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Current Use of Intraoperative Neurophysiology in Neurosurgery: Supratentorial Part 1

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ABSTRACT

The general aim of the neurosurgical practice is to both anatomically and physiologically preserve functional neurological structures to ensure a higher quality of life. Intraoperative neuromonitorization (IONM) helps the neurosurgeon physiologically identify and assess the functional integrity of said neurological structures. The uses of IONM in neurosurgery practice are categorized into three areas; brain (supratentorial and infratentorial), brain stem, and spinal. For every anatomical region and surgical procedure, characteristic differences in electrophysiological methods exist for both recording and interpretation. In this first three-part paper, electrophysiological methods used in supratentorial surgeries for tumor, vascular, and epilepsy pathologies and their key points will be reviewed in detail. The second part uses infratentorial and brain stem surgeries; in the third part, uses in spinal surgery will be detailed.

KEYWORDS: Neuromonitoring, Multimodality, Intraoperative neurophysiology, Vascular surgery, Epilepsy surgery, Brain tumor surgery

INTRODUCTION

Intraoperative neurophysiological monitoring (IONM) evaluates the crucial neural structures of the patients by electrophysiological methods during surgeries that jeopardize the nervous system. IONM offers neurosurgeons two primary data; first is identifying primary motor, somatosensory, language, and visual pathways; second is assessing cranial nerves and these pathways during surgery objectively.

Modern neurosurgery has needed a detailed neurophysiological assessment for accessing all kinds of the lesion without damaging neurological structures. For that reason, the intraoperative practice of neurophysiology has progressively come into prominence in neurological surgery and offered functional guidance to the surgical team.

The IONM of neurosurgery practice uses two techniques called mapping and monitoring by using electrophysiological methods to achieve the goal. The mapping procedure labels the neuroanatomical structure in the surgical area while monitoring techniques continuously assess critical neurological pathways. Commonly used electrophysiological methods contain evoked potentials, electroencephalography (EEG), and electromyography (EMG). There are also new techniques and methodologies such as cortico-cortical evoked potentials (CCEPs), olfactory evoked potentials, and dynamic mapping, which are still in development.

Tumor, vascular, and epilepsy surgery constitute the majority of supratentorial pathologies for which IONM is utilized. During tumor surgery, IONM allows the neurosurgeon to physiologically identify both the cortical structures and subcortical white matter pathways such as corticospinal tract and arcuate fasciculus on the surgical corridor and assess their functional integrity during resection. In vascular surgery, primarily cortical perfusion is evaluated, assessing the vulnerability of cortical and subcortical structures to ischemic injury. In epilepsy surgery, IONM both makes the mapping of the formal structures and intraoperative evaluation of the epileptogenic zone possible.

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This paper will focus on using IONM for supratentorial brain surgeries after explaining mapping and monitoring techniques and essential details about interpretation.

Electrophysiological procedures with methods and essential points about their recording and interpretation in supratentorial surgery

In general, a critical point for supratentorial surgery is that only one method cannot predict all neurophysiological changes. Therefore, combinations should be done according to the structures to be protected. The combination of MEP and SEP is the most common practice in supratentorial surgery. Table I summarizes all recommended and also promising methods for supratentorial procedures.

Anesthesia is another crucial point to reliable responses and interpretation. Total intravenous anesthesia (TIVA) consisting of propofol and opioid is used for reliable responses. In some circumstances, such as propofol contraindication, inhalation agents in a low mean alveolar concentration (less than 0.5 MAC) with an opioid are recommended for use (41). In this case, unstable responses can be observed in some patients.

Motor evoked potential: Motor evoked potential (MEP) is obtained by stimulating the motor cortex and recording muscles in the limbs or spinal cord (D waves). The motor cortex can be stimulated transcranial or direct cortical way. In transcranial stimulation, selected montage and stimulation intensity are the essential points for accurate investigation in supratentorial surgery. Scalp electrodes (C1, C2, Cz, C3, C4) are placed according to the international 10–10 system coordinates (27). Lateral montage (C3/C4 or C4/C3 electrodes) and higher stimulation intensity generate extended stimulation whole motor pathway from the motor cortex to the level of the foramen magnum and may give false-negative results since it also stimulates motor tract distal to a lesion (35,46). Moreover, lateral montage and higher stimulus intensity lead to patients moving, which hinders the surgery. On the contrary, transcranial with inter-hemispheric (C1/C2 or C2/C1) or hemispheric (C3/Cz or C4/Cz) and direct cortical stimulation (DCS) from strip/+6 make focal stimulation of motor cortex possible (Figure 1A-C). Particularly, DCS from strip/+6 is required less stimulation intensity and provides a very focal and superficial motor cortex stimulation (48).

