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An Overview on Intraoperative Neurophysiological Monitoring

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ABSTRACT

Intraoperative neurophysiological monitoring (IONM) has become an essential adjunct in modern neurosurgery and complex surgical procedures for preserving neural function and minimizing postoperative neurological deficits. It encompasses multiple modalities including somatosensory evoked potentials, motor evoked potentials, electromyography, electroencephalography, brainstem auditory evoked potentials, and visual evoked potentials, each targeting specific neural pathways. This review highlights the anatomical and physiological basis, basic principles, clinical applications, anesthetic considerations, perioperative factors affecting monitoring accuracy, limitations, complications, and current evidence-based indications of IONM in neurosurgical practice. Multimodal IONM, particularly when integrated with optimized anesthetic techniques such as total intravenous anesthesia, enhances surgical safety by facilitating early detection of neural compromise and allowing timely intraoperative intervention. Despite technical limitations and susceptibility to physiological and pharmacological influences, IONM remains a cornerstone in reducing morbidity and improving outcomes in neurosurgery..

Key Words: Intraoperative neurophysiological monitoring; Somatosensory evoked potentials; Motor evoked potentials; Electromyography; Neurosurgery; Total intravenous anesthesia.

INTRODUCTION

Intraoperative neurophysiological monitoring (IONM) helps assess the integrity of neural structures and consciousness during surgical procedures. It includes both continuous monitoring of neural tissue as well as the localization of vital neural structures. The goal of IONM is to identify intraoperative neural insults that allow early intervention to eliminate or to significantly minimize irreversible damage to the neurological structure and prevent a postoperative neurologic deficit. The use of neurophysiological monitoring during surgical procedures requires specific anesthesia techniques to avoid interference and signal alteration due to anesthesia (1).

Different modalities of intraoperative neurophysiological monitoring (IONM) are available, each monitors a specific neural pathway, and they are (1):

1. Evoked potentials including somatosensory evoked potential (SSEP), motor evoked potential (MEP), brainstem auditory evoked potential (BAEP), visual evoked potential (VEP)
2. Electromyography (EMG) .
3. Electroencephalography (EEG)

Multimodal intraoperative neuromonitoring (IONM) is recommended as an effective way to avoid permanent neurologic injury during surgical procedures (2).

I. Anatomy and Physiology

Each technique of intraoperative neurophysiological monitoring monitors a specific neural pathway.

Somatosensory Evoked Potential (SSEP): SSEP monitors the dorsal column–medial lemniscus pathway, which mediates tactile discrimination, vibration, and proprioception. Stimulation of sensory receptors in the skin initiates peripheral sensory nerves, which extend through the nerve root to the ipsilateral dorsal root ganglia at spinal levels. The projections from these first-order neurons form fasciculi gracilis and cuneatus, which carry impulse from the lower and upper extremities, respectively. The first synapse occurs in the lower medulla, then the impulses cross over at the level of the brainstem and form medial lemniscus. The impulse then ascends to the contralateral thalamus and relay information to the primary sensory cortex in the parietal lobe. In the upper extremities, the median and ulnar nerve are monitored, whereas, in the lower extremities, the posterior tibial and peroneal nerve are monitored (3).

Motor Evoked Potential (MEP): MEP monitor motor pathways, transcranial electrical stimulation elicits excitation of corticospinal projections at multiple levels. Depending on the intensity of stimulation and the placement of electrode, motor evoked potentials are generated at different levels of the brain, including superficial white mater just underneath the motor cortex, the deep white matter of the internal capsule, and pyramidal decussation. The electrical potential is recorded at the spinal cord or muscles. MEP is generated and transported via the pyramidal tract **(1)**.

Visual Evoked Potential (VEP): VEP measures the functional integrity of the optic pathways from the retina to the brain's visual cortex in response to light stimulus. Visual stimulus is converted into nerve signals in the retina. These signals are transmitted via the optic pathway to the brain, from the retina to the optic nerve, optic chiasma, optic tract, lateral geniculate body, optic radiation, and visual cortex occipital lobe (**4).**

Brainstem Auditory Evoked Potential (BAEP): BAEP monitors the function of the auditory nerve and auditory pathways in the brainstem. The auditory signal travels from the cochlear hair cell to the primary auditory cortex via the vestibulocochlear nerve, superior olivary complex, lateral lemniscus, inferior colliculus, and medial geniculate body (**5).**

Electromyography (EMG): EMG monitors somatic efferent nerve activity and evaluates the functional integrity of individual nerves. EMG monitors intracranial, spinal, and peripheral nerves during surgeries. Depolarization of a motor nerve produces electrical potential within the muscles innervated by that specific nerve, and the generated electrical activity is monitored using subdermal or intramuscular electrodes (**6).**

