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Intraoperative Neurophysiological Monitoring During Spinal Cord Stimulation Surgery: A Systematic Review

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ABSTRACT

Objectives: This study aims to describe the state of literature regarding the use of intraoperative neurophysiological monitoring (IONM) during spinal cord stimulator surgery.

Materials and Methods: A systematic review of the use of IONM during spinal cord stimulation (SCS) surgery was performed using the following three data bases: PubMed, Ovid MEDLINE, and Embase. Research techniques included systematic research following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses protocol by Cochrane, and backward searching. Qualitative analysis of included articles was performed using the methodologic index for nonrandomized studies assessment tool. Direction of effect, consistency across studies, and cost-effectiveness were narratively synthesized.

Results: A total of 15 records were identified through data base searching. All records used IONM methods under general anesthesia for guidance of epidural lead placement. IONM techniques used for determining lateralization in the found articles were compound muscle action potentials (CMAPs) ($n = 8$), somatosensory evoked potentials (SSEPs) ($n = 3$) or both ($n = 4$). Motor evoked potentials were used in three trials for neuroprotection purposes. Two studies were comparative, and 12 were noncomparative.

Conclusions: We found a good body of level II evidence that using IONM during SCS surgery is a valid alternative to awake surgery and may even be superior regarding pain management, cost-effectiveness, and postoperative neurologic deficits. In direct comparison, the found evidence suggested using CMAP provided more consistently favorable results than using SSEP for midline placement of epidural leads under general anesthesia. Selection of IONM modality should be made on the basis of pathophysiology of disease, individual IONM experience, and the individual patient.

Keywords: Evoked potentials, implantable neurostimulators, intraoperative neurophysiological monitoring, IONM, spinal cord stimulation

INTRODUCTION

Spinal cord stimulation (SCS) is a neuromodulatory intervention for treating medically refractory chronic neuropathic pain. It has become an effective treatment for various conditions, such as persistent spinal pain syndrome, complex regional pain syndrome, ischemic limb pain, angina pectoris, and peripheral neuropathy, in addition to some forms of visceral pain.[1,2] To date, the exact mechanism of action for SCS remains not known. However, its basis originates from the gate control theory of Melzack and Wall[3] proposed in 1965. They described a pain gate located in the substantia gelatinosa coding nociceptive inputs. Depending on the activation of small and large neural fibers, the gate could be opened or closed and thus modify pain perception. Antidromic activation of Aβ afferents, blocking of spinothalamic tract transmission, supraspinal inhibition, and release of neurotransmitters and neuromodulators also are suspected to be involved.[4]

Given correct placement of the spinal cord stimulating electrode is crucial for postoperative pain relief, the surgery is commonly performed under conscious sedation.[5] This allows patient interaction to assess the overlap between stimulator-induced paresthesia and the painful area. However, with local anesthesia, there is always the risk of loss of airway during surgery because of oversedation.[6] Other factors, such as patient discomfort or movement, unreliable responses due to sedatives, language barriers, medical comorbidities, dissection of extensive epidural scarring due to previous back surgeries, or need for head immobilization during high cervical placement, can impede this approach or even render it impossible.[7–10]

The technical advances of intraoperative neurophysiological monitoring (IONM) over the past two decades opened up possibilities of performing electrode implantation under general

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anesthesia, precluding patient interaction and eliminating the previously mentioned risk factors during surgery.

To date, there are two common techniques for IONM during spinal cord stimulator lead placement surgery for pain: evoked potential methods related to somatosensory pathways or evoked potential methods related to muscle responses.

Electromyography/Compound Muscle Action Potentials

Electromyography is a neurophysiological method to record spontaneous or triggered muscle activity. A compound muscle action potential (CMAP) is a triggered muscle response after stimulation of the corresponding nerve. Free-running electromyography (EMG) is generally used during SCS surgery. Shils and Arle found such an approach to be appropriate for signal detection.[11] With the EMG method, the observer may continuously assess CMAPs after stimulation through the epidural leads over the dorsal column (DC). The elicitation of CMAPs after stimulation of the DC can be explained through what is known as the centrally activated H-reflex.[11,12] The H-reflex, also referred to as the Hoffmann reflex, is a mono- or oligosynaptic reflex activated by stimulation of Ia afferents running to the spinal cord.[13] Ia afferents form synaptic connections to the a-motoneurons after entry through the dorsal horn. When stimulated, an orthodromic action potential travels through the Ia afferents. At the synapse, it initiates a volley of activation in the motor nerve, causing a muscle contraction.[13–16] This mechanism allows elicitation of a measurable CMAP after stimulation of the DC.[14–16]

