14

Utility of Intraoperative Neuromonitoring

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Abbreviations

ACDF	Anterior cervical discectomy and fusion
CSM	Cervical spondylotic myelopathy
IONM	Intraoperative neurophysiological monitoring
MAP	Mean arterial pressure
MEP	Motor evoked potential
MR	Magnetic resonance
SCI	Spinal cord injury
S-EMG	Spontaneous electromyography
SSEP	Somatosensory evoked potential
tcMEP	Transcranial motor evoked potential
TIVA	Total intravenous anesthesia

Pearls

1. Mostly useful in two situations:
   (a) With very tight stenosis, with turning a patient prone (with pre-turn and post-turn monitoring) to ensure adequate head position
   (b) With deformity correction
2. Consider using monitoring with an arterial line, as these patients may be very sensitive to MAP and spinal perfusion.

Pitfalls

1. Lack of communication among the surgeons, the neurophysiologist, and the anesthesia teams. Notably with anesthesia turnover during the case. Excellent communication among all members is essential.

Key Points

- The purpose of intraoperative neurophysiological monitoring (intraoperative neuromonitoring, IONM) is to try to detect neurological irritation or injury during high-risk spine surgery.

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- Several intraoperative neuromonitoring modalities are currently available including somatosensory evoked potentials (SSEP), transcranial motor evoked potentials (tcMEP), and spontaneous electromyography (S-EMG).
- Surgeons should have a plan or checklist for review in the event of compelling neuromonitoring alerts to allow a prompt and appropriate response.
- Multimodal monitoring is routinely used during cervical spine surgery to maximize diagnostic efficacy as it offers a more comprehensive assessment of the spinal cord as compared with unimodal applications.
- Controversy exists in the utility of the routine use of intraoperative neuromonitoring for "low-risk" anterior cervical discectomy and fusion (ACDF) for degenerative conditions without associated deformity.
- The utility of intraoperative neuromonitoring (IONM) in decompressive surgery for cases of severe cervical myelopathy and/or radiculopathy where nerve conduction pathways may already be dysfunctional is controversial.
- The utility of neuromonitoring to detect delayed C5 palsy is questionable.

Introduction

The prevention of neurological injury is a central tenet of spine surgery. Unfortunately, the surgical treatment of spine disease may place the spinal cord or spinal nerve roots at some risk of injury. As a result, postoperative neurological deficits due to intraoperative injury may occur in up to 4% of anterior cervical discectomy and fusion (ACDF) cases and in up to 30% (average 4.7%) of posterior procedures [19, 22, 46, 53]. Etiologies of intraoperative irritation of, or injury to, the spinal cord or nerve roots include systemic causes such as hypoperfusion of the spinal cord due to hypotension or anemia, reperfusion injuries following decompression, neck manipulation during positioning, surgical decompressive maneuvers, instrumentation during fusion cases, and distraction during deformity correction [2, 9, 19, 46]. In the cervical spine, spinal cord injury (SCI) can have significant negative consequences.

Intraoperative neurophysiological monitoring (intraoperative neuromonitoring, IONM) enables the evaluation of the functional integrity of the spinal cord and nerve roots during surgery and may allow the early detection and possibly the reversal of neurological injury during high-risk spine surgery. Since its inception, IONM has demonstrated an ability to detect neurological deficits due to traction, compression, or ischemia of the spinal cord in thoracolumbar deformity surgery [9, 47, 69]. As a result of these successes, IONM has become adopted as an adjunct in the surgical treatment of other conditions, including degenerative cervical myelopathy and radiculopathy. However, debate exists over the use of IONM in the management of degenerative diseases of the cervical spine as the evidence for its utility for predicting and mitigating postoperative neurological deficits following anterior or posterior cervical spine surgery remains limited (Table 14.1) [2, 13, 18, 43].

Intraoperative Neuromonitoring Modalities

Monitoring plans are determined after consultation between the operating neurosurgeon, neurophysiologists, and anesthesiologists. In creating a monitoring plan, consideration must be given to preoperative neurological deficits, relevant anatomy, planned procedure, relevant comorbidities, planned anesthetic, and previous electrophysiological testing, when available, as all of these factors may influence the methodology and reliability of IONM. Each technique described below has its own advantages and disadvantages, and the choice of one or a combination of several should be carefully considered on a case-by-case basis.