MEP warning criteria for supratentorial surgery are still a matter of controversy. The most commonly used criterion is 50%-80% amplitude decrement for muscle MEP (18). However, it was experienced that physiologic fluctuations stemmed from the surgical process influence MEP waveform and amplitudes during surgery. Thus, solely amplitude decrements not exceeding the physiological amplitude fluctuations were considered a reason for false-positive warnings (48). Threshold criteria for dcMEP and tcMEP were also studied, and recommendations were shared in the literature (1,31,37,46).

Somatosensory evoked potential (SEP): SEP for supratentorial intraoperative procedures is elicited by stimulating the median or ulnar nerve at the wrist and the posterior tibial nerve at the ankle and recording from the somatosensory cortex. It is known that cortical cerebral perfusion affects SEP response in a close relationship. When the cerebral perfusion falls below 18ml/100 g/min, the cortical decline in cortical SEP amplitude may be observed, and it becomes lost when perfusion rates fall below 12ml/100 g/min (3). Thus, SEP monitoring is vital in vascular surgery to detect impairment of cortical perfusion by intended or inadvertent vessel occlusion (48).

Regarding SEP recording, different recordings montages (for instance, C3'-Cz, C4'-Cz for tibial SEPs signal to noise ratio) select the best montage with a low signal-to-noise ratio and a robust and reliable response, and thus quickly evaluation (17,48). Besides, noncephalic SEP called subcortical or peripheral distinguishes cerebral or peripheral causes of amplitude alteration with the cortical recordings. Different recording montages and subcortical recordings from noncephalic points are especially recommended for vascular procedures performed against time (17,48).

Traditional SEP warning criteria consist of >50% amplitude reduction or >10% latency prolongation from baseline. However, the importance of baseline drift or reproducibility is emphasized while interpreting (17).

Brainstem auditory evoked potential (BAEP): BAEP are very small auditory evoked potentials in response to an auditory stimulus, recorded from A1, A2 as active and Cz or Fz as reference electrodes placed on the scalp. It consists of seven positive waves and measures the function of the auditory nerve and auditory pathways in the brainstem. It is commonly used in acoustic neuroma surgery, neurovascular compression syndrome, and brainstem tumor resections. Among intraoperative BAEP changes, the latency of Peak V is the most frequently observed phenomenon. Abolition of wave V is related to deafness. A 50% decrement of wave V and a latency increment of more than 0.5ms are used as warning criteria for intraoperative interpretation (29,32).

Table I: Supratentorial Procedures and Recommended IONM Techniques

Procedure	Recommended techniques	Promising techniques for extended setup
Brain tumors	MEP, SEP, EEG, ECoG, BAEP and VEP according to possible risks on these pathways	CCEP and SCEP, olfactory evoked potential
Vascular surgery	MEP, SEP, EEG, if necessary BAEP and VEP	
Epilepsy surgery	MEP, SEP, EEG, ECOG, if necessary VEP	CCEP and SCEP

***MEP:** Motor evoked potential, **SEP:** Somatosensory evoked potential, **EEG:** Electroencephalography, **ECoG:** Electrocorticography, **BAEP:** Brain stem evoked potential, **VEP:** Visual evoked potential, **CCEP:** Corticocortical evoked potential, **SCEP:** Subcorticocortical evoked potential.*

