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Localization of cervical and cervicomedullary stimulation leads for pain treatment using median nerve somatosensory evoked potential collision testing

Clinical article

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Object. Spinal cord stimulation (SCS) is being currently used to treat medically refractory pain syndromes involving the face, trunk, and extremities. Unlike thoracic SCS surgery, during which patients can be awakened from conscious sedation to confirm good lead placement, safe placement of paddle leads in the cervical spine has required general anesthesia. Using intraoperative neurophysiological monitoring, which is routinely performed during these cases at the authors' institution, the authors developed an electrophysiological technique to intraoperatively lateralize lead placement in the cervical epidural space.

Methods. Data from 44 patients undergoing median and tibial nerve somatosensory evoked potential (SSEP) monitoring during cervical laminectomy or hemilaminectomy for placement or replacement of dorsal column stimulators were retrospectively reviewed. Paddle leads were positioned laterally or just off midline and parallel to the axis of the cervical spinal cord to effectively treat what was most commonly a predominant unilateral pain syndrome. During SSEP recording, the spinal cord stimulator was activated at 1.0 V and increased in increments of 1.0 V to a maximum of 6.0 V. A unilateral reduction or abolishment of SSEP amplitude was regarded as an indicator of lateralized placement of the stimulator. A bilateral diminutive effect on SSEPs was interpreted as a midline or near midline lead placement.

Results. Epidural stimulation abolished or significantly reduced SSEP amplitudes in all patients undergoing placement for a unilateral pain syndrome. In 15 patients, electrodes were repositioned intraoperatively to achieve the most robust SSEP amplitude reduction or abolishment using the lowest epidural stimulation intensity. In all cases in which a significant unilateral reduction in SSEP was observed, the patient reported postoperative sensory alterations in target locations predicted by intraoperative SSEP changes. Placement of cervical spinal cord stimulators for bilateral pain syndromes often resulted in bilateral but asymmetrical SSEP changes. In no cases were significant SSEP changes, other than those induced using the device to directly stimulate the dorsal surface of the spinal cord, observed. No case of new postoperative neurological deficit was observed.

Conclusions. Somatosensory evoked potentials can be used safely and successfully for predicting the lateralization of cervical spinal cord stimulator placement. Moreover, they can also intraoperatively alert the surgical team to inadvertent displacement of a lead during anchoring. Further studies are needed to determine whether apart from assisting with proper lateralization, SSEP collision testing may help to optimize electrode positioning and improve pain control outcomes. *(DOI: 10.3171/2010.5.JNS091640)*

Key Words • **spinal cord stimulation** • **somatosensory evoked potential** • **intraoperative monitoring** • **pain**

Epidural SCS has been practiced for more than 40 years and has become an evidence-based treatment for chronic pain disorders such failed back–surgery syndrome, complex regional pain syndrome, and peripheral vascular disease.[6,8,11,17,19,22,25,26,32,34,38] Cervical SCS is less commonly used but has also proven effective for pain syndromes such as upper-extremity complex regional pain syndrome, intractable facial pain, angina pectoris, and postamputation limb pain.[1,3,7,9,16,17,37] Thoracolumbar epidural electrodes are commonly placed after administration of a local anesthetic and conscious sedation so the patient may communicate with the surgical team and confirm that regions of pain are satisfactorily "covered" by stimulation-induced paresthesias.[10,23] However, placement of surgical cervical epidural leads has required general anesthesia for reasons of safety, patient comfort, and

Abbreviations used in this paper: SSEP = somatosensory evoked potential; SCS = spinal cord stimulation.

This article contains some figures that are displayed in color online but in black and white in the print edition.

the need for head pin immobilization. Although modern multicontact electrode arrays have expanded the capability for manipulating the distribution of perceived stimulation postoperatively, the initial location of the electrode lead is the predominant factor that determines whether stimulation will be superimposed on painful regions. Moreover, stimulation of regions not involved in the pain syndrome may cause patient discomfort and therefore limit the therapeutic efficacy of the ultimate treatment by altering the tolerance threshold of stimulation parameters. Since paddle-type electrodes are placed in the epidural space via a partial laminectomy or hemilaminectomy, it can be difficult to control their medial-lateral trajectory. Intraoperative fluoroscopy is helpful for estimating lead laterality but will not ultimately confirm if one or both sides of the spinal cord will receive clinically significant stimulation. Consequently, after the surgeon's best efforts to position a paddle electrode, there has been a need to develop a method to objectively confirm the location of cervical epidural electrodes without patient cooperation.

