Intraoperative Neuromonitoring

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Intraoperative neurophysiological monitoring (IONM) is the evaluation of the nervous system during surgical procedures where injury is possible. IONM can be divided into 2 areas: (1) detection of an iatrogenic injury allowing for reversal or minimization of the injury; and (2) localization (mapping) of critical neural structures during the procedure to avoid damaging those structures.[1] As of today, IONM is a standard of care in a variety of surgical procedures such as scoliosis correction, intramedullary spinal cord tumor resection, and acoustic neuroma resection. In other procedures, it is used to improve surgical decision making.[1–5] To properly interpret IONM data, the neurophysiologist needs to know the physiological state of the patient, the competency of the technologist operating the equipment, the state of the monitoring equipment, what the surgeon is doing, the preoperative examination of the patient (including the patient's history), and the anesthesia administered to the patient.[6] In addition, the anesthesiologist needs to understand how anesthetics can affect the monitoring. This chapter will focus on the interaction between the anesthesiologist and the IONM neurophysiologist/technologist by describing the interactions between the anesthetic agents and the IONM tools.

IONM data are either obtained quasi continuously [sensory and motor evoked potentials (SSEP and MEP), electroencephalography (EEG), and free-run electromyography (fEMG)] or at specific time points such as for functional-anatomic localization (direct nerve and cortical stimulation). For evoked potential testing, a stimulus is applied at one point in the nervous system while recording the response of the

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stimuli at another point. To achieve optimal responses, all neural elements (axon, synapse, and neuromuscular junction) in the signal pathway need to be functioning at some minimal level. The role of anesthesia, on the other hand, is 4-fold: (1) to block noxious stimuli, (2) to produce unconsciousness, (3) to induce amnesia, and (4) to prevent unwanted patient movement. Anesthesia accomplishes these goals by altering synaptic transmission in the nervous system. The anesthesiologist and neurophysiologist need to work synergistically to optimize patient outcome. Certain anesthetic techniques tend to be favored with some IONM techniques (eg, minimizing the use of inhalational anesthetics), emphasizing the key interaction between the anesthesiologist and the IONM team to produce interpretable, neurophysiological signals for monitoring.

Analysis of electrophysiological signals is based on 3 properties of the recorded signals: (1) the amplitude, or height of the response, referenced to some baseline or between the highest and lowest recorded points; (2) the latency, or time of the response from the start of the stimulation; and (3) the wave shape (determined by the frequency or spectral content of the activity). With preexisting neural compromise, these properties can be altered from normal, and additional anesthetic effects can hinder signal interpretation. Knowledge of how the normal nervous system responds to anesthetic agents helps in the initial choice of the anesthetic as well as adjustments to improve the IONM effectiveness. Furthermore, anesthetic management can alter the patient's physiology (eg, blood pressure, cerebral blood flow, intracranial pressure), which can also alter the neurophysiological data.[7] Hence, the anesthesiologist needs to work closely with the IONM team to establish a favorable anesthetic at the start of the procedure (baseline).

Once established, the anesthesiologist should attempt to keep the anesthetic constant so that changes in the IONM responses reflect neural changes rather than fluctuations in the anesthetic dosing. This is particularly important at critical times, such as cross-clamping during carotid endarterectomy, so that the IONM team does not misinterpret anesthetic changes as iatrogenic resulting in a surgical modification, which is not necessary.

Constant communication between the anesthesiologist and the neurophysiologist can help minimize the confusion that dosing changes can impart. In addition, the duration of anesthetic action varies between drugs and can affect the IONM interpretation at critical points in the procedure (eg, interpreting pedicle screw thresholds when neuromuscular blocking agents may not have completely worn off). Although rare, some IONM modalities have the potential of causing iatrogenic injury, such as seizures during MEP testing (particularly during direct cortical stimulation), and the choice of anesthetic agent may help in minimizing this risk (or be used to terminate the seizures).

■ Modalities

As described above, neurophysiological data consist of either recording background activity or as the result of an evoked response. Commonly used IONM modalities include: (1) SSEPs that evaluate the sensory pathway from specific peripheral nerves through the large Ia fibers of the dorsal column, through the sensory thalamus, and to the sensory cortex; (2) MEPs that evaluate the largest 2% of fibers in the corticospinal tract from the brain to the muscle through the α motor neuron connecting the primary and secondary motor neurons; (3) fEMG that records muscle activity that results from potential irritation of a nerve innervating that muscle; (4) triggered EMG (tEMG) that records muscle activity in response to stimulation of a nerve; (5) brainstem auditory evoked responses (BAER) that evaluate the sensory pathways of the auditory system from the cochlea through the auditory brainstem nuclei; (6) direct nerve recordings that evaluate signal conduction through specific nerve segments; (7) EEG that records the background activity of the superficial cortical layers of the brain; and (8) single-cell microelectrode recordings that record the activity of individual neurons for localization purposes.

