode with a similar concept but not the same. Kurokawa used two twisted tips of exposed coated fine copper wires placed in the epidural space for stimulation and recording^{16,21}. The placement of the epidural electrodes can be carried out by exposing the laminae and by partially removing the ligamentum flavum or performing a laminectomy. As a matter of course, they can be introduced by epidural puncture with a Tuohy needle, but it is recommended that a proficient expert such as an anesthesiologist or a trained spine surgeon should perform the procedure.

For spinal cord tumors, both electrodes are preferably placed in the subarachnoid space because cerebrospinal fluid leakage causes a change in current conductivity between the

electrode and the spinal cord. The pattern of the evoked potential will subsequently be deformed.

During stimulation, polarity should be ascertained to make the site of the recording electrode negative. The strength of the stimulation is approximately 10 mA or supra maximum, with a frequency of 30-50 Hz. One sample potential can be recorded in an average of 30-50 signals. This fact indicates that one sample potential can be observed within 1 second. Thus, most real-time monitoring can be performed by repeated recordings.

Every original evoked potential recorded from the spinal cord has an extremely low amplitude. Therefore, the electrode should be connected to the input box using shielded cables to prevent noise contamination and to obtain a low average frequency and a quick response. Further care should be taken to prevent fine changes in the spatial relationship between the recording electrode and the spinal cord caused by the movement of the tip of the electrode or derotation maneuver during the surgical treatment of scoliosis²³.

(b) Effect of anesthesia and other factors

In this method, the potential is not transferred via synapsis and the neuromuscular junction. The potentials can accordingly be recorded under any inhalational anesthesia combined with a neuromuscular blocking agent.

(c) Recorded potential and its analysis

The initial spike wave is composed of potentials of large-diameter fibers transferring signals in the dorsolateral tracts, such as the posterior spinocerebellar tract and lateral corticospinal tract, and large-diameter fibers in any tract. Subsequent multiphasic potential of low amplitude is transferred through small-diameter fibers in the dorsal column¹⁷⁻²⁰ (Fig. 2). The amplitude of the multiphasic potential is smaller than that of the initial spike wave. Thus, the change in its pattern and amplitude is frequently ignored intraoperatively. This intentional disregard can be a reason for a false-negative finding^{24,25}. Moreover, a 50% decrement in the spike wave amplitude is critical empirically and experimentally^{26,27}. A critical decrement in the multiphasic wave can be like that in the initial spike wave. Solitary use of this potential results in false-negative findings in patients with intramedullary spinal cord tumors^{24,25,28}. The concomitant use of motor-related potential has been recommended²⁸.

(d) Strengths and weaknesses

Strengths:

- Independence from anesthetic and related agents.
- Records large amplitudes compared to other evoked potentials (e.g., the SEP).
- One sample potential can be obtained within 1 s.
- Recording and analysis can be conducted using basic instruments for routine electromyography.

Weaknesses:

- Invasiveness of the electrode setting especially for a nonsurgeon.
- Monitoring is primarily on the sensory-related tracts.
- Paravertebral muscle contraction caused by stimulation may interfere with surgical procedures.

