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Intraoperative Neurophysiological Monitoring in Cranial and Spinal Surgery- Essential or Luxury

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Introduction

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In recent decades neurosurgery has seen significant advancements, moving away from radical procedures and emphasizing on safer surgical approaches leading to maximal safe resection with functional preservation. To achieve these various adjunctive techniques have been developed and intraoperative neuromonitoring (IONM) is one of the most important tools. IONM relies on real-time physiological monitoring to continuously assess neural tissue function. This proactive approach helps prevent neural injury or promptly identify any damage before it becomes irreversible, allowing timely interventions to mitigate the risk and optimize surgical outcomes.

Intraoperative neurophysiologic mapping and monitoring (IONM) procedures are increasingly favoured for preventing neurological deficits during various surgeries. Mapping techniques are used to identify and preserve functionally viable neural tissue, while monitoring techniques either continuously and intermittently detect early reversible neurophysiologic dysfunction thus guiding adjustments in surgical and anaesthesia management to prevent permanent injury. The preventive benefits of intraoperative neurophysiology not only enhance patient safety and care but also significantly reduces healthcare costs associated with adverse postoperative neurological outcomes, such as motor function loss. Consequently, IONM is almost always employed in high-risk and complex surgical procedures to ensure safety and recently in many centres, IONM is almost being used for most of the neurosurgical procedures where neurological pathways and their function can be monitored.

However, mastering intraoperative neurophysiology presents unique challenges. Proficiency in this field requires a strong understanding of neurophysiology fundamentals and the ability to promptly interpret real-time recordings during surgeries. This includes familiarity with the technical aspects of neurophysiological methods, understanding critical surgical steps, and awareness of how anaesthesia affects neurophysiologic recordings. IONM experts must develop situational awareness to incorporate these factors into data interpretation. Additionally, effective communication of neurophysiological findings to the multidisciplinary team in a timely manner is crucial for ensuring the safe and successful completion of surgical procedures.

Artificial intelligence and its applications in healthcare are undergoing a revolution. In medical fields where data sets are easily retrievable digitally, such as intraoperative neuromonitoring (IONM), AI can assist physicians in analysing, interpreting, and evaluating results either physically or remotely. This capability is undoubtedly a significant advancement. The utility of AI in IONM can help established IONM centres further refine their practices and develop training modules, while newer centres can receive remote assistance from more experienced centres.

It is beyond the scope of this article to describe the principles of IONM in entirety, and hence, the conventional concepts of IONM with an overview of the evolving concepts are described. This article describes in a concise manner, the various modalities, their applications and flaws with a focus on practical issues of the most relevant and frequently performed IONM procedures in various brain and spine surgeries. Some insights regarding the electrophysiological basis of stimulation and recordings, and techniques such as electromyography (EMG), electroencephalogram (EEG) and electrocorticogram (ECoG), evoked potentials including somatosensory evoked potentials (SSEPs), brainstem auditory evoked potentials (BAEPs), visual evoked potentials (VEPs) and motor evoked potentials (MEPs), as well as triggered EMG are provided. We also discuss the pros and cons of IONM and try to briefly describe the future direction.

The various kinds of injuries that can occur intraoperatively to nervous tissues are mechanical (e.g: direct/ retraction), vascular (e.g: ischemia due to vascular injury), positional (e.g: brachial plexus injury in prolonged lateral position surgery), physiological (e.g: hypotension causing ischemia during temporary clipping of aneurysm).

The various IONM modalities available are explained in Figure 1. The stimulation and recording parameters with the alarm criteria of each of these modalities have been explained in Table 1. Each of the modalities has been explained in brief and its application in the various neurosurgeries has been defined in Table 2.

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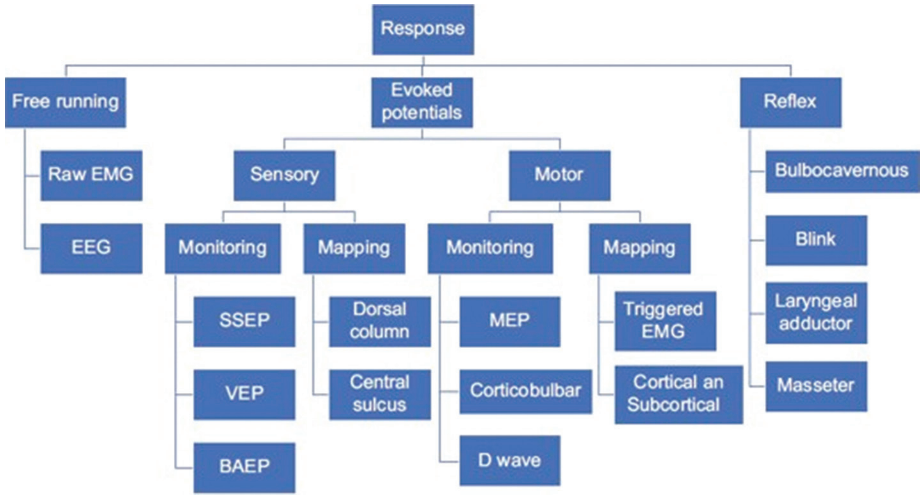

Figure 1: Classification of various techniques involved in Intraoperative neurophysiological monitoring

Free running response

Electrocorticogram (ECoG)

Electrocorticogram is a measure of the spontaneous electrical activity of the brain measured from the cortex. It can be recorded using surface (strip or grid electrode) or depth electrodes. In neuro-oncological practice, it is used in tumours associated with seizures. Epileptogenic activity is noted in and around the tumour area. After tumour resection, the electrodes are placed again and electrical activity of the cortical region is recorded for at least for 5 minutes to confirm the completeness of resection of the epileptogenic foci. Apart from the ECoG, an electroencephalogram (EEG) can also be used to measure the depth of anesthesia, monitor the intraoperative seizure activity, and also assess for ischemic insults in brain and spine surgeries (carotid endarterectomy, temporary clipping in aneurysm surgery) in the form of slowing of electrical waves.[1,2]

Free running electromyogram (EMG)

Free running EMG consists of continuous recording of the muscle activity without any stimulation. The corresponding muscle groups, chosen on the basis of the nerve root at risk, are continuously monitored and any mechanical irritation occurring during the resection can be recorded. EMG spikes, bursts, trains, and neurotonic discharges are used to alert the surgeon during tumours resection, regarding an impending neurological deficit caused by the surgical intervention.

Evoked potentials

Somatosensory evoked potentials (SSEP)

SSEPs are used to continuously monitor the integrity of large fiber sensory system, which constitutes the dorsal column (within the spinal cord), dorsal spinocerebellar tract (within the brainstem), the ventrolateral tract (within the subcortex) and the post-central gyrus (within the cortex). Stickers or needle electrodes placed over the peripheral nerves (median, ulnar, posterior tibial, or trigeminal nerve) are stimulated and the evoked potentials are recorded over the cervical spine and scalp through corkscrew electrodes. SSEPs are altered during damage in the pathway due to vascular compromise, compression, stretching, edema, inhalational anesthetics, hypothermia, acidosis and hypotension. It is not affected by muscle relaxation and total intravenous anesthesia (TIVA).[3-7] SSEP are a sensitive modality in spine surgeries and are best said to be used in conjunction with motor evoked potentials which have high specificity.[8,9]

Visual evoked potential (VEP)

Visual evoked potentials are obtained using light stimulation (using a light emitting diode [LED]) through the retina, and the response is recorded from the occipital cortex, to monitor the excision of tumours that are involving the visual pathway, such as suprasellar and anterior skull base tumours. An electroretinogram (ERG) is recorded simultaneously with a VEP to ascertain that the flash stimuli to the retina has been adequately delivered. Inability to identify the laterality, lack of a standard alarm criteria, non-reproducibility

Table 1: Commonly used IONM modalities and their technical details

Modality	Anaesthesia				Stimulating parameters	Recordings	Alarm criteria
	Tiva	Volatile	Muscle Relaxants	Opioids			
SSEP	✓	✓	✓	✓	Electrode: sticker or needle over peripheral nerve Parameter Settings: Pulse Duration: Monophasic rectangular pulses of 100-300 μs duration Stimulation Rate: 2-5 Hz Stimulation Intensity: median nerve, 15-20 mA tibial nerve, 20-40 mA.(above motor threshold)	Electrode: For UL corkscrew electrodes placed over the scalp at C3'-Cz and C4'-Cz and for LL at the Cz'-Fz position. Parameter Settings: Time Base: 5-15 μs/div. Sensitivity: range of 0.3-1 μV/div Filter Settings: 30-300 Hz. Keep the notch filter off. Number of Trials: 250 to 1000	1.>50% amplitude decrease compared to the baseline 2. >10% increase latency in N20 or P37 from the baseline.
MEP	✓	✓	X	✓	Electrode: corkscrew electrodes over the scalp at the C3-Cz and C4-Cz Stimulation Parameter: Train Configuration: 3-9 stimuli delivered sequentially Stimulation Intensity: 250 mA. Pulse Duration: 0.5 ms Intra-Train Repetition Rate: 250-500 Hz	Electrode Placement: needle electrode inserted into the corresponding muscle group associated with the targeted motor response. Parameter: Sensitivity: 50 μV/div	1. Amplitude: more than 50% decrease compared to baseline 2. Increased latency >10% 3. Increase in current threshold for stimulation 4. Change in morphology: biphasic form
Corticobul-bar MEP	✓	✓	X	✓	Electrode: Corkscrew over C3/C4, or C1/C2, C3 Cz and C4Cz Parameter: double train with the first train consisting of 3-5 stimuli at 200 mA intensity and 0.5 ms duration,	Electrode Placement: needle electrode inserted into the corresponding muscle group associated with the targeted motor response.	1. Amplitude: more than 50% decrease compared to baseline 2. Increased latency>10%

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Table 1: Contd...