Given that the main areas of anesthetic action are at the synapse and the overall effects of anesthetic agents on axonal membrane properties (ie, nerve conduction) are negligible, except at extremely high doses, modalities that involve only axon to axon recordings are least affected by anesthesia. The usual rule is that the more synapses a neural signal has to travel through, the greater the anesthetic effect. Yet, even a signal synapse, such as the one between the upper and lower motor neuron (αMN), can be significantly affected by anesthesia due to the effects of anesthesia on neural networks. Each monitoring modality is affected differently by anesthetic agents depending on the drug effects on specific neurotransmitters and the types of synapses involved in the monitored pathway. The modalities are also affected differently depending on the location and mechanism of neural dysfunction or injury (eg, neural or vascular). The anesthesiologist should consider the specific surgical procedure, preexisting patient abnormalities, the desired neurophysiological management of the patient, and IONM techniques used when planning the anesthesia management.

■ EEG

The EEG monitors the averaged extracellular field potentials of the spontaneous activity of cortical neurons near the recording electrodes. The number of neurons recorded is a function of the location of the electrode (scalp, cortical, or intraparenchymal), the size of the electrode, the distance between the electrode and the neurons, and the tissue between the

neurons and the electrode. For recordings, there is an "active" and "reference" electrode, such that the total activity recorded is the difference in activity between these electrodes. The activity in locations distant from the electrodes will have no impact on the recorded data such that important activity in other areas may not be observable, unless indirect effects occur. Hence, the EEG is usually recorded using several pairs of electrodes (montage) in the areas of interest. When recording the EEG using a standard 21-channel montage, based on the 10 to 20 electrode localization system,[8] (Fig. 1) the spatial resolution is approximately 6 cm.[9] A common intraoperative technique is to use 8 electrodes, which approximate a spatial resolution of approximately 10 to 12 cm (extrapolating from

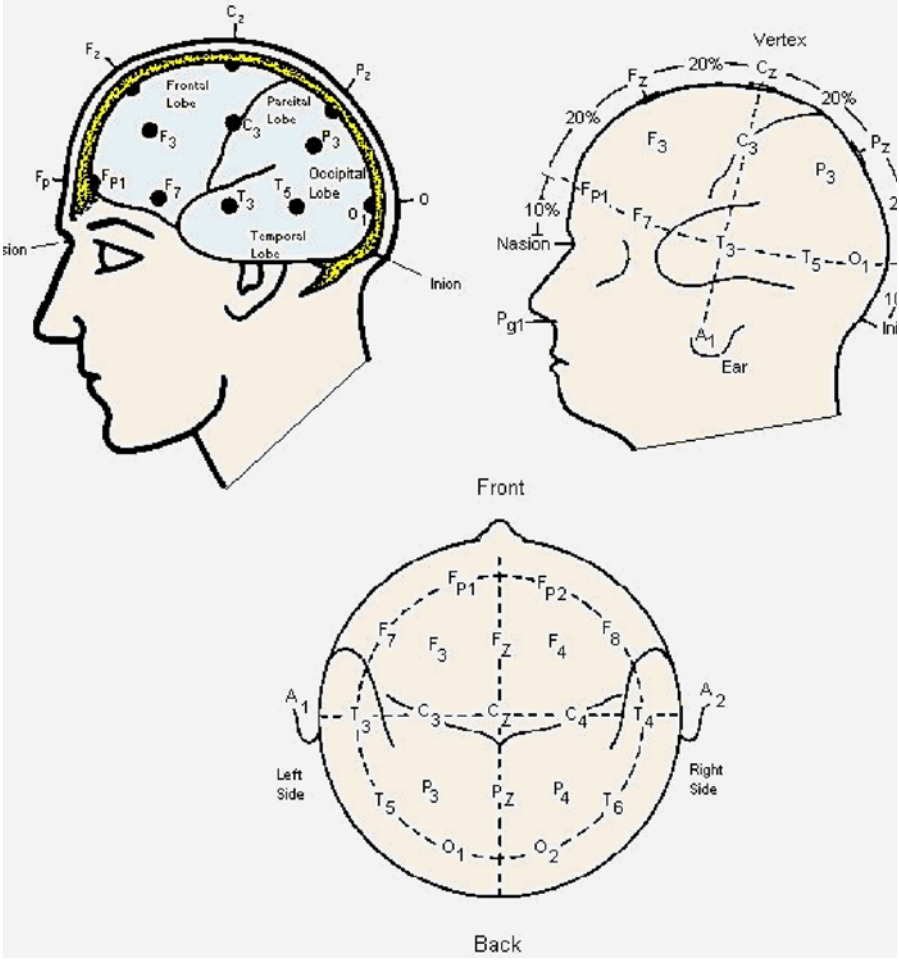

Figure 1. *The 10 to 20 electrode placement system. Each of the electrode positions is based off of a 10% or 20% measurement based on 4 head landmarks. The landmarks are the Nasion, Inion, and both preauricular points (Courtesy of Natus Neurology Incorporated).*[9] full color online

