OXFORD SPECIALIST HANDBOOKS IN ANAESTHESIA

NEUROANAESTHESIA AND NEUROCRITICAL CARE

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Chapter 3

Intraoperative neurophysiological monitoring

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General principles of neurophysiological monitoring
Neurophysiological monitoring in spinal surgery
Electroencephalogram monitoring

General principles of neurophysiological monitoring

Introduction

- Intraoperative neurophysiological monitoring (IONM) includes several electrophysiological modalities utilised in tumour, vascular and epilepsy surgery to facilitate maximal surgical resection while safeguarding the integrity of neural pathways during cranial and spinal surgery.
- A sound understanding of how physiological and pharmacological factors can impact IONM allows tailoring and titration of general anaesthesia for optimal capture.
- Anaesthetists play a crucial role in achieving the success of IONM, and a key part of this is the maintenance of a stable physiological and pharmacological milieu.
- When IONM is compromised intraoperatively, there are a range of potential causes necessitating a team-based approach for prompt investigation and action.
- There are also practical considerations for operating teams regarding the placement and removal of neuromonitoring electrode needles.

Modalities

- There are two broad categories of IONM: 'free-running' signals (spontaneously generated) and evoked potentials (artificially generated).
- Electroencephalography and electromyography (EEG and EMG) are generally free-running signals, although EMG can occasionally be stimulated.
- Evoked potentials are produced by delivering a stimulus at one end of a neural pathway and measuring a corresponding voltage response at the other (see Table 3.1).
- Variables of note include the latency between stimulus and response, the amplitude of that response and the pattern (waveform shape).
- General anaesthetic agents (both inhalational and intravenous) have a more pronounced effect on IONM amplitude reduction than latency prolongation. This is because general anaesthetics impact synaptic function more than neuronal conduction.
- ≥50% reduction in amplitude and ≥10% increase in latency raises concern.

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- Equally, an increasing current required to produce the same response over time will prompt concern. In order of decreasing sensitivity, the IONM modalities are ranked as follows: MEP, SSEP, BAEPs (those most affected have more synaptic junctions).
- EMG monitoring appears resistant to the effect of anaesthetic agents (except for eradication with NDMRs). See Table 3.2.
- Outside the OR, visual evoked potentials (VEPs), free-running and stimulated EMG, language mapping and brainstem reflexes are used. Due to the significant impact of general anaesthesia and difficulties with interpretation, VEPs are not often used.

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Table 3.1 Core components of common IONM modalities.

Modality	Stimulating electrode	Recording electrode
SSEP	Peripherally	Mainly at the scalp above the primary sensory cortex
MEP	Primary motor cortex or close to motor axon	Corresponding peripheral muscle
BAEP	A click signal (sound)	At mastoid or at the brainstem
Other	EMG and EEG are spontaneously generated (no stimulus) and recorded as 'free running'	

Evoked potentials (EPs) used most often are somatosensory-evoked potentials (SSEPs), motor-evoked potentials (MEPs), and brainstem auditory evoked potentials (BAEPs)

Table 3.2 Pharmacological factors affecting IONM and practical considerations

Drug group	Effect on IONM and practical considerations
Volatile anaesthetics	Dose-dependent reduction in amplitude and increase in latency of EPs. IONM is only possible with a MAC of <0.5. MEPs are affected at lower concentrations than SSEPs. Cortical SSEPs are affected more than sub-cortical SSEPs. BAEPs and EMG are relatively preserved.
Intravenous anaesthetics	***TIVA:*** Can have a similar effect to volatile agents on IONM waveforms but to a much lesser extent. IONM readily obtained with usual doses of propofol TCIs and with remifentanil (even at high doses). ***Ketamine:*** Amplifies both MEPs and SSEPs at low doses. High doses (>1 mg/kg) can impair MEPs. Epileptogenic due to increases in EEG amplitude and frequency.
Neuromuscular blocking agents	MEP and EMG signals are eradicated. Single dose NMB for intubation is usually worn off/reversible prior to baseline studies. TOF monitoring can highlight lingering effects of NMB. Endotracheal intubation without the use of NMBAs can be considered, e.g. using TIVA at sufficient dosages to facilitate intubation.
Other medications	***Opiates*****:** variable effects, most pronounced with boluses. remifentanil shows no effect. ***Benzodiazepines*****:** no effect on IONM at low doses. ***Alpha-2 agonists:*** Dexmedetomidine has dose-dependent effects: minimal with low dose infusions (ideally TCI). Higher doses may impair transcranial MEPs. Clonidine may impair MEPs during spinal surgery. SSEPS are not affected by alpha-2 agonists. ***Nitrous oxide:*** depresses all EPs more than halogenated agents, generally avoided. ***Etomidate:*** May enhance SSEP and MEP amplitudes when used at a low dose. **Gabapentinoids:** Commonly used as preoperative preventive analgesia. Currently, there is no clinical data to suggest interaction with IONM. **Magnesium:** Currently, no clinical data suggests interaction with IONM. ***IV lidocaine infusion***: no effect at 1 mcg/kg/h