Modality	Anaesthesia				Stimulating parameters	Recordings	Alarm criteria
	Tiva	Volatile	Muscle Relaxants	Opioids			
					second single pulse after 4090msec to detect peripheral responses	Parameter: Sensitivity: 50 μV/div	3. Increase in current threshold for stimulation 4. Change in morphology: biphasic form
D wave	✓	✓	✓	✓	Electrode: C1–C2/Cz–Fz or C3-4 Parameter: Single rectangular pulses with a pulse width of 0.5 milliseconds. Stimulating rate: 1-2 Hz, Pulse frequency: 1 to 2/sec.	Electrode Placement: catheter electrode positioned over either the epidural or subdural space Parameter: Sensitivity: 10μV/div.	1.>50% amplitude decrease 2.Interpreted along with MEP>10% increased latency
VEP	✓	X	✓	✓	Visual Stimulation: flashing light, retinogram/ googles. LED flash stimuli 660 nm Temporal Frequency: 1 to 3 per second	Electrode Placement: Oz -Fz. Recording Parameters: The EEG activity is typically recorded using scalp electrodes with a reference electrode placed at a non-visual area to minimize artifact contamination. Parameter: Time base 200ms Sensitivity 20μV/div, 101000Hz filter	1. >50% decrease in the amplitude of P100. (Latency more affected by anaesthetics)
BAEP	✓	✓	✓	✓	Electrode: Foam ear tips transducer is placed over the ear. Parameter: Intensity: 80 dB to 110 dB Duration: 0.1 milliseconds	Electrode Placement: Corkscrew A1-Cz and A2-Cz. A1 and A2 (A1 left and A2 the right) Parameter: Time Base: 1-15 ms	1.>50% amplitude decrease

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Table 1: Contd...

Modality	Anaesthesia				Stimulating parameters	Recordings	Alarm criteria
	Tiva	Volatile	Muscle Relaxants	Opioids			
					Frequency: 10 Hz to 40 Hz. Contralateral Masking: 40 dB	Sensitivity: 0.5-1 μV/div Filter Settings: 100-150 to 2500-3000 Hz. Number of Trials: 1200-1500.	2.1ms increase in latency of I & V wave, IIII time, IIIV Time
RAW EMG	✓	✓	X	✓	-	Electrode: Needle electrode over corresponding muscle group Parameter: Time base 50200ms/ div sensitivity 50μV/div 33000 Hz filter	Spikes, bursts, trains and neurotonic discharges for any type of mechanical irritation. Audio feedback will help.
Triggered EMG	✓	✓	X	✓	Electrode: Mono/bipolar stimulator Parameter: 0.55 mA 0.2ms duration	Electrode: Needle electrode over corresponding muscle group Parameter: Time base 50200ms/ div sensitivity 50μV/div 33000 Hz filter	Surgeon should be alerted for positive response and current intensity. Audio feedback will help.
ECoG	✓	✓	✓	✓	-	Electrode: Strip/Grid electrode over the cortex Parameter: Sensitivity: 50200 μv/div	After discharges, slowing of waves and SEF are monitored and alerted
Central sulcus mapping	✓	✓	X	✓	Electrode: Contralateral median or posterior tibial nerve Parameter: Current single pulses 1025 mA, average 200300, pulse width 0.3 ms	Electrode: Strip/Grid electrode perpendicular over central sulcus Parameter: Time base 57ms/div, Sensitivity 10μV/div 130 to 2501500 Hz 2550 trials	Phase reversal between N20 and P20 marks the site of central sulcus
Cortical and subcortical motor mapping	✓	✓	X	✓	Electrode: Mono/ bipolar/grid electrode over motor cortex Parameter:	Electrode: Needle electrode over corresponding muscle group Parameter:	-

Contd...

Table 1: Contd...

Modality	Anaesthesia				Stimulating parameters	Recordings	Alarm criteria
	Tiva	Volatile	Muscle Relaxants	Opioids			
					46 train Width 0.5ms intensity 1-25 mA 250500 Hz frequency	Time base 515ms/div, Sensitivity 50μs/div	
Reflex	✓	✓	X	✓	Electrode: stimulation to nerves-sensory Parameter: Train Pulses: 1-7 pulses per train. ISI (Interstimulus Interval):2ms Intensity: 20-40 mA Stimulation rate 0.5 Hz	Electrode: cutaneous-motor Parameter: CMAP (continuous muscle amplitude potential)	Amplitude decreases and latency changes
Speech mapping				✓	50 or 60Hz Rectangular pulses (4-10ma) on the speech cortex	Awake patient, Impaired speech symptoms	Observe for speech arrest.

Table 2: ??? AQ3

of the procedure, and a high anesthetic sensitivity, are some of the drawbacks of this modality.[10,11]

Brainstem auditory evoked potentials (BAEP)

Brainstem auditory evoked potentials are obtained by applying sounds or clicks over the external auditory meatus and the response recorded from vertex. This brief auditory stimulus can assess conduction through the auditory pathway up to the midbrain. It comprises of 5 waves in 10 millisec, waves I to V. Parameters such as amplitude, interpeak latency, amplitude ratio of the V/I, or IV and V/I, and the inter-ear peak differences and interpeak latencies (I-V, I-III and III–V latencies) are commonly measured. While the main advantage of BAEP is that the waves are resistant to anaesthetic agents, it does have a lot of disadvantages, such as, the presence of complex wave forms, the difficult interpretation, and the interference induced in them during surgical drilling and cauterization.[12]

Central sulcus mapping

Phase reversal is the technique used to identify the central sulcus electro-physiologically. A change in polarity occurs across the central sulcus, when SSEPs are recorded directly on the cortex and when a strip or grid electrode is placed perpendicularly across the central sulcus. Though the lesions or its oedema distorts the anatomy, this technique allows for a precise assessment of functional-anatomic relationship. This modality can be used to preserve eloquence while operating on lesions around the central sulcus.[13-15]

Dorsal column mapping

Inability to identify the neurophysiological midline while operating on an intramedullary spinal cord tumour, cord edema, cord rotation, or due to displacement of tracts, can be overcome using this modality. Bilateral posterior tibial nerves are stimulated and recorded over the width of spinal cord at the level of lesion. Physiological midline is the point in between the two highest amplitude waveforms obtained from a miniature strip electrode.[16-19]

Motor evoked potential (MEP)

MEPs are used to assess the integrity of corticospinal tract, triggered by transcranial electrical or magnetic stimulation. Transcranial magnetic stimulation is very susceptible to anaesthetics, thus transcranial electrical stimulation is used for intraoperative neuromonitoring. A constant electrical current is delivered trans cranially (using corkscrew electrode: tcMEP); using direct cortical stimulation (using strip electrode: dcMEP); or, subcortically (using monopolar electrode: scMEP). This depolarizes the lateral corticospinal tract and action potentials are recorded from distal muscle groups. This modality can be used for spinal cord, supratentorial and infratentorial tumours. Direct cortical and subcortical stimuli use current intensity upto a maximum of 25mA, avoiding the deeper stimulation of motor tracts. This technique is useful for mapping motor tracts at the precentral gyrus, internal capsule, brainstem and spinal cord. Corticobulbar MEPs are used to monitor the functional integrity of the corticobulbar tract as well as the cranial nerves. In order to avoid stimulating nerves surrounding the tumour directly, which can happen when using a single train stimulus, a double train stimulus with a low current is given (so that the electricity is not dispersed).