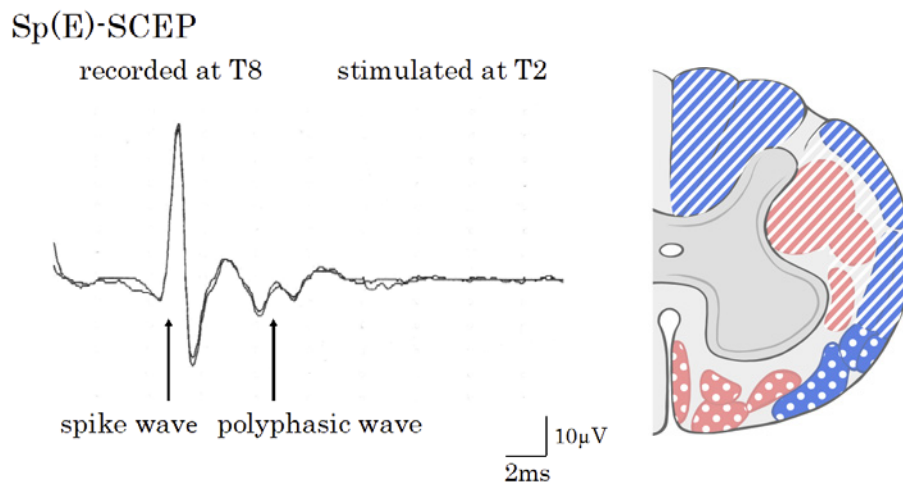


Figure 2. Spinal cord evoked potential after electrical stimulation of the spinal cord. The typical pattern of the spinal cord-evoked potential after electrical stimulation of the spinal cord consists of an initial spike wave and following polyphasic waves. Stimulation was delivered at T5 (fifth thoracic level of the spine) and recorded at the level of L1 (first lumbar spine level) with a tube-type electrode placed in the subarachnoid space. With an epidurally placed electrode, a similar pattern potential may be recorded, but it may have low amplitude. An initial spike wave is transferred mainly through the tracts located at the dorsolateral part of the spinal cord and large-diameter nerve fibers in any tract, and the subsequent polyphasic low-amplitude wave is transferred through small-diameter fibers in the dorsal column.

(3) Spinal cord-evoked potential after electrical stimulation of the peripheral nerve [Pn(E)-SCEP] (Fig. 3)

In 1972, Shimoji et al.²⁹⁾ recorded ascending evoked potentials from the epidural space of the spinal cord level by stimulating the tibial nerve at the popliteal fossa. In 1983, Jones et al.³⁰⁾ subsequently used this method for intraoperative monitoring of spinal cord function, and they called this potential “the spinal SEP.” The action potentials that provoke the SEP at the cerebral sensory area are recorded from the spinal cord of the transmission pathway. The amplitude of this potential is higher than that of the SEP, and the averaging frequency may be small, which indicates that one recording time is short. Recording and observation can thereafter be performed frequently.

(a) Electrode setting and recording of potential

A bipolar tube-type electrode or two twisted insulated wires with an exposed tip can be used. However, when recording spinal cord-evoked potentials, we should keep in mind that these potentials have a smaller amplitude compared to evoked muscle potentials. To avoid noise contamination and reduce the average frequency, shielded cables should be used to feed the signal into the input box of the differential amplifier.

Surface electrodes are used for the stimulation of the lower limb nerve trunk, but a cathode should be used on the recording electrode side (i.e., the rostral side). A sufficient amount of electrode glue should be used, and the electrode should be fixed with an adhesive tape, which would ensure that the amount of current flow to the nerve trunk is not de-

creased by the impedance increment due to drying or electrode displacement during long-term monitoring. If a needle electrode is used properly, this issue is avoided.

(b) Effect of anesthesia and other factors

In this method, evoked potentials can be recorded under any kind of anesthesia and are stable against blood pressure changes and use of neuromuscular blocking agents. Variations in stimulation frequency of 2-20 Hz do not affect evoked potentials³⁰⁾.

(c) Recorded potential and its analysis

Multiphasic spike waves are observed (Fig. 3). Jones et al. reported that the recorded potentials can be resolved into three components and that if the stimulating frequency is upregulated, the second component decreases in amplitude³⁰⁾. However, its clinical relevance has not been well studied. The critical point of amplitude decrement for this method has not been well documented. In an animal experimental study³¹⁾, a 50%-70% decrement was associated with spinal cord sequelae. However, an average amplitude of more than 50% or the complete loss of one component can signify spinal cord impairment³⁰⁾.

(d) Strengths and weaknesses

Strengths:

- Independence from anesthetic and related agents.
- Potentials have a large amplitude compared to the SEP. Therefore, recording requires a short time period.
- The recording electrode can be inserted easily during the posterior surgical approach to the spine.
- The selection of the stimulation side enables the detection of the laterality of a dorsal column injury.