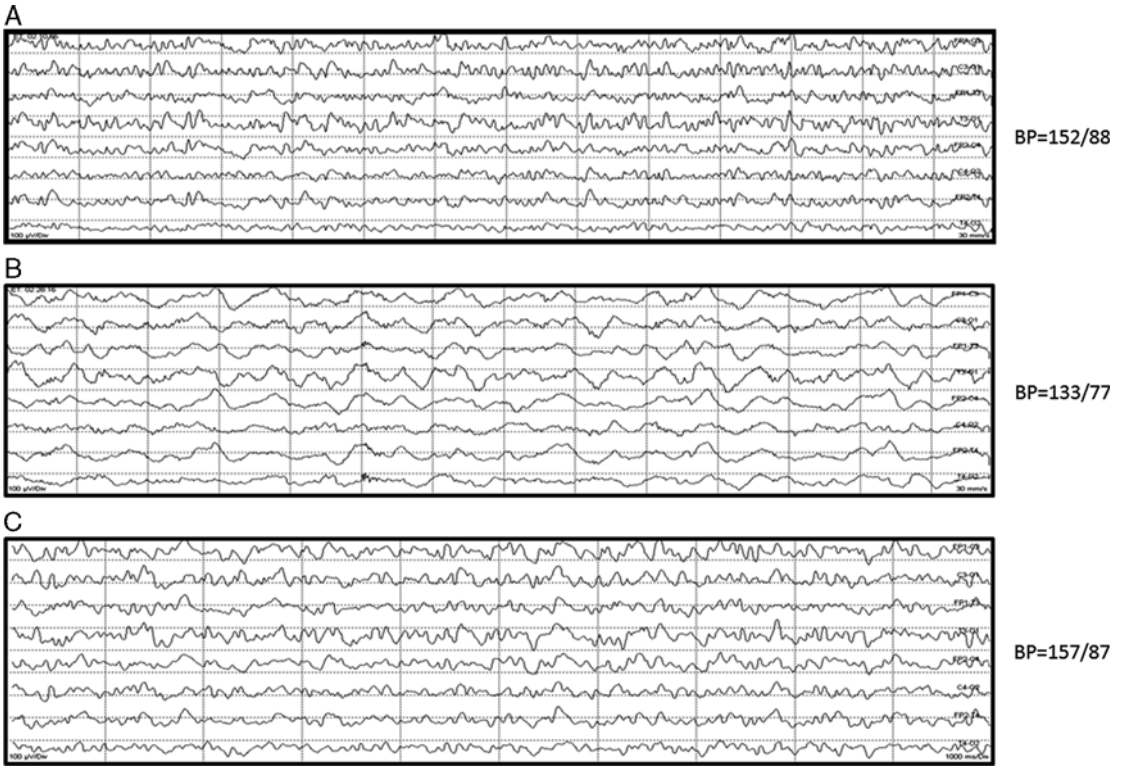

Figure 2. *An example of cortical ischemia related to a change in the blood pressure during a carotid endarterectomy procedure. A, The baseline EEG under general anesthesia with no burst suppression during surgical exposure. B, The effect of a reduction in the blood pressure. Notice the generalized δ activity and loss of higher frequency activity. C, A return to baseline activity. The generalized δ is gone and the higher frequency θ is returning.*

Gevins et al[10]), thus focal effects may be missed. To have a large change reflected in the EEG, the change needs to occur directly under an electrode or a large volume of neurons need to be involved.

The overall electrical activity of the brain is dependent on the availability of metabolites, including oxygen. When these are compromised, it is reflected quickly in loss of synaptic function. Intraoperative EEG therefore reflects cortical ischemia (Fig. 2). A second valuable quality is the unique ability to detect electrical seizure activity. Thus, the most common procedures where EEG is used are where the chance of vascular insult is high, with intracranial motor mapping procedures to identify seizure activity resulting from cortical stimulation, epilepsy ablation procedures, and during cardiac procedures.

As the spectral content of the EEG is critical to localizing insult to the brain, many systems include tempero/spectral plots to show the energy in the key EEG spectral bands. These bands are: Delta, (δ) which is 1 to 4 Hz; Theta (θ), which is 4 to 8 Hz; Alpha (α), which is 8 to 12 Hz; and Beta (β), which is usually between 12 and 30 Hz. α and β are dominant when awake and as anesthesia starts to affect the brain. As unconsciousness starts, the higher frequency activity is replaced by lower frequency activity and the common term is called "slowing." In general, critical nonanesthetic-induced changes in the EEG are a reduction in the overall amplitude, a shift to low-frequency activity, and in some cases, progression to burst suppression and electrocerebral silence (Fig. 3) due to reductions in the amount of synaptic activity.[12]

Inhalational agents (Table 1) at low doses cause an increase in both EEG voltage and frequency.[29] In general, as the patient moves to unconsciousness, α activity moves anteriorly, whereas β activity moves posteriorly.[30] This leads to an initial depression in the overall cortical activity followed by a slowing of the dominant frequency. Continued depression of activity eventually leads to burst suppression and finally electrocerebral silence at very high doses (Fig. 3).[31] With isoflurane, desflurane, and sevoflurane, burst suppression will occur at doses associated with anesthesia, whereas for enflurane and halothane this will not occur.[32] At high doses, this reduction in EEG activity affects the interpretation and interferes with IONM. Most importantly, as the reduction in oxygenation of the brain produce a diffuse slowing of activity that will eventually become electrically silent, higher doses of inhalational agents may mimic ischemia. For example, burst suppression at the time of cross-clamping during carotid endarterectomy significantly affects the ability to interpret ischemic changes, which is the primary reason for monitoring during those cases.