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Table 3.3 Physiological factors and practical considerations relating to IONM

Physiological variable	Effect on IONM and practical considerations
Temperature	15% reduction in conduction speed per 1°C reduction in temperature with resultant increasing latency. Hyperthermia has minimal impact unless >39°C.
Carbon dioxide	Low $PaCO_2$ and cerebral vasoconstriction can affect signal acquisition. Mild hypercapnia of little clinical significance for MEPs/SSEPs.
Hypoxia and haemodilution	Hypoxia causes progressive reduction in SSEP amplitude and increased latency. Reductions in O_2 carrying capacity can have similar impact.

Haemodilution	Reductions in O_2 carrying capacity can have similar impact.
Blood pressure	MAP outside cerebral autoregulatory range will reduce amplitude and increase latency—aim for normotension. MAP augmentation to 20% above baseline, may be indicated with signal loss.
Practicalities	Electrode placement by the neurophysiologist may begin in the anaesthetic room (if feasible). Final checks and baseline signals are best achieved in theatre, with the patient positioned for surgery. If high risk of positional nerve damage, baseline signals pre and post positioning may be informative. An interval before baseline IONM allows for steady-state infusions or an equilibrium state of anaesthesia to be achieved.

Clinical cases in cranial surgery

See Boxes 3.1 and 3.2.

Box 3.1 IONM in acoustic neuroma resection

A 37-year-old female presents for elective resection of a left-sided acoustic neuroma, which is known to be causing brainstem compression on pre-operative imaging. A pre-operative briefing includes mention of the lower cranial nerves that are potentially at risk. A TIVA technique using TCI infusions of propofol and remifentanil is used to provide general anaesthesia and a dose of rocuronium at 0.5mg/kg is used to facilitate tracheal intubation. Two lateral tongue electrodes are placed by the neurophysiologist, an ETT with an electrode wrapped around it as a 'lower cranial nerve monitor' and then a bite block is placed, sitting firmly between the molars, on the side contralateral to the tongue electrodes. Processed EEG is used to monitor anaesthetic depth throughout.

As well as MEP and EMG monitoring for the facial nerve, the lower cranial nerves and long tracts are monitored using both MEPs and SSEPs. BAEPs are not indicated as hearing on the side of the tumour has already been lost. Baseline IONM is successfully done after positioning (allowing time for steady-state concentrations of the TCI infusions to be reached), producing satisfactory signals for all IONM modalities.

The integrity of lower cranial function helps to confirm a plan for postoperative extubation and subsequent feeding with confidence that swallowing is likely intact (pending formal assessment).

Box 3.2 IONM in low-grade glioma awake resection

A 45-year-old male has a history of persistent headaches. His GCS is 15, he has never suffered a seizure or changes to his speech or experienced any other neurological deficit. Imaging reveals a space-occupying lesion, suspected to be a low-grade glioma in the right frontal region, in proximity to the eloquent cortex for speech. He is scheduled to undergo an awake craniotomy with IONM and continuous clinical assessment of speech integrity by a Speech and Language therapist. The IONM modalities to be measured intra-operatively are cortical and sub-cortical speech mapping, sub-cortical motor mapping and motor monitoring from a strip electrode placed over the motor cortex. Free-running EMG and electrocorticography are also monitored.

Anaesthesia is undertaken with TCI propofol and remifentanil. A processed EEG monitor facilitates the monitoring of anaesthetic depth and seizure activity. An i-Gel supraglottic airway is placed following induction of anaesthesia and removed for the awake phase. Meticulous attention is given to the prevention of an intra-operative seizure, recognising the increased risk with IONM for awake craniotomies involving speech and motor mapping. Prevention strategies include pharmacological prophylaxis with levetiracetam and magnesium sulfate and judicious uses of local anaesthetic mixtures to mitigate lowering of seizure thresholds.

Sub-clinical ictal activity and impending speech arrest prompts preventive action during cortical stimulation. Ice-cold saline applied directly to the cortex by the neurosurgeon terminates pre-seizure activity on two occasions and no clinical seizures are witnessed.

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Neurophysiological monitoring in spinal surgery

Introduction

Indications

- Monitoring the functional integrity of neuronal tracts in spinal surgeries with a high risk of postoperative nerve deficits, such as spine deformity correction, spinal cord tumour excision, spinal neurovascular surgery, or untethering of the spinal cord.
- Mapping of nerve roots when differentiating between neural and non-neural tissues.