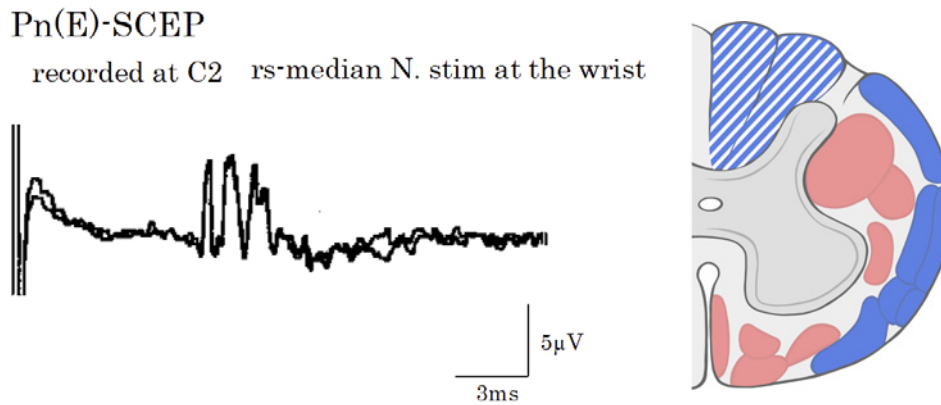


Figure 3. Spinal cord evoked potential after electrical stimulation to the peripheral nerve.

Spinal cord-evoked potential recorded with an electrode placed in the epidural space at the C2 level after the electrical stimulation of the median nerve at the wrist. The recorded potential is consistently multiphasic. This evoked potential is composed with the potential delivered through the dorsal column of the spinal cord similar to the SEP.

Weaknesses:

- Monitoring is limited only to the dorsal column of sensory-related tracts.
- The invasiveness of the recording electrode setting for nonsurgeons.

2) Methods to monitor motor-related tracts

(1) Muscle-evoked potential after electrical stimulation of the brain [Br(E)-MsEP] (Fig. 4)

In 1980, Merton and Morton published a paper in *Nature* regarding their findings in stimulating the cerebral cortex in humans³². In their study, they delivered transcranial electrical stimulation to the motor cortex in awake subjects and succeeded in detecting evoked action potentials from the forearm muscles with surface electrodes. The stimulating current needed to be tolerable without anesthesia. Therefore, the current used had a short duration and high voltage. Merton and Morton mentioned that a lower extremity muscle contraction was occasionally observed, but they presented only evoked potentials from the forearm muscles in their manuscript. This discovery made a significant contribution to the subsequent observation of the motor-related spinal neural tissue and intraoperative spinal cord monitoring. However, further advancement in medical science technology was needed before this method became universal for the recording of this potential during surgery under general anesthesia.

In this method, to stimulate the contraction of peripheral muscles under general anesthesia by delivering impulses from the motor cortex, the activity of the spinal motor neurons must be maintained. Under inhalation anesthesia, the activity of the motor neurons is extremely reduced so that myoelectric potentials cannot be recorded from limb muscles. Thus, in 1986, Boyd et al.³³ recorded downstream action potentials after stimulating the motor cortex at the level

of the spinal cord and used this activity to monitor spinal cord motor-related tracts. In 1991, Jellinek et al. succeeded in recording muscle action potentials from the lower extremities after stimulating the motor cortex under anesthesia with propofol³⁴. A further contribution that made this method a routine in the operating theater is the development of stimulating technology (i.e., the multiple train electrical stimulation method for the brain)³⁵.

However, this potential has an unstable amplitude and latency compared to potentials used for other monitoring methods³⁷. This instability occurs because the excitation of cerebral motoneurons is influenced by various factors and the firing of spinal anterior horn motoneurons may not be triggered only by the potentials descending from the pyramidal tract³⁶. The mechanism of the generation of these potentials must be elucidated in the future. However, we should understand that, at present, the input of the stimulus is applied to the black box, and the myoelectric potential as the output is used as the index to observe the motor-related neural tissues of the spinal cord.

(a) Electrode setting and the recording of potentials

Two stimulating electrodes are placed symmetrically at a site 5 cm lateral and 2 cm anterior from the Cz (i.e., center of the skull) based on the method of Matsuda and Shimazu³⁸. One electrode is the anode, and the other electrode is the cathode. The anode side of the motor cortex is stimulated, and by changing the polarity of the stimulus, left and right discrimination of a spinal tract disorder is possible. As the stimulating electrode, a corkscrew-type needle electrode for electroencephalography or a surface electrode is used. To deliver a stimulating current to a living body using a surface electrode, the impedance between the surface electrode and the skin should be maintained by preventing the electrode paste from drying. Burn injury caused by Joule heating under the electrode should be avoided.