Somatosensory Evoked Potentials

Somatosensory evoked potentials (SSEPs) provide a measurement of sensory conduction from the peripheral nerves to the DC to medial lemniscus pathways. They can be recorded on every level between the stimulation site and cerebral cortex. SSEPs can be elicited by either cutaneous or dermatomal sensory nerve stimulation. SSEPs are much smaller in amplitude than a CMAP and thus can be difficult to measure because of cortical background noise or electromagnetic disturbance from the environment.[15,16] In contrast to the single pulse recorded CMAP, SSEPs are averaged potentials. Collision studies also can be performed using SSEPs because the neural pathways involved in SSEP measurement are identical to those activated from SCS.[8,13] Collision of orthodromic action potentials from peripheral nerves and antidromic action potentials elicited from epidural electrodes would thus lead to reduction or elimination of the signal travelling to the cortex, similarly to negative interference of waves. Selection of anesthetics should be carefully considered given various sedative medications affect SSEPs.[16]

The efficacy of SCS has already been proven multiple times,[1,17–19] and protocols exist for different methods of IONM during electrode placement surgery.[13] However, to our knowledge, there is no review of the available literature about this topic. This study provides a summary of the state of the art regarding the use of intraoperative neurophysiological monitoring during SCS surgery.

MATERIALS AND METHODS

A literature search following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses protocol for systematic reviews by Cochrane[20] was conducted in three electronic data bases for medical-scientific literature, PubMed, Ovid MEDLINE, and Embase, between July 2022 and January 2023. The literature search was systematically conducted following a Population, Intervention, Comparison, and Outcomes search strategy presented in Table 1.

MeSH terms and keywords used in the search were "spinal cord stimulation," "monitoring, intraoperative," "implantable neurostimulators," and "SCS," "intraoperative monitoring," and "intraoperative neuromonitoring," respectively.

Studies were only included in the analysis if published in English or German language, if the full text was available, and if published after January 2010.

RESULTS

There were 1444 records identified among all data bases through searching (Fig. 1). After subtraction of duplicates found in multiple data bases and filtering from January 1, 2010 onward, 771 records remained. These documents were then title- and abstract-screened for eligibility, whereby 717 papers were excluded for not fulfilling the previously mentioned criteria. The remaining 54 publications were full-text reviewed, and backward searching was used to cover any missed records in the search. Another seven publications were found through backward searching, yielding 61 records in total; 46 of the 61 records were excluded because of unavailability of full text, no direct use of IONM for lead placement, or not appropriate outcome (eg, stimulator model comparison) or study design (eg, animal studies, protocols).

The remaining 15 identified records were assessed qualitatively using the methodologic index for nonrandomized studies (MINORS)[21] (Table 2). The IONM techniques used for placement of epidural stimulators in the identified studies were CMAP/EMG (n = 8), SSEP (n = 3), or both (n = 4). Two of the 15 records were comparative studies[9,24]; the remaining 13 were noncomparative trials. All but the two comparative trials used IONM under general anesthesia without comparison with an awake control group. Number of patients, stimulation characteristics, and electrode types, in addition to number of columns per lead used, are listed in Table 2, as far as was identifiable in the publications.

EMG/CMAP

Eight records measuring CMAPs were found, two of which were the only comparative trials found in the systematic research.[9,24]

Four of the eight records reported outcomes related to pain scores. Visual analog score (VAS) or numeric rating scale (NRS) were most used. Shils and Arle reported an average reduction in VAS of 52.11% at least one month postoperatively with paddle lead placement under general anesthesia.[11] Average VAS before surgery was reported at 7.51 (± 1.93) and after surgery at 3.63 (± 2.47).[11] Falowski et al reported a similar reduction in NRS score of 52.2%, 24 weeks after implantation under general anesthesia.[24] However, the comparison with the reduction in NRS in the awake group of 55% in this study did not show statistical significance.[24] Hwang et al showed a reduction from baseline NRS of 29.23% in 40 of 46 patients.[25] In our study, Schlaeppi et al[30] reported a mean NRS reduction in a cohort of 20 patients from 8.2 to 3.6 (56%) at the three-month follow-up. Two studies reported reductions in subjective pain relief or pain coverage.[7,10] Mammis and Mogilner documented that 82% of patients reported pain relief at latest follow up.[10] Similar numbers were described by Air et al[7] at 84.2% of patients with adequate stimulation coverage and good pain

Table 1. Population, Intervention, Comparison, and Outcomes Search Strategy.

P (Population)	Patients who undergo SCS implantation surgery
I (Intervention)	SCS implantation with the use of IONM
C (Comparison)	SCS implantation without the use of IONM
O (Outcome)	Pain relief, cost-effectiveness, neuroprotection, lead migration

Pain relief is summarized as all measurements for postoperative pain coverage such as pain questionnaires (Oswestry disability index, VAS, McGill pain questionnaire, pain catastrophizing scale) or subjective pain relief.

relief. Pain-paresthesia overlap postoperatively was reported by Schlaeppi et al to be at 100% for 18 of 20 patients, with the remaining two reporting a 90% overlap. One study investigated device failure rate in awake vs asleep placement.[9] Device failure was defined as any reoperation secondary to traumatic break of the SCS system, device malfunctioning, or stimulator removal due to lack of efficacy.[9] This study showed an incidence of device failure in awake placement and under general anesthesia of 29.7% and 14.94%, respectively.[9]

Symmetry and amplitude of CMAP response were used in all seven studies to determine midline placement of the paddle leads over the DC. Shils and Arle[11] and Collison et al[23] also used a plotting technique based on CMAP elicitation for individual contacts or columns of the lead to determine physiological midline.