Electroencephalography (EEG): The electrical activity measured by EEG is generated by groups of pyramidal neurons, which has cell bodies in the 3rd and 5th layer of the cerebral cortex (**7).**

BASIC PRINCIPLES

The goal of IONM is either the early detection of intraoperative nerve damage or the precise localization of major nerves that are susceptible to intraoperative damage, thereby minimizing the risk of postoperative neurological deficits. Toward that goal, IONM involves monitoring of neural pathways, cerebral blood flow, and the level of neural function during surgery. This not only ensures the safety of patients, but also helps them, their legal guardians, and their medical team to confidently approach the surgery, especially if that surgery is particularly technically challenging **(8).**

IONM uses diverse neurophysiological testing techniques that have been developed to diagnose patients with neurological disorders. The types of neurophysiological testing that have been adapted for IONM include motor evoked potentials (MEPs) for monitoring the descending motor pathways, somatosensory evoked potentials (SSEPs) for ascending sensory pathways, brain auditory evoked potentials (BAEPs), visual evoked potentials (VEPs), and electroencephalography (EEG) for recording the electrical activity of the brain, and electromyography (EMG) for monitoring peripheral neuromuscular systems. Transcranial Doppler (TCD), which is a type of ultrasonography, can also be used. Among these diverse modalities, appropriate tests of choice can be chosen according to the particular type of surgery and its inherent risks **(8).**

Application of modalities of IONM in different surgeries

Somatosensory Evoked Potential (SSEP) and Motor Evoked Potential (MEP)

Spine and spinal cord surgery including scoliosis and Kyphosis correction with instrumentation, spinal cord decompression/stabilization, anterior and posterior spinal fusions (cervical, thoracic, and thoracolumbar), the release of tethered cord, correction of spina bifida, resection of the tumor, cyst, aneurysm or arteriovenous malformation of the spinal cord

Brain and brain stem surgeries including craniotomy for tumor removal, craniotomy for aneurysm repair, arteriovenous malformation repair, localization of cortex during craniotomy, thalamotomy

Cerebrovascular surgery, including clipping of intracranial aneurysms, interventional neuroradiology

Stereotactic surgery on the brain stem, thalamus, and cerebral cortex

Pelvic fracture surgery

Thoracoabdominal aortic aneurysm repair

Repair of coarctation of the aorta

Brachial plexus and lumbosacral plexus surgery

Peripheral nerve repair

Carotid endarterectomy

Thyroid surgery

Brainstem Auditory Evoked Potential (BAEP)

Acoustic neuroma resection

Vestibular nerve section

Vascular loop decompression

Vestibular schwannomas

Facial nerve decompression

Brainstem tumor resection

Auditory brainstem implant

Posterior fossa procedures

Functional localization of the cortex with direct cortical stimulation

Assess auditory pathways within the brainstem

Assess ischemia at the cochlea and eighth nerve

Visual Evoked Potentials or Response (VEP):

Monitoring the visual system during optic nerve surgery

Orbital surgery

Pituitary gland surgery

Electromyography (EMG)

To monitor cranial nerve function during procedures including acoustic neuroma resection, microvascular decompression of the facial nerve, parotid tumor resection, vestibular neurectomy for Meniere disease, neurotologic/otologic procedures.

Nerve root or spinal cord monitoring during spinal surgeries including spinal instrumentation (e.g., pedicle screw placement), a mechanical spinal distraction

Resection of skull base tumors, spinal tumors

Surgical excision of cranial nerve neuromas of motor cranial nerve

Brachial or lumbosacral plexus surgery

Neck surgery including thyroid surgery, neck dissections

Electroencephalogram (EEG):

Carotid endarterectomy

Cerebral aneurysm clipping

Epilepsy surgery

Monitoring depth of anesthesia

Pre operative planning &set up:

An appropriately skilled intraoperative neurophysiological monitoring (IONM) team should be assigned for each patient and procedure. After a detailed preop evaluation (history, physical exam, and review of the medical record) and discussion with the surgeon to review the imaging, relevant neural anatomy, physiology, and planned procedure, the IONM team determines the appropriate modalities IONM required for the scheduled procedure. The team discusses IONM procedures and their risks with the patient and documents patient's data. IONM personnel discusses planned monitoring with nursing staff and determines a suitable location for monitoring equipment in the operating room. IONM personnel set up and check all the equipment before the patient arrives in the operating room. A suitable anesthesia plan is discussed with the anesthesia team as required for the surgical procedure and specific neuromonitoring modality. The technique of IONM involves the placement of electrodes or other monitoring devices under all aseptic skin preparation, acquisition, recording, and interpretation of high-quality data (**9).**