To record the evoked myoelectric potential from the pe-

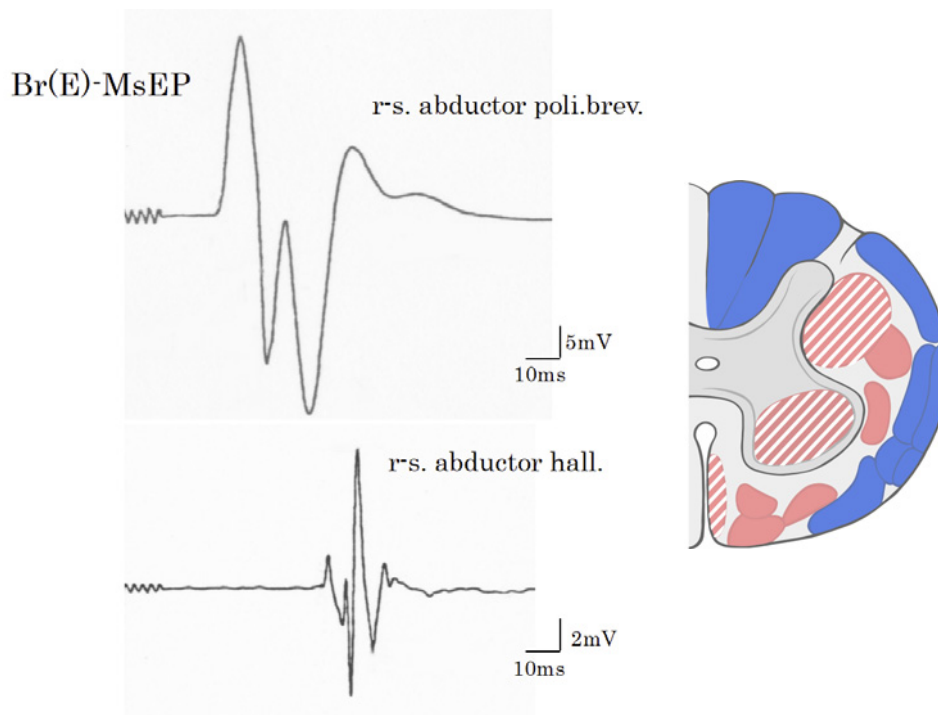


Figure 4. Muscle evoked potential after electrical stimulation to the brain.

The upper muscle action potential is recorded from the adductor pollicis of the contralateral to the anode stimulation. The bottom trace is detected at the abductor hallucis of the contralateral foot. The wave pattern of the evoked potentials shows no regularity.

This potential indicates the activity of the corticospinal tract and the anterior motor neuron of the spinal cord.

ripheral muscle, surface electrodes are generally used, but needle electrodes can be utilized to record stable and high-amplitude potentials. The tendon-belly method (i.e., placing one electrode on the muscle of the belly and the other on the tendon) may be employed at that time.

Train stimulation is used to stimulate cortical neurons effectively. The most commonly used is the modality that repeats five stimuli at 2 ms intervals³⁵. However, a multitrain stimulation method that provides a repeated stimulus several times at 50- to 100-ms intervals has also been used³⁹.

(b) Effect of anesthesia and other factors

An anesthetic method that does not reduce motor neuron activity must be used. The most used method is the intravenous anesthesia with propofol. Narcotics (e.g., fentanyl, remifentanyl, and ketamine) are supplemented to reduce the quantity of anesthetics and to control pain⁴⁰. They do not affect the potential prominently. Inhalation anesthetics such as desflurane and sevoflurane can be used with meticulous care, but propofol has less inhibitory effect on the activity of motor neurons.

The most important aspect is to keep the depth of anesthesia constant after recording the baseline potential. In addition, neuromuscular blocking agents have a significant effect on muscle action potentials by decreasing or extinguishing the potential. Therefore, they are not recommended. However, when using these agents, the effect of the neuromuscular blocking agent must be quantitatively moni-

tored under the control with “train of four” monitoring⁴¹. Therefore, when the amplitude of the muscle-evoked potential decreases intraoperatively, the change in anesthesia depth and the condition of neuromuscular blocking should be checked.

(c) Recorded potential and its analysis

Each waveform is different because the recorded potentials are the action potentials of peripheral muscles (Fig. 4). Therefore, no standard pattern of potentials exists⁶. Owing to this irregularity in wave pattern, the amplitude change against the baseline potential is used as an indicator of spinal cord impairment. Provided that the amplitude and waveform of the potentials are liable to change, false-positive results may be determined. To avoid interference of the surgical procedure due to a false-positive judgment, multimodality monitoring and improvements in the quality of the monitoring team are necessary.