A statistically significant reduction ($p = 0.018$) in operation time for placement under general anesthesia compared with the awake procedure was reported by one study.[24] Reported operation time for general anesthesia was 88.9 (± 51.2) vs 125.2 (± 37.9) minutes during awake placement.[24] The rate of extraneous paresthesia in the general anesthesia group (16.7% ± 23.1) was significantly lower ($p < 0.001$) than in the awake group (71.2% ± 30.3) in the same study.[24] Collison et al[23] reported a correlation between cerebrospinal fluid thickness and postoperative energy consumption. They stated that this could greatly influence battery selection and prevent unnecessary expenses in device selection.[23]

Reduction in baseline opioid use after device implantation was reported in 17 of 24 patients (70.83%) for one trial.[25] Lead repositioning from apparent anatomical midline according to neurophysiological testing was reported by Shils and Arle[11] in 15.9% of the cases. Hwang et al[25] were the only group to use percutaneous implanted electrodes instead of paddle-type electrodes. One study used a different approach in CMAP elicitation using a double train stimulation paradigm to differentiate DC activation from CST

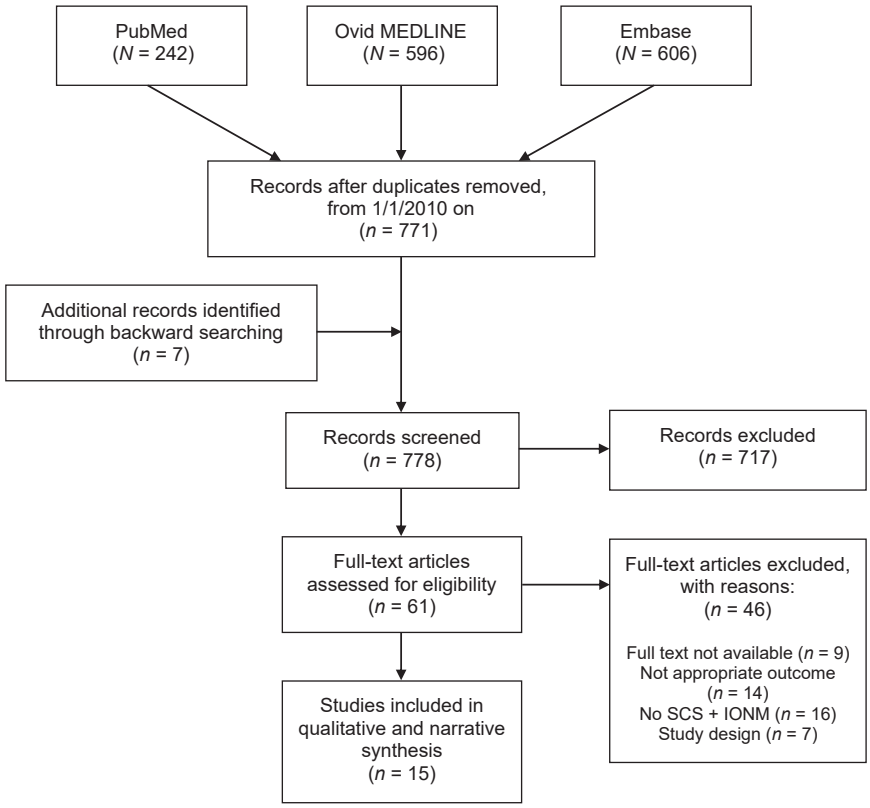

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses flow diagram. Number of records identified using the search strategy for the three data bases PubMed, Ovid MEDLINE, and Embase with consecutive review and eventual exclusion process.

Table 2. MINORS Performed in Human.

Author	Air et al[7]	Balzer et al[8]	Choi et al[22]	Collison et al[23]	Falowski et al[9]	Falowski et al[24]	Hwang et al[25]	Mammis and Mogilner[10]	Muncie et al[26]	Penar and McSherry[27]	Roth et al[6]	Schoen et al[28]	Shils and Arle[11]	Tamkus et al[29]	Schlaeppi et al[30]
Item 1	2	2	2	1	2	2	1	2	2	–	2	2	2	2	2
Item 2	2	2	2	2	2	2	2	2	2	–	2	2	2	2	2
Item 3	0	1	1	2	0	2	1	0	0	–	2	0	0	0	2
Item 4	2	2	2	2	2	2	2	2	2	–	2	2	2	2	2
Item 5	1	1	2	1	2	2	1	1	1	–	2	1	2	2	2
Item 6	2	1	2	2	2	2	2	2	2	–	2	1	2	2	2
Item 7	2	2	2	2	1	2	0	2	2	–	1	2	2	2	2
Item 8	1	1	1	1	2	2	1	1	1	–	2	1	2	1	0
Item 9	–	–	–	–	2	2	–	–	–	–	–	–	–	–	–
Item 10	–	–	–	–	1	2	–	–	–	–	–	–	–	–	–
Item 11	–	–	–	–	0	1	–	–	–	–	–	–	–	–	–
Item 12	–	–	–	–	2	2	–	–	–	–	–	–	–	–	–
Total	12	12	14	13	18	23	10	12	12	–	15	11	14	13	14