IONM personnel acquires baseline responses for needed monitoring modalities, informs and discusses alert criteria and testing strategies with the surgical and anesthesia team to coordinate monitoring as required during the procedure. IONM personnel also reviews the anesthesia regimen with the anesthesia team to optimize anesthesia maintenance during the procedure. The IONM record contains surgical event times, communication between teams, alert issued to surgical and anesthesia team, anesthesia drugs, and dosages used. Significant changes in the dose of anesthesia medications and physiological parameters, including heart rate, blood pressure, and temperature, are also recorded **(1)**.

Technique

The most commonly used intraoperative neurophysiological monitoring (IONM) techniques for surgical procedures include:

Somatosensory sensory evoked potential (SSEP)

Motor-evoked potential (MEP)

Spontaneous and triggered electromyography (EMG) (**10)**

Sensory evoked potential technique involves applying a stimulus that generates a neuronal response, measured as a graph of time (mS) on the x-axis and voltage(mV) on the y-axis, two significant characteristics of the measured waveform is amplitude and latency. SSEP sensory evoked potentials are very low amplitude and require averaging and summation across multiple stimulations to enhance their quality and distinguish these potentials from background noise. The time interval between electrical stimulation of neural structure and measuring the evoked response at the cerebral cortex is defined as latency. **(1)**.

The somatosensory evoked potentials (SSEP) are electrical potentials generated within the neuroaxis in response to stimulation of a peripheral nerve (e.g., the median nerve at the wrist or the posterior tibial nerve at the ankle) . These potentials travel from the periphery to the brain and are recorded by electrodes placed over the scalp and along the transmission pathway. SSEP is monitored continuously throughout procedures that give close to real-time monitoring of the sensory pathway (**11).**

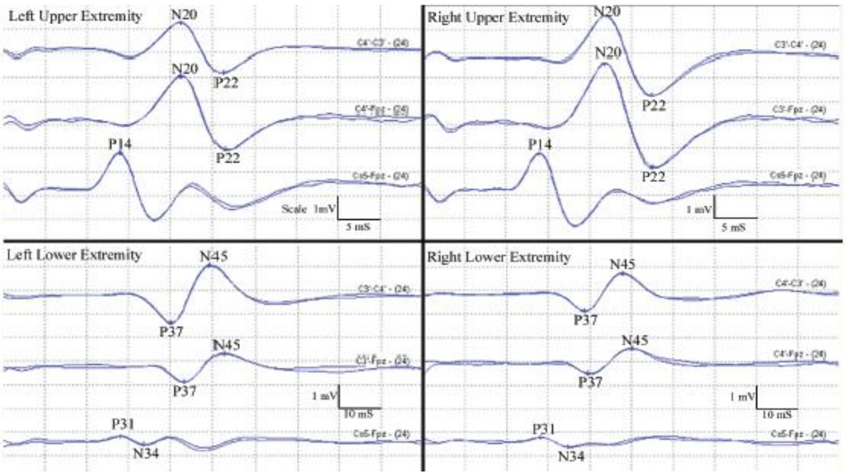

Figure 1. Normal representations of SSEPs from median nerves and posterior tibial nerves, including cortical and subcortical waveforms (12).