Modalities of IONM in spinal surgery

- Modalities of IONM for spinal surgeries include somatosensory-evoked potentials (SSEP), motor-evoked potentials (MEP), electromyography (EMG), electroencephalography (EEG), and the Stagnara wake-up test. A combination of modalities is commonly practised, improving sensitivity and specificity for detecting potential neural injuries.
- Any substantial change in latency, amplitude, or pattern may indicate the nerve pathway has been injured or compromised in some way. The aim is to detect developing neural injury prior to the point it becomes irreversible. However, a variety of technical, pharmacological, and physiological factors can also lead to alterations in these neural signals and may interfere with an early detection of true sequelae.

Somatosensory-evoked potential (SSEP)

- Monitors dorsal column integrity in transmitting action potentials from the peripheral sensory nerve to the somatosensory cortex, including fine touch, two-point discrimination, proprioception, and vibration (excluding pain and temperature) ➲ Chapter 7.
- Stimulating electrodes placed at the peripheral nerves (e.g. median or ulnar nerve at the wrist and posterior tibial nerve at the ankle) produce continuous electrical signals that travel via the dorsal nerve roots, ascending tracts and thalamus to the somatosensory cortex.
- The resulting action potentials are detected at recording electrodes placed at various locations, including the periphery (Erb's point, popliteal fossa), cervical spine (subcortical SSEP) and somatosensory cortex (cortical SSEP). Electrical signals need to be averaged, leading to a time delay for signal acquisition.
- Generally, amplitude decrease >50% and latency increase > 10% are considered significant findings and warrant further investigation.
- Specificity approaches 100%, while sensitivity may be as low as 43% to detect neural injuries.
- They do not measure anterior columns and do not provide real-time data due to a time delay.

Motor-evoked potentials (MEPs)

- Monitors the integrity of the descending corticospinal tract at the anterior horn of the spinal cord, which is responsible for motor function.

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The resulting action potentials can be measured as direct (D) waves at the spinal cord or as compound muscle action potentials (muscle MEP) at target muscles in all four limbs.

D waves

- Obtained by single transcranial electrical stimulation and is often used in spinal tumour surgeries. They are insensitive to anaesthetic agents.
- Action potentials are measured by an epidural/subdural electrode, placed below the site of potential neural injury.
- If the amplitude decreases >50% from the baseline value, it indicates a high probability of severe nerve injury.

Compound muscle action potentials (muscle MEP)

- Stimulation is given by transcranial electrical stimulation with short trains of 5–7 square-wave stimuli. They are sensitive to anaesthetic agents.
- Action potentials are measured by recording electrodes placed on the muscles of the upper and lower limbs.
- If amplitude decreases >50% from the baseline value is concerning for postoperative motor deficit.
- Electrical stimulations are given at distinct intervals and not performed continuously. MEPs do not need signal averaging, providing real-time clinical information.
- High sensitivity and specificity approaching 100%.
- Potential complications include seizures, tongue laceration due to bite injury, scalp burn, and interference with implanted devices such as pacemakers.

Electromyography

- Spontaneous EMG passively monitors specific nerve roots at risk via electrodes in the innervated muscle.
- At baseline, free-running EMG is normally of low amplitude and frequency. When nerve root irritation occurs due to electrical stimulation/surgical manipulations, spikes of activity (neurotonic discharges) are triggered and detected in the corresponding muscle.
- EMG has high sensitivity but low specificity.
- Its use is limited in patients with underlying neurological conditions such as myasthenia gravis and muscular dystrophy.
- Another variation of EMG, the triggered EMG, is performed via electrically stimulated pedicle screws, which leads to neurotonic discharges when there is malpositioning of the screw (near the nerve root). This allows repositioning of the pedicle screw.

Stagnara wake-up test

- This clinical test evaluates the integrity of the motor pathways by instructing the patient to make a specified muscle movement, usually in the lower limbs, midway through the surgery.
- When the wake-up test is to be performed, the patient will be gradually awakened with complete antagonism of neuromuscular blockade. Once conscious, the patient is asked to perform a motor function above the level of spinal cord injury (usually in the upper limbs) as control. If the patient is able to do so, he is then instructed to move his lower limbs. Corrective measures are immediately performed if the patient cannot move their lower limbs.
- Disadvantages of this modality include unsuitability for uncooperative patients, risk of inadvertent tracheal extubation or fall, and inability to perform continuous monitoring of motor pathways. As such, it is reserved for situations in which other IONM modalities are not available, fail or generate ambiguous results.

Perioperative management

A pneumonic perioperative checklist is useful. An example is demonstrated in Figure 3.1.

Preoperative	
Note existing defects and limitations of movement	

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Note existing defects and limitations of movement	☐
Explore contraindications (monitoring-drugs- pre-existing disease)	☐
Avoid excessive premedication	☐
Establish good teamwork and communication	☐
Intraoperative	
Start patient warming before induction	☐
Use total intravenous anaesthesia with EEG monitoring	☐
Use short acting neuromuscular blockade on induction – avoid further dose	☐
Optimal tube fixation	☐
Bite block for MEPs	☐
Optimal prone positioning	☐
Prevent pressure sores from monitoring wiring	☐
Consider adjuvants to minimise TIVA dose	☐
Maintain euvolaemia	☐
Maintain normotension (according to patient and intraoperative factors)	☐
Normal oxygenation—normocapnia	☐
Normal haemoglobin concentration	☐
Avoid excessive use of vasopressors	☐
Postoperative	
Aim for early emergence and clinical assessment	☐
Follow ERAS protocol	☐

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Figure 3.1 Anaesthetic perioperative checklist when using IONM.