Item 1, A stated aim of the study. Item 2, Inclusion of consecutive patients. Item 3, Prospective collection of data. Item 4, End point appropriate to the study aim. Item 5, Unbiased evaluation of end points. Item 6, Follow-up period appropriate to the major end point. Item 7, Loss of follow-up ≤5%. Item 8, A control group having the gold standard intervention. Item 9, Contemporary groups. Item 10, Baseline equivalence of groups. Item 11, Prospective calculation of the sample size. Item 12, Statistical analyses adapted to the study design.

Table 3. Overview of Study Characteristics, End Points, and Stimulation Parameters for the Final Fifteen Records.

Author, y	No. of patients	IONM technique	End points	Stimulation parameters	Major results
Air et al[7]	19	EMG/CMAP	Subjective stimulation coverage postop	>50 Hz, 0.2–0.3 ms	84.2% of patients with adequate stimulation coverage and good pain relief.
Collison et al[23]	24	EMG/CMAP	Neurophysiological midline 1 d postop vs intraoperative tested midline CST and energy requirements	60 Hz, 0,3 ms, 0.5V–10V, 0.5–10 mA	Correlation between CST and post-operative energy consumption.
Falowski et al[9]	387	EMG/CMAP	Efficacy of first-time awake placement vs under general anesthesia with IONM comparing device failure rate	3–5 Hz, 0.1–0.6 ms, 0–12 mA	Device failure in awake placement reported as 29.7% compared with general anesthesia placement of 14.94%.
Falowski et al[24]	30	EMG/CMAP	Operation time Pain-paresthesia overlap NRS Extraneous paresthesia Subjective pain relief	4–40 Hz, 0.1–0.5 ms, 0–12 mA	Reduction in NRS of 52.2% pre- vs postoperatively after 24 wk in IONM group. Significant reduction in operation time in general anesthesia group.
Hwang et al[25]	46	EMG/CMAP	NRS Oswestry disability index McGill pain questionnaire Pain catastrophizing scale Beck depression inventory Opioid use baseline Patient satisfaction Willingness to repeat surgery	60 Hz, 0.3 ms, 0–10 mA	Reduction from baseline NRS of 29.23% in 40 of 46 patients post-operatively. Reduction of baseline opioid use after operation in 17/24 patients (70.83%).
Mammis and Mogilner[10]	78	EMG/CMAP	Postoperative and follow-up pain coverage	5–10 Hz, 0.2–0.3 ms	Improvements in subjective pain relief or pain coverage. 82% of patients stated pain relief at latest follow up.
Shils and Arle[11]	155	EMG/CMAP	Pre- vs postoperative VAS Number of repositions during testing In-house score	60 Hz, 0.21 ms, 0.5-mA increments, 0.5-mV increments	Reduction in VAS of 52.11% pre- vs postoperatively in IONM group.
Balzer et al[8]	44	SSEP	Postoperative evaluation of pain relief	SSEP 2.45 Hz, 0.2 ms, Stimulator; 50–60 Hz, 1V–6V	Excellent pain coverage in patients with unilateral pain syndrome.
Muncie et al[26]	6	SSEP	Pain relief after 2 wk and 2 y	60–160 Hz, 0.25–0.3 ms, 0.5–5 mA	5/6 patients with pain relief 2 y after surgery ranging from 40%–80%.
Penar and McSherry[27]	1	SSEP	Stimulation coverage Pain relief	4 Hz, 0.2 ms, 0.9–1.2 mA	Excellent pain coverage and relief postoperatively.
Choi et al[22]	25	EMG/CMAP, SSEP	Relief in baseline pain	CMAP: 60 Hz, 0.3 ms, 1V, 1–10 mA SSEP: not described	Subjective pain relief in baseline pain of ≥50% in 17/25 patients 1 wk postoperatively.
Roth et al[6]	73	EMG/CMAP, SSEP	Beck depression inventory McGill Pain questionnaire Oswestry disability index Pain catastrophizing scale VAS Incidence of reoperation	CMAP: 60 Hz, 0.3 ms, 0.5–10 mA SSEP: not described	Significant reductions in 4/5 utilized pain scores.