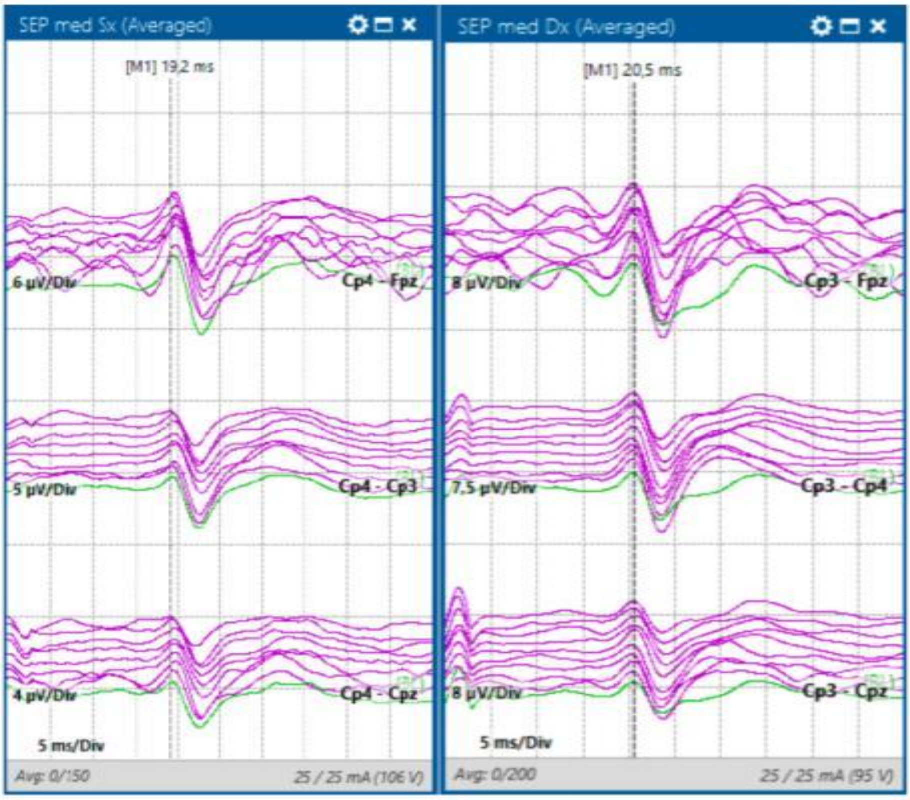

Figure 2. SSEPs of the upper limbs with stimulation from the median nerve using adhesive electrodes and recording from the scalp with corkscrew electrodes positioned according to the International 10–20 system (13).

Motor evoked potential (MEP) is generated by transcranial electrical stimulation using surface or subdermal needle electrodes on the scalp or direct electrical stimulation on the brain. Motor Evoked potential are measured over the spinal cord below the surgery level or in the muscle of interest. At the spinal level, the evoked response is measured in the epidural or intrathecal space. Compound muscle action potential (CMAP) is routinely measured due to their sensitivity, specificity, and minimal invasiveness. The electrodes are placed on the muscle innervated by specific brain regions, nerve root, or cranial nerve needed to monitor. Frequently used sites are thenar muscles, tibialis anterior, and abductor hallucis; muscle group above the surgery level is used as a control (**14).**