Different from the other inhalational agents that suppress spontaneous interictal spikes, sevoflurane and enflurane have been shown to provoke interictal spike activity and can cause seizures.[33,34] Nitrous oxide (N_2O), when used alone at concentrations causing unconsciousness,

Table 1. *Anesthetic Effects on the EEG*

	References	Light	Mild	Moderate	Deep	Heavy	Notes
Halothane	11	15-25 Hz predominant frequency with reduced amplitude	Low-amplitude β activity superimposed on high-amplitude activity θ activity	β activity lost: shifting to predominantly high-amplitude δ activity		BS*	No seizure activity
Isoflurane	12	Loss of α activity and development of faster activity including high-frequency β bursts	Low-amplitude β activity superimposed on δ, θ high-amplitude activity	β activity lost shifting to predominantly high-amplitude δ, θ activity	Burst suppression with alternating periods of low-amplitude and high-amplitude activity (low-amplitude θ and high-amplitude δ, θ)	ES	No seizure activity
Enflurane	13	Global increase in frequency and amplitude	Shift of α activity to the frontal regions from the posterior regions	Decrease in frequency (moving to δ, θ activity): increase in amplitude of this low-frequency activity	Burst suppression		Can produce high-frequency and high-voltage activity on EEG that can progress to spike wave activity and seizure activity. This can occur at doses less than necessary for satisfactory anesthesia
Sevoflurane	14	Similar to isoflurane	Similar to isoflurane	Similar to isoflurane	Similar to isoflurane	Similar to isoflurane	Can increase spikes in patients with epilepsy and may cause seizure activity in healthier patients
Desflurane	10	Similar to isoflurane	Similar to isoflurane	Similar to isoflurane	Similar to isoflurane	Similar to isoflurane	No seizure activity
N_2O	15		Loss of α activity (30%-40%)	Increase in β activity (50%)	Primarily θ activity (75%-80%)		May increase motor activity
Propofol	16–18	Shift from α to β activity	Initial marked depression of EEG and then increase in rhythmic	Polymorphic δ activity	Burst suppression	ES	Reduces seizure duration and can suppress both ictal and interictal and both clinical and

Table 1. (*continued*)

	References	Light	Mild	Moderate	Deep	Heavy	Notes
			spindle–like activity				electrographic seizures and is thus increasing as an anticonvulsant. There are some reports of propofol generating seizures in some epileptic patients during induction and emergence, which is thought to be related to rapid changes in propofol concentrations at these times. But in general the consensus is that propofol is more beneficial than detrimental
Opioids†	19,20	Shift to α activity progressing to lower frequencies with eventually disappearance of the α rhythm and minor increase in θ activity at the frontal electrodes	Increased θ activity with disappearance of α and β	Increased δ activity shifting to the lower δ frequency range	Continuous high-amplitude δ activity	ES	No suppression at safe and normal levels Quick recovery of normal EEG and is dependent on the dose given. At higher doses frontal sharp waves have been noticed in some patients, but this does not appear to be seizure activity
Barbiturates	21,19	Frontal β activity (≳ 15 Hz): first initially frontal and	Frontal α spindles with loss of consciousness as the activity slows	Diffuse polymorphic δ activity (1-3 Hz)	Burst suppression	ES	Note: rapid injection can cause the EEG to go

		then spreading posteriorly					directly to slow waves
Etomidate	22	Diffuse θ activity with random δ waves and precentral spindles	Sleep spindles and K-complexes start	Increasing δ activity and slower spindles with irregular K-complexes	Continuous high-amplitude δ activity with no isolated K -complexes		Can produce BS or ES
Ketamine	23	High-amplitude frontally dominant θ activity	Frontally dominant rhythmic δ activity with interspersed θ activity and β activity	Polymorphic δ activity with some spike wave patterns	Polymorphic δ activity interspaced with low-amplitude β activity		Can produce seizure activity in patients with epilepsy
Benzodiazepines	24	Disappearance of α activity and increase of β activity	Increase in β activity	Continuation of β activity with random scattered θ activity	No Burst suppression	No ES	Will not go into BS or ES: each benzodiazepine will have different time course but all follow same pattern
Dexmedetomidine	25–28		No significant changes in the EEG: small decrease in all power bands	Increase in δ and θ activity with decrease in β activity and abundant spindle activity			Overall power increase: no BS or ES and even high levels. The EEG levels show spindle activity similar to stage 2 sleep

*Burst suppression not reached in clinically relevant doses.
†This description is based on fentanyl but other opioids follow the same pattern with differences in the time of onset.
BS indicates burst suppression; EEG, electroencephalography; ES, electrocerebral silence.