(Continues)

Table 3. *Continued*

Author, y	No. of patients	IONM technique	End points	Stimulation parameters	Major results
Schlaeppi et al[30]	20	Double Train (EMG/CMAP)	Pain reduction in NRS Comparison intra- and post-operative best stimulation contacts Pain-paresthesia overlap	Double train: 0.5–10 mA, 3–5 pulses of 0.5 ms pulse duration, within-train interstimulus interval 2–4 ms	NRS reduction from 8.2 to 3.6 pre/postoperative. Best intraoperative contact matching, best postoperative contact. 90% of patients with 100% pain-paresthesia overlap.
Schoen et al[28]	103	EMG/CMAP, SSEP	Reoperation rate	EMG: 60–70 Hz, 100–400 mV SSEP: 40 mV	Reduced complication rate with 13.6% of patients who underwent subsequent revision when using IONM.
Tamkus et al[29]	111	EMG/CMAP, SSEP	IONM alerts during surgery Postoperative complications SSEP and EMG efficacy on laterality placement	CMAP: not described SSEP: 0.5–5 Hz, 0.2–0.3 ms, 5–50 mA	Lead reposition rate based on neuromonitoring with a rate of 18.6%.

activation.[30] This stimulation technique was first described by Deletis et al.[12,30]

SSEP

Three of the 14 records used SSEPs for placement of stimulator leads under general anesthesia. Two of the three trials used an SSEP-Collision technique.[8,26] Balzer et al[8] determined that a reduction in cortical SSEP amplitude >75% from baseline suggests lateralization if unilateral or midline positioning if bilateral. Muncie et al stated any decrease in cortical SSEP amplitude from baseline to be an orientation for midline placement.[26] One group evaluated symmetry of response from SCS-elicited SSEPs compared with ulnar-nerve elicited SSEPs.[27] The stimulated nerves for baseline SSEP recording in the three studies included ulnar nerve ($n = 2$), median nerve ($n = 2$), peroneal nerve ($n = 1$), and tibial nerve ($n = 2$). Postoperative pain relief was assessed in all three studies using SSEPs. Balzer et al reported excellent pain coverage in all patients with unilateral pain syndrome ($n = 25$) and sensory alterations in all patients with bilateral pain syndrome ($n = 19$) immediately after surgery.[8] Muncie et al[26] reported five of six patients experiencing pain relief two years after surgery, ranging from 40% to 80%. In the single case report, Penar and McSherry[27] reported excellent pain coverage and relief postoperatively.

CMAP/SSEP Combined

Four studies combined the two previously mentioned techniques to determine definitive placement of electrodes. Three of the four used the SSEP collision technique and CMAP response symmetry for determining physiologic midline.[6,22,29] Schoen et al[28] did not further specify whether SSEP collision testing was used. Choi et al[22] and Tamkus et al[29] interpreted any SSEP amplitude reduction as a criterion for lateralization. Roth et al determined lateralized lead placement as a reduction in amplitude of ≥40%.[6] Nerves stimulated for SSEP acquisition across the found studies were ulnar ($n = 1$), median ($n = 2$), and tibial nerve ($n = 2$). Choi et al[22] recorded motor evoked potentials (MEPs) in addition to CMAP and SSEP solely for neuroprotective purposes. They defined the warning criteria as a decrease in muscle MEP.[22] Two alerts occurred during their series.[22] No postoperative neurologic deficits were observed.[22] Tamkus et al[29] similarly investigated occurrence of IONM alerts during paddle lead placement. They reported two alerts in their series in 111 patients, with no subsequent neurologic injury.[29]

Two groups quantified pain perception after surgical intervention.[6,22] Choi et al[22] reported subjective relief in baseline pain of ≥50% in 17 of 25 patients one week after implantation. Roth et al[6] reported statistically significant changes ($p < 0.05$) in four of five used pain scores. One group considered the reoperation rate using combined CMAP and SSEP for stimulator placement[28]; 13.6% of their patients underwent subsequent revision or removal of the stimulator.[28]

Roth et al[6] reported a rate for CMAP and SSEP predicting paresthesia coverage of the painful areas with 82.7% and 69%, respectively.

Lead repositioning based on IONM feedback for optimal midline placement was reported by one study at a rate of 18.6%,[29] similar to that reported by Shils and Arle.[11]

The different IONM techniques are summarized and compared in Table 3.

DISCUSSION

The neuromodulation appropriateness consensus committee (NACC) recommended the definition of successful SCS implantation to be ≥50% pain relief from baseline, as originally stated by Kumar et al.[19,31] Falowski et al[24] presented the only two comparative studies to date with a head-to-head comparison of the procedure performed awake with that performed under general anesthesia using the CMAP technique.[9] They showed that pain relief in the general anesthesia group was almost identical to that in the awake group at latest follow-up, with both groups reaching the >50% pain relief on group average defining successful implantation as stated by the NACC.[24,31] Despite being a nonrandomized trial with possible group heterogeneity, this study shows that performing SCS implantation with neurophysiological guidance under general anesthesia is at least equally as effective as the awake procedure. The studies by Mammis and Mogilner[10] and Shils and Arle[11], although nonrandomized and noncomparative, show consistency with the findings of Falowski et al, with similar results for surgery under general anesthesia using CMAP. In addition, Falowski et al[24] presented other considerable outcomes in the same study. Operation time in the general anesthesia group with an average of 94.4 minutes was reported to be significantly shorter ($p = 0.01$) than in the awake group, with an average of 130.6 minutes. This could seriously affect the cost-effectiveness of the procedure, favoring general anesthesia over the awake procedure. Furthermore, paresthesia coverage and extraneous sensory alterations were reported to be significantly lower in the general anesthesia group ($p = 0.05$ and $p < 0.001$, respectively).[24] This addresses other important aspects of pain management, with considerable impact on quality of life other than pain relief itself.