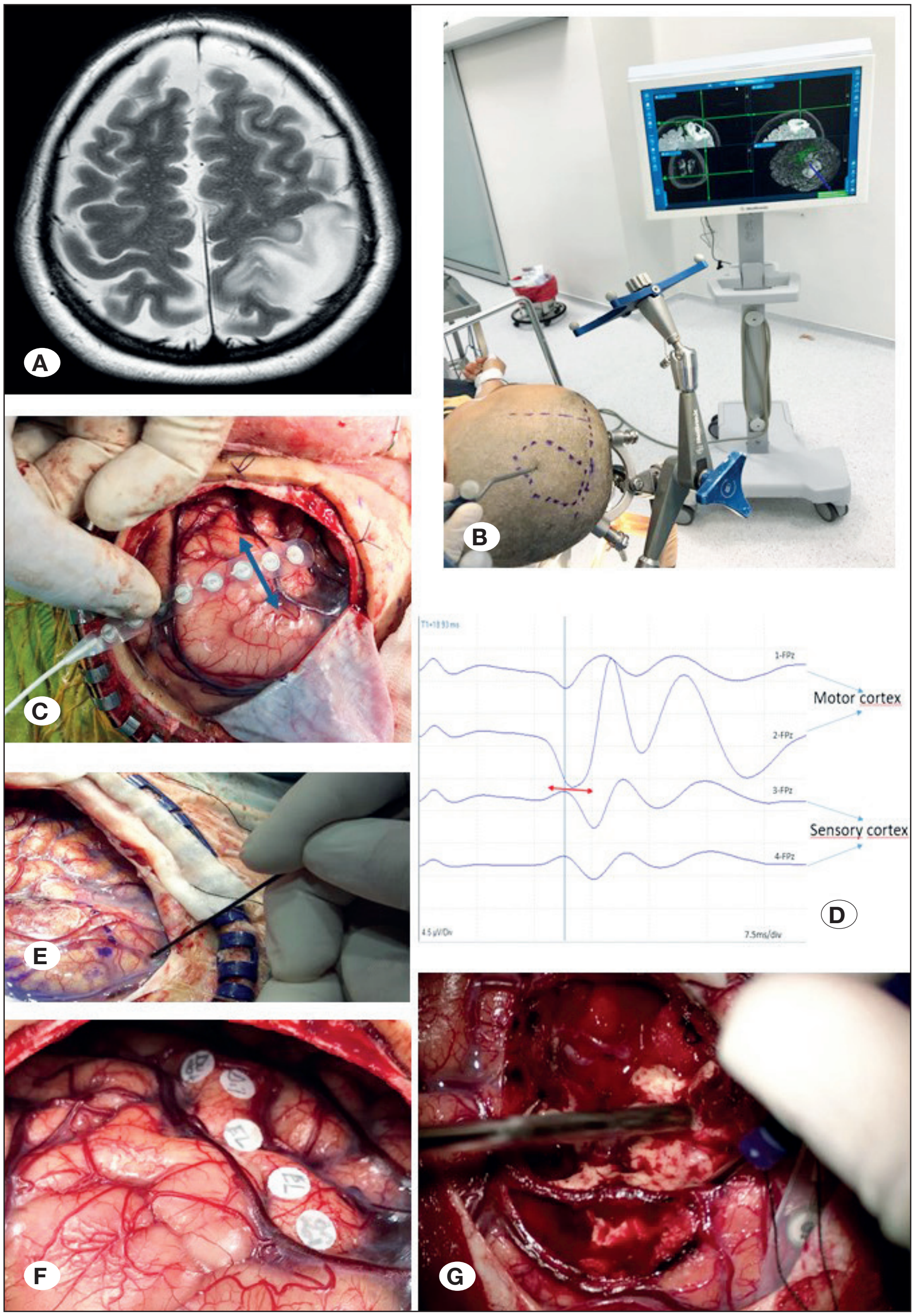

Figure 1: A) T2W axial slice showing a mass lesion located in the pre- and post-central gyri in the left frontoparietal region. **B)** The patient is registered to a neuronavigation device that helps to delineate the projection of the mass on the scalp and plan the skin incision and craniotomy. **C)** Phase reversal technique to identify electrophysiological central sulcus. The image shows the placement of a strip electrode perpendicular to the predicted anatomical central sulcus according to the neuronavigation device. **D)** The reversal in polarity at median SEP recording considered electrophysiological central sulcus was found between 2nd and 3rd contacts (blue arrow on C). **E)** The image illustrates direct cortical stimulation by the monopolar probe to confirm the localization of the motor cortex. **F)** Cortical mapping revealed hand, forearm, lip, and tongue areas labeled with tags on motor cortex with direct cortical stimulation. **G)** Direct electrical stimulation in the subcortical area to determine the distance to the CST.