Preoperative management

- Preoperative assessment should focus on evaluating and documenting existing neurological deficits in order to correlate with intraoperative baseline recordings from IONM techniques. This will also facilitate postoperative assessment of new neurological injuries.
- Relative contraindications for MEPs should also be noted, such as underlying epilepsy disorder, cortical lesions, increased intracranial pressure, loose teeth, intracranial electrodes, vascular clips, cardiac pacemakers, or other implantable medical devices.

Intraoperative management

- Drug selection should be based on the table above. Propofol is the most commonly used hypnotic agent.
- Principles for intraoperative use include using the lowest dose needed to maintain an adequate depth of anaesthesia (guided by processed and raw EEG waveforms), maintaining a steady anaesthetised state, and avoiding the administration of large boluses.
- If MEPs are used, an appropriately sized bite block should be inserted after endotracheal intubation between the molars to prevent tongue or lip laceration from bite injury.
- A short-acting NMB may facilitate intubation, but its complete reversal should be checked and documented before the commencement of MEP or EMG monitoring.
- In exceptional circumstances, there may be a need for NMB use to eliminate spontaneous EMG signals to facilitate SSEP and D-wave monitoring.
- Table 3.3 details recommendations for specific intraoperative physiological parameters.

Management of IONM warnings

In the event of IONM warnings, it is crucial to have a systematic plan and a team-based approach to identify the cause and take remedial actions (➲ Chapter 13, Intraoperative emergencies).

Postoperative management

If there are no contraindications, patients should be woken up and extubated to facilitate early evaluation of motor function and for the detection of postoperative complications.

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Special note on IONM use in neonates/infants
The myelination process of nervous tissues happens gradually and is completed at 36–40 months of age, occurring first in the sensory nerves before the motor nerves. As a result, SSEP and MEP signals in the very young may not be readily measurable or may require a higher stimulating current to trigger a response.

Electroencephalogram monitoring

Background

Processed electroencephalogram (pEEG) based depth of anaesthesia monitoring supports the safe maintenance of surgical hypnosis. To help with the interpretation of the raw EEG, a dimensionless index from zero to one hundred, based on an undisclosed algorithm, was introduced.

With the increasing use of such monitors in the last decade came criticism of the sole reliance on the proprietary indices produced by these devices. International guidelines now call for the anaesthetist to possess skills in basic interpretation of the raw EEG, which should be displayed by all monitoring systems.

EEG elements

Index

- All commercially available Depth of Hypnosis (DoH) monitors display an indexed number between 0 and 100. An index of 100 represents a fully awake patient, whereas zero implies isoelectricity.
- A decreasing index number represents a decrease in the patient's consciousness. Each monitor defines an index range consistent with surgical hypnosis, with an increasing risk of accidental awareness under general anaesthesia (AAGA) if the number is increasing above the upper limit, and an increased risk of an undesirable outcome, such as hypotension, delirium, or postoperative cognitive decline (POCD), if the index drops below the index range.
- As the index number is calculated by undisclosed algorithms and complicated by a time-lag of 10–60 seconds, there are growing calls to move away from using the index alone and instead interpret the raw EEG and the derived parameters directly.

Raw EEG

- At induction, the EEG shows typical changes from a high-frequency/low-amplitude to a low-frequency/high-amplitude pattern. This has been postulated to represent a shift from chaos to synchronicity, resulting in a loss of consciousness and failure to form memory.
- The raw EEG comprises an array of different frequency waveforms and can be divided into its components using the fast Fourier transform. This process splits the complex EEG waveform into its spectrum of constituent waves.
- The fast Fourier transformation process results in five constituent waveforms, defined by their frequency bands: gamma (30–45 Hz); beta (13–29 Hz); alpha (8–12 Hz); theta (5–7 Hz); delta and slow waves (below 4 Hz). The amplitude, or power, of each band represents how strongly it contributes to the original EEG waveform.

Spectral edge frequency (SEF)

- SEF describes the frequency below which 95% of the power of the EEG lies. An increase in high-frequency activity results in an increase in the SEF, which indicates a move into a lighter state of hypnosis.
- The SEF in a patient with adequate DoH lies typically in a range from 10 to 15 Hz. On the Bispectral Index (BIS™) monitor it is independently influenced using the low-frequency filter.

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It only uses frequencies below 30 Hz to be calculated, which means it should be less influenced by EMG or artefact.