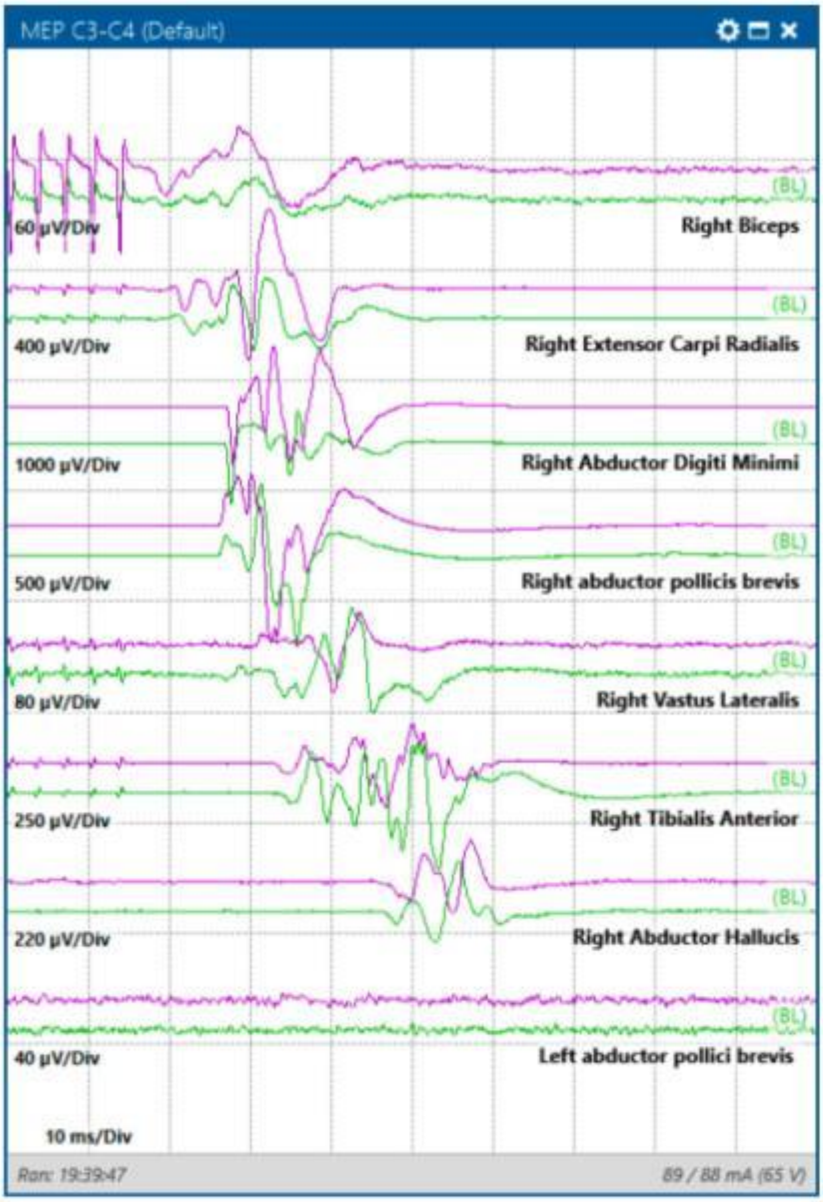

Figure 3. Transcranial motor evoked potentials (MEP) obtained by stimulating with corkscrew electrodes in the C3–FZ position at a threshold of 90 mA in a case of left parietal lesion (13).

Electromyography (EMG) records myoelectric signals from peripheral musculature to monitor selective nerve root function. One muscle group per nerve is monitored by using spontaneous EMG or triggered EMG technique. Spontaneous EMG, needle electrode is directly inserted into a muscle to record the electrical activity of that muscle; no stimulation is performed, surgical manipulation such as compression, stretching, or pulling of nerves produces myoelectric signals in the corresponding innervated muscles which are recorded. Triggered EMG, a monopolar electrode, Subdermal needle electrodes are placed in the appropriate muscle groups to record electrical activity in response to the stimulation. Direct stimulation of nerve root using less than two mA can ensure an electrical activity in the appropriate muscle group. Triggered EMG is used to check proper pedicular screw placement; if the screw breaches the medial or inferior pedicle wall, it significantly reduces the stimulation threshold and increases the risk of damage to the exiting nerve root **(1)**.

Brain stem auditory evoked potential (BAEP), are recorded by delivering an auditory stimulus to one ear; the stimulus is loud, repetitive ticks produced by a device placed over or in the auditory canal. The response is measured from electrodes placed on the scalp or external ear to record ipsilateral and contralateral signals **(1)**.

An electroencephalogram (EEG) measures the activity of the cerebral cortical neuron via the scalp electrode. Each scalp electrode collects around 6 cm2 synchronous cortical activity. This electrical activity is the summation of the postsynaptic potentials (inhibitory and excitatory) from pyramidal cells near each recording electrode (**7).**

Anesthesia during IONM

During neurosurgery that involves the use of IONM, careful consideration must be given to selecting the optimal anesthetic plan (***10*****).**

The sensitivity and accuracy of collected neurophysiological data are significantly influenced by the chosen anesthetic technique. All anesthetic medications exert some level of interference with evoked potentials and thus need to be maintained at consistent levels throughout the surgery. The use of intravenous bolus infusions or abrupt alterations in the minimum alveolar concentrations of inhaled anesthetics could potentially compromise the precision of signal measurements (***10***). For reliable evoked potential measurement, it is essential to maintain stable alveolar and serum concentrations of the anesthetic agents. Achieving this is most effectively done through continuous intravenous infusions of anesthetic agents. Currently, the preferred method in IONM is total intravenous anesthesia (TIVA) or target-controlled infusion (TCI) without the use of neuromuscular blocking agents. In particular, the preferred hypnotic agent is propofol, with remifentanil or sufentanil as analgesic drugs (***10***).

In recent times, the utilization of low doses of dexmedetomidine has emerged as a viable option as an adjuvant in neuroanesthesia. This is attributed to its dual benefits of providing analgesia and reducing the need for other anesthetic agents while aiding IONM (***15*****).**

Very recently, remimazolam has been introduced in clinical practice. Remimazolam is a new ultrashort-acting benzodiazepine with high water solubility and metabolism via tissue esterases. Few reports exist on the use of remimazolam during IONM. In healthy volunteers, remimazolam induces at the EEG an initial increase in beta activity and a late increase in the delta frequency band. The increase in beta activity may explain why some patients could not reach deep sedation with remimazolam, as monitored with EEG-derived indexes (see below). Remimazolam has also been shown to not interfere with the SSEPs, VEPs, and MEPs (***16*****).**

Neuromuscular blocking agents cannot be used since they interfere with EMG and MEPs if administered close to the IONM assessment. However, rocuronium, a non-depolarizing neuromuscular blocking agent, could be used at low doses (0.3 mg·kg) at induction of anesthesia, to facilitate airways management, laryngoscopy, and tracheal intubation (***17*****).** This dose is the effective dose (ED_{95}), as it induces 95% depression of muscle contraction within 3 to 5 min and it secures 25% recovery of the motor response within 30 min. In addition, rocuronium has the advantage of a specific antidote (i.e., sugammadex), which can be administered to immediately revert the neuromuscular block (***18*****).**