Visual evoked potential (VEP): VEP is an evoked potential recorded from O1, O2, and Oz as active electrodes with reference at the vertex to Cz reference electrode at the scalp over the occipital cortex in response to light stimuli. In cases of occipital brain lesions, subdural strip electrodes can be used for recording. VEP monitoring has recently gained interest for use during surgeries with increasing TIVA use, simultaneous recording of the electroretinogram (ERG), new technological advancements in light-emitting diodes (LEDs) manufacturing, and implementation of white light stimulation (9,12). As an essential point, ERG is recorded simultaneously with the VEP to be sure that there are adequate flash stimuli delivered to the retina since dislocation of googles might cause inadequate stimulation to the retina. VEP may not be recordable in patients with visual acuity less than 0.1 and/or a visual field defect larger than hemianopsia. The most commonly used warning criteria are 50% decrement of the response (12). 20% or more amplitude decrement was recently used as an alarm criterion in a study that used white LEDs (9). Further studies are needed to identify a more common warning criterion.

Electroencephalography (EEG) and electrocorticography (ECoG): EEG is one of the oldest electrophysiological monitoring methods to record the brain's electrical activity. EEG and ECoG are currently used to evaluate after-discharges during cortical mapping to avoid epileptic seizures due to electrical stimulation, defining tumor margins in epilepsy surgery and some cerebral tumors, and monitoring cerebral function in neurovascular cases.

Electromyography (EMG): It records the electrical activity of muscle tissue and is used for various aims; to define subtle movements during mapping in awake cases, cranial nerve monitoring in skull base cases, nerve root monitoring, and testing spinal surgery.

Cortico-cortical evoked potential (CCEPs) and subcortico-cortical evoked potential (SCEP): CCEP and SCEP are obtained by averaging ECoGs in real-time to the electrical stimuli. These methods, defined by Matsumoto R and Yamao Y, respectively, provide an opportunity to track connectivity among various functional areas defined by cortical/subcortical electrical stimulation (19,20). CCEP has been applied to identify seizure propagation pathways and monitor the cortical motor network and dorsal language pathway in intraoperative and extra-operative investigations (19). The technique is still new and not standard for intraoperative use.

Olfactory evoked potential: The feasibility of monitoring the sense of smell and taste under general anesthesia has been a curiosity for many years. Cortical responses to olfactory stimuli were recently demonstrated in a feasibility study (22). Nevertheless, it needs more data to adapt it into intraoperative use.

Electrophysiological procedures

a. Cortical and subcortical mapping

The mapping method identifies cortical and subcortical functional structures. Cortical and subcortical mapping can be performed intraoperatively for a patient who is awake or under general anesthesia and intraoperatively in the presurgical evaluation of epilepsy surgery. In this paper, we will only focus on intraoperative use.

When mapping is performed in awake surgery, the patient's response to simple motor tasks can be visually evaluated during stimulation. Complex muscle responses, language, and other cognitive functions can also be visually assessed but require a high level of cooperation between the patient and the participating medical team (42). Besides, the observation of muscle responses with multichannel EMG is suggested to identify subtle movements that might be unrecognized during awake brain surgery (54). Surface or subdermal needle electrodes that were shown well tolerable for patients undergoing awake surgery can be used for EMG and MEP (44).

When mapping is performed under general anesthesia, TIVA consisting of propofol and opioid is optimal for reliable responses. In some circumstances, such as propofol contraindication, inhalation agents with a low mean alveolar concentration (less than 0.5 MAC) with a current opioid are recommended for use (41). Patients' motor reaction to electrical stimuli under general anesthesia is evaluated by surface or needle electrodes placed into muscles.

Mapping methods

SEP phase reversal technique is a mapping method that can be used for identifying the central sulcus (Figure 1A-C). As shown in Figure 1C, SEPs are recorded from strip electrodes placed perpendicularly on the predicted central sulcus according to the navigation system by stimulating the median or tibial nerve. The place where the reversal in polarity at SEP recording appears is considered the central sulcus (Figure 1D). This technique is not a direct mapping method for the motor cortex. DCS is needed to confirm the localization of the motor cortex after central sulcus identification (Figure 1E, F). Figure 1E and F show an example for direct cortical mapping after phase reversal response.

Motor cortical mapping is applied by two stimulation techniques (30,50). The Penfield technique is the oldest traditional way of cortical stimulation, still the most preferred technique in awake surgery. It comprises a 50 or 60 Hz stimulation frequency of pulses with classical 1 msec pulse duration for 1 to 4 seconds depending on intended targets. A stimulation duration of 1 second for the cortical motor functions and a longer duration of 3-4 seconds for speech and other higher cortical functions are suggested (42). A bipolar electrode tip spaced 5mm apart with biphasic current (pulse frequency 60 Hz, single pulse phase duration 1 msec) stimulation is the most used combination.