Table 14.1 Key points

The purpose of intraoperative neurophysiological monitoring (intraoperative neuromonitoring, IONM) is to detect and possibly reverse neurological injury during high-risk spine surgery
Several IONM modalities are currently available for spinal surgeries including somatosensory evoked potentials (SSEP), transcranial motor evoked potentials (tcMEP), and spontaneous electromyography (S-EMG)
Surgeons should have a checklist for review in the event of compelling IONM alerts to allow prompt and aggressive detection and possibly reversal of neurological injury
Multimodal monitoring is routinely used during cervical spine surgery to maximize diagnostic efficacy as it offers a more comprehensive assessment of the spinal cord as compared with unimodal applications
Controversy exists in the utility of the routine use of intraoperative neuromonitoring for "low-risk" anterior cervical discectomy and fusion (ACDF) for degenerative conditions without deformity
The utility of IONM in decompressive surgery for cases of severe cervical myelopathy and/or radiculopathy where nerve conduction pathways may already be dysfunctional is not established
The utility of IONM to detect delayed C5 palsy is questionable

Somatosensory Evoked Potentials

Prior to 1977, the gold standard for detecting intraoperative neurological insults involved waking a patient intraoperatively to assess voluntary lower extremity function [68]. Known as the Stagnara wake-up test, this method was uncomfortable for the patient, difficult to perform repetitively during complicated surgeries, and often failed to identify the surgical step responsible for any witnessed deficit and did little to prevent reversible injury.

In 1977 the development of somatosensory evoked potential (SSEP) monitoring significantly advanced the capabilities of IONM. Measured SSEPs reflect the sequential activation of neural structures along somatosensory pathways. Decrements in SSEP amplitude or latency imply damage to the posterior columns of the spinal cord rostral to nerve root levels, where afferent somatosensory activity enters the cord. As a result, SSEP monitoring enables the surgeon to evaluate the functional integrity of ascending sensory pathways travelling from peripheral nerves through the dorsal roots and dorsal columns of the spinal cord and onto the sensory cortex [35, 47]. Typically, stimulation needle electrodes are placed in standard locations including the median and ulnar nerves in the upper extremity and the posterior tibial nerve in the lower extremity. Recording electrodes are placed following set standards, such as the International 10–20 system, and measurements are taken at anatomically accessible sites [37]. Abnormal findings are typically suggested by a 30–60% drop in the SSEP wave amplitude or a 10% delay in the SSEP latency (Fig. 14.1a, b), although thresholds vary according to institutional guidelines and no defined criteria exist [2].

A number of studies have examined the efficacy of SSEP monitoring in cervical spine surgery. For posterior cervical procedures, the sensitivity and specificity of SSEP monitoring range from 21% to 25% and 94% to 100%, respectively, suggesting that greater utility may lie in the negative predictive value of SSEP monitoring [27, 51]. In comparison, the utility of SSEP monitoring for anterior cervical spine surgery remains unclear as outcomes of surgery using intraoperative SSEP monitoring during anterior cervical discectomy and fusion (ACDF) surgery in non-myelopathic patients have not proven superior to unmonitored cases [59, 64].

While SSEP monitoring provides easy setup, monitoring is limited to the afferent tracts of the ascending dorsal column-medial lemniscus pathway and does not provide information about the descending efferent motor fibers of the corticospinal tract or the spinal cord gray matter. Furthermore, recorded SSEPs are summed responses which are filtered to remove artifacts and require averaging over multiple stimulation pulse trains occurring over time to improve the signal-to-noise ratio. As a result, abnormal findings or significant changes may significantly lag behind clinically important changes.