Various investigators have reported regarding associated critical points. In 1997, Morota et al.⁴² reported that a 50% decrement was a critical point. Following this report, Langeloo et al.⁴³ proposed a critical point of 80%, and Kobayashi et al.⁴⁴ proposed a critical point of 70%. By contrast, Kothbauer et al.⁴⁵ concluded that even if the muscle-evoked potential after stimulating the brain [Br(E)-MsEP] disappeared and the D wave (i.e., spinal evoked potential after stimulating the motor cortex) maintained more than 50% in amplitude in intramedullary tumor surgery, the neurological prog-

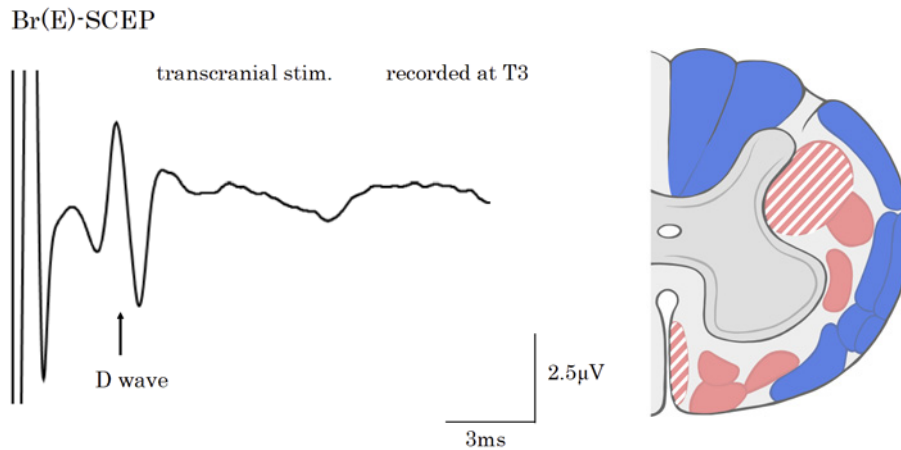


Figure 5. Spinal cord evoked potential after electrical stimulation of the brain. The potential was recorded at the T9 level after delivering stimulations to the motor cortex. The spike shape potential is the D wave, and the following low-amplitude potentials are regarded to be the I wave. This potential is transferred through the corticospinal tracts.

nosis of the patient was good at 3 months postoperatively.

As described previously, to simply and clearly determine the critical point may not be appropriate⁴⁶. However, an amplitude decrease of more than 70% may be judged, with high probability, as an indication of an abnormality occurring in the motor-related neural tissue. Clinicians must understand that a single method allows the interpretation of only a limited part of the spinal neural tissue. Therefore, multimodality monitoring that incorporates multiple monitoring methods to observe as much neural tissue as possible is necessary, especially during a surgical maneuver that has a high risk of selective neural tissue injury, such as intramedullary spinal cord tumor surgery.

Furthermore, the results of animal experiments demonstrated that the monitoring efficiency of this method for spinal nerve root injury is only approximately 50%⁴⁷. Thus, the detection rate of the spinal nerve root and cauda equina injury appears to be low. Furthermore, this potential is so vulnerable to ischemic insult of the spinal cord that employing this potential to monitor vascular compromise is not appropriate⁴⁸.

When this potential is recorded during a long operation, a gradual decrement of the potential amplitude without any change in anesthesia may be observed. This phenomenon is called “anesthetic fade”^{49,51} and is attributed to a gradual change in the excitability of the neurons in the brain or spinal cord. The mechanism of this evidence is not well understood, although this gradual decrement of amplitude without any neurological sequela should be considered.

The most serious but influent complication of electrically induced jaw muscle contraction is bite injury of the lip and tongue. Broken tooth injury and mandibular fracture may be encountered. To prevent these complications, the preoperative observation of the tooth and the preparation of an adequate bite block are necessary⁵².

(d) Strengths and weaknesses

Strengths:

- This method enables the monitoring of motor-related neural tissues of the spinal cord.
- The stimulating and recording electrodes are easily placed without employing any invasive technique.