The short train technique (STT) is a relatively new stimulation technique. It was provided to elicit MEP and objectively assessment of motor pathway under general anesthesia. It was recently reported as a possibility for language mapping in patients during awake craniotomy (2,52). Technically, STT comprises short trains, four to nine monophasic rectangular electrical stimuli of 200-500 microseconds duration with an interstimulus interval of 2-4 msec (corresponding to 250-500Hz) (13,45,50). Anodal stimulation is accepted as more effective for cortical stimulation (44). It is used in both cortical mapping and monitoring for the motor cortex and corticospinal tract. Cathodal stimulation seems better for stimulation of subcortical white matter. In case the use of the STT in awake surgery is partly new, and a single stimulus or a short train consisting of 2–4 pulses (individual pulse width 0.3–0.5 msec, anodal constant-current stimulation; interstimulus interval 4 msec, stimulation close to motor threshold) usually seems sufficient to elicit muscle MEP (44).

The Penfield technique can be performed in two approaches in awake surgery; one uses the motor threshold of the primary motor cortex, and the other uses an after-discharge threshold to be confident in the negative mapping (5,7,39).

Regarding the choice of stimulation probe and technique, the traditional combination is a bipolar stimulation probe with PT or monopolar stimulation probe with STT. Different combinations are also possible in practice depending on the surgical interest (4,49).

European Low-Grade Glioma Network published a stimulation guideline in 2017 (42). This guideline recommends assessing every stimulation point three times and a control test without stimulation between 2 stimulations. It is also recommended to not stop mapping after identifying one eloquent site and maintaining to search for possible redundancies because negative mapping may not be protected (42). Besides, it should be kept in mind that an area infiltrated by a tumor might require higher stimulus intensity than stimulation intensity for neighboring healthy tissue. Although rare, intraoperative seizures can be seen during electrical stimulation. Thus, intraoperative ECoG might help detect after-discharges resulting from electrical stimuli (38).

b. Subcortical mapping and distance to the corticospinal tract (CST)

Subcortical stimulation is considered the gold standard for defining neurological pathways at the subcortical level. The main aim for supratentorial procedures, particularly in glial tumor surgery, is to estimate the distance from the resection cavity to the CST for preventing persistent mechanical injury to the motor pathway. The relation between stimulus intensity and CST distance was shown in the literature that is summarized in Table II (11,26,28,33,40). As shown in Table II, studies have a correlation that remains uncertain, whether linear or non-linear. Discrepancies reported in these studies are reckoned as different results based on technical aspects (39). Currently, the vague rule of thumb “1mA correlates to 1mm” in subcortical cathodal monopolar stimulation gained acceptance during supratentorial brain tumor surgeries (39). It is recommended that surgical resection should be done until reaching a safe-distance margin to the CST for preventing motor pathway injury. Safe margins for subcortical stimulation vary among surgical centers in the context of histopathology, targeted resection limits, infiltration of immediate areas, and method of hemostasis (4,21,26,33,38,39).

Prabhu et al. reported that the possibility of neurological deficits was increased when the distance to the CST from the probe was less than 5 mm (33). Seidel et al. noticed that the risk of CST injury was associated with mapping motor threshold. Nevertheless, cortical MEP monitoring is continually required with subcortical stimulation to avoid more proximal ischemic injury. On the other side, if DCS-MEP monitoring remains stable, mapping thresholds even equal/below 3mA might be safe at the same time (38,39). In case of preoperative motor deficit, Plans et al. recommended stopping subcortical resection before obtaining a subcortical motor threshold at 3mA (31).

Continuous subcortical mapping as a new approach

More recently, continuous subcortical mapping was practiced in some centers (21,34,38,40). As known that, subcortical mapping is classically done intermittently by interrupting the resection. A monopolar stimulation probe integrated into the classical surgical suction device or a cavitronic ultrasonic surgical aspirator (CUSA) continues stimulation in this approach while tumor resection is going on. It seems valuable for tumors very close to the CST with a combination of MEP monitoring (36,38).

c. Monitoring techniques

Monitoring techniques continuously assess the functional integrity of the functional systems such as primary motor, somatosensory, language and visual pathways, and the cranial nerves during surgery.

The motor pathway is evaluated by quantitative analysis of MEP or examining motor movement in awake surgery. STT with monopolar anodal stimulation is accepted as the best option for accurate MEP monitoring under general anesthesia due to quantitative MEP analysis since STT provides a time-locked MEP response with a defined latency and amplitude (14,15).