D Wave

Epidural MEP or D wave is used to assess the integrity of the corticospinal tract. Transcranial stimulation of the motor cortex elicits a response in the descending motor tract recorded from the surface of spinal cord through an electrode placed in the epidural or subdural space. The amplitude of D wave depends on the thickness of the corticospinal tract; hence, it is less reliable at the lumbar region. The disadvantages of D wave are that it does not have a laterality and is unreliable below the thoracic 10 level. One can proceed with surgery using D wave recording without using muscle MEPs, as D waves are more specific and resistant to inhalational anaesthetics (as they do not involve synapses). While resecting spinal cord tumours, the D wave above the lesion is taken as a reference wave.[20,21]

Cortical and subcortical mapping

This modality is used during surgery for superficial cortical and subcortical tumours involving eloquent areas and the speech area. Speech mapping needs to be done in an awake state, while motor mapping can be done in both the awake state as well as general anaesthesia. A constant current using a monopolar, bipolar or strip electrode placed over the cortex is delivered for mapping the motor area. A suction stimulator is used simultaneously to stimulate motor tracts while performing tumour resection in the subcortical area. Based on Coulomb's law, the rule of thumb is that with a 1 mA stimulation, the current spreads to a 1mm distance. Thus, one can

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assess the approximate distance of the surgical site from the vital structures using this technique.[22-25] Certain disadvantages of this lack of cooperation by the subject, the occurrence of fatigue, exhaustion, or seizures, and the false alarms raised due to the subject's inability to perform the given tasks. During general anaesthesia, motor mapping can be done using the EMG recording over the respective muscle group; however, there is a high chance of negative mapping if all the muscle groups are not used for EMG recording.[26-31]

Triggered or stimulated EMG

Current applied directly on the motor nuclei or on the cranial nerve elicits a response in the corresponding muscle group. Monopolar probe stimulation is very sensitive, hence, it is used for identifying regional neural structures during tumour decompression; while bipolar probe stimulation is very specific and is used for identifying the precise location of neural structures, for example, stimulating on a fibre-like structure after tumour decompression. It is used to assess the integrity, course and mapping of nerve roots and cranial nerves in the vicinity of tumours in areas such as the cerebellopontine angle and the brainstem.

Pedicle screw testing is one such application of triggered EMG. Here the screw is directly stimulated with a monopolar stimulation probe. For example, at the thoracic level a positive stimulation at lower currents (threshold of 8-10 milli amperes) implies that the pedicle screw has caused a cortical breach causing stimulation of concerned nerve root and has to be repositioned.

Reflexes

This modality can continuously monitor the function of peripheral nerves, the Plexi, and the nerve roots.

Bulbocavernous reflex (BCR) indicate the patency of the lower sacral reflex arc (S2,3,4 nerve roots). It is elicited by stimulating the dorsal nerve of penis/clitoris and recording the reflex in the external anal sphincter. A unilateral stimulation results in the elicitation of bilateral BCR reflexes. It can be used for real-time monitoring during excision of spinal cord tumours involving the sacral roots, during detethering of the cord. The lacunae in literature of proper protocols, the limited data available, and the lack of standard alarm criteria, are the drawbacks of this modality.[32-34]

Blink reflex can monitor the integrity of the brainstem reflex arc with the sensory component of the reflex arc being the trigeminal nerve, and the motor component being the facial nerve. It is elicited by stimulating the supraorbital nerve to elicit a response in the orbicularis oculi muscle. This modality can be used during the resection of intrinsic brainstem lesions and cerebellopontine angle tumours.[35]

Laryngeal adductor reflex is the most crucial among all brainstem reflexes. It protects the airway from aspiration by adducting the vocal cords and by closing the laryngeal inlet. This modality can be used for brainstem tumours and cerebellopontine angle tumours.[36-40]

Masseter reflex is a trigemino-trigeminal reflex, which connects the midbrain and mid-pons. Unilateral stimulation of the masseter nerve causes jaw jerk. This modality can be during the excision of intra-axial brainstem tumours.[41,42]

Anesthesia and Ionm

All inhalational anaesthetics cause a dose-dependent increase in latency, and a decrease in amplitude by inhibiting the spinal motor neurons at the anterior grey column or by depressing concentration (MAC) value of more than 0.5 affects all evoked potentials. D waves are resistant to inhalational anaesthetics as there are no synapses between the stimulating and recording electrodes. Intravenous opioids have little effect on evoked potentials. Propofol and thiopental depress the evoked potentials when given in a bolus, and have a minimal effect when given in a steady infusion state. Ketamine increases the amplitude of SSEP and MEP but has adverse effects such as raising the intracranial pressure and causing hallucinations. Muscle relaxants should be avoided if the muscle MEPs (EMG, MEP, reflex) are to be monitored. All evoked potentials, including MEP, SSEP, BAEP are sensitive to vascular compromise and mechanical compression. Stable hemodynamics, normal pH, normocarbia and normothermia should be maintained throughout the duration of performing the IONM procedure.[44-46] Total intravenous anaesthesia with propofol and remifentanyl with target-controlled infusion (TCI) pumps are considered a gold standard technique. Dexmeditomidine infusions do not affect IONM signals at clinical infusion dose and can be a good additive.

Special Considerations

IONM in awake patients is always challenging. Patient selection, cooperation and good rapport between the patient and anaesthesiologist are prime components for the conduction of a successful awake craniotomy. Anaesthesiologist and neurophysiologist need to discuss in detail with the patient preoperatively the questions and the procedure that will be done during the procedure. Asleep-awake-asleep and monitored anaesthesia care are the techniques that are used for tumours involving eloquent area and epilepsy surgeries. Scalp block with adequate analgesics and sedatives are titrated such that the patient is comfortable and co-operative throughout the procedure. Awake-asleep-awake is the most common technique used; however, whenever a longer duration surgery is performed, problems may arise in patient positioning, and in management of intraoperative seizures, blood loss and anxiety.[47,48]

It is challenging to do neurophysiological monitoring in the paediatric age group in view of the immature nervous system, as maturation occurs at about 13 years of age. Furthermore, the children are more prone to develop hypothermia, blood loss and hemodynamic fluctuations due to an immature nervous system, which can alter IONM responses.[49-51]

Neurophysiological monitoring during pregnancy involves a multidisciplinary team approach involving neuroanesthesiologists, neurosurgeons, and obstetricians. Keeping the voltage minimum for MEP, reducing the number of MEP stimulation trains, and monitoring of foetal heart rate and uterine tone are some of the strategies considered in pregnant patients. Drugs crossing fetoplacental circulation and causing foetal depression should be used cautiously and only if needed to avoid unnecessary false alarm. Preoperative and postoperative foetal wellbeing should be documented. The risk of foetal loss and emergency caesarean section during the procedure should be explained.[52]

Checklist

Every team member is important and has a role when neurosurgery is performed under IONM. There are various factors that can affect IONM signals and should be checked before a drop in signal can be attributed to operative procedure. The factors that needs to be taken into consideration are hypotension, hypoxia, blood loss, hypothermia, anaesthetic boluses and technical factors like disconnection or electrical noise. Anaesthesiologist, neurophysiologist, Surgeon should be communicative and have to take corrective measures whenever there is a significant change in IONM recording.[53] Figure 2 is one such checklist every team should incorporate into their practice.

Complications

Complications include tongue bite (0.2%); thermal skin and neural injury, burns around the electrode; the precipitation of seizures, muscle pain and hematoma, transient blood pressure changes, cardiac arrhythmia; wrong electrode placement; and displacement of electrodes due to patient movements.[53-55]

The relative contraindications during the MEP monitoring include the presence of epilepsy, cortical lesions, skull defects, and the presence of intra-cranial electrodes, vascular clips or shunts, and biomedical implants. Preexisting structural or physiological damage to eloquent areas/long tracts makes the IONM unreliable. For instance, if the grade of muscle power in the patient is less than 3, eliciting an MEP response will be difficult and unreliable. The drawback of IONM is that the simultaneous monitoring of all modalities is difficult and might miss alarming electrophysiological responses at critical points of resection.

Intraoperative neurophysiological monitoring based on locations

Cortical mapping

Intraoperative neurophysiological monitoring (IONM) is indispensable, particularly in cortical surgery involving eloquent areas such as the sensorimotor cortex, premotor cortex, or language areas. Its primary goal is to delineate the functional relationships between the tumour's edge and the adjacent critical structures.

Various modalities are employed for precise cortical mapping and assessment. Electrocorticography (ECoG) provides insight into the brain's electrical activity, aiding in the delineation of functional boundaries. Somatosensory evoked potentials (SSEP) are utilized to pinpoint the central sulcus using the phase reversal technique, crucial for accurate localization during surgery (Figure 3). Additionally, direct cortical stimulation (DCS) is employed to map vital structures, which can be conducted in either awake or asleep states, depending on patient and procedural requirements.