Somatosensory evoked potentials have become the workhorse of neurophysiological monitoring in spine surgery due to their high sensitivity and specificity for identifying spinal cord injury and proven ability to reduce new postoperative neurological deficits.[5,15,28,35] The potential of SSEPs to assist with localization in the nervous system has been shown by their ability to identify functional regions of the human cortex during brain surgery.[12,31,36] Several studies have demonstrated that SCS reduces the amplitudes of short and midlatency SSEPs, and this decrease of primary somatosensory cortical activity may contribute to the analgesic effect of SCS.[4,21,30,40] We have taken further advantage of routine intraoperative SSEP monitoring to correctly lateralize and optimize electrode position during cervical and cervicomedullary SCS surgery.

Methods

Patient Population

After obtaining institutional review board approval, we performed a retrospective review of a prospectively acquired database of patients undergoing cervical or cervicomedullary spinal cord stimulation at the University of Pittsburgh Medical Center. Between May 2004 and January 2009, neurophysiological monitoring of median SSEPs was performed in 44 patients during 48 consecutive operations for the placement or replacement of cervical or cervicomedullary electrodes for SCS. Twenty-one patients (48%) were women and 23 patients (52%) were men. The median age of the patient sample was 48 years (range 20–78 years). Pain syndromes were bilateral in 19 patients (43%) and unilateral in 25 patients (57%). Patient demographic and clinical data are summarized in Table 1.

TABLE 1: Patient demographic and clinical characteristics

Variable	No. (%)
no. of patients	44
age (yrs)	
median	48
range	20–78
sex	
male	23 (52)
female	21 (48)
location of SCS	
cervical	29 (60)
cervicomedullary	19 (40)
location of pain	
bilat	19 (43)
unilat	25 (57)
no. of cases	48
trial or initial placement	40 (83)
revision	8 (17)

Surgical Technique

All operations were performed by a single neurosurgeon (J.J.M.) after induction of general anesthesia. Apart from revisions, cervical and cervicomedullary stimulators were placed via 2 stages. In the first stage, cervical or cervicomedullary electrodes were placed with the patient prone in Mayfield head pins, and the wiring from the lead was connected to an external pulse generator for a 3-day trial. Pain reduction of at least 50% was required for patients to undergo the second stage of surgery during which a lateral decubitus position was used to place connecting wires and the internalized pulse generator. Cervical stimulation was used for patients with pain syndromes involving the upper extremity, shoulder, neck, and chest wall. Electrodes were placed at the cervicomedullary junction if the pain syndrome involved the face, jaw, or head. Our surgical technique for cervical stimulation used a single or multilevel hemilaminotomy for unilateral pain syndromes. The location of the hemilaminotomy was based on the patient's dermatomal topography of the pain, electrodiagnostic testing such as electromyography and nerve conduction studies, and previous surgeries so that the SCS electrode contacts would lie cephalad to the most rostral painful dermatome (for example, to treat a C5–7 dermatomal pain syndrome, the electrode would be placed epidurally via a C-5 laminotomy so that proximal contacts would lie at C-5 and distal electrodes would sit superior to C-5). In cases in which patients had undergone prior posterior cervical approaches, electrodes were placed more cephalad to the prior surgical site to avoid epidural scarring. In some cases, the level of electrode placement was guided by the location of a prior placed percutaneous electrode, which gave the patient successful pain control.

Cervicomedullary junction electrodes were placed using a C-1 hemilaminotomy with or without a small occipital craniectomy; an occipital craniectomy was performed if the patient's facial pain involved the V1 trigeminal dermatome. Cervical electrodes were either placed superiorly or inferiorly into the epidural space; however, all cervicomedullary electrodes were placed inferiorly into the epidural space from the cervicomedullary junction so that proximal contacts were near the cervicomedullary junction and distal contacts were located more

inferiorly. For the majority of cases, SCS was performed using the quadripolar Resume electrode lead (Medtronic), although Specify and Resume TL electrodes were also used. All patients underwent postoperative evaluation by several physicians including the senior author (J.J.M.) to determine whether pain coverage and reduction were sufficient.