Monitoring the depth of anesthesia is also crucial during surgeries, particularly when IONM is employed. If sedation is too light, the patient might inadvertently move during the procedure, which could disrupt the surgical process and compromise patient safety. On the other hand, excessive sedation can potentially dampen the signals from IONM, affecting the quality of the collected data. To attain the desired depth of anesthesia, brain function monitors are utilized. These monitors provide the depth of sedation by analyzing the EEG signal from a small number of frontal electrodes and generate a numerical scale ranging from 0 (indicating burst suppression) to 100 (indicating a fully awake patient). Typically, the optimal range of sedation falls between 40 and 60 on this scale (***19*****).**

Finally, other factors, such as hemodynamic stability, and other variables (changes in glycemia, electrolytes, gas exchange, hypothermia, reduced circulating blood volume and cerebral blood flow, and increased pressure in the superior vena cava) could potentially disrupt the accurate capture of signals during IONM procedures and may provide misleading information to the surgical team (***10*****).**

Perioperative factors affecting intraoperative neuromonitoring

The following sections summarise the effect of physiological and pharmacological factors on IONM, comprising a spectrum of evidence from animal studies to clinical trials.

Physiological factors

Several physiological factors affect IONM signal acquisition and are important for the anaesthetist to consider. A stable physiological milieu is crucial in enabling optimal and reproducible IONM signals. Complementary to this, more research is warranted regarding the effect of patients' characteristics on the feasibility and accuracy of IONM **(20)**.

Temperature

Central neuronal conduction is significantly delayed by hypothermia, with a reduction of 15% per degree Celsius decline.

Effects on the axon and synapse are additive, with pathways involving multiple synapses being affected to a greater extent. This explains the larger effect of hypothermia on cortical compared with spinal SSEPs seen in animal studies, with additional decrease in conduction along the lemniscal-thalamic pathway **(21)**.

Electrophysiological changes include decreased amplitude of evoked potentials and decreased nerve conduction velocity, resulting in increased latency. Regarding the electroencephalogram (EEG), in patients undergoing cardiac surgery with cardiopulmonary bypass, for each degree Celsius change in temperature during cooling, the patient state index (PSI) using SedLine depth of anaesthesia monitoring, decreased by a mean of 0.8 points. Brainstem auditory evoked potentials are more resistant to mild hypothermia, with amplitude affected variably **(22)**.

Hyperthermia can likewise exert deleterious effects, with animal studies demonstrating that although a temperature increase from 37°C to 39°C causes cortical and subcortical SSEP latencies to decrease by 5–7%, a further increase in temperature prolongs latency and can result in neuronal damage. According to such evidence, core temperature should be maintained within ~2°C of baseline during intracranial surgery **(21).**

Hypo- and hypercapnia

Hyperventilation resulting in hypocapnia causes cerebral vasoconstriction. The resultant reduction in O2 delivery can be more pronounced in patients with compromised vasculature or when compensatory autoregulation has been exhausted. Hypocapnia can therefore lead to difficulty with IONM signal acquisition. Where this occurs, it is important for the anaesthetist to check and optimise blood pH and Paco2. In clinical studies, hypercapnia up to Paco2 6.7 kPa has no effect on SSEPs, with no convincing evidence for an effect on MEPs **(21)**.

Hypoxia and haemodilution

Progressive hypoxia is associated with decreased SSEP amplitude and increased latency, with eventual loss of cortical SSEP waves, as demonstrated in animal studies. Cortical SSEPs are more sensitive to hypoxia than subcortical potentials, possibly attributable to subcortical regions having a lower metabolic rate. Haematocrit plays an important role in maintaining O2 carriage, with evoked potential latency increasing with associated amplitude decrease when haematocrit is reduced to 10–15%. Signal change may nevertheless occur at an increased haematocrit with concurrent hypoperfusion. It is therefore advisable for the anaesthetist to check the haemoglobin concentrations and maintain haematocrit >30%, according to local guidance **(22)**.

Hypotension

An isolated decrease in mean arterial pressure (MAP) results in a variable effect on IONM modalities. While SSEP and MEP amplitudes decrease with associated increased latency as MAP is reduced below the autoregulatory threshold, a cerebral perfusion pressure of <30 mmHg is required in paediatric patients with central nervous system disease, before BAEP signals are obliterated. If combined with hypoxaemia or haemodilution, IONM modalities in animal studies are affected to a greater degree **(21)**.