Weaknesses:

- The pattern and latency of this evoked potential are not consistent, and it may result in false-positive findings.
- The depth of anesthesia and the amount of induced neuromuscular blocking agents affect the potentials.
- A limited lesion in the spinal anterior motor neuron and spinal nerve root may not be detected (approximately 50% possibility).
- Lip and tongue bite injury and tooth injury may occur after jaw muscle contraction.

(2) *Spinal cord-evoked potential after electrical stimulation of the brain [Br(E)-SCEP (D and I wave)] (Fig. 5)*

The spinal cord-evoked potential after delivering transcranial high-voltage stimulation in humans was recorded by Boyd et al. in 1986³³, as previously mentioned. They intended to use this potential for intraoperative monitoring of spinal cord function. In Japan, Tsubokawa et al.⁵³ stimulated surgically exposed cortex and detected signals from the cervical epidural space. However, their pioneer method at that time was not accepted by researchers in other specialties because of its invasiveness.

After the development of the transcranial brain stimulation technique, this method was widely accepted by surgeons who had no concerns regarding placing the recording electrode into the epidural space during the course of the posterior approach surgery to the spine. By increasing the strength of stimulation, Boyd et al. recorded the first spike wave and small polyphasic waves in patients, which corresponded to the D wave and I wave, respectively³³. They were initially named by Patton and Amassian in animal ex-

perimental studies⁵⁴). To date, the D wave and I wave are used in clinical settings (Fig. 5).

The D wave is a potential generated by the direct stimulation of the corticomotor neuron of the motor cortex, and the I wave is a potential of corticomotor neuron firing caused by transmitted impulses from other neurons via cortical synapsis⁵⁴). Ordinarily, the I wave is small in amplitude and is not constantly recorded. Therefore, the D wave has been employed to observe the conductivity of the motor-related tracts in the spinal cord.

(a) Electrode setting and recording of the potential

Selection of the stimulating electrode and its setting is similar to that of Br(E)-MsEP (i.e., the muscle-evoked potential after stimulating the brain). The recording electrode is set in the epidural or subarachnoid space at the caudal side of the surgical site, but this potential cannot be recorded from the level of the cauda equina. For recording the potential, a bipolar tube-type electrode or two twisted insulated wires abrading their tip are used. The current recorded from the spinal cord had a very small amplitude. Thus, care must be taken to avoid noise. Please refer to subsection 1)

(2)(a).

(b) Effect of anesthesia and other factors

Anesthesia influences the activities of the motor neurons of the cortex; thus, it must be carefully performed as described in the section Br(E)-MsEP 2)(1)(a). However, a neuromuscular blocking agent can be used for recording this potential.

(c) Recorded potential and its analysis

As described previously, the initial D wave and subsequent I waves of low amplitude are recorded. However, I waves are not consistently recorded because of their vulnerability against anesthesia, and they are not utilized for monitoring (Fig. 5).

The D wave is used as an indicator for the monitoring of the motor-related tracts of the spinal cord. This potential decreases in amplitude when the recording electrode is moved caudally, and a fine change in the relationship between the electrode and the spinal cord may cause a wave pattern change²³).

The critical level of the decrement of the amplitude is regarded as 50%, which is similar to that of the Sp(E)-SCEP. Kothbauer et al. reported a good prognosis of 3 months after surgery if the D wave maintains an amplitude of 50% or more even after the Br(E)-MsEP [subsection 2)(1)] disappears during the removal of the spinal cord intramedullary tumor⁴⁵).

(d) Strengths and weaknesses

Strengths:

- This method facilitates monitoring of motor-related neural tracts of the spinal cord.
- The spinal cord and motor-related tracts are monitored even if the Br(E)-MsEP cannot be observed because of the use of neuromuscular blocking agents.

Weaknesses:

- Invasive placement of the recording electrode that re-

quires a medical license.

- The anterior motor neuron of the spinal cord cannot be monitored.
- Lip and tongue bite injury and tooth injury may occur after jaw muscle contraction.

(3) *Muscle-evoked potential after electrical stimulation of the spinal cord [Sp(E)-MsEP] (Fig. 6)*

In this method, spinal motor-related functions are monitored by observing the muscle-evoked potentials generated by the stimulation of the spinal cord with an epidurally placed electrode.