When evaluating the SSEP technique for epidural simulator placement, less strong evidence was found. Balzer et al[8] performed the largest retrospective review to date using the SSEP-Collision technique in 44 patients. They reported excellent pain relief for all patients.[8] Muncie et al[26] and Penar and McSherry[27] provided consistency with similar results. However, cohort sizes in the latter were considerably smaller, with six patients and one patient, respectively, causing us to consider the results with caution. Furthermore, none of the three papers using SSEP for placement of stimulator leads used an objective assessment for pain at baseline and after intervention, relying solely on subjective statements.

In a head-to-head comparison of the two techniques for SCS implantation under general anesthesia, we found more consistent data favoring the use of CMAP than that of SSEP. Roth et al[6] reported that CMAP had a higher prediction rate for lead lateralization than did SSEP, with 82.7% over 69%. None of the seven studies using SSEP alone or in combination with CMAP stated a greater efficacy of SSEP than that of the EMG-based technique, showing consistent favoring of the CMAP. Furthermore, the applicability of the two techniques needs to be considered. Although SSEP techniques require trained personnel for measurement and interpretation, CMAP techniques are more robust and may be performed guided by the surgeon. This makes the CMAP modality more accessible for surgeons than measuring SSEP.

The two techniques also may find different fields of application based on the underlying pathology of the disease. For example, in patients with peripheral sensory nerve disorders, such as diabetic polyneuropathy, no or pathological SSEP would be obtainable, preventing reliable assistance for midline lead placement. In contrast, CMAP cannot be elicited and used as the placement criteria in diseases affecting the lower motoneuron, such as spinal muscle atrophy. Epidemiologically, peripheral sensory nerve disorders have a higher prevalence than do denervating diseases, implying a wider applicability of CMAP than of SSEP for epidural lead placement. Nevertheless, we deem the potential of SSEP for determining physiologic midline under general anesthesia useful.

The use of MEPs was described as an adjunct for neuroprotective purposes and did not serve as a tool for midline determination. However, using

IONM to provide instant feedback on several neural structures and their integrity during a procedure is another beneficial aspect of intraoperative neurophysiological monitoring. As described by Balzer et al[8] and Tamkus et al,[29] IONM can successfully aid in detection of imminent neurologic injury and prevent postoperative neurologic deficits during surgery. Although the rate of such complications is reported to be low,[29,31,32] consequences are dramatic. IONM delivers a safe approach in preventing such incidents even further.

When comparing the benefits of SCS implantation with IONM under general anesthesia with those of awake conditions, several factors must be considered. Anesthetic agents can have a major impact on the reliability of the mentioned IONM techniques and should be carefully considered.[16] For example, CMAP measurement is only possible if muscle relaxants are avoided or if their effect has completely worn off after intubation. MEPs and SSEP latency or amplitude also can be affected by multiple halogenated agents used for anesthesia.[16] This proves, as stated above, that IONM needs a well-trained team for correct application and reliable interpretation.

Another aspect when performing the procedure awake is the risk of airway loss due to oversedation,[6,7,10,11,24] especially given general practice is to place the patient in a prone position. A history of spinal surgeries with need for extensive scar tissue dissection, intolerance of certain local anesthetics, medical comorbidities, or anxiety can be other factors precluding the procedure under awake conditions.[7,11,25,26]

Shils and Arle,[11] in addition to Tamkus et al,[29] showed that the lead reposition rate from anatomic midline due to IONM feedback was between 16% and 19%. The lead reposition rate in the study by Schlaeppi et al[30] using the double train stimulation paradigm was 45%. This implies that the anatomic and physiologic midline of the spinal cord can vary and are not necessarily congruent. Therefore, using IONM aids optimizing lead placement and thus helps maximize pain relief and reduce risk of extraneous paresthesia. This gives IONM another significant advantage in performing the surgery under general anesthesia rather than awake for optimal outcome.

With the elaborated criteria listed above, we state that the use of intraoperative neurophysiological monitoring, especially CMAP, for epidural lead placement under general anesthesia is a valid alternative to the awake procedure. We found solid evidence proving the method to be at least as beneficial as, if not superior to, the awake procedure regarding postoperative pain relief, extraneous paresthesia, neuroprotection, and cost-effectiveness.

However, this review is not free of limitations. The main risk lies in the level of evidence in the covered literature. No randomized controlled trials were found in the systematic research, and only two records compared their intervention with a control group. In addition, outcomes were often vaguely described as good or excellent pain relief. These valuations are considered very subjective and lack objective parameters such as pain questionnaires for cross-comparison. It also is possible that the search strategy did not

sufficiently retrieve relevant records or gray literature. Backward searching of found articles was performed to cover any missed studies and reduce the risk of insufficient research output. No additional records contributing to the results of this review were identified. Another limitation is the intercomparability of the included studies. Group heterogeneity in the form of patient populations, pain conditions, surgical technique, and stimulation parameters limited the ability to pool end points. This systematic review should serve as an overview of the strengths, weaknesses, and possibilities of IONM during epidural lead placement.