The time allocated for cortical mapping encompasses the identification of functional landmarks, determination of optimal working currents and entry points, and the meticulous

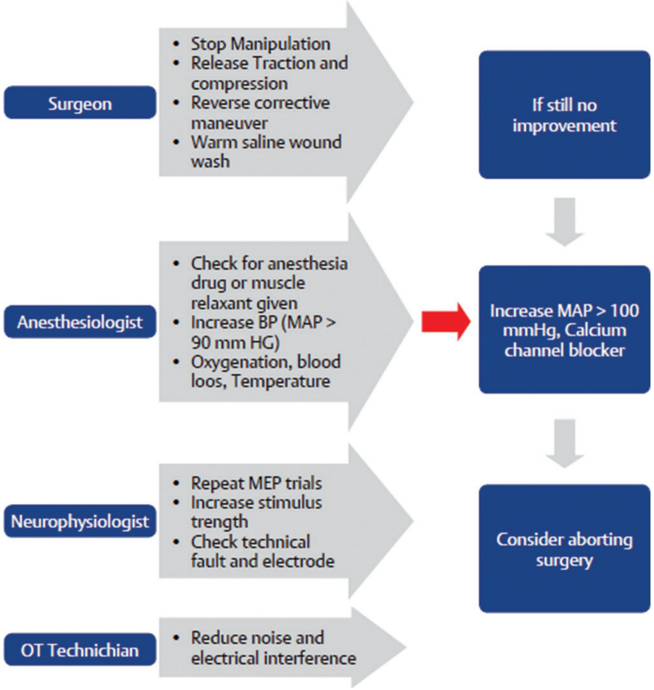

Figure 2: Checklist and troubleshooting actions following an alarm for signal drop

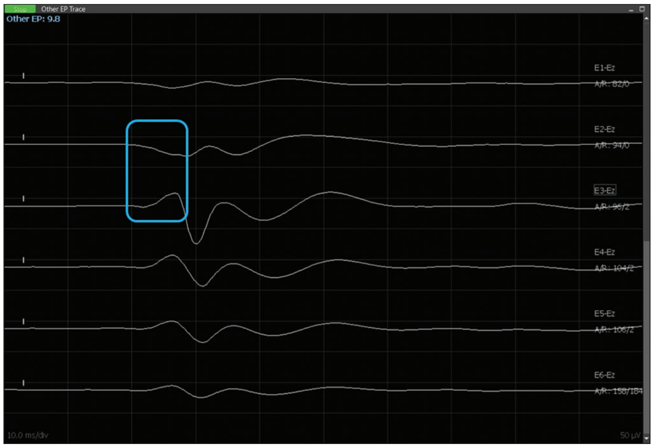

Figure 3: Central sulcus mapping with phase reversal (within the blue outline) using strip electrode

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planning of the extent of corticotomy. This meticulous process typically ranges from 5 to 15 minutes, ensuring comprehensive assessment and precise surgical navigation.[56-59]

Duffau *et al*. (2005) reported a significantly lower morbidity rate of just 3% when employing both cortical and subcortical mapping for resecting low-grade gliomas in eloquent brain areas. This contrasts sharply with historical data, where morbidity rates ranged from 30% to 50% when these advanced mapping techniques were not used.[60] Similarly, Berger and Ojemann (1992) found that the introduction of awake craniotomy combined with cortical mapping in glioma surgeries dramatically reduced the incidence of permanent neurological deficits from around 30% (without mapping) to less than 10%. These findings underscore the critical role of mapping techniques in minimizing postoperative morbidity and preserving essential neurological functions.[61]

Recent advances in IONM have further refined cortical surgery techniques. Integration of advanced imaging modalities, such as functional MRI and diffusion tensor imaging, facilitates preoperative planning and intraoperative navigation, enhancing the accuracy of cortical mapping. Additionally, the incorporation of artificial intelligence algorithms enables real-time analysis of neural signals, optimizing surgical decision-making and patient outcomes.

Direct Cortical Stimulation Techniques

Direct electrical stimulation of the brain is a fundamental tool in neurosurgery, evoking excitatory and inhibitory responses in neuronal networks, synaptic connections, and fibre tracts. However, the delicate balance between effective mapping and avoiding inadvertent tissue damage presents surgical nuances that demand meticulous attention.

Subthreshold stimulation poses a risk of falsely categorizing tissue as non-functional, potentially leading to surgical deficits. Conversely, suprathreshold stimulation may inadvertently activate adjacent cortical areas, yielding misleading functional signs or symptoms and potentially resulting in incomplete resections. Inadequate functional brain mapping correlates with lower rates of gross total resection and increased post-operative morbidity.[62]

Recent updates in surgical techniques emphasize the importance of identifying optimal stimulation parameters. Determining the maximal current intensity that avoids interference with function or the onset of after-discharges (ADs) on electrocorticography (ECoG) serves as a critical endpoint for assessing non-functional tissue. Detection of ADs on ECoG signals a threshold beyond which further current escalation could precipitate a seizure.[62]

Common pitfalls, such as failing to adjust stimulation parameters when exploring new areas or resuming stimulation after a pause, highlight the need for surgical teams to maintain vigilance and adaptability throughout the procedure. The integration of direct electrical stimulation and ECoG provides real-time electrophysiological feedback, empowering neurosurgeons to make informed decisions during surgery.

De Witt Hamer PC *et al* in 2012 did a meta-analysis which evaluates the impact of IONM on outcomes of glioma surgery, focusing on onco-functional balance. A systematic review identified 90 reports from 1990 to 2010, encompassing 8,091 adult patients undergoing surgery for supratentorial infiltrative glioma, with or without IONM. Which showed late severe neurologic deficits occurred in 3.4% (95% CI, 2.3%-4.8%) of patients with IONM, compared to 8.2% (95% CI, 5.7%-11.4%) without ISM (adjusted odds ratio, 0.39; 95% CI, 0.23-0.64). Gross total resection rates were 75% (95% CI, 66%-82%) with IONM and 58% (95% CI, 48%-69%) without IONM. Glioma resections with IONM are associated with fewer late severe neurologic deficits and higher rates of extensive resection, particularly in eloquent locations. IONM should be considered standard of care for glioma surgery.[63]

IONM in resection of tumours involving Language area

Language mapping presents distinctive challenges compared to motor mapping, necessitating its execution under awake conditions. Confirmation of the language mapping area is essential, typically requiring validation through multiple iterations before designating it as eloquent. Throughout lesion resection procedures, a series of language tasks are systematically performed, providing crucial feedback to guide surgical decisions.

Maintaining a vigilant approach, surgeons prioritize the preservation of functional tissue by meticulously measuring and safeguarding a 1-cm margin around each identified positive language site during resection. This precautionary measure aims to mitigate the risk of inadvertent damage to critical language functions.

The adoption of awake mapping techniques in language-dominant areas has yielded notable benefits, notably contributing to a reduction in post-operative permanent aphasias to less than 2%. This significant decrease underscores the pivotal role of intraoperative language mapping in enhancing patient outcomes and minimizing post-operative morbidity.[64-74]

Senai *et al* in 2008 published data on 250 glioma patients involving the language area. In which 145 (58.0%) experienced stimulation-induced speech arrest, 82 patients exhibited anomia, and 23 patients presented with alexia. Preoperatively, 159 patients (63.6%) had intact speech. One-week post-surgery, baseline language function was maintained in 194 patients (77.6%), worsened in 21 patients (8.4%), and 35 patients (14.0%) developed new speech deficits. However, six months after surgery, only 4 out of 243 surviving patients (1.6%) had a persistent language deficit. Cortical maps generated with intraoperative language data revealed notable variability in language localization within the dominant hemisphere.[75]

Subcortical technique

Subcortical surgery marks a pivotal phase in tumour resection, significantly influencing both the extent of resection and the functional outcomes of the procedure. Integral to this phase is the meticulous integration of IONM, which entails consistent mapping procedures conducted either alternately or continuously. Employing subcortical mapping methods during this critical phase facilitates the identification of functional boundaries surrounding the tumour, ensuring precise delineation of resection margins while preserving vital neural networks.[64,67,73]

Recent advancements in neurosurgical techniques, such as tractography, fibre dissection, and connectomes, have revolutionized the assessment of subcortical white matter, enhancing the accuracy of functional mapping during routine procedures. Notably, the evolution of connectomes underscores the necessity of assessing and monitoring subcortical functions, particularly in proximity to language areas and the motor cortex. The application of awake subcortical monitoring has emerged as a standard practice, enabling real-time assessment of critical neural pathways and minimizing the risk of postoperative deficits.[56,67,70-73]

Preservation of common language pathways, identified with reproducibility using stimulation techniques, is paramount in mitigating the risk of speech disturbances postoperatively. These include subcallosal fibres, periventricular white matter, arcuate fasciculus, and insulo-opercular connections, all of which play crucial roles in language function.[59,69]