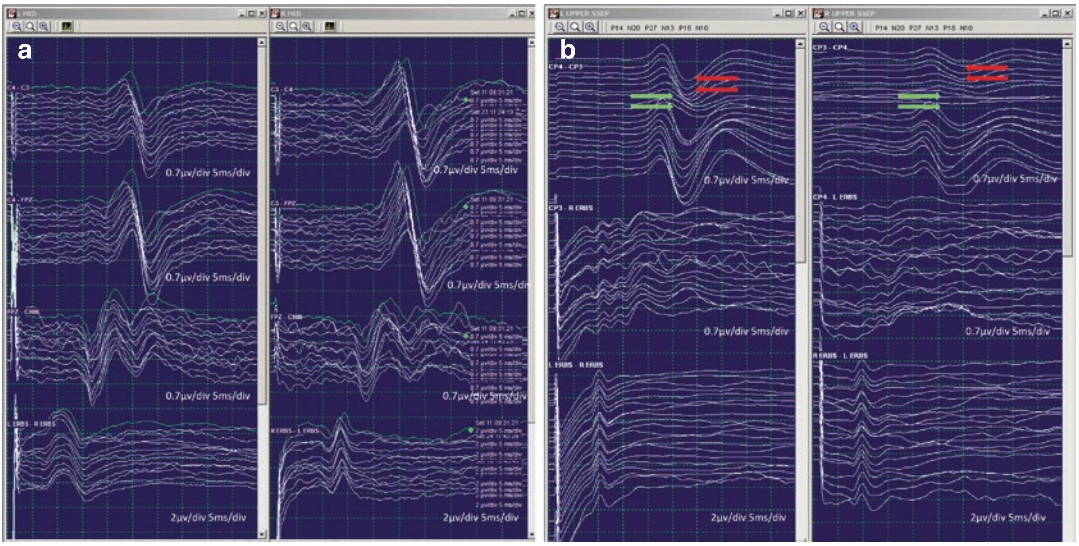

Fig. 14.1 Intraoperative somatosensory evoked potential (SSEP) recordings. (**a**) Representative cases demonstrating reliable SSEP recording. Stimulation electrodes were placed along the median nerve, and bipolar stimulation was used to propagate repetitive action potentials along the peripheral nerves to the dorsal column pathways of the spinal cord and eventually to the contralateral sensory cortex. Bilateral SSEPs were reliably recorded at anatomically accessible sites including Erb's point (ERBS), the Fpz-CHIN region, the C4-Fpz region, and the C4-C3 region according to the International 10–20 system [37]. (**b**) Representative case demonstrating loss and subsequent return of bilateral SSEPs. Bilateral SSEPs were reliably recorded at ERBS, the CP3-R ERBS region, and the C4-C3 regions. Loss (green arrows) and subsequent spontaneous return (red arrows) of SSEP signal amplitudes became apparent during surgery suggesting loss and return of dorsal column conductivity (left greater than right). No new postoperative deficit was encountered

Transcranial Motor Evoked Potentials

In response to concerns over the low sensitivity of SSEP monitoring in detecting postoperative motor deficits, a technique of monitoring neurogenic evoked motor potentials was initially developed to measure peripheral nerve signals elicited from spinal cord stimulation cephalad to levels of interest [50]. However, subsequent neurophysiologic studies demonstrated that this technique likely measured retrograde signals transmitted via the dorsal columns with inaccurate representation of the descending corticospinal motor tracts [66]. Consequently, a method of measuring transcranial motor evoked potentials (tcMEP) was developed to reliably monitor the descending corticospinal motor tract [10].

The technique of tcMEP monitoring involves using electrical scalp stimulation to produce an electrical current within the motor cortex of the brain which then progresses through the descending corticospinal motor pathways. These motor pathways primarily comprise the lateral corticospinal tract and are located within the lateral and the ventral funiculi of the spinal cord. Recording needle electrodes are placed in the muscles of interest throughout the four extremities including the abductor pollicis brevis, first dorsal interosseous, extensor carpi radialis, triceps, biceps, deltoid, abductor hallucis, and anterior tibialis [2]. Muscle motor evoked potentials (MEPs) are then recorded. Measurements are taken as a baseline before surgery and then during intervals during the surgery, following the approach and critical portions of the procedure, and during the surgical closure. During surgery, signal amplitude, duration, and latency are monitored for significant changes (Fig. 14.2a). In general, tcMEPs are described as an "all-or-none" phenomenon, but accepted thresholds vary by institutional protocols, and no strictly defined criteria exist. Commonly, rapid and reproducible loss of