Somatosensory pathways are controlled by SEP monitoring that is essentially used to detect impairment of cortical perfusion for supratentorial surgery, as mentioned in the first part.

Table II: The Relation Between Stimulus Intensity and CST Distance

Author	Methods	The relation and clinical result
Kamada et al., (11)	MP, CS, 5 ST, 0.2msec PD, postop MRI	1.8mA as the Th for direct CST contact
Nossek et al., (26)	MP, CS, 5-7ST, 0.2msec PD, 300Hz, intraop USG and navigation	linear correlation with 0.97mA for every 1 mm of brain tissue
Prabhu et al., (33)	MP, AS, 5ST, 0.3-0.5msec PD, 500Hz, intraop MRI tractography	a trend toward worsening of neurological deficit at the distance from probe to the CST was below 5 mm
Shiban et al., (40)	MP, AS and CS, 5 ST, 0.3-0.7msec, 500Hz, titanium clip artifact in postop MRI and postop DTI	nonlinear correlation between stimulation intensity and distance to the CST
Seidel et al., (37)	MP, CS, 5ST, 0.5msec PD, 250Hz, intraop MEP changes (clinical evaluation)	irreversibl changes/loss of cortical MEP in subcortical mapping group: 0% in >11mA 10% in 4 to 10mA, 20% in 1 to 3 mA

***MP:** Monopolar probe, **CS:** Cathodal stimulation, **AS:** Anodal stimulation, **ST:** Stimulus train, **PD:** Pulse duration, **MRI:** Magnetic resonance imaging, **intraop:** Intraoperative, **postop:** Postoperative, **USG:** Ultrasonography, **MEP:** Motor evoked potential, **Th:** Threshold **CST:** Corticospinal tractus (Modified from ref. 38).*

VEP monitoring has recently become spoken for IONM with technological advancements in light-emitting diodes (LEDs) manufacturing and size reduction (12). It can be easily monitored for surgeries of tumors or vascular lesions that carry a risk of damage to the visual pathways.

A precise language monitoring is possible by a neuropsychiatric assessment during awake surgery. However, intraoperative CCEP and SCEP monitoring, new advancements in monitoring methods, seem clinically helpful for evaluating the integrity of the language network. A 32% decrease of CCEP amplitude was shown as not producing persistent language impairment (53). However, it is noticed that information coming from more patients and different groups is needed to establish the promising parameter and/or particular cut-off value to check for its clinical utility (21). Moreover, further studies with large patient cohorts would establish its clinical utility for mapping functional brain networks as a part of presurgical evaluations (19).

Cranial nerves are mainly monitored by EMG and corticobulbar MEP (CoMEP), but mostly monitoring cranial nerves is required in the brainstem and angle tumor surgeries such as vestibular schwannoma.

1) IONM for supratentorial brain tumors

IONM is a part of the modern neurosurgical approach to resect a tumor near an eloquent area, such as the Rolandic region and frontotemporal speech areas, to determine functional boundaries to either improve survival or to avoid postoperative neurological deficits. Maximal safe resection is critical to achieving success and directed by mapping and monitoring methods in such surgeries (39). The gold standard for localization of eloquent cortex and white matter tracts at different stages of tumor resection is cortical and subcortical mapping, respectively. The critical strategy for protecting the CST is to practice continuous MEP monitoring to remove tumors from within or adjacent to the central region and insular tumors extending deeply toward the internal capsule. The limit of tumor resection is determined according to the rate of decrease in amplitude of MEP. Sensory impairment alone is not accepted as a criterion to stop tumor resection (39). For that reason, SEP monitoring is commonly used as a complementary method to MEP monitoring for brain tumor surgeries (39). However, it is reported that SEP may also have valuable information if the tumor involves vessels in the Sylvian fissure or the transsylvian approach that may lead to significant vasospasm (25).

In addition, visual pathways can be monitored by VEP in resection of intrinsic brain lesions that are close to visual pathways and associated areas such as temporal, temporoinsular, parietal, or parietooccipital lesions.