Incorporating imaging modalities like tractography and intraoperative assistance such as navigation enhances surgical precision, aiding in the early identification of functional margins during subcortical resection. Surgeons' adept in anatomical knowledge can initiate subcortical monitoring when approximately 1 cm of tumour wall thickness remains post-internal decompression, ensuring timely intervention to preserve critical neural structures.[74-77]

The integration of subcortical stimulation during glioma surgery has been shown to markedly reduce the risk of permanent motor deficits. Duffau *et al*. (2003) demonstrated that incorporating subcortical mapping during the resection of low-grade gliomas reduced the incidence of permanent motor deficits from approximately 30% without mapping to just 5-10% with mapping.[78] Similarly, Mandonnet *et al*. (2010) found that in surgeries involving insular gliomas, the use of subcortical mapping significantly decreased the rate of permanent neurological deficits from 40-50% without mapping to around 15%.[79]

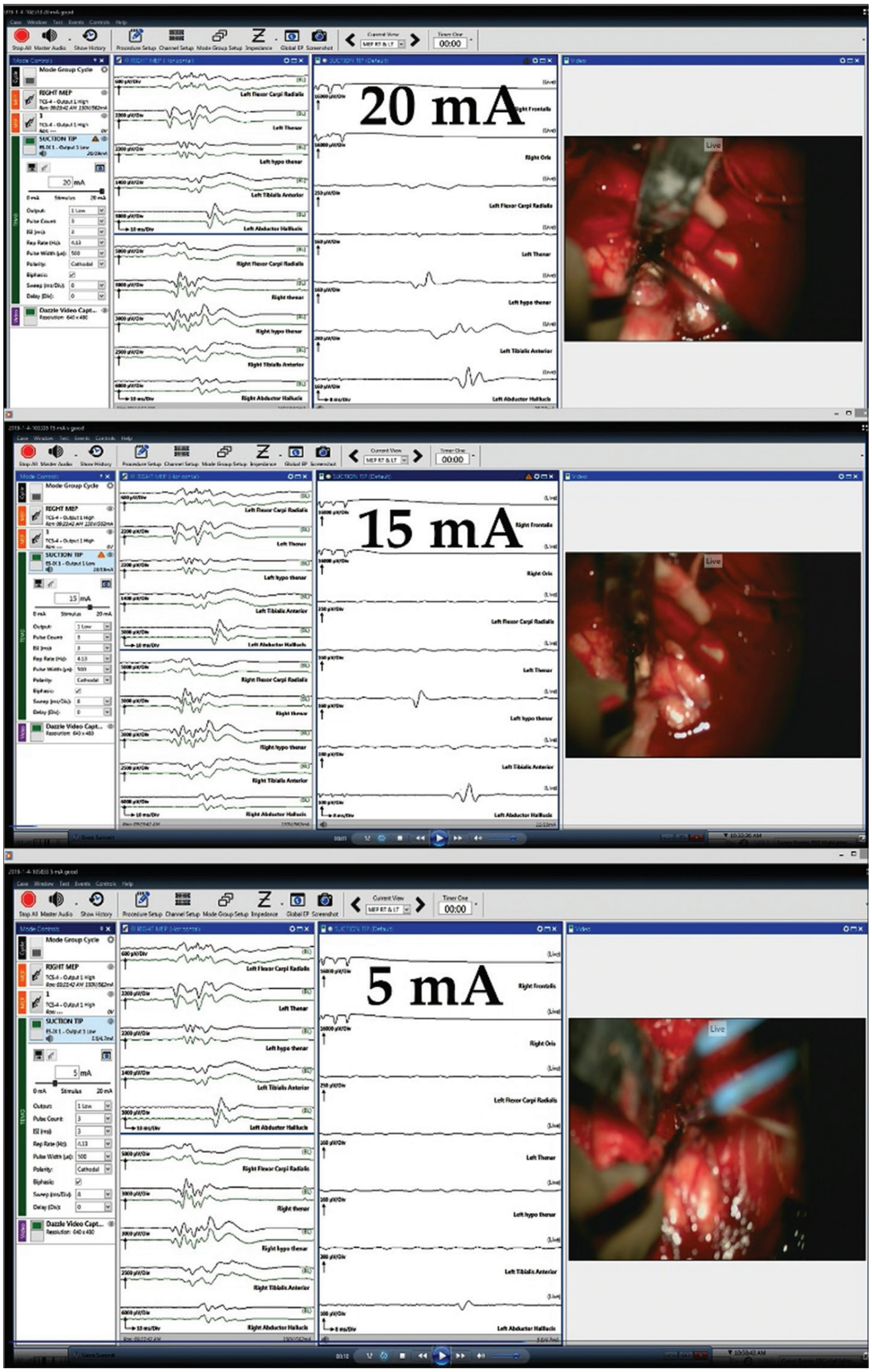

Figure 4: Subcortical stimulation done using suction stimulator in a right insular glioma surgery. Reduction in stimulus strength as surgical plain gets closer to functional tracks(5mA=5mm) AQ2

These findings highlight the critical importance of subcortical stimulation in preserving neurological function during complex brain surgeries.

Evaluation of functional outcomes postoperatively is essential, with neurological examinations, neuropsychological assessments, and psycho-oncological evaluations providing comprehensive insights. Notably, subcortical stimulation during resection has demonstrated low rates of long-term deficits, further highlighting its utility as a valuable surgical adjunct, particularly in lesions involving motor or speech areas.

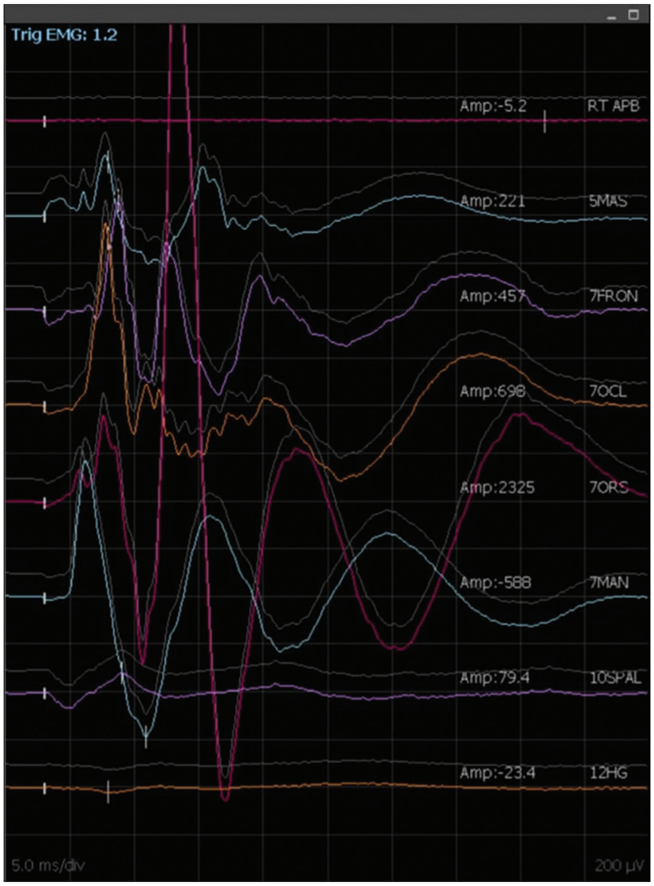

Figure 5: Triggered EMG facial nerve monitoring in a CP angle vestibular schwannoma

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IONM for Cerebello-Pontine Angle Tumours

IONM techniques tailored for tumours situated in the cerebello-pontine (CP) angle encompass a comprehensive array of modalities to ensure meticulous preservation of critical neural structures. Essential components include free-run electromyography (EMG) and triggered EMG assessments of the fifth, sixth, seventh, and lower cranial nerves, along with motor evoked potentials (MEP) encompassing both corticospinal and corticobulbar pathways, somatosensory evoked potentials (SSEP), brainstem auditory evoked potentials (BAEP), and reflexes such as blink, masseter, and laryngeal adductor reflexes.

Common tumours encountered in this location include vestibular schwannomas, epidermoids, and CP angle meningiomas, each demanding tailored monitoring strategies to ensure optimal surgical outcomes. Baseline assessments of MEP, SSEP, and BAEP are imperative prior to surgical intervention, providing crucial reference points for real-time monitoring during the procedure.

During tumour dissection, meticulous attention is directed towards the arachnoid dissection from extra axial lesions, with triggered EMG assessments of the seventh and lower cranial nerves guiding surgical manoeuvres. Continuous monitoring of free-run EMG activity during tumour decompression enables prompt detection of nerve proximity, with sustained activity ≥100 msec warranting immediate alertness and subsequent triggered EMG assessments for nerve localization.

Continuous monitoring of BAEP and SSEP waveforms offers invaluable insights into the integrity of neuronal pathways, with alterations in waveform characteristics indicative of compromised vascular supply or traction in the resection vicinity. MEP assessments conducted at regular intervals further enhance the precision of surgical navigation, enabling timely intervention to mitigate potential motor deficits.