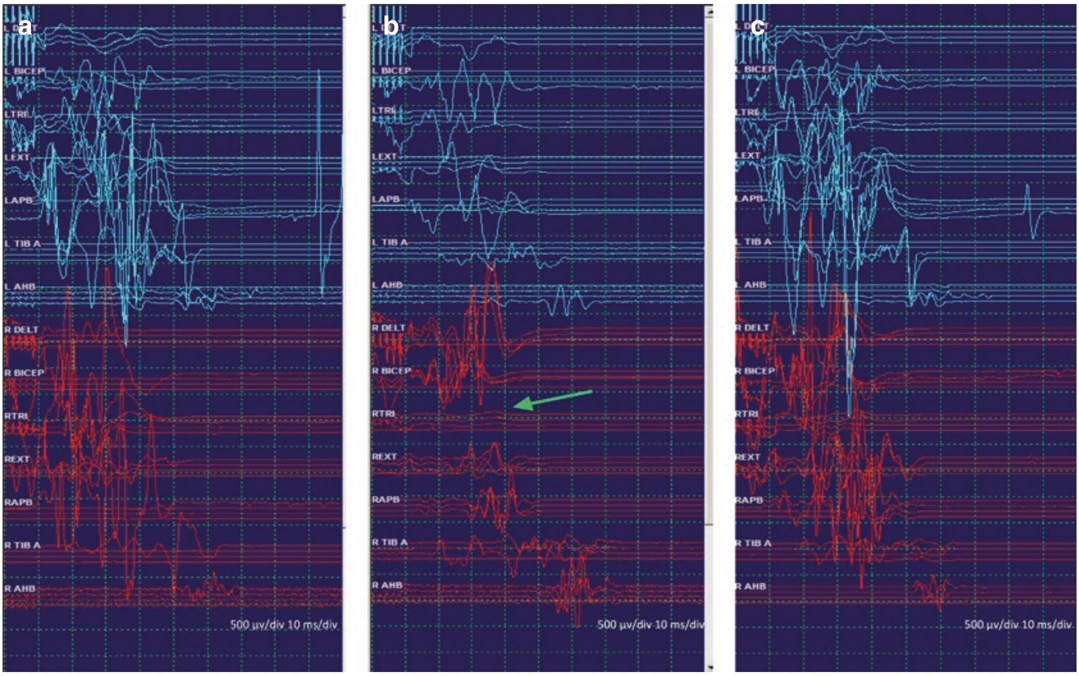

Fig. 14.2 Intraoperative transcranial motor evoked potential (tcMEP) recordings. (**a**) Bilateral upper and lower extremity tcMEPs were recorded at the deltoid (DELT), bicep, triceps (TRI), extensor carpi radialis (EXT), abductor pollicis brevis (APB), tibialis anterior (TIB A), and abductor hallucis (APB). The excellent amplitude and reproducibility provided a baseline for intraoperative monitoring. (**b**) A decrement in the right triceps tcMEPs (green arrow) prompted surgical pause and prompt and aggressive management of its source. (**c**) A modest return of right triceps tcMEP signal was measured prior to wound closure. This signal was less robust and lacking in complexity compared with other tcMEPs measured in other muscles on that side. Notably, the patient awoke without evidence of a postoperative neurological deficit

50–80% tcMEP amplitude is considered to represent a significant monitoring change (Fig. 14.2b, c) [2, 13, 40, 41]. However, even partial attenuation may actually represent injury within the cervical spine as associated muscles have multiple innervations at the level of both the gray matter and the nerve roots which can mask clinically relevant changes [4].

Limitations to tcMEPs exist, and successful baseline tcMEP recording can be influenced by patient age, lesion location, and preoperative neurological deficits as nerve conduction pathways may already be dysfunctional in some patients [12, 41]. As a result, identified changes require a careful appraisal to gauge representation of potential injury. Elicitation of tcMEPs can cause significant patient movement, thus limiting their use during critical portions of some procedures. Finally, the intermittent nature of tcMEP monitoring only reflects events since the last recording and may make differential identification of a specific etiology of intraoperative injury difficult.

Despite these limitations, studies have demonstrated tcMEP monitoring provides earlier detection of neurological injury and is a more sensitive indicator of neurological injury than SSEP monitoring alone, with associated sensitivity and specificity in cervical spine cases ranging from 75% to 100% and 92% to 100%, respectively [13, 27, 38, 56]. However, tcMEP monitoring also produces a rate of false-positive alerts approaching 5.8% and a rate of false-negative alerts approaching 5.0%, in particular with regard to monitoring for C5 palsy, precluding consensus on its true clinical value [42, 52, 63].

Spontaneous Electromyography

Spontaneous electromyography (S-EMG) is an additional IONM modality routinely used to monitor and alert the surgical team to nerve root irritation occurring in a specific myotomal distribution [5, 48, 49]. As S-EMG does not require stimulation, it provides continuous, "real-time" monitoring of nerve action potentials induced by various types of manipulation, including stretch, blunt trauma, compression, and ischemia. Typically, recording electrodes are placed in or near the muscles corresponding to the nerve roots at risk during surgery. The most reliably sampled muscles include the deltoid, biceps, triceps, thenar and hypothenar muscles, the vasti, anterior tibialis, gastrocnemius, abductor hallucis, and first dorsal interosseous, with the trapezius employed for C4 nerve root coverage [55]. In contrast to other IONM modalities, a lack of significant myogenic activity is interpreted as evidence of functionally intact nerve roots, whereas the occurrence of spontaneous spike activity and/or sustained bursting or train activity of S-EMG waves may represent true neurophysiologic changes (Fig. 14.3a, b) [40]. S-EMG is particularly useful in surgeries with risk of radicular injury.