Neurophysiological Monitoring

Somatosensory evoked potentials are routinely monitored for all posterior cervical spine surgery cases at our institution, and no additional monitoring equipment or preparation time was required for determining electrode localization. Baseline SSEPs were obtained after induction of general anesthesia and prior to patient positioning in all cases. Upper- and lower-extremity stimulation was performed simultaneously throughout. The upper-extremity nerve to be stimulated was chosen based on the level(s) at which the decompression/electrode placement was to occur, and the lower-extremity nerve was chosen on the basis of which response was most robust.

Median/Ulnar Nerve SSEPs

The median or ulnar nerve was stimulated at the wrist bilaterally in an alternating fashion using subdermal needle electrode pairs. Scalp electrodes were placed at P4/Fz and P3/Fz (according to the international 10-20 system)[14] to record cortical SSEPs (N20 and P30 SSEP components) and at either mastoid and referenced to Fz to record subcortical SSEPs (N13 SSEP component). Constant voltage stimulators using sufficient intensity to evoke a consistent response produced evoked sensory potentials. Stimulation frequency was 2.45 Hz with a single pulse duration of 0.2 msec. Bandpass filters were set at 3–300 Hz with a gain of 20,000 for cortical recordings and 30–1000 Hz with a gain of 50,000 for subcortical recordings. Averaged SSEPs were computed for 128 trials.

Peroneal/Tibial Nerve SSEPs

Alternating bilateral tibial nerve stimulation was used unless reproducible SSEPs were unattainable in which case the peroneal nerve was stimulated. The tibial nerve was stimulated at the ankle using subdermal needle electrode pairs with proximally placed cathodes and the anode placed approximately 1 cm distally. The peroneal nerve was stimulated using pairs of subdermal needles located at the head of the fibula and medially in the popliteal fossa. Recordings were obtained from the scalp by using subdermal electrodes. Scalp electrodes were Pz/Fz and P3/P4 (according to the international 10-20 system)[14] to record cortical SSEPs (N37 SSEP component) and at either mastoid and referenced to Fz to record subcortical SSEPs (N30 SSEP component). Evoked sensory potentials were produced by constant voltage stimulators using sufficient intensity to evoke a consistent response. Stimulation frequency was 2.45 Hz with a duration of 0.2 msec. Bandpass filters were set at 3–300 Hz with a gain of 2000 for cortical recordings and 30–1000 Hz with a gain of 5000 for cervical recordings. Averaged SSEPs were computed for 128 trials.

Alarm Criteria and Significant Change

Initial SSEP recordings, made after induction of anesthesia and prior to positioning, served as baselines. The SSEPs were collected continuously (defined as without user interruption) throughout the procedure. For purposes of detection of iatrogenic injury due to patient positioning or root and/or cord insult, persistent and consistent reduction in primary somatosensory cortical amplitude or subcortical response by greater than 50% or prolongation of response latency (> 10%) at any time during the procedure that was not related to significant changes in anesthesia, was viewed as being significant and the surgeon was informed. These criteria have been previously validated and agreed on in the literature as being of optimal sensitivity and specificity for detecting iatrogenic injury in the spinal cord. It should be noted that while a 50% change in amplitude and 10% increase in latency are widely accepted as being significant, caution should always be taken, and interpretation of significance should be considered on a case by case basis.