Patients with baseline abnormal cerebral perfusion or impaired autoregulation are at increased risk of neuronal ischaemia. Accordingly, management of MAP should be guided by MEPs, SSEPs, or both, and if there is signal change, MAP should be increased to at least 20% above baseline, according to local practice. However, a very brief reduction in MAP, such as when using adenosine to facilitate aneurysm clipping, has not been found to affect MEP/SSEP signals, even with repeated doses **(23)**.

Positioning

Given that the patient's position may lead to compromised perfusion or nerve damage, it is important to maintain close vigilance to neck and extremity position (particularly the shoulders and arms) during surgery. For example, neck flexion for posterior fossa surgery and lateral positioning may both cause both neural compression or vascular compromise. If a patient is deemed to be at high risk of positional injury, measuring evoked potentials before and after positioning may alert the multidisciplinary team to possible positioning-related issues, allowing for readjustment before commencement of surgery **(21)**.

Pharmacological factors

Each IONM modality is affected differently by anaesthetic agents, depending on the effect of each drug on specific neurotransmitters, and the number and type of synapses involved within each monitored pathway. Generally, anaesthetic agents exhibit a dose-dependent suppression of evoked potential transmission, with MEPs being comparatively more sensitive than SSEPs. In contrast, BAEPs are relatively resistant to the effects of anaesthetic agents, as is EMG (with the exception of neuromuscular blocking agents; NMBA) **(24)**.

With reproducible waveforms needed in order to detect critical events during surgery, agents must be chosen that minimise amplitude depression or prolonged latency. This is especially important where baseline amplitude is low and variability increased, for example with SSEPs in the elderly and in those with pre-existing neurological dysfunction. Baseline IONM recordings should be made once stable anaesthetic conditions are reached, after induction of anaesthesia **(21)**.

It is essential for the anaesthetist to know how each agent affects IONM signal acquisition and interpretation. Furthermore, it is important to maintain anaesthetic stability during surgery, with care taken to avoid variation of technique **(21)**.

Clinical Applications of Neuromonitoring

IONM has revolutionized the field of neurosurgery by significantly enhancing the safety and precision of various neurosurgical procedures. Despite the enormous development of technologies applied to brain mapping and monitoring, IONM is still the gold standard. Whether it is intracranial tumor resection, neurovascular, epilepsy, or spinal surgery, IONM is used as a technique that allows surgeons to monitor and safeguard neural structures, thereby reducing the risk of complications and improving patient outcomes. Table 1 summarizes the IONM techniques with their aims and possible applications during neurosurgery **(13).**

Table 1. Intraoperative neuromonitoring techniques and possible applications (13).

	Aim of the Technique	**Evidence-Based Indications in Neurosurgery**
Electro-corticography (ECoG)	Identification and preservation of cerebral cortical areas	Neurovascular surgery, epilepsy surgery
Stereo-electroencephalography (SEEG)	Identification of epileptogenic zones and the “eloquent cortex”	Intracranial tumor resection, neurovascular surgery, epilepsy surgery
Electromyography (EMG)	Identification and preservation of peripheral nerves	Spinal surgery, peripheral nerve surgery
Somatosensory evoked potentials (SSEPs)	Warning of potential damage to the sensory pathways	Intracranial tumor resection, spinal surgery
Motor evoked potentials (MEPs)	Evaluation of the motor pathways	Intracranial tumor resection, spinal surgery
Direct cortical stimulation (DCS)	Evaluation of the motor pathways through direct stimulation of the cortex	Intracranial tumor resection, epilepsy surgery
Brainstem auditory evoked potentials (BAEPs)	Monitoring the functionality of the auditory nerve and the auditory pathways within the brainstem	Intracranial tumor resection
Visual evoked potentials (VEPs)	Assessing the functional integrity of the optic pathways	Intracranial tumor resection

Parameters to ensure accurate IONM

The risk of development of neuro-deficit following spinal surgery with or without any recognizable adverse event is known. Intraoperative neurophysiological monitoring (IONM) use during spinal surgery, including motor-evoked potentials (MEPs), somatosensory-evoked potentials (SSEPs), and electromyography (EMG), leads to early recognition and management of any signal changes during the procedure, thus predicts a favorable surgical outcome. Loss of IONM signals or any variation from baseline IONM signal during surgery indicates a neural injury and predicts postoperative neuro deficits' development (**1).**