Artefactual S-EMG activity can be produced by irrigation, metal-metal contact within the surgical field, or movement of the surgeon's body weight or equipment against a limb. In addition, ensuring adequate sampling within a monitored muscle is critical as activity in each muscle may reflect injury to a number of nerve roots innervating it. While S-EMG is relatively insensitive to anesthetics, it is profoundly affected by neuromuscular blockade. Historically, S-EMG has high sensitivity and low specificity for predicting postoperative neurological deficits and is best used in combination with other monitoring modalities [24].

Evaluation of Signal Changes

Persistent changes in any IONM modality may signal neurological irritation or impending or established injury. Surgeons should have a plan in place or a checklist for review in the event of a major alert to allow prompt and aggressive management of its source (Fig. 14.4) [20]. Routine considerations include adjusting stimulation parameters and checking electrode placement to rule out technical error; analyzing administered anesthetics to rule out the use of inhalational agents, large bolus injections, or long-acting muscle relaxants; ensuring a mean arterial pressure (MAP) >90 mmHg, temperature >36.5 °C, and hemoglobin >10 g/dL;

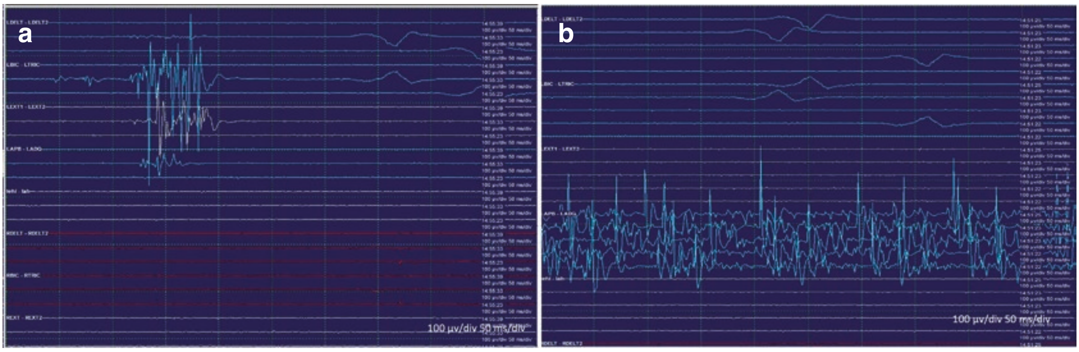

Fig. 14.3 Spontaneous electromyography (S-EMG) recordings of the bilateral upper extremities demonstrating activity in multiple nerve roots as a result of irritation. Sampled muscles include deltoids (DELT), biceps (BIC), triceps (TRI), extensor carpi radialis (EXT), and abductor pollicis brevis (APB). (**a**) Intraoperative S-EMG demonstrates irritation in the region of the left BIC-TRI, EXT, and APB. (**b**) S-EMG demonstrating persistent irritation in the region of the left APB. In comparison to other IONM modalities, a lack of significant myogenic activity is interpreted as evidence of functionally intact nerve roots

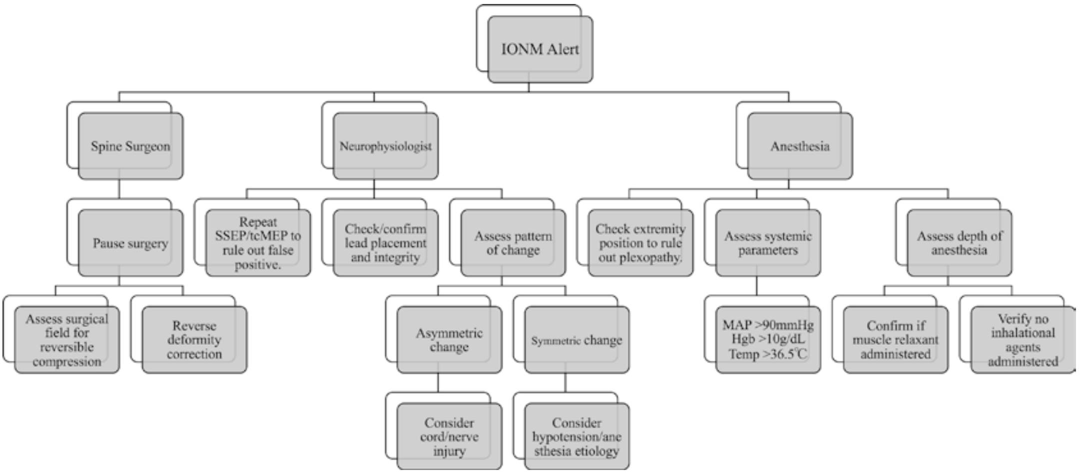

Fig. 14.4 Algorithm for response to IONM alert. IONM intraoperative neuromonitoring, SSEP somatosensory evoked potential, tcMEP transcranial motor evoked potential, MAP mean arterial pressure, Hgb hemoglobin. (Modified from Vitale et al. [69]. and Ziewacz et al. [72])