Two orthopedic spine surgeons contributed to the development of this technology. This method was initially reported by Machida et al.⁵⁵). However, they were suspected of having this potential under ordinary inhalational anesthesia, although no detailed description regarding anesthesia exists. Therefore, recording conditions were difficult and not universal. In 1993, Taylor et al. utilized paired stimulations of 1-2 ms interval under propofol anesthesia and demonstrated that muscle-evoked potentials were constantly recorded³⁶). They proposed that such phenomena resulted from temporal summation of evoked postsynaptic potential in the anterior motor neurons and in the interneurons. This method has been widely used in clinical practice by experts who have no concerns regarding placing electrodes into the epidural space. By contrast, groups of neurologists and neurophysiologists have criticized the procedure's invasiveness⁴⁹) and proposed that the impulses firing the motor neurons are transmitted antidromically in the dorsal column sensory tracts. However, animal experimental studies have proved that after resecting the dorsal column, these potentials can be recorded continuously^{56,57}).

(a) Electrode setting and recording of potential

A bipolar catheter-type electrode or twisted wire-type electrode can be used. The caudal side should be the cathode to send impulses caudally. Paired electric currents are approximately 10 mA in strength with 0.2 ms duration, and the stimulus interval is 1-2 ms. Alternatively, the train stimulation of five stimuli with similar strength and duration is used in a clinical scene⁵⁸). For the recording of the muscle activity, a surface or needle electrode is set at the muscle belly as described in subsection 2)(1)(a).

(b) Effect of anesthesia and other factors

This potential is the result of firing of anterior motor neurons that generate impulses that travel down to the neuromuscular junction to trigger a muscle contraction. Therefore, this potential is affected by anesthetic substances and neuromuscular blocking agents. A similar anesthesia protocol is used, as recorded in subsection 2)(1)(b) for Br (E)-MsEP. Intravenous anesthesia with propofol and fentanyl is recommended.

(c) The recorded potential and its analysis

A multiphasic potential is recorded (Fig. 6). Taylor et al.³⁶) mentioned that the recorded potential is grouped into two types, although it may be modified with the location of re-

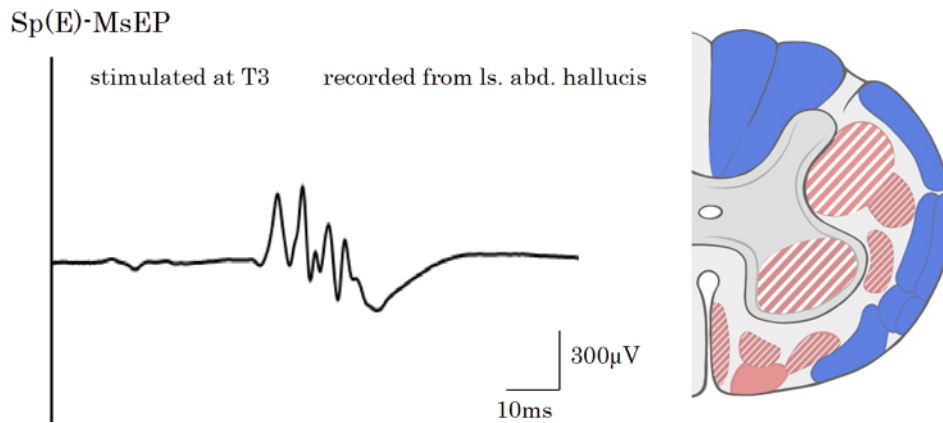


Figure 6. Muscle evoked potential after electrical stimulation of the spinal cord.

The electrical stimulations were delivered at the level of T3 to the spinal cord from the epidural space. The potential was recorded from the abductor hallucis. The wave pattern shows no regularity, which is a similar finding as that of the muscle-evoked potentials after the electrical stimulation of the brain.

This potential can be understood reflecting the motor-related activities of the spinal cord. Mainly the corticospinal tract and anterior motor neurons of the gray matter.

cording electrodes. No unified opinion exists regarding the critical point as a warning level. It is considered similar to that of muscle-evoked potential after stimulating the motor cortex [i.e., Br(E)-MsEP].

(d) Strengths and weaknesses

Strengths:

- Motor-related neural tissues of the spinal cord can be monitored.
- Electrode setting can be performed during a surgical posterior approach to the spine and spinal cord.
- The potentials are stable compared to the Br(E)-MsEP, and the anesthetic fade phenomenon may be avoided.