- Burst suppression also results in an (paradoxical) increase in the SEF, which does not indicate a move to a lighter state of hypnosis.
- The evidence for the accuracy of the SEF to detect specific DoH is low, mainly due to the influence of opioids and other drugs.

Power spectrum and density spectral array

- The strengths of the distribution of the component EEG waves can be graphically displayed in the form of a power spectrum, which some monitors display as a near real-time readout of the state of the brain over the last few seconds.
- Stacking up these brief snapshots, and colour-coding the relative powers of the different frequency components (with cold colours for low powers and warm colours for high powers) results in a typical density spectral array (DSA).
- In the anaesthetised patient, two bands of high power in the alpha and delta spectrum should be seen, representing adequate surgical hypnosis (see Figure 3.2). Absence or relative weakness of the alpha band in the power spectrum might be indicative of an older, more frail brain.

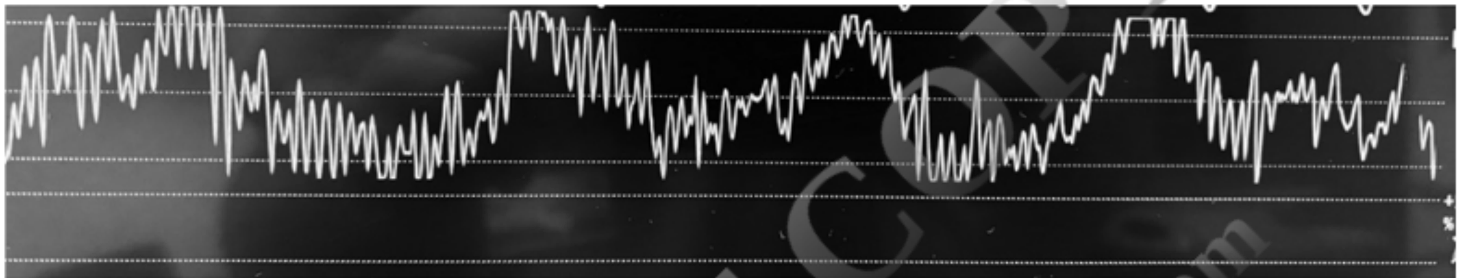

Figure 3.2 pEEG (BIS™ monitoring system) showing delta waves and a trace consistent with adequate surgical hypnosis.

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Burst suppression ratio

- Excessive depth of hypnosis creates a burst suppression pattern which approaches complete isoelectricity with increasing DoH (see Figure 3.3 and Box 3.3). Monitors represent the time spent by the raw EEG in a burst-suppressed state as a ratio, the burst suppression ratio (BSR).
- Although beneficial in some well-defined neurosurgical, cardio-thoracic, and critical care settings, burst suppression is generally regarded as excessive DoH with the potential for the undesirable patient outcomes described above in the context of low DoH indices.

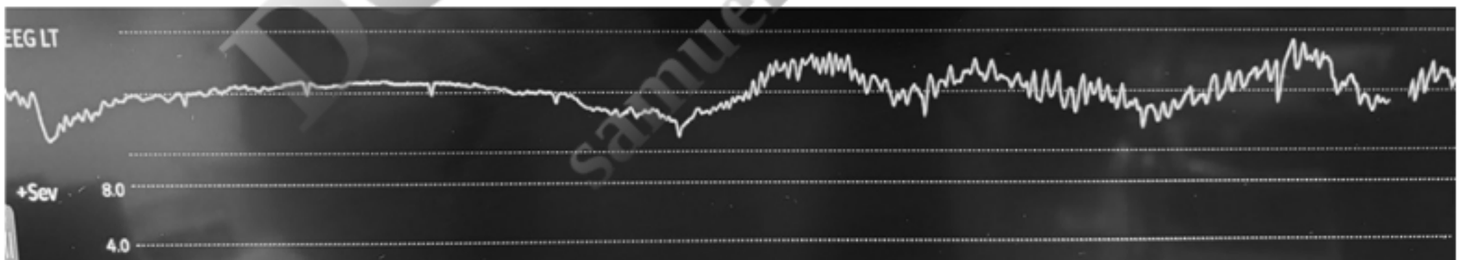

Figure 3.3 pEEG (BIS™ monitoring system) trace showing a short period of burst suppression followed by delta waves.

Box 3.3 Key points in the use of EEG intraoperatively

- Raw EEG and the index number should be interpreted in context of other physiological monitoring.
- In TIVA, calculated effect-site concentration of propofol at loss of consciousness is the first indicator of the amount of propofol the patient requires for maintenance.
- The fading of the alpha band in the DSA could indicate an accumulation of propofol.