and evaluating possible position changes such as removing tape from the shoulders, repositioning the neck, releasing deformity corrections, or removing implants. When possible, multiple IONM modalities should be correlated to confirm injury [23, 28, 58, 69]. Consideration should always be given to the fact that false-positive alerts can occur and that some subsequent interventions may actually cause harm.

In the setting of persistent evidence of injury, and dependent on the postoperative neurological exam, consideration should be given to admitting the patient to an intensive care unit where the need for optimization of spinal cord perfusion can be evaluated. Additionally, for new postoperative deficits, consideration should be given to treatment with intravenous steroids. Magnetic resonance (MR) imaging may be considered to evaluate for compression of neurological elements when clinical suspicion is high (Table 14.2). It is important to note that challenging clinical conditions, such as severe myelopathy, spinal cord tumors, obesity, or peripheral neuropathy, can make interpretation of neuromonitoring difficult or at times impossible [13].

Table 14.2 Checklist for the management of persistent IONM changes with corresponding neurological deficit

Consider aborting the surgery and staging procedure
Consider admission to neurological intensive care unit
Evaluate benefit of optimizing spinal cord perfusion (ensure MAP >90 mmHg and Hgb >10 g/dL)
Consider IV steroid therapy
Consider MRI

Modified from Vitale et al. [69] and Ziewacz et al. [72]
IONM intraoperative neuromonitoring, *MAP* mean arterial pressure, *Hgb* hemoglobin, *IV* intravenous, *MRI* magnetic resonance imaging

Utility of Neuromonitoring

The routine use of IONM has reduced the risk of neurological injury in deformity surgery [56, 65]. Extrapolation of these data has resulted in the routine incorporation of IONM in the surgical management of degenerative cervical myelopathy and radiculopathy [1, 27]. However, while the utility of IONM during spinal deformity surgery is considered established [15, 56, 69], the efficacy of IONM in cervical spine surgery is still debated [14, 27, 34, 43, 63, 67]. Reservations are primarily grounded in the evidence of high false-positive rates, low efficiency, and lack of established reliable warning criteria for current IONM modalities. Furthermore, the role of neuromonitoring in patients without severe deformity or with already irreversible preoperative neurological deficits is unknown and carries large economic implications [14, 67]. As a result, the use of IONM may be of limited value in routine, nontraumatic, or non-severe deformity cases in the cervical spine. Importantly, IONM requires multidisciplinary cooperation between neurophysiologists, anesthesiologists, and neurosurgeons to properly and efficiently use these technologies.

Multimodality Neuromonitoring

In general, multimodality monitoring—with a combination of tcMEP, SSEP, and S-EMG—is used to improve the overall sensitivity and maximize the diagnostic efficacy of the individual modalities as it is believed to offer a more comprehensive assessment of the spinal cord as compared with unimodal applications [17, 19, 29, 34, 35, 43, 44, 54, 61, 62]. Sensitivity of multimodal IONM ranges from 50% to 83.3%, with a specificity of 99–100% during cervical spine surgery [18, 40]. However, increased sensitivity carries with it the risk of increased false positives that may not necessarily manifest as a new postoperative neurologic deficits and may result in aborted procedures or potentially harmful alterations in standard surgical techniques [42]. As a result, some continue to argue that unimodal intraoperative monitoring has higher specificity than multimodal monitoring and may minimize subclinical intraoperative alerts [2], which can significantly influence surgical decision-making [42].

Preoperative Deficits

In the presence of significant preoperative weakness, nerve conduction pathways may already be dysfunctional and the utility of IONM in decompressive surgery for cases of severe cervical myelopathy [15, 36, 67] and/or radiculopathy is not well established [15, 36, 41, 67]. In particular, the presence of preoperative myelopathy may be a strong risk factor for IONM changes in cases of cervical spondylotic myelopathy [45]. However, severe preoperative spinal cord dysfunction is associated with worsened baseline tcMEP amplitude, duration, and latency making intraoperative interpretation complicated. In addition, the sensitivity of IONM may also vary based on patient comorbidities and age [13]. Regardless, decreased intraoperative tcMEPs have been shown to correlate with postoperative neurological deficits in cases of cervical myelopathy [13]. While more studies are necessary to better understand and further establish significant alarm thresholds in cases of myelopathy, interpretation of worsened tcMEP monitoring should always be evaluated relative to preoperative baselines specific to each individual case [70].