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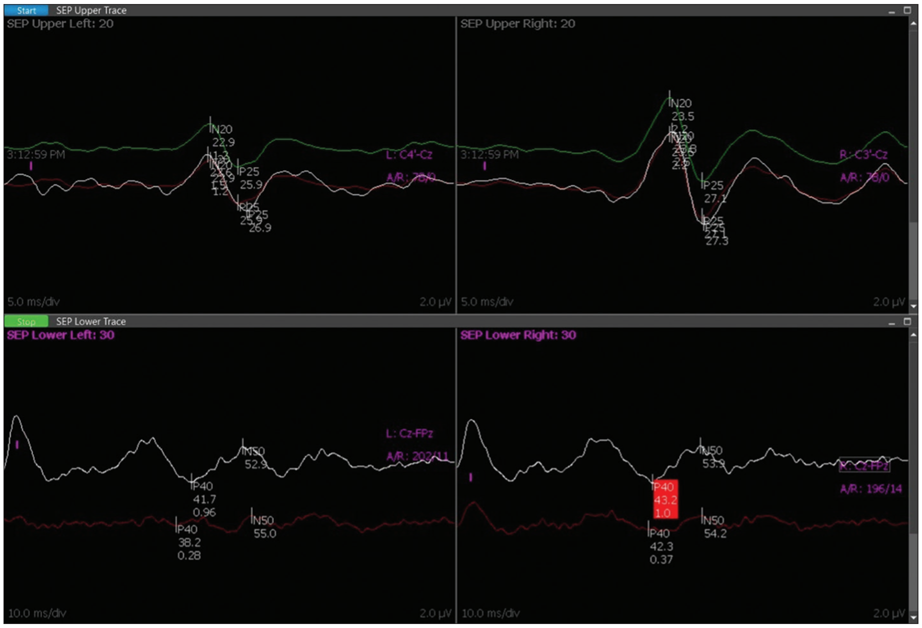

Figure 6: SSEP monitoring in a 4th ventricular tumour AQ2

The assessment of blink, masseter, and laryngeal adductor reflexes serves as a critical indicator of the integrity of local reflex arcs within the brainstem, providing additional feedback on neural function and tissue viability.

A study by Yingling CD, they analysed 9 studies consisting of 1000 patients who were followed up for minimum of 6 months which showed 12% of Grade 5 and above facial palsy in un monitored patients versus 4% in monitored patients. [80]

IONM for Intrinsic Brainstem Lesions and Fourth Ventricular Tumours

Precision in surgical interventions for intrinsic brainstem lesions and fourth ventricular tumours hinges on meticulous mapping and continuous IONM. Prior to accessing the floor of the fourth ventricle, mapping of the facial colliculus, vagal triangle, and hypoglossal triangle is imperative to delineate critical neural structures.[81,82]

Upon entry into the brainstem, a comprehensive monitoring protocol is initiated, encompassing both corticospinal and corticobulbar MEPs, SSEP, BAEP, and reflex assessments including laryngeal adductor and blink reflexes. For tumours within the fourth ventricle, such as medulloblastomas or ependymomas, continuous SSEP and BAEP monitoring is essential, supplemented by intermittent assessments of MEPs to ensure the integrity of corticospinal and corticobulbar tracts.

The real-time feedback provided by IONM during tumour resection enables prompt detection of early electrophysiological changes, facilitating timely intervention to prevent irreversible neurological deficits. Of particular concern are cranial nerves, which are highly sensitive to manipulation during surgery. Mechanical forces, such as stretching or compression, as well as surgical techniques including irrigation, bipolar cauterization, and ultrasonic surgical aspiration, pose significant risks of nerve conduction block or spontaneous activity in free-run EMG.

In a study by Philipp J. Slotty in 305 brainstem and 4th ventricular tumour surgeries, IONM changes were observed in 158 (51.8%) out of 305. Cranial nerve changes occurred in 130 (42.6%), and SSEP/MEP changes were seen in 43(14.0%). Both SSEP/MEP and CNs were observed in 15 cases (4.9%). These INOM changes translated into neurological sequelae in 98 cases (32.1%). The sensitivity and specificity for detecting CN deficits were 98% and 77%, respectively, and for long-tract deficits, they were 95% and 85%, respectively. Brainstem and petro-clival lesions were closely associated with concurrent CN IONM and SEP/MEP changes.[82]

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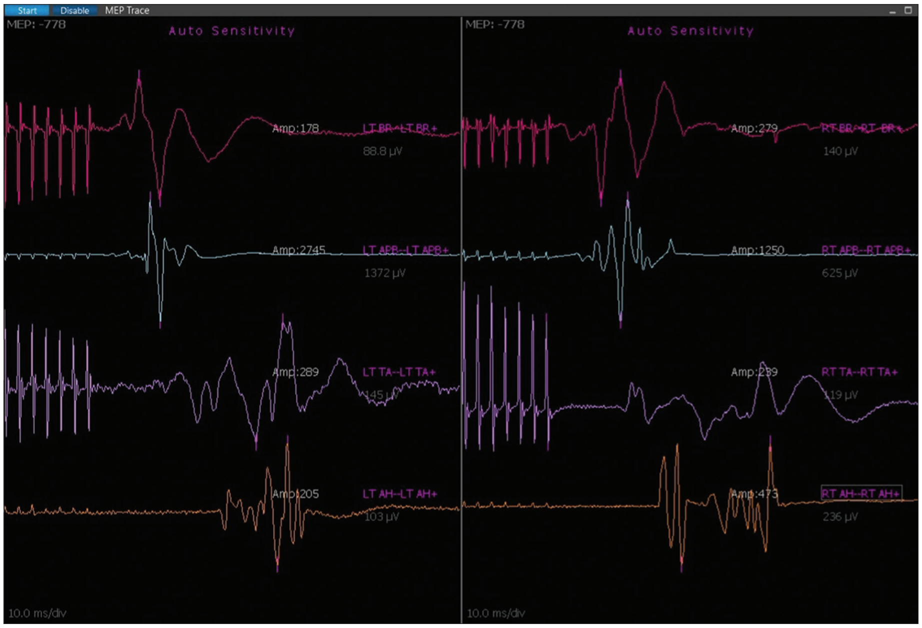

Figure 7: MEP monitoring in a petroclival meningioma

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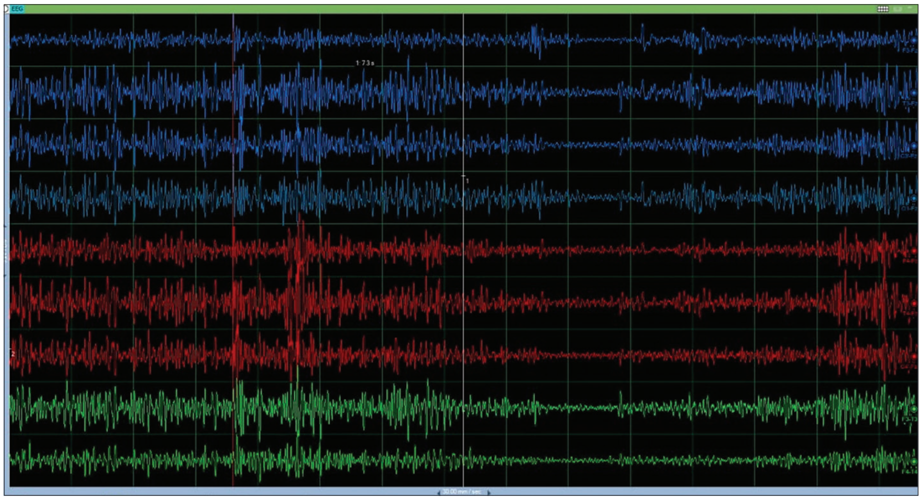

Figure 8: EEG shows beta background with periodic suppression suggestive of ischemia while MCA aneurysm clipping

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IONM for Skull Base Tumours

IONM are paramount in enhancing surgical precision and minimizing neurological complications during the resection of skull base tumours. While the endonasal transsphenoidal approach for pituitary macroadenomas traditionally involves visual evoked potential (VEP) monitoring, its routine application is discouraged due to inconsistent results and variability in interpretation.[51]

For more complex lesions such as clival chordomas and petroclival meningiomas, a multifaceted monitoring strategy is imperative which includes extraocular muscle electromyography (EMG), monitoring of cranial nerves including the fifth, sixth, seventh, and lower cranial nerves, alongside continuous assessment of MEP, SSEP, and BAEP, is essential for mitigating the risk of postoperative deficits.