Specific neurosurgical considerations

Technical challenges and electrode placement

- The surface EEG, derived from skin electrodes on the forehead, measures tiny potential differences (microvolts) and is therefore prone to interference. During cranial neurosurgery, the EEG is registered in close proximity to sources of interference like mechanical manipulation, diathermy, or drilling. There is also a potential for interference from neurophysiological monitoring.
- During cranial neurosurgery, the space for electrode positioning is often near the surgical field, which ideally requires very small sticking electrodes or preferably needle electrodes. During spinal surgery in the prone position, the patient's head often rests for an extended period on a spongy positioning device, which carries the risk of pressure sores to the forehead. Again, this requires very careful positioning of the sticky electrodes or, ideally, the use of needle electrodes.
- Due to the proximity to the surgical field, it is often impossible to place the electrodes in the position recommended by the manufacturer.
- The best way around this is using a monitor that enables the use of needle electrodes (Narcotrend®), which almost guarantees a sensible positioning in agreement with the surgeon and the manufacturer's recommendations.
- For monitors not offering this option, alternative Bispectral Index strip positions are currently under investigation, with the infraorbital (nasal) montage seeming to show the best correlation with standard frontal electrode position.
- Alternative locations include the post-auricular and supralabial areas.

Bilateral EEG monitoring

During surgery with a unilateral pathology, it is recommended to monitor the healthy side. Some devices offer the option of bilateral EEG monitoring, which might be advantageous in some settings. Potential benefits include early detection of hypoperfusion and detection of vasospasm after subarachnoid haemorrhage, or during cerebrovascular aneurysm coiling.

Despite obvious theoretical benefits to bilateral EEG monitoring, it has so far not been shown to confer benefit in larger studies. It is therefore imperative to discuss the utility of bilateral EEG monitoring with the neurosurgical team, ahead of its application. The surgeon and anaesthetist should agree on the levels of disparity in hemispheric activity that would be considered clinically significant, and if any surgical or anaesthetic manoeuvres could be undertaken to address concerns, should such disparities arise.

Seizures

- There is a potential for seizure detection using pEEG monitoring. The index has been shown to move up, down, or remain unchanged during verified seizure activity, so it lacks utility in this regard. However, the raw EEG might show typical seizure activity, depending on the location of the focus.
- The detection of typical seizure-induced EEG changes (low frequency/high amplitude, rhythmic polyspikes) can prove a seizure. However, its absence will not exclude seizure activity. See Figures 3.4 and 3.5.

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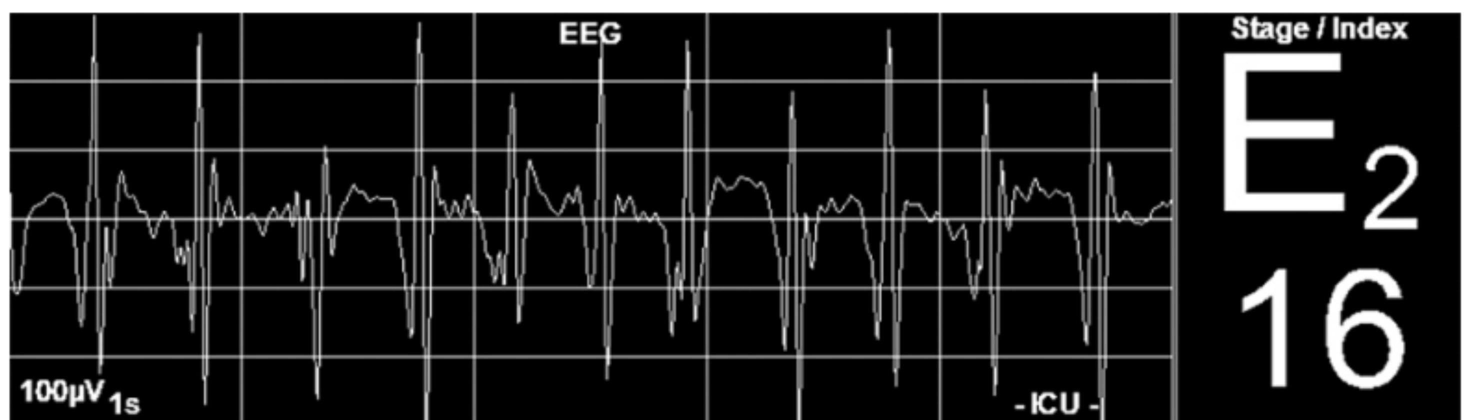