Weaknesses:

- Invasive placement of the stimulating electrode for a nonsurgeon.
- No clinical research has reported a critical point, but the critical point may be estimated as a 70% decrement of potential similar to the Br(E)-MsEP.

3. Strategies to Manage a Critical Situation

As mentioned earlier, building a reliable team for effective monitoring in the operating room is important^{4,5}. Surgeons often tend to make biased judgments based on their own clinical experience in analyzing and responding to data obtained by clinical neurophysiological techniques^{4,5}. However, as mentioned previously, the surgeon has to make the final decision and is responsible for the results. Therefore, wherever possible, the surgeon should have appropriate knowledge to take the right decisions as fast as possible. To accomplish this, surgeons should share the information with the monitoring staff accurately and smoothly.

Several proposals regarding the schedule of a checklist for intraoperative changes in neurophysiological responses have

been proposed^{59,60}. Vitale et al. proposed a checklist with the final decision determined by a wake-up test⁶⁰.

The authors of this article would like to propose a strategy for dealing with a change in potential from a practical point of view. The most important thing in composing a team is to foster relations of mutual trust among team members, which include an anesthesiologist, neurologist or neurophysiologist, neuromonitoring personnel, and nurses. Surgeons must create an atmosphere in which every member can voice and exchange opinions without any hesitation when problems arise. Thus, surgeons should be informed of any evidence that may be related to a neurological sequela. For this purpose, respect to the expertise of the team members and their opinions is important. Furthermore, sharing understanding of common terminology and technology among team members is important.

When any change in a potential is observed, this change should be confirmed by performing at least three recordings. Checking whether the change has occurred rapidly or gradually is a clue to find the cause of the change. A change in artifact pattern, which is started by stimulation and is spread through tissues, should be recognized, although it is often ignored. If the pattern remains unchanged, then the delivered electric current is constant, and the recording condition is stable. In this situation, a change in the evoked potential strongly indicates the deterioration of neural tissue activity.

The aforementioned countermeasures are summarized, as follows:

- ① Basic issues of team composition
 - (a) When a team member recognizes that a problem has occurred, he or she must point it out, and opinions must be exchanged without any hesitation.
 - (b) Respect to the expertise of every team member and their opinion.

- (c) Use of common terminology.
- ② Responses to changes in the characteristics of potential
- (a) Changes should be confirmed by at least three recordings.
- (b) When the wave pattern suddenly changes, the following factors should be checked:
- The surgical procedure, accidental lesion to the spinal cord, aggressive distraction, derotation, etc.
 - Hardware-related issues, electrode dislodgment, cable lesion, and amplifier and stimulator problems. If these issues occur, the artifact pattern is affected.
 - Changes in the volume of the anesthetic agent and neuromuscular blocking agent.
- (c) When the wave pattern gradually changes, the following factors should be checked:
- Safety of the surgical procedure.
 - Slowly increasing or sustaining compression, distraction to the spinal cord; in addition, secondary disorders should be considered such as circulatory disorders and spinal cord and brain edema.
 - Changes in the depth and method of anesthesia and accumulated dose of the neuromuscular blocking agent.
 - General conditions such as hypotension, hypovolemia, hypoxemia, and hypothermia.
 - Positioning of extremities and spine to avoid peripheral nerve, brachial plexus, and spinal cord impairment⁽⁶¹⁾.
 - For Br(E)-MsEP monitoring, anesthetic fade should be considered. To confirm that the artifact pattern is stable, anesthesia is constantly maintained.
 - Impedance changes in the stimulating and recording electrodes cause changes in artifact pattern.

4. Conclusion

This is an era in which spine and spinal cord surgeons are strongly required to perform surgery under the intraoperative monitoring of spinal cord function. However, no existing method can reflect all complex spinal cord functions. Within this constraint, efforts must be focused on performing complete monitoring whenever possible depending on the surgeon and the patient. Intraoperative neuromonitoring is a team effort. Thus, effective intraoperative spinal cord function cannot be monitored unless the team exchanges information smoothly and effectively. Spine and spinal cord surgeons, who are in charge of the operative procedure and responsible for the prognosis of the patient, must be aware of this principle. To this end, surgeons must understand the strengths and weaknesses of the selected method and must communicate closely with the monitoring staff. Furthermore, a surgeon may contribute to more effective monitoring by utilizing their expertise.

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