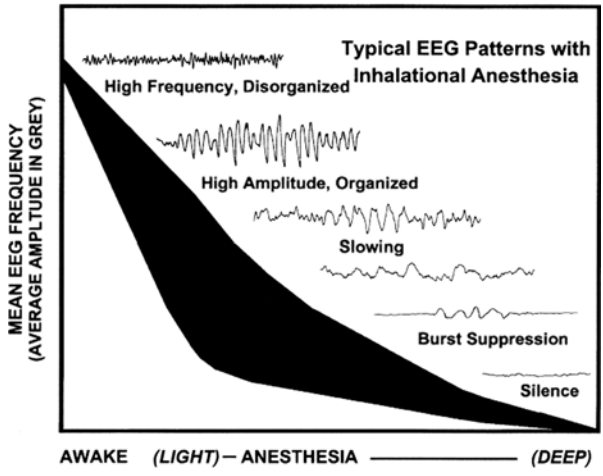

Figure 3. *A generalized image of the EEG at different anesthetic states. In the awake state, the EEG shows low-amplitude higher frequency activity (in this case, the EEG is showing a predominant α activity). As the anesthetic starts to take effect, the α is reduced and a low-amplitude β activity starts shifting eventually to higher amplitude activity with modulated by some lower frequency θ and δ activity. As the patient gets deeper, the higher frequencies are completely lost, and the most predominant activity moves from θ to δ activity eventually to burst suppression and finally to electrocerabral silence.*[11] *EEG indicates electroencephalography. Reprinted with permission.*

produces fast oscillatory activity in the frontal regions. It is often used in combination with other agents where the overall effect of N_2O is additive to the other agents. In general, most intravenous drugs cause a reduction in overall amplitude and increase in slow wave activity (Table 1). Ketamine is somewhat different in that lower doses generate an excitation of the brain with increases in α and β activity.[25] Etomidate and methohexital at low doses also excite the brain and have been used to enhance native epileptic foci during electrocortiography.[29]

■ SSEP

SSEPs are used to monitor sensory pathway integrity by recording at points distal and proximal to the surgical field, or in regions that may be indirectly affected by surgery (ie, carotid surgery potentially causing ischemic effects at the sensory cortex). With the SSEP, a distal nerve is stimulated and responses are recorded at specific neural junctures along the ascending sensory pathway. Given the low amplitude of this signal, it is very difficult to obtain a quality response using a single stimulus; thus, multiple tests are conducted and the results of those tests are averaged to remove the noise and enhance the signal.

The location of the surgery dictates the stimulus and recording locations. Common SSEP stimulation sites are: (1) posterior tibial nerve

Table 2. *Anesthesia Effects on the Cortical SSEPs*

	References	Latency	Amplitude	Notes
Halothane	35,36	Increase	Decrease	Similar to isoflurane
Isoflurane	35	Increase	Decrease	Morphologic changes under deep concentrations. Usually recordable at ½-1 MAC
Enflurane	35	Increase	Decrease	Similar to isoflurane
Sevoflurane	35,36	Increase	Decrease	Morphologic changes under deep concentrations
Desflurane	36	Increase	Decrease	Similar to isoflurane
N_2O	36	Increase	Decrease	Additive effect to other agents
Propofol	35,36	Increase	Decrease	Effect is less than inhalational anesthetics, but at higher doses does cause significant decrimental effect on the SSEP. Rapid metabolism allows quick recovery except at long infusions
Opioids	36	No effect	Minimal effect: effect is mostly seen at longer latencies	
Barbiturates	35,36	Dose-dependent increase in latency	Very minimal to no effect	Transient changes immediately after induction. The effect on the SSEP is very minimal even at doses that cause coma
Etomidate	35,37	No effect	Increase at low doses; this increase can be as much as 400%	Myoclonus after induction
Ketamine	36,38	No effect	Minimal increase at low doses	Maximum effect 2-10 min after bolus
Benzodiazepines	35,36	Increase	Decrease	Mild to moderate effect at normal doses
Dexmedetomidine	35,39	No effect	No effect	Can blunt the effect of isoflurane

SSEP indicates sensory evoked potentials.

at the medial ankle; (2) the common peroneal nerve behind the knee; (3) the median nerve at the wrist; (4) the ulnar nerve at the wrist; and (5) the ulnar nerve at the cubital tunnel in the elbow. Recording electrodes are placed at peripheral locations (popliteal fossa and Erb's point), along the spine [cervical spine (C7) and/or thoracolumbar spine (T12)], and over the sensory cortex (Fpz and C3′, C4′, Cz′) (Fig. 1). The auditory SSEP (BAER) is monitored by recording the response of brainstem nuclei following an auditory click applied to the ear canal, making it useful for brainstem surgery.