3) IONM for supratentorial vascular surgery

Intraoperative neuromonitoring is commonly used in supratentorial aneurysms, arteriovenous and cavernous malformation surgeries. One of the most worrying complications of vascular surgery is cerebral ischemia and associated ischemic stroke. IONM aims to identify impending ischemia related to the vascular territories of surgical interest and alter the intraoperative management of these cases to avoid ischemic stroke. SEP monitoring in cerebral aneurysms has a long history from the 1980s (6). Other monitoring systems such as MEP, BAEP, and VEP were implemented later based on the location of the vascular lesion and probable risks, with developing technical aspects on modalities in the neurosurgical operations.

Vascular territories and recommended recordings for specific intracranial aneurysms and AVM locations are shown in Table III.

a. IONM for aneurysm surgery

Several maneuvers or intraoperative events in aneurysm surgery have potential risks for brain ischemia: the manipulation of the aneurysm, premature aneurysm rupture, unintentional vessel occlusion by clip placement, induced vasospasm, and vascular compromise by retractor placement (46,48). It is reported that ischemia can occur either within the vascular territory of the aneurysm-bearing vessel or in the vicinity of surgical manipulation (46,48).

SEP monitoring is primarily helpful to detect impairment of cortical perfusion by intended or inadvertent vessel occlusion because of the close relationship between cortical response and cortical cerebral perfusion, as mentioned before. Essential points on SEP monitoring mentioned in the monitoring techniques section are especially crucial during aneurysm surgery performed against time.

In this regard, median nerve SEP provides information about the primary somatosensory parietal cortex representing the hand supplied by the internal carotid artery (ICA) and middle cerebral artery (MCA). It also carries knowledge on thalamic activity supplied by the posterior cerebral artery (PCA) and thalamocortical sensory axons supplied by lenticulostriate branches of the middle cerebral and anterior choroidal arteries. In contrast, posterior tibial nerve SEP represents the legs and gives selective information about parasagittal somatosensory parietal cortex supplied by the anterior cerebral artery (ACA) (17). Median nerve SEPs are monitored in aneurysms of MCA, ICA, and anterior choroidal artery (AcoA) originating from ICA. Tibial nerve SEPs are essential for ACA and anterior communicating artery (AComA) that connects the left and right anterior cerebral arteries aneurysm (17).

When a vessel occlusion occurs during surgery, usually increment of latency followed by amplitude decrement is observed in SEP recordings. These changes can occur within seconds or as long as 30 minutes, depending on the failure of collateral circulation (48).

MEPs are required to monitor MEP monitoring in aneurysm surgery, especially in all anterior circulation aneurysms, to monitor perforating vessels that supply subcortical motor pathways (48). Commonly bilateral arm muscle MEP is performed for ICA and MCA aneurysms while leg muscle MEP for ACA and AComA aneurysms, and pericallosal artery with the interhemispheric approach. In addition, facial MEP may be added if the ICA bifurcation is involved and hand MEP for ACA aneurysm because the perforating arteries of

Table III: Recommendations for IONM Techniques to Use in the Cerebrovascular Procedures and Related Vascular Territories

Aneurysm and AVM surgery	*Recommendations	*Extended setup
ICA PCoA AChoA Ophtalmic arter	median nerve SEP, upper extremity MEP	VEP
Complex ICA bifurcation aneurysm	median nerve SEP, upper extremity MEP	facial MEP, tibial nerve SEP, lower extremity MEP
MCA	median nerve SEP, arm MEP, lower facial MEP	tibial nerve SEP, leg MEP
ACA AComA Distal ACA (A2)	tibial nerve SEP, lower extremity MEP	median nerve SEP, upper extremity MEP
Pericallosal artery with interhemispheric approach	tibial nerve SEP, lower extremity MEP	
Vertebrobasiler PCA SCA PICA	median nerve SEP, upper extremity MEP, BAEP	tibial nerve SEP, lower extremity MEP

*Bilateral recordings are required, the ipsilateral side serving as reference.

***ICA:** Internal carotid artery, **PCoA:** Posterior communicating artery, **ACoA:** Anterior choroidal artery, **MCA:** Middle cerebral artery, **ACA:** Anterior cerebral artery, **AComA:** Anterior communicating artery, **PCA:** Posterior cerebral artery, **SCA:** Superior cerebral artery, **PICA:** Posterior inferior cerebral artery, **SEP:** Somatosensory evoked potential, **MEP:** Motor evoked potential, **BAEP:** Brain stem evoked potential, **VEP:** Visual evoked potential (Modified from ref. 45).*

the ACA supplying motor pathways, including corticonuclear efferents and fibers descending toward cervical motoneurons. According to studies on MEP changes and clinical outcomes in aneurysm surgery, permanent MEP loss is associated with the long-term severe motor deficit, and reversible loss or alteration is related to the frequently transient motor deficit (24,47). Some data are reporting false-negative results about the neurological outcome (54,55).