CONCLUSIONS

To our knowledge, this is the first systematic review of the use of IONM for spinal cord stimulator placement surgery. We deliver a solid body of level II evidence that using IONM during SCS surgery is a valid alternative to awake surgery. We found evidence for superior pain relief, fewer postoperative neurologic deficits, and less extraneous paresthesia, in addition to shorter operation times improving cost-effectiveness for neurophysiologically guided lead placement in the asleep patient. We state a B degree of recommendation for performing SCS lead placement under general anesthesia with the use of IONM. However, more research in the form of large randomized controlled trials with objective outcome parameters is needed to further evaluate and eventually set IONM as the new standard of SCS lead placement under general anesthesia over the awake procedure. In direct comparison, the found evidence suggests using CMAPs provides more consistently favorable results than does the use of SSEPs for midline placement of epidural leads under general anesthesia. The selection of IONM modality should be based on the pathophysiology of disease, personal IONM experience, and the individual patient.

Authorship Statements

Raphael Schreen and Janine-Ai Schlaeppi prepared the manuscript draft with important intellectual input from all coauthors. All authors participated in the design, structure, and completion of the study, approved this manuscript, and agreed with submission to *Neuromodulation*.

Conflict of Interest

Janine-Ai Schlaeppi is a consultant for Abbott and Nevro. Claudio Pollo is cofounder of Aleva Neurotherapeutics and reports consultancy fees from Boston Scientific and Abbott in the field of deep brain stimulation. Raphael Schreen and Kathleen Seidel reported no conflict of interest.

Stimulation parameters are listed as far as specified in the publication.

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REFERENCES

1. Falowski S, Celii A, Sharan A. Spinal cord stimulation: an update. *Neurotherapeutics*. 2008;5:86–99.
2. Deer TR, Raso LJ. Spinal cord stimulation for refractory angina pectoris and peripheral vascular disease. *Pain Phys*. 2006;9:347–352.
3. Melzack R, Wall PD. Pain mechanisms: a new theory. *Science*. 1965;150:971–979.
4. Kunnumpurath S, Srinivasagopalan R, Vadivelu N. Spinal cord stimulation: principles of past, present and future practice: a review. *J Clin Monit Comput*. 2009;23:333–339.
5. Barolat G, Massaro F, He J, Zeme S, Ketcik B. Mapping of sensory responses to epidural stimulation of the intraspinal neural structures in man. *J Neurosurg*. 1993;78:233–239.
6. Roth SG, Lange S, Haller J, et al. A prospective study of the intra- and postoperative efficacy of intraoperative neuromonitoring in spinal cord stimulation. *Stereotact Funct Neurosurg*. 2015;93:348–354.
7. Air EL, Toczyl GR, Mandybur GT. Electrophysiologic monitoring for placement of laminectomy leads for spinal cord stimulation under general anesthesia. *Neuromodulation*. 2012;15:573–579 [discussion: 9–80].
8. Balzer JR, Tomycz ND, Crammond DJ, et al. Localization of cervical and cervicomedullary stimulation leads for pain treatment using median nerve somatosensory evoked potential collision testing. *J Neurosurg*. 2011;114:200–205.
9. Falowski SM, Celii A, Sestokas AK, Schwartz DM, Matsumoto C, Sharan A. Awake vs. asleep placement of spinal cord stimulators: a cohort analysis of complications associated with placement. *Neuromodulation*. 2011;14:130–134 [discussion: 4–5].
10. Mammis A, Mogilner AY. The use of intraoperative electrophysiology for the placement of spinal cord stimulator paddle leads under general anesthesia. *Neurosurgery*. 2012;70(2 suppl Operative):230–236.
11. Shils JL, Arle JE. Intraoperative neurophysiologic methods for spinal cord stimulator placement under general anesthesia. *Neuromodulation*. 2012;15:560–571 [discussion: 71–72].
12. Deletis V, Seidel K, Sala F, et al. Intraoperative identification of the corticospinal tract and dorsal column of the spinal cord by electrical stimulation. *J Neurol Neurosurg Psychiatry*. 2018;89:754–761.
13. Shils JL, Arle JE. Neuromonitoring for spinal cord stimulation lead placement under General Anesthesia. *J Clin Neurol*. 2018;14:444–453.
14. Ferrante MA. *Comprehensive Electromyography: With Clinical Correlations and Case Studies*. Cambridge University Press; 2018.
15. Rubin DI, Daube JR. *Clinical Neurophysiology*. 4th ed. Oxford University Press; 2016.
16. Møller AR. *Intraoperative Neurophysiological Monitoring*. 3rd ed. Springer; 2011.
17. Kapural L, Peterson E, Provenzano DA, Staats P. Clinical evidence for spinal cord stimulation for failed back surgery syndrome (FBSS): systematic review. *Spine (Phila Pa 1976)*. 2017;42(suppl 14):S61–S66.
18. Burchiel KJ, Anderson VC, Brown FD, et al. Prospective, multicenter study of spinal cord stimulation for relief of chronic back and extremity pain. *Spine (Phila Pa 1976)*. 1996;21:2786–2794.
19. Kumar K, Taylor RS, Jacques L, et al. Spinal cord stimulation versus conventional medical management for neuropathic pain: a multicentre randomised controlled trial in patients with failed back surgery syndrome. *Pain*. 2007;132:179–188.
20. Moher D, Liberati A, Tetzlaff J, Altman DG, PRISMA Group. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: the PRISMA statement. *Ann Intern Med*. 2009;151:264–269, W64.
21. Slim K, Nini E, Forestier D, Kwiatkowski F, Panis Y, Chipponi J. Methodological index for non-randomized studies (MINORS): development and validation of a new instrument. *ANZ J Surg*. 2003;73:712–716.
22. Choi JG, Ha SW, Son BC. Multimodal, intraoperative monitoring during paddle lead placement for cervicothoracic spinal cord stimulation. *Stereotact Funct Neurosurg*. 2015;93:271–281.
23. Collison C, Prusik J, Paniccioli S, et al. Prospective study of the use of intraoperative neuromonitoring in determining post-operative energy requirements and physiologic midline in spinal cord stimulation. *Neuromodulation*. 2017;20:575–581.
24. Falowski SM, Sharan A, McInerney J, Jacobs D, Venkatesan L, Agnesi F. Nonawake vs awake placement of spinal cord stimulators: a prospective, multicenter study comparing safety and efficacy. *Neurosurgery*. 2019;84:198–205.
25. Hwang R, Field N, Kumar V, et al. Intraoperative neuromonitoring in percutaneous spinal cord stimulator placement. *Neuromodulation*. 2019;22:341–346.
26. Muncie LM, Ellens NR, Tolod-Kemp E, Feler CA, Winestone JS. Intraoperative electrophysiological monitoring for C1-2 spinal cord stimulation. *J Neurosurg Spine*. 2017;26:183–189.
27. Penar PL, McSherry J. Cortical evoked potentials used for placement of a laminotomy lead array: a case report. *Neuromodulation*. 2011;14:326–328 [discussion: 8–9].
28. Schoen N, Chieng LO, Madhavan K, Jermakowicz WJ, Vanni S. The use of intraoperative electromyogram during spinal cord stimulator placement surgery: a case series. *World Neurosurg*. 2017;100:74–84.
29. Tamkus AA, Scott AF, Khan FR. Neurophysiological monitoring during spinal cord stimulator placement surgery. *Neuromodulation*. 2015;18:460–464 [discussion: 464].
30. Schlaeppi JA, Schreen R, Mija R, Nowacki A, Pollo C, Seidel K. Intraoperative motor evoked responses to double-train paradigm stimulation for guiding lead placement and postoperative programming in spinal cord stimulation for pain. *Neuromodulation*. 2023;26:147–156.