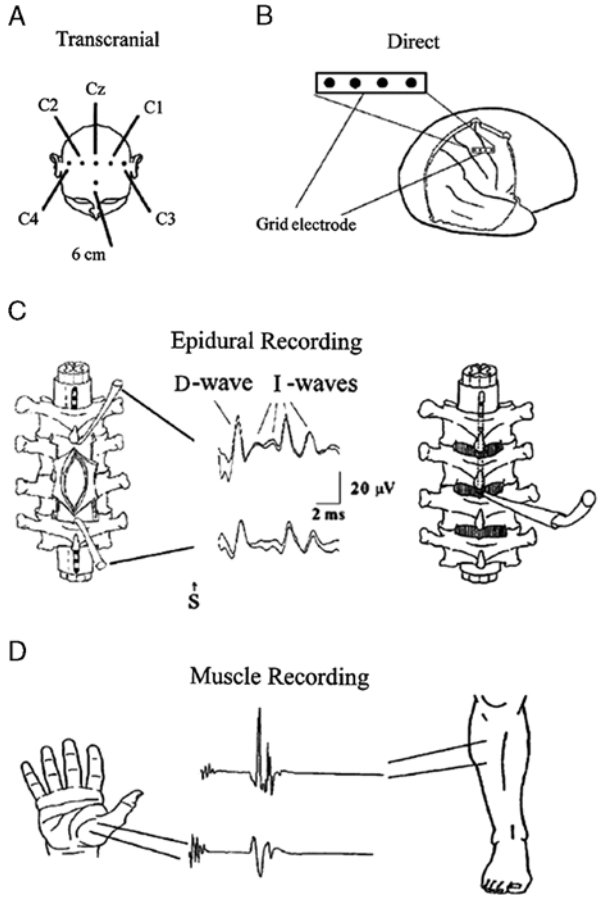

Figure 4. *The various responses that can be elicited from motor cortical stimulation. Stimulation can be applied either (A) transcranial with electrodes placed on the scalp or (B) directly on the cortical surface. (C) Reponses can be recorded directly on the spinal cord or dura as shown in (D) from the muscle as compound muscle action potentials (CMAP).*[47] *Reprinted with permission.*

Multiple factors affect the transmission of these signals such as height, temperature, nerve compression, neural perfusion, anesthetic type and dose, as well as some metabolic diseases. As the primary effect of anesthetic agents is on synaptic transmission, the greater the number of synapses between the stimulus and recording sites the greater the effect of the anesthetic agent. In addition, the impact of anesthetic effect can also alter certain neural networks.[35] With respect to the sensory pathways, anesthetic effects can block sensory transmission in the thalamus, resulting in a marked reduction in transmission to the sensory cortex (ie, reduced cortical SSEP response), whereas in the motor

Table 3. *Anesthesia Effects on the Muscle MEPs*

	References	Latency	Amplitude	Notes
Halothane	36,52	Increase	Decrease	At ½-1 MAC the average MEP CMAP response was <25% of the response without anesthesia and may not be recordable in some patients even when <0.25 MAC
Isoflurane	36,49	Increase	Decrease	Similar to above
Enflurane	36	Increase	Decrease	Similar to above
Sevoflurane	36	Increase	Decrease	Similar to above: but there is a slightly left-shifted response
Desflurane	36	Increase	Decrease	Similar to above
N_2O	49,54	Increase	Decrease	Mimics the effects of isoflurane: by 60% N_2O the amplitude of the MEP CMAP response is down to 10% of baseline amplitude and increases the latency by around 3 ms, yet there are differences in how N_2O affects different muscles
Propofol	49		Decrease	Rapidly metabolized so drug concentrations can be adjusted quickly for adequate MEP recordings. Pattern is similar to that of inhalational agents, yet standard anesthetic doses allow for MEP monitoring. If large doses are needed, propofol can significantly affect MEP recordings
Opioids	49,55	Mild increases	Mild decrease	Dose related. About a 15%-20% reductions in amplitude at peak dose of drug, but higher variable trending toward less reduction
Barbiturates	49	Increase	Decrease	Effect prolonged after use during induction
Etomidate	55	None	Variable amplitude decrement, yet at low doses may enhance the MEP	Causes myoclonus within first few minutes after induction that may interfere with MEP recordings. Note that in 1 patient with pronounced myoclonic movements the amplitudes significantly increased
Ketamine	49,56	Minor increases	Increase at lower doses that do not cause spike wave activity on the EEG and decrease at high doses	
Benzodiazepines	49,56	None	Sustained depression of the MEP	Effects last for >30 min in doses that cause sedation
Dexmedetomidine	39		Decrement at higher doses making recording very difficult	

CMAP indicates muscle compound action potential; EEG, electroencephalography; MEP, motor evoked potentials.