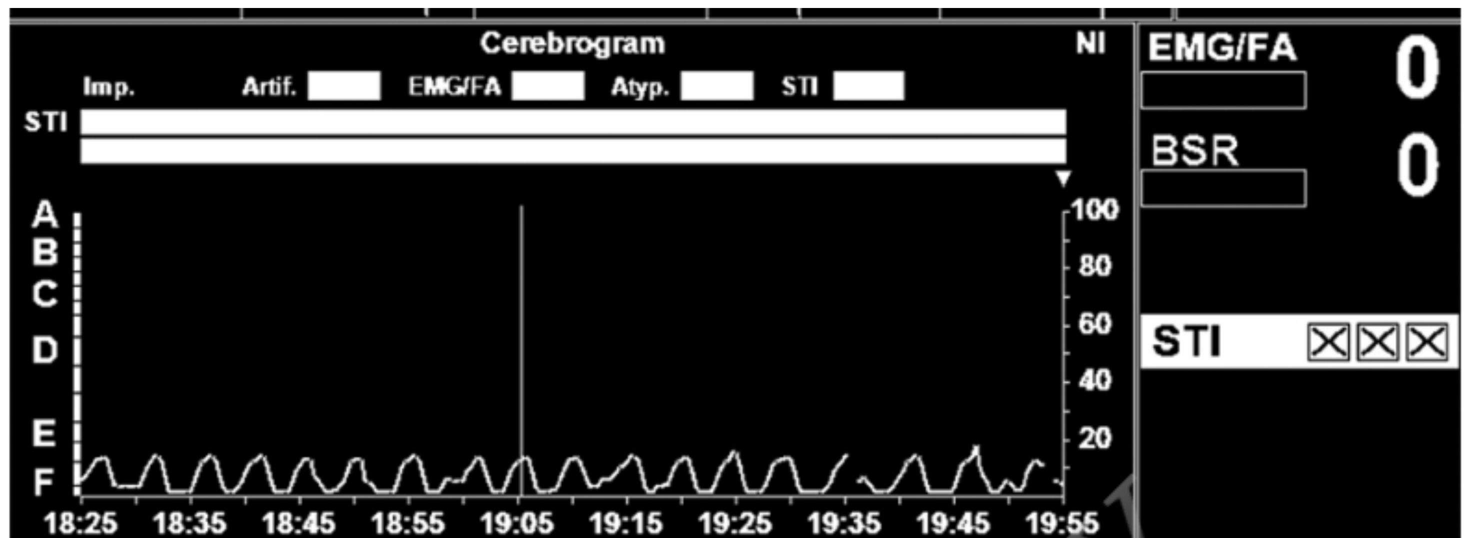

Figure 3.4 Narcotrend® monitor showing seizure activity and flagging up sharp transient intensity (STI).

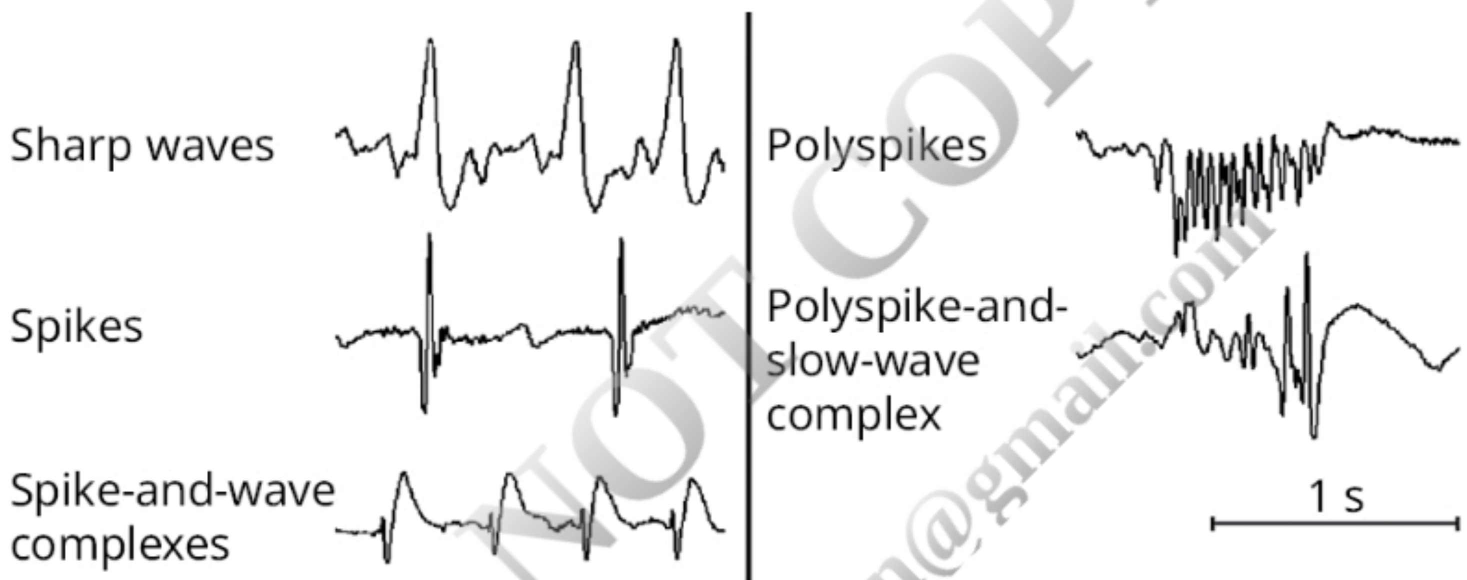

Figure 3.5 Different waveforms of epileptiform potentials. Copyright MT MonitorTechnik.