31. Deer TR, Mekhail N, Provenzano D, et al. The appropriate use of neurostimulation of the spinal cord and peripheral nervous system for the treatment of chronic pain and ischemic diseases: the neuromodulation appropriateness consensus committee. *Neuromodulation*. 2014;17:515–550 [discussion: 550].
32. Levy R, Henderson J, Slavin K, et al. Incidence and avoidance of neurologic complications with paddle type spinal cord stimulation leads. *Neuromodulation*. 2011;14:412–422 [discussion: 422].

COMMENTS

This systematic review regarding the use of IONM during spinal cord stimulator surgery gives a profound overview about the actual state of the art and future directions. Despite the valid recommendations of this study, future research in the form of large randomized controlled trials with objective outcome parameters is needed.

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At times, we encounter patients who prefer not to be awakened midprocedure during neuromodulator implantation. In addition, patients may not be cognitively intact when roused from sedation, compromising their ability to respond clearly to commands. Addressing this issue, IONM during spinal cord stimulation implantation offers a viable solution that benefits both patient comfort and procedural outcomes. Using IONM allows us to keep patients under general anesthesia throughout the procedure. This approach does not compromise the outcome; rather, it could potentially enhance it. Furthermore, avoiding the necessity for patients to be awake during testing can significantly expedite the implantation process, thus boosting patient satisfaction. It is essential to note that the successful implementation of IONM necessitates additional trained personnel to monitor and interpret the data. This requirement may present a hurdle for some practitioners. However, it is worth noting that neurosurgery routinely uses this technique to mitigate nerve injury during spinal surgeries, indicating its practicality and value. In conclusion, the integration of IONM during spinal cord stimulation implantation offers a promising avenue to improve patient comfort, procedure efficacy, and overall satisfaction. Although it requires more resources, the potential benefits may well justify the investment.

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Surgical spinal cord stimulator lead placement is sometimes required when a percutaneous lead placement is difficult or not possible due to anatomical restrictions. Such paddle lead placements require a spine surgery which necessitates general anesthesia and monitoring the neurological functions during such surgery will enhance the safety profile for this surgery.

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