The integration of IONM during skull base tumour resection has demonstrated a significant reduction in the incidence of cranial nerve deficits, with reported rates varying from 8% to 70% without IONM compared to a substantially lower incidence of 2.8% when IONM is concurrently employed. This highlights the indispensable role of

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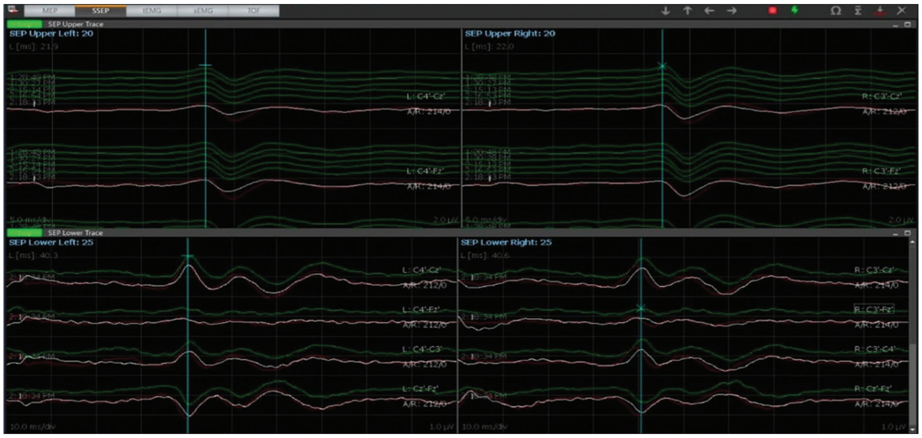

Figure 9: Lower limb SSEP in a L3-4 IDEM tumour removal

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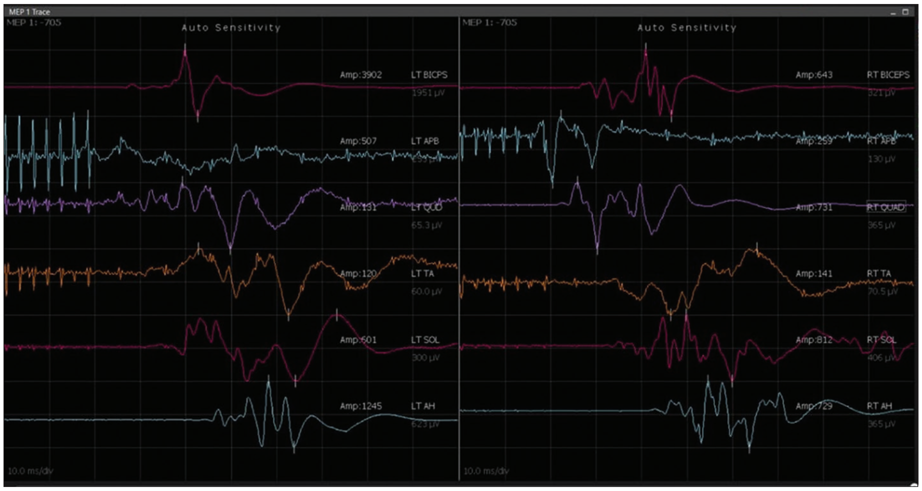

Figure 10: MEP Monitoring in scoliosis deformity correction surgery

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real-time electrophysiological feedback in preserving neural integrity and optimizing surgical outcomes.[83-85]

IONM for Vascular surgeries and Neuro intervention

In vascular surgeries where there is a risk of cerebral ischemia, IONM is essential. Common techniques include EEGs, SSEPs, MEPs, BAEPs and VEPs.

Cerebral blood flow (CBF) typically measures around 50 mL/100 g/min. Neuronal dysfunction can occur when CBF falls below 22 mL/100 g/min, which can be detected by a decrease in EEG amplitude or EEG slowing. A significant drop in EEG amplitude is defined as a reduction greater than 30% or changes lasting more than 30 seconds. The initial changes in SSEPs are observed at a CBF of 18 mL/100 g/min, and SSEPs disappear entirely at a CBF of 15 mL/100 g/min. EEG and SSEP changes are sensitive and they immediately correspond with cerebral hypoperfusion. Corrective measures which increase the cerebral perfusion will result improvement in EEG and SSEP.

Monitoring specific neural pathways is critical, especially when they are at risk. For example, in a middle cerebral artery aneurysm, the hand area is monitored using contralateral median nerve stimulation. In an anterior communicating artery aneurysm, the leg area is monitored using posterior tibial nerve stimulation. For a posterior communicating artery aneurysm, both hand and leg areas are monitored. SSEPs provide an estimate of the “deadline” to restore blood flow above 18 mL/100 g/min to prevent prolonged brain ischemia.

Surgeons often use temporary clips on the parent vessel during these procedures. The current practice dictates that if SSEP amplitudes drop by 50%, the temporary clips should

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be removed or retractors adjusted. After removing the clips, the surgeon waits for the responses to recover before reapplying the clips if necessary.

MEPs have also proven beneficial in these cases, offering an earlier warning than SSEPs and being useful in coiling procedures. A drop in muscle MEP (mMEP) amplitude greater than 50% is considered significant. However, caution is needed when using MEPs due to the risk of jerking movements during stimulation and the possibility of activating deeper descending tracts, which could bypass the ischemic area.

During the embolization of a cerebral aneurysm, IONM detected a decrease in SSEP amplitude, indicating potential ischemia. Immediate adjustment of the microcatheter position restored normal SSEP signals, preventing a possible stroke.

In a carotid artery stenting procedure, EEG monitoring detected changes in brain wave activity suggestive of cerebral hypoperfusion. Prompt intervention restored adequate blood flow, averting neurological damage.

BAEPs are used in posterior circulation or lesions involving brainstem, such as basilar artery aneurysm. VEPs are used in procedures near the optic pathways, like aneurysms in the anterior cerebral circulation.

Multiple studies have demonstrated the usefulness of IONM in vascular surgery. In a study by Skarp B *et al*, a retrospective analysis of data showed that in temporary clipping group 4(12.5%) patients had changes in MEPs and of the 4, 2 also had SSEPs change which were improved by removing temporary clips. Postoperatively patients didn't have any deficits. In Permanent clipping group 7 patients had drop in MEPs. Out of which 5 patients had improvement to baseline after repositioning the clips. Other 2 didn't had any deficits post operatively. Of the 2-one had CT hypodensity and seizure postoperatively. Intraoperative transcranial doppler increases the sensitivity of the vessel narrowing.[86]

IONM for Spine

A: Spinal Cord Tumours

IONM represents a cornerstone in the surgical management of spinal cord tumours, encompassing intramedullary, intradural extramedullary (IDEM), and extradural lesions. Comprehensive monitoring protocols, MEP and SSEP, are universally employed across all types of spinal cord tumours. Baseline waveform assessments are conducted both pre- and post-patient positioning to ensure optimal signal quality and consistency.

Several factors impact the importance and methods of spinal cord monitoring, includes preexisting myelopathy, surgical approaches, instrumentation, and cord manipulation. Preexisting myelopathy is a significant risk factor associated with SSEP deterioration.

SSEPs can sometimes be abolished during the resection of intramedullary tumours, sometimes it may recover at the time of closure or in the immediate postoperative period. This is likely due to neurapraxia of dorsal column axons when a midline myelotomy is performed to access the tumour. Under these circumstances, MEP monitoring is considered essential.

In the context of intramedullary and IDEM tumours, direct spinal motor evoked potentials (D-waves) serve as a crucial adjunct, with baseline measurements obtained prior to dural opening. Placement of the D-wave electrode below the tumour in the epidural space facilitates accurate waveform comparisons before, during, and after tumour resection. Preoperative dorsal column mapping is essential for intramedullary lesions to mitigate the risk of inadvertent injury during midline myelotomy, particularly in cases where tumour distortion complicates anatomical landmarks. D-waves are considered to be the gold standard for intramedullary tumours IONM.

Triggered electromyography (EMG) emerges as a valuable tool during spinal tumour resection, enabling real-time monitoring of selective nerve root function and peripheral musculature activity. This dynamic monitoring approach not only enhances surgical precision but also minimizes the risk of postoperative radiculopathy, especially during spinal instrumentation procedures such as pedicle screw placement.

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Specialized reflex assessments, including the anal sphincter reflex and bulbo-cavernous reflex, are integral components of IONM for tumours involving the conus and cauda equina, providing critical insights into neurological function and tissue integrity at these lower spinal levels.[87-90]

B: Spine Instrumentation

In spine deformity corrective surgeries or degenerative spine surgeries, the placement of pedicle screws often a "blind" technique, leading to a high incidence of pedicle screw misplacement. Triggered electromyography is useful in these cases to ensure accurate screw placement. Accurate screw placement is essential to avoid complications such as nerve damage, spinal instability, and impaired function. Misplaced screws can breach the pedicle wall, leading to neurological deficits and the need for revision surgery.