system the effect of anesthesia is to reduce the reflex pathways in the spinal cord that cause withdrawal from a noxious sensory stimulus. This reduces the transmission of descending motor pathways to muscle (ie, reduced myogenic MEP responses). Furthermore, the effects of anesthesia with preexisting pathology in the nervous system may make the response unrecordable. In general, the effects of anesthetics on the SSEP are dose dependent, with increasing doses causing increases in latency and decreases in cortical amplitude. A specific anesthetic's effect is dependent on that agent's influence on different neurotransmitters and specific portions of neural pathways.[36]

Compared with intravenous anesthetics, the volatile anesthetics affect a wide spectrum of synapses (Table 2) and, in general, cause greater depression of the cortical SSEP. However, in most patients, moderate doses still allow for acceptable recordings. The effect varies with the potency of the agent (isoflurane being the most potent and halothane the least). It is interesting to note that although sevoflurane and desflurane are similar to isoflurane at a steady state, their insolubility leads to a more rapid onset and offset so that they may appear more potent at times of increasing concentrations.[37] Table 2 gives a general overview of the effects of the most common anesthetics on the SSEP. Without N_2O, cortical SSEP are usually recordable with isoflurane, halothane, and enflurane at up to 1.0 MAC[37,38]; yet as the concentration increases above MAC, the recorded signal amplitude drops at a much faster rate. N_2O will augment these effects.[42] The effect on the spinal responses is much less, allowing recordings at higher concentrations. Opioids, etomidate, ketamine, and dexmedetomidine show no appreciable effect on the latency of the SSEP, but at low concentrations ketamine and etomidate may actually cause an augmentation of the SSEP cortical response.[37–41] All other intravenous drugs cause a dose-related reduction in the amplitude, as will ketamine and etomidate at higher concentrations. Anesthetic effects are minimal on the BAER allowing any anesthetic choice unless another IONM modality is also used.

■ EMG

EMG monitors the spontaneous (background, fEMG) or "triggered" (tEMG) activity in muscles by placing 2 electrodes into the body of the muscle approximately 1 cm apart. (In some cases, single needles may be placed in multiple muscles and then each muscle referenced to another muscle. In this case specificity is lost to assure complete coverage of the nerves of interest. Some users will use surface electrodes to record EMG activity. This is not a common technique in the operating room, given a greater propensity for dislodgement and the fact that the tissue between

the muscle and the electrode can act as a low pass filter possibly obscuring the responses.) The fEMG method allows for continuous monitoring of any mechanical or metabolic iatrogenic irritation of the nerves without the need for the surgeon to use an instrument to stimulate the nerve. In some surgical procedures, the surgeon needs to be able to accurately locate the nervous tissue that may not easily be differentiated in the surgical field or to "map" the nervous structures in the surgical field. This is done using a probe that applies a focused stimulus (trigger) to the tissue while monitoring for time-locked responses that indicate that the nervous tissue was activated. Procedures where this technique is invaluable include detethering procedures, selective dorsal rhyzotomies, peripheral nerve procedures, and skull base and/or ENT procedures where cranial and facial nerves may not be easily identified or entry points may need to be localized. Using variations in stimulus intensity needed to activate the nerve, response amplitude and response delay help determine the relative position of the nerve to the stimulator probe.

In general, the effect of anesthesia medications on EMG recording is minimal, with the exception of neuromuscular blocking agents. The EMG requires the neural signal to pass through the neuromuscular junction, which is where the muscle relaxants block nerve transmission (see Sloan[43] for a more comprehensive review of the subject). The most common method to assess the degree of neuromuscular blockade (NMB) is the train-of-four (TOF) response, where 4 stimuli are applied at 2 Hz and the number of responses counted. Another common technique is to look at the response amplitude from single pulse stimulation and compare it with a baseline unblocked response (T1 response). To assure the best possible EMG response, a majority of groups recommend that the TOF response should be 4/4.[44] To get the most appropriate TOF result, the test should be conducted on the muscles where the critical EMG response is being observed.[44]

Most studies on the effect of NMB pertain to MEP and triggered EMG responses. In a study by Van Dongen et al[45] on patients undergoing cardiothoracic procedures, it was found that at a T1 level of between 45% and 55% the MEP response was stable and robust enough for recording (note that they compared this with a 5% to 15% T1 response). Cai et al[46] demonstrated that the facial nerve is consistently monitorable by tEMG when the T1 response was at least $\geq 50\%$ compared with baseline; yet when the T1 response was $<25\%$, no responses were recordable. (It is important to note that as the NMB level increased the stimulation intensity necessary to elicit a response also increased.) When evaluating the effects of NMB agents on fEMG, there are insufficient data to make recommendations for NMB use. As NMB may make small responses difficult to identify, the avoidance of NMB is usually recommended with fEMG monitoring.[43]