Recent evidence suggests that tcMEP use may be limited in patients with preoperative motor deficits consistent with radiculopathy causing Medical Research Council (MRC) grades less than 3 as the frequency of successful recordings diminishes substantially [41]. However, if a baseline tcMEP or SSEP can be recorded successfully, the utility of intraoperative neuromonitoring can actually increase [13]. In such cases, attempts to increase stimulus intensity, duration, or interval may improve the success rate of tcMEP monitoring despite a higher risk of seizure, tongue biting, cardiac arrhythmias, and scalp burns with high voltage tcMEP stimulation [3, 32, 33, 57]. Additional techniques for improving the reliability of IONM have been described for patients with severe neuromuscular weakness, impaired spinal cord function, Duchenne muscular atrophy, or Rett syndrome with some success [33]. These techniques involve preconditioning stimulation preceding multiple transcranial electrical stimuli to elicit a larger MEP and facilitate a weak response. In the setting of preoperative weakness of a given muscle, S-EMG monitoring may demonstrate baseline activity in that muscle which then dissipates with decompression [6, 48]. In comparison, chronically compressed motor nerve roots may not fire spontaneously or with stimulus, and a quiet S-EMG does not necessarily mean that the root is not undergoing injury [15].

Anterior Versus Posterior Surgical Procedures

Symptomatic cervical spine disease may be treated by anterior, posterior, or combination (360°) approaches with the degree of surgical complexity varying with approach, surgical goals, anatomic variants, and patient clinical status. Multimodality IONM has become routinely incorporated in cervical spine surgery for symptomatic spondylosis. However, documented rates of neurological injury following anterior and posterior cervical spine surgery for degenerative disease are low, ranging from 0% to 18% in monitored cases [18, 42, 67], with a slightly higher risk in cases involving corpectomies. As a result, there has been debate over the utility and cost-efficacy of routine IONM for these "low-risk" procedures [2]. Unfortunately, studies examining the utility of IONM in cervical spine surgery remain limited by the heterogeneity of procedures and perceived risks. As a result, sensitivity and specificity of the various monitoring techniques differ depending on the patient's diagnosis and the procedure performed [15, 52].

In general, the limited available evidence suggests that multimodal IONM is useful for detecting neurological injury in posterior cervical operations, in particular in the high cervical region [40]. However, IONM may be of limited value in routine, nontraumatic, or non-severe deformity cases as these cases are thought to have lower rates of iatrogenic neurological injury.

Similar controversy exists over the routine use of IONM for anterior cervical spine surgeries for degenerative conditions without deformity. Early proponents of IONM for anterior cervical spine surgery touted improved outcomes due to early detection of impending neurological injury [19]. However, the utility of IONM with, or without, multimodal monitoring in anterior cervical spine surgery has since been found to be of limited value for limiting the frequency of neurological injuries [8, 59, 64]. This is in part due to the low risk of neurological injury with anterior cervical approaches for symptomatic spondylosis and in particular, the low risk of neurological injury in non-myelopathic patients [59].

As a result of these data, a national practice guideline in 2009 gave no recommendation in support of the routine use of IONM for anterior cervical spine surgery for degenerative conditions due to a lack of specificity, a lack of demonstrated clinical improvement, and conflicting class I evidence of monitoring parameters [52]. A recent systematic review further showed that IONM specifically did not influence the risk of neurological injury after anterior cervical discectomy and fusion (ACDF) procedures [2]. Importantly, while these authors did note that procedures involving a corpectomy may carry a higher risk of neurological injury, insufficient data were available to perform a comparative statistical analysis between ACDF alone and procedures involving corpectomies. As a result, no formal recommendation was given regarding the use of IONM in procedures involving a corpectomy. No similar guidelines exist for the use of IONM in posterior cervical spine surgery. Consequently, the decision to use IONM remains guided by surgeon choice and experience, with critical attention paid to the perceived risk of neurological injury.