Cathodal monopolar stimulation can be used by stimulating either the drilled hole or the screw. The frequency of stimulation is 4.1 Hz with a pulse duration of 300 µs. Compound muscle action potentials (CMAPs) can be recorded from the lower extremity muscles. If no responses occur at 10 mAmps, there is probably no breach. Each centre should develop its standards, as multiple factors can affect the stimulus threshold, such as varying pedicle thickness at different spinal levels and chronic nerve injury, such as in radiculopathy, which can result in higher stimulus thresholds to elicit CMAP responses.

Several factors can influence the accuracy of CAMP responses. Excessive use of muscle relaxants or current shunting can lead to false negatives. In cases where current shunting is suspected, voltage stimulation may be preferred over current stimulation to ensure reliable results.

A combination of SSEP and MEP monitoring has been used in scoliosis surgery for many years to monitor both ascending and descending pathways. Adding spontaneous EMG and triggered EMG can improve the detection of nerve root injuries. Several studies have shown that the combined sensitivities and specificities for multimodal neuromonitoring can approach 100%.[91,92]

In 2011, Hamilton *et al.* reported on new neurological deficit rates in over 100,000 patients operated on by Scoliosis Research Society members. For cases using multimodal neuromonitoring, which mostly involved a combination of SSEPs with transcranial MEPs or EMG, the sensitivity for detecting new spinal cord deficits was 43%, for new nerve root deficits was 13%, and for new cauda equina deficits was 29%.[93]

IONM for DBS

Deep brain stimulation (DBS) is an advanced neurosurgical procedure used to treat various neurological disorders such as Parkinson's disease, essential tremor, dystonia, and epilepsy. IONM like MEPs, somatosensory evoked potentials SSEPs, and cortical visual evoked potentials (CVEPs), can be done in patients who require general anaesthesia for placement of electrodes. These neuromonitoring techniques provide real-time feedback on the functional integrity of motor, sensory, and visual pathways, ensuring accurate electrode placement and optimal therapeutic outcomes. Advances in neuromonitoring technology continue to improve the efficacy and safety of DBS.[94]

Pros and Cons

Intraoperative neurophysiological monitoring (IONM) plays a significant role in various neurological surgeries. Here are the pros and cons, as well as a discussion on whether it's considered a luxury or a necessity:

Pros of IONM

1. **Enhanced Safety:** IONM helps in real-time monitoring of the nervous system during surgery, reducing the risk of neurological damage.
2. **Improved Surgical Outcomes:** It allows surgeons to make informed decisions during complex procedures, potentially reducing complications.
3. **Tailored Surgical Approach:** Provides valuable information about neural function, allowing surgeons to adapt their approach based on real-time feedback.
4. **Early Detection of Issues:** Alerts surgical teams to any potential problems affecting nerve function promptly, allowing for immediate corrective action.

5. **Patient-Specific Benefits:** Particularly useful in surgeries involving eloquent areas where precision is critical.
6. **Training surgeons:** Trainee surgeons can fine tune their surgical skills without endangering functional deficit.

Cons of IONM

1. **Cost:** Implementation and maintenance of IONM systems can be very expensive for small centres and who do not perform high volume complex surgeries, including equipment and consumables. Translational research is needed in this field to develop monitoring systems made in our country so the cost can be bought down.
2. **Complexity:** Requires specialized expertise to interpret and act upon the monitoring data effectively, which may not be available in all medical settings.
3. **Potential for False Positives/Negatives:** Interpretation errors or technical issues with the equipment could lead to misleading results.
4. **Duration of surgery:** Approximately an hour of the time is lost for setting up and also for monitoring
5. **Personnel:** Lack of enough clinical neurophysiologist/ neurotechnicians/ neuroanasthesiologist to cater to the need.
6. **Training:** Lack of structured training courses with defined curriculum even in premium teaching institutions.

Luxury or Necessity?

Whether IONM is considered a luxury or a necessity depends on several factors

- **Type of Surgery:** For high-risk neurosurgical procedures involving critical neural structures, IONM is often considered a necessity to ensure patient safety and optimal outcomes. In fact, for few neurosurgical procedures operating under IONM is now become gold standard and mandatory
- **Availability of Alternatives:** In some cases, alternative monitoring methods or experienced surgical techniques might suffice without IONM, making it less of a necessity.
- **Resource Availability:** Hospitals and surgical centres in well-developed healthcare systems may more readily afford and utilize IONM compared to those in resource-constrained settings. The availability of trained personnel is luxury which only a few centres can afford.
- **Medicolegal:** In the current era of patient care, outcome analysis has become essential, requiring evidence to satisfy authorities regarding the necessary care provided by health care physician. In this context, intraoperative neuromonitoring (IONM) remains a crucial procedure for ensuring optimal treatment delivery.

Future of Intraoperative Neurophysiological monitoring (IONM)

Artificial Intelligence (AI)

The future of IONM is set to be transformed by advancements in artificial intelligence (AI) and remote monitoring technologies. These innovations promise to enhance the accuracy, efficiency, and accessibility of IONM, ultimately improving patient outcomes and surgical safety.

AI algorithms can be trained to analyse IONM data instantaneously, identifying patterns and anomalies with high precision. This real-time analysis can provide immediate feedback to the surgical team, enhancing decision-making and reducing the risk of neural damage.

AI can leverage large datasets to predict potential complications before they occur. Machine learning models can identify subtle changes in neural signals that may indicate impending issues, allowing for pre-emptive adjustments during surgery. AI can improve the accuracy of signal interpretation by filtering out noise and standardizing responses across different patients. This leads to more reliable monitoring and better surgical outcomes. AI can automate the adjustment of monitoring protocols based on real-time data analysis, ensuring optimal neural monitoring throughout the surgical procedure.

Remote Monitoring in IONM

1. **Telemonitoring:** Remote monitoring allows neurophysiologists to oversee multiple surgeries simultaneously from a centralized location. This can be particularly

beneficial for hospitals with limited access to specialized neurophysiologists. Secure, high-speed internet connections and advanced telemonitoring platforms enable real-time data transmission and feedback.

2. **Access to Expert Consultation:** Remote monitoring can connect local surgical teams with expert neurophysiologists from anywhere in the world. This ensures that even in remote or underserved locations, patients receive the highest standard of care.
3. **Cost-Effectiveness:** The cost of maintaining an in-house team of neurophysiologists can be high for many healthcare facilities. Remote monitoring can reduce costs by centralizing neurophysiology services and optimizing the utilization of specialists. This can make IONM more accessible and affordable for a wider range of healthcare providers.

The integration of AI and remote monitoring can provide a synergistic effect, combining the precision of AI with the accessibility of remote monitoring. AI algorithms can assist remote neurophysiologists by providing real-time data analysis and predictive insights, enhancing the overall quality of IONM. AI systems can continuously learn and improve from the data collected across multiple surgeries and locations. This ongoing learning process can refine monitoring protocols and predictive models, leading to continuous improvements in IONM practices.

Ongoing research is focused on developing more sophisticated AI algorithms capable of deeper analysis and better prediction of neural events during surgery. Integrating IONM with broader telemedicine platforms to create comprehensive remote surgical support systems. Addressing regulatory and ethical challenges related to the implementation of AI and remote monitoring in IONM, including data privacy, security, and the need for standardized guidelines.[95,96]

Conclusions

Intraoperative neuromonitoring (IONM) plays a pivotal role in enhancing the safety of neurosurgeries from both patient and surgeon perspective. By enabling precise real-time functional monitoring and assessment during procedures, IONM significantly mitigates risks and contributes to improved surgical outcomes. This advancement has prompted numerous centres across the country to recognize IONM as a crucial component of neurosurgical care, with some considering it the gold standard.

Despite its recognized benefits, the widespread adoption of IONM encounters several challenges. Financial considerations pose a significant barrier, given the substantial costs associated with equipment, maintenance, and personnel training. Additionally, the availability of adequately trained specialists proficient in neuromonitoring techniques remains a critical concern with not many training centres in the country. Moreover, ensuring that surgical teams operate in well-equipped environments capable of supporting IONM adds further complexity.

The future of IONM is poised for significant advancements with the integration of AI and remote monitoring. These technologies will enhance the precision, efficiency, and accessibility of neuromonitoring, leading to improved surgical outcomes and patient safety. As research and development continue, the implementation of these innovations will transform the landscape of intraoperative neuromonitoring, setting new standards for excellence in surgical care.

The debate over whether IONM should be viewed as a luxury or a necessity hinge largely on socioeconomic factors in our country. Nonetheless, contemporary medical practice increasingly regards IONM as standard of care for various neurosurgical procedures. Its role in enhancing surgical precision and reducing risks has firmly established it as an indispensable tool in modern neurosurgery, marking its evolution from an elective to an essential component in clinical settings.

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Conflicts of interest

There are no conflicts of interest.

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