■ MEP

MEPs monitor the efferent motor pathways from the motor cortex and fibers in the internal capsule to the muscle through the largest 1% to 2% of axons in corticospinal (or corticobulbar) tracts.[47] To evoke the MEP, transcranial electrical stimulation using a cathode (− electrode) placed on the ipsilateral scalp overlying the motor strip is referenced to an anode (+ electrode) placed on the contralateral scalp (TcMEP). In general, it is easier to activate upper limb muscles with electrodes placed at C1(+)-C2(−)(right muscles)/C2(+)-C1(−) (left muscles) and lower limb muscles using electrodes placed at C3(+)-C4(−)/C4(+)-C3(−) (Fig. 1). If these montages do not give an adequate response, electrodes placed 6 cm behind Fz (−) referenced to Cz (+) may also be used (Fig. 1).[47,48] TcMEPs are produced when stimuli directly activate the axons of the large Betz cells located in the motor cortex, not the cell bodies. This fact is important as stronger stimulation activates the motor pathway deeper in the brain. Hence, for monitoring when the motor cortex is at risk, "large" stimulation amplitude may activate corticospinal axons by *jumping* over the actual area of surgical interest to deeper structures, thus missing iatrogenic injury in the cortex.[47,48] During open cranial procedures, MEPs may also be generated by directly stimulating the cortex and/or subcortical white matter (direct cortical stimulation).

Once an action potential is initiated, the activity travels down the corticospinal tract to activate the α motor neurons in laminae IX of the spinal cord to produce muscle compound action potentials (CMAPs) (Fig. 4). TcMEP stimulation requires stimulus intensities from 100 to 400 V or 40 to 200 mA and a pulse width of between 50 and 500 μs.[47,48] In the unanesthetized human, CMAPs can be generated with a single pulse applied to the area overlying the motor strip.[49]

The response of motor cortex stimulation can also be recorded as traveling waves along the spinal cord. These responses consist of 2 waves: a direct wave (D-wave) that is the action potential generated in the corticospinal axons followed by indirect waves (I-waves), which are action potentials resulting from cortical activation of internuncial neurons (Fig. 4).[50] Unlike the CMAP, the D-wave involves no synapses such that anesthetics, at normal concentrations, have very little effect.[37] Single stimulation pulses can be used to generate D-waves essentially eliminating movements and minimizing anesthetic constraints. In general, this technique is only used when the spinal cord is exposed (eg, intramedullary surgery), although in most cases they are used in conjunction with muscle MEPs.

The temporal summation of the D and I waves is sufficient to depolarize the αMN in the unanesthetized human. As mentioned above, the effect of anesthetics on the motor pathway (especially within the spinal cord) is sufficient to prevent the recording of myogenic MEPs

with a single transcranial stimulation pulse. Compounding this effect is that I-waves are also reduced with anesthesia due to effects on the synapses involved in their generation.[51] This makes the CMAP very difficult to record during anesthesia. To overcome this problem, a multipulse technique consisting of a train of 3 to 9 pulses with an interstimulus interval between 1 and 4 ms is utilized.[52,53] This multipulse technique can cause significant patient movement. In most cases, this movement is acceptable; yet, in addition to anesthetic constraints listed below, a key precaution is the addition of biteblocks to minimize tongue and lip lacerations.[54]

Table 3 gives a general overview of the effects of the most common anesthetics on the MEP. As with the SSEP, the effect of volatile anesthetics on the myogenic responses is quite significant, whereas for epidural recordings (D-wave) the effect is minimal.[37] Thus, when muscle MEPs are being monitored, the use of minimal inhalational anesthetics is optimal. In some patients with minimal preexisting pathology, muscle responses can be recorded with up to 0.5 MAC of a volatile agent. It is important to note that many intravenous drugs also affect the amplitude and latency of the muscle MEP, but the effect is more gradual and at doses that are larger than commonly used. Although propofol has a dose-related inhibitory effect on the MEPs, it usually allows for adequate anesthesia and IONM.[38] In a study by Chen[59] comparing propofol and isoflurane using BIS values monitoring, the author found that propofol allowed for recordable MEPs at all BIS values ranges, whereas isoflurane restricted recording to only 58.8% of patients for BIS values > 55 and 17.8% for BIS values < 55. Opioids show a minimal effect on muscle MEPs and are recommended for use as a constant infusion to minimize transient bolus effects at critical points in the surgical procedure.[51] Similar to SSEPs, ketamine and etomidate may enhance the MEP at low does.[57,58] Ketamine has been used as an adjunct in anesthetic management to reduce propofol utilization. In patients where the MEP is difficult to record, anesthesia with only intravenous agents is often used (total intravenous anesthesia).

■ Conclusions

In general, the conduct of anesthesia is often a balance of providing sufficient anesthesia while facilitating interpretable electrophysiology data for IONM. This is particularly true in patients with preexisting neurological compromise. In addition, anesthesia effects can alter the neurophysiology, which can influence neural function. On the other hand, the function of intraoperative neurophysiology is to extract low-amplitude functional neural information in a potentially compromised nervous system under conditions that enhance the signal reduction and,

because of background noise from electrical surgical equipment, increase the noise level in the recorded signal. Hence, good communication between the anesthesiologist and the neurophysiologist is important for effective IONM. Depending upon the surgical procedure and the goals for that procedure, a better understanding of IONM by the anesthesiologist will help in preparing the most optimal anesthetic plan for the particular patient.

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