On the other hand, MEP is also valuable for identifying posterior circulation and brainstem ischemia with a combination of SEPs and BAEPs. VEP monitoring may be added to the setup for aneurysms of ICA, including posterior communicating artery, ACoA, and ophthalmic artery (12,48). However, it is pointed out that significant involvement of cranial nerve nuclei of the reticular formation may go undetected by all of those recordings (48).

Definition of critical changes and possible interventions in response to critical changes

Stable recordings in critical surgery steps such as temporary or permanent vessel occlusions allow the surgeon to maintain the surgery for an optimal surgical result (48). In case of the IONM changes, the following steps are recommended. Anesthesia and vital signs are quickly checked, and surgical steps of the past minutes are reconsidered. Cerebral retraction is reduced, if possible, by releasing or readjusting, temporary aneurysm clips are repositioned or removed, the permanent clip is repositioned. If vasospasm is suspected, topically applied diluted nimodipine and raised central arterial pressure can help to restore sufficient blood flow within a brief period (16).

SEP and MEP monitoring with BAEP and/or VEP when required are accepted as valuable tools for detecting postoperative deficit on aneurysm surgery (6,24,46-48). However, there is still a debate about the efficiency of IOMN (8,10). Undetected neurophysiological changes can be a reason for this debate. These changes may result from far lateral stimulation or much higher stimulus intensity in terms of ischemic stroke. For this reason, controlled randomized studies that are carried out according to essential points on IONM recording and interpretation mentioned in the first part are recommended to determine evidence for the clinical utility.

b. Vascular malformations

IONM with mapping and monitoring techniques are helpful during the surgical resection of vascular malformations located near the central region or close to the sensorimotor pathways (6,23). Monitoring modalities are similar to that in aneurysms. The lesion location, vascularization, and perforating arteries at risk determine the type of SEPs and MEPs to be recorded during monitoring. SEP recording may warn for inadvertent damage to the structures from local factors, such as retractor placement or heat from electrocoagulation in the surgical area. In addition, the blood supply to the vascular malformations may come from adjacent brain areas, including sensory regions, and occlusion of the feeding arteries may impair cortical perfusion (25). SEP recording will allow for test occlusion of those vessels. In addition, MEP monitoring helps avoid new motor deficits without compromising the surgical result if that motor function is endangered.

MEP and SEP monitoring in benign lesions, such as cavernoma (CM), are also used if the lesions are close to the motor tract. The surgery and surgical reactions are similar to surgery of metastasis. If the surgeon wants to remove adjacent hemosiderin-stained brain in CMs with seizures, IONM can guide the surgeon for safe resection by determining the distance from the resection cavity to the CST and controlling the functionality of long pathways.

IONM for epilepsy surgery

Epilepsy surgery is a challenging but exciting area consisting of both lesional and nonlesional procedures in neurosurgery practice. Many recent advances such as diffusion tensor imaging, magnetoencephalography, and high-frequency oscillations have helped epilepsy neurosurgeons to achieve the best outcome for patients. DCS and ECoG, intraoperatively or extraoperatively, are well-known methods used in epilepsy surgery. However, modern epilepsy surgery needs to use multimodal IONM, especially in the surgery of extratemporal epilepsy and also nonlesional epilepsy that is intimately related to eloquent brain regions. Over the years, IONM techniques were utilized for multimodality to assist modern epilepsy surgery (43,51). The aim is similar to other surgeries to some degree. The primary motor, somatosensory, language and visual pathways are identified using direct stimulation and preserved by continuous monitoring. ECoG can identify the after-discharges during electrical stimulation, define the extent of resection in epilepsy surgery and tumor margins of some cerebral tumors, and monitor cerebral function in neurovascular cases. CCEP with SCEP can be applied to identify seizure propagation pathways and monitor the cortical motor network and dorsal language pathway (19-21).

AUTHORSHIP CONTRIBUTION

Study conception and design: TE, SK

Data collection: TE, SK

Analysis and interpretation of results: TE, SK

Draft manuscript preparation: TE

Critical revision of the article: SK

All authors (TE, SK) reviewed the results and approved the final version of the manuscript.

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