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Ketamine

- While ketamine causes an effect on almost all frequency bands in different brain regions, the most important effect for the pEEG and the resulting Index value, is an increase in gamma frequency (25–55 Hz) in the frontal brain regions. See Figure 3.6.
- This effect can be mitigated by propofol, which might explain why a significant effect can be seen in some patients even with relatively low doses of ketamine (0.2–0.5 mg/kg), while no effect is seen in other patients even with higher doses.
- Despite this huge variability, it is important to remember at time of giving ketamine to draw the correct conclusion from a potential increase in the index number and changes in the DSA.

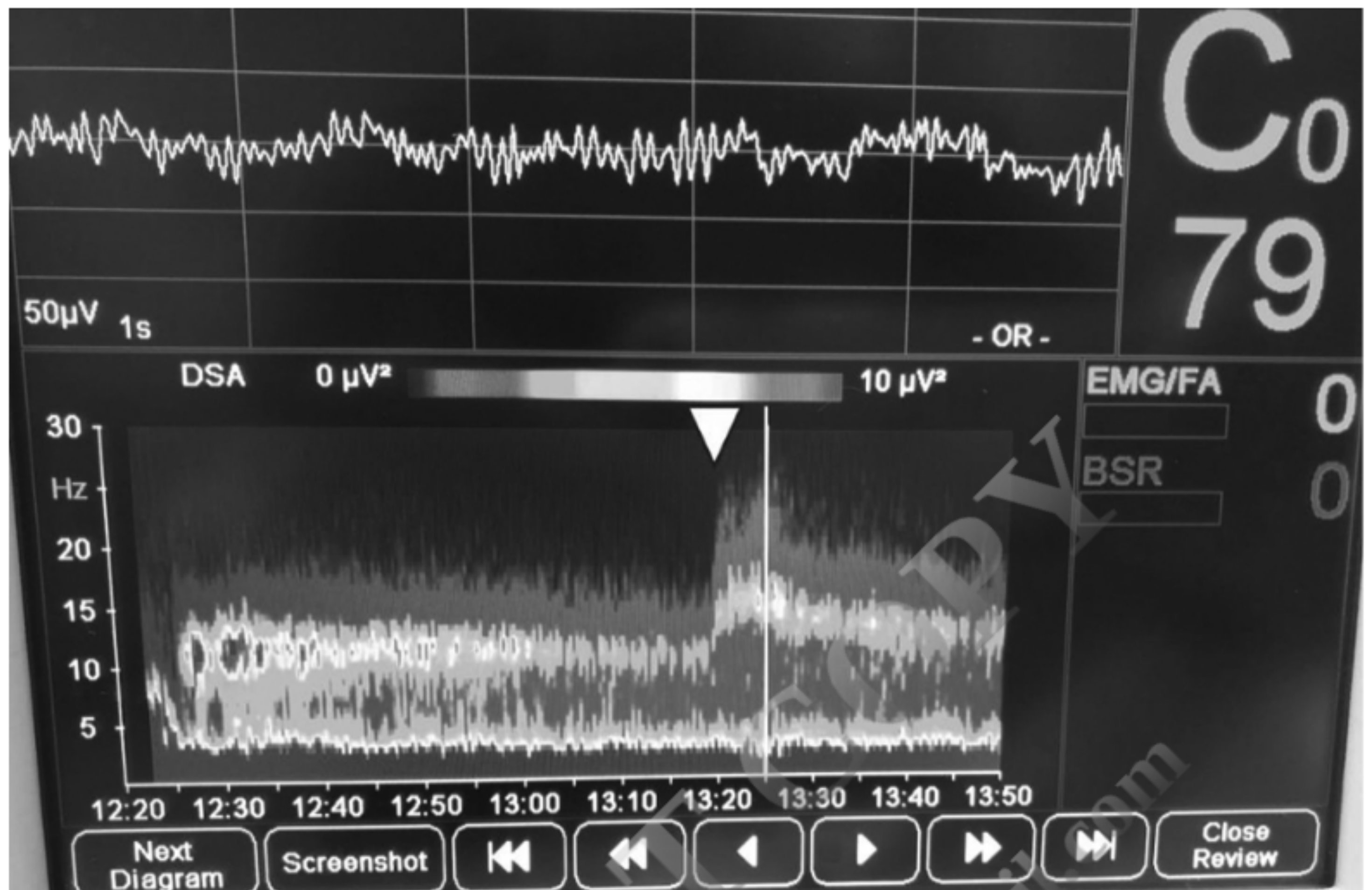

Figure 3.6 Effect of ketamine on EEG. DSA response to 0.5 mg/kg ketamine given at the time of the inverted triangle. The index is raised, displayed at the time of the white vertical line. Copyright MT MonitorTechnik.

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