C5 Palsy

C5 nerve root palsy is a rare, debilitating, often transient complication following both anterior and posterior decompression surgery in the cervical spine [7, 11, 21, 25, 39, 53]. Suggested etiologies of iatrogenic C5 palsies include chronic cord ischemia secondary to compression with reperfusion injury following decompression, posterior migration of the spinal cord resulting in nerve root tethering, thermal damage due to nearby drilling, vascular compromise, or direct injury during screw insertion. Interestingly, C5 palsies often present in a delayed fashion following surgery confusing its etiology.

Neuromonitoring using SSEP, tcMEP, and S-EMG recordings from the deltoids and biceps has been used to detect intraoperative injury to the C5 nerve root [7, 21, 31, 34, 45], with at least one study citing a dramatic reduction in the incidence of C5 palsies [31]. However, while some have reported success with IONM monitoring for the detection of intraoperative C5 nerve injury [40], other studies have shown that delayed C5 palsy without IONM alerts is possible [18, 60, 63]. Unfortunately, as C5 palsies often present in a delayed fashion, the efficacy of multimodal IONM may be restricted in its utility for detection and prevention to injuries occurring during surgery [40, 60]. Similarly, identification and reporting on delayed C5 palsies may also contribute to lower-than-expected reported sensitivities with multimodal IONM recording [40].

Cervical Deformity

Cervical spine realignment through screw and rod systems is a widely accepted, safe, and efficacious surgical technique for the treatment of craniocervical, mid-cervical, or cervicothoracic deformity. However, the utility of IONM in cervical deformity has not been adequately defined as the majority of data is from small retrospective series and case reports. Similar to the efficacy of IONM in degenerative cervical myelopathy and radiculopathy, the presumed benefits in cervical deformity have been extrapolated from the successes in thoracolumbar deformity surgery [9, 47, 69].

Lateral mass and pedicle screw instrumentation of the cervical spine has evolved as a primary construct used in the posterior correction of cervical alignment. Stimulus-evoked pedicle screw EMG is a method used to detect a screw breach with the hopes of preventing or reversing injury of neural or vascular elements [16, 30, 71]. For each screw, the lowest current at which the first stimulus-evoked EMG response is observed and recorded. Low EMG thresholds have been shown to correlate to medial screw placement and as such may be an effective means to rule out medial placement of lateral mass screws [71]. The possibility of screw malposition warrants exploration, repositioning, or possibly removal depending on the pretest probability of a potentially dangerous screw placement [16].

Economics

The addition of neuromonitoring to degenerative cervical surgery has important financial implications. To date, cost-benefit analysis has not demonstrated significant benefits [19, 38, 64, 67]. As a result, some authors have argued that IONM for degenerative anterior cervical spine surgery has little utility when examined from a medical, cost-benefit, or medicolegal standpoint [1, 26, 67].

Traynelis et al. [67] reported no persistent postoperative neurological deficits in patients undergoing cervical spine surgery for symptomatic spondylosis without IONM in their economic analysis of 720 patients and estimated that they saved an hourly rate of $633.32 and a total of $1,024,754 in 2011 US dollars for reimbursement at the 2011 Medicare rate. The authors concluded that decompression and reconstruction/fusion for symptomatic cervical spine disease without IONM may reduce the cost of treatment without adversely impacting patient safety. This rationale stemmed from low rates of postoperative neurological deficits in combination with a million dollars of estimated additional costs.

Conclusion

Intraoperative neurophysiological monitoring (IONM) permits the evaluation of the functional integrity of the spinal cord and nerve roots and provides an opportunity to detect and possibly reverse neurological injury during high-risk spine surgery. As a result, IONM has become commonly used as a surgical adjunct in cases of degenerative cervical myelopathy and radiculopathy. In general, multimodality monitoring is preferred to maximize diagnostic potential, and current evidence suggests that this technique may improve detection of intraoperative neurological injury and outcomes. However, the efficacy of IONM may be restricted in "low-risk" anterior cervical spine surgery, cases of significant preoperative myelopathy and/or radiculopathy, and in the detection and prevention of delayed-onset C5 palsies. To date, data regarding the use of IONM have been primarily derived from retrospective studies of low methodological quality that are further limited by the heterogeneity that exists among various surgical procedures and their associated risks, the heterogeneity of IONM modalities and techniques, and availability of criteria for defining a significant alert. Furthermore, all studies to date suffer from strong selection bias, as election to use IONM is more strongly considered in patients with severe myelopathy and complex pathology where there is an intrinsic higher risk of neurologic injury. Consequently, there is no sufficient body of evidence in the literature to provide definitive answers regarding the utility of IONM in cervical spinal surgery.

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