Factors affect IONM

Multiple factors, including anesthetic agents, blood pressure, body temperature, oxygenation, hypocapnia, and any technical problem, can affect the IONM signal. Intravenous anesthetics are compatible with IONM; inhaled anesthetics leads to dose-dependent suppression of amplitude and increases in latency; muscle relaxants are only used for intubation as they block neurotransmission. Mechanical compression of neural tissue increases latency and decreases amplitude; a decrease in blood supply decreases amplitude (**1).**

Evoked potentials signal changes with the change in body temperature, so it has been recommended to maintain a temperature close to baseline within a range of +/- 2 degrees C to 2.5 degrees C; at core temperatures below 28 degrees C, no MEPs, and SSEPs are recorded. The partial pressure of carbon dioxide levels less than 20 mmHg causes cerebral vasoconstriction leading to neural tissue ischemia associated with a change in cortical MEP and SSEP readings (**1).**

Contraindications

There is no absolute contraindication for any of the techniques of intraoperative neurophysiological monitoring (IONM). Relative contraindications for motor evoked potentials are the presence of vascular clips, intracranial electrodes, pacemakers, other implanted bio-mechanical equipment, cortical lesions, skull defects, increased intracranial pressure, and history of epilepsy. According to the guideline of the American Clinical Neurophysiology Society (ACNS), transcranial motor evoked potential (MEP) can induce seizures. The incidence is very low, so the history of epilepsy is not considered a contraindication to MEP monitoring (**25).**

Limitations of IONM

When employing IONM, it is imperative to acknowledge potential limitations that may contribute to an elevated rate of false positives. These limitations may stem from a variety of factors, such as spontaneous muscular activity or twitches, electromagnetic interference, technical artifacts, the influence of anesthetic drugs, hemodynamic instability leading to hypoperfusion, hypothermia, patient movement, or positional changes during surgery **(13).**

The misinterpretation of electrical activity originating from muscles as neural activity is a significant challenge during surgical procedures where precise SSEP monitoring of neural structures is needed. This artifact is exacerbated by the proximity of muscles to the nerves under surveillance, as the electrical signals generated by muscle contractions can inadvertently interfere with the monitoring process. Although improving the quality of SSEP monitoring, the use of neuromuscular blocking agents is not possible if multimodal IONM, including MEPs, DCS, or EMG, is used (***17*).**

Artifacts can be generated by electromagnetic interference or technical artifacts related to inadequate grounding, insulation of monitoring electrodes, or the presence of wireless medical equipment in the operating room (***26*).**

Another technical artifact is the potential crossover that may occur during MEPs. Crossover is a frequent phenomenon occurring when cortical stimulation induces activation of ipsilateral motor evoked responses. In brain surgery, the presence of cross-activation presents a significant challenge as neural structures are activated distal the area of interest. Addressing crossover issues may entail activating the motor pathway proximal to the surgical site, potentially mitigating the occurrence of false-negative responses (***27*).**

Another issue that must be considered is the change in patient positioning or loss of signal. Patients undergoing spinal surgery are anesthetized in the supine position and afterward prone-positioned for the surgery. In this population, up to 43% of patients may face signal alterations, and in up to 10% of patients, IONM may severely attenuate or even lose the signals. During cervical spine surgery, the rate of IONM loss of signal is lower (around 3%); in most cases, the sole patient repositioning caused a complete restoration of potentials (***28*).**

These concerns could result in misunderstandings and unnecessary alerts, potentially steering the surgical team off course during the neurosurgical procedure. Hence, precise electrode positioning, effective insulation methods, a comprehensive understanding of techniques, a well-planned anesthesia strategy, and careful patient positioning are imperative to reduce the likelihood of false-positive outcomes **(13).**

Complications

The overall risk of intraoperative neurophysiological monitoring (IONM) is low. Electrical safety is paramount in the operating room. Patients under anesthesia cannot report discomfort or pain; so, it is vital to ensure that IONM equipment is checked before a safe operation. Monitoring equipment malfunctioning can lead to local skin burns and other serious complications. An additional reported risk is seizure activity, high frequency (50 to 60 Hz) electrical brain stimulation can lead to seizure activity due to abnormal neuronal discharges **(1).**

Masseter muscles' stimulation and forceful jaw movement during MEP monitoring can lead to a tongue laceration, tooth fracture, or mandible fracture. These risks can be avoided by using bite blocks. In rare cases, patients may experience tingling, bruising, soreness, and swelling at the needle insertion sites. Invasive electroencephalogram monitoring during epilepsy surgery may also lead to adverse events; the risk is low, but some reported incidents are superficial infection, cerebral infections, and elevated intracranial pressure **(29).**

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