For purposes of electrode localization, once in the epidural space, the electrode was connected to an external pulse generator under the control of a manufacturer representative. Stimulation from the external pulse generator used frequencies of between 40 and 60 Hz and began at 1.0 V and was increased in increments of 1.0 V to a maximum of 6.0 V. Median nerve SSEPs were used for collision testing in all patients. The pulse generator SCS was often recorded as a high frequency signal on the SSEP channels, and all artifact rejection algorithms for SSEP recordings were turned off. If required, the SCS artifact was resolved by increasing SSEP averaging to 256 trials per average. A significant unilateral reduction (75% or greater) or abolishment of SSEP cortical or subcortical amplitude was interpreted as lateralized placement of the electrode, and a bilateral 75% SSEP reduction or abolishment of SSEPs indicated a midline or near-midline electrode placement. In patients with unilateral pain syndromes, failure of abolishment or significant unilateral reduction (> 75%) of SSEP amplitudes ipsilateral to pain during SCS was interpreted as poor lateralized placement and prompted repositioning of the electrode. For patients with bilateral pain, failure of bilateral SSEP amplitude abolishment or 75% reduction was interpreted as poor midline placement of the electrode and prompted repositioning. In all 48 operations, the cervicomedullary or cervical electrode was repositioned by the surgeon and not anchored until the aforementioned intraoperative neurophysiological criteria for proper lateralized or midline positioning were met. Interpretation of significant change due to the stimulator being turned on at various voltages was very straightforward and easily interpreted except for instances in which noise from the handheld pulse generator introduced noise into the recordings. In these and any cases in which noise interference became an issue, routine digital filtering of the signal was used to successfully resolve the signals and any SSEP changes.

Results

In all 25 patients with unilateral pain syndrome, cer-

vical and cervicomedullary SCS consistently abolished or significantly reduced (> 75% suppression) median nerve cortical and subcortical SSEP amplitudes ipsilateral to the pain syndrome without modifying the contralateral median nerve SSEP. A representative case of bilateral significant SSEP amplitude reduction during intraoperative cervical SCS in a patient suffering from bilateral pain is shown in Fig. 1. In 15 patients (60%), after correct electrode lateralization was confirmed with SSEP monitoring, electrodes were intraoperatively repositioned to obtain the most robust and greatest decrease in SSEP amplitude using the lowest intensity output of the spinal cord stimulator. Postoperatively, all 25 patients (100%) with unilateral pain experienced excellent unilateral pain coverage with sensory alterations elicited on the side of pain predicted by SSEP suppression in the operating room. No patient experienced unpleasant or painful contralateral SCS-induced paresthesias. An SCS voltage of 3.0–4.0 V was required to abolish unilateral SSEP in most patients.

In 19 patients (100%) with bilateral pain syndrome, cervical and cervicomedullary SCS produced bilateral reduction in SSEP amplitudes intraoperatively, and all patients had bilateral postoperative sensory alterations. Although SSEP amplitude suppression was observed bilaterally in these cases, it was often asymmetrical.

No new neurological deficits occurred. The SSEP collision testing added approximately 5–15 minutes of time to each operative case.

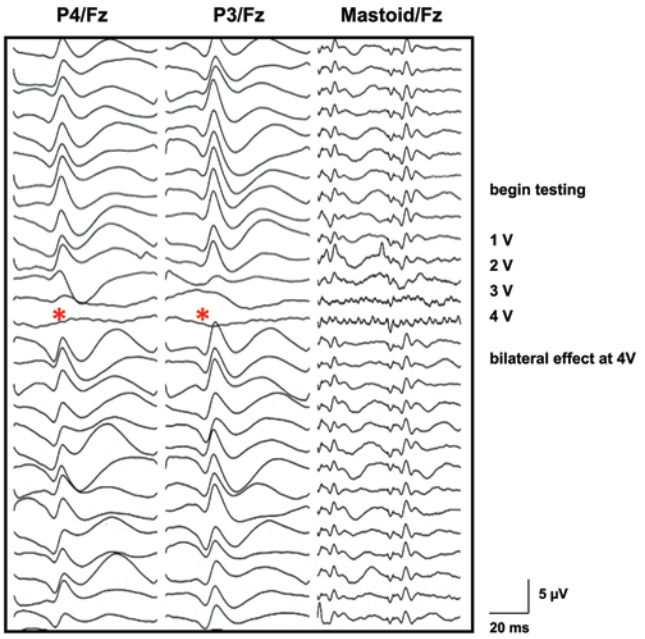

Fig. 1. Representative case. A 58-year-old woman who presented with bilateral jaw, shoulder, and arm pain underwent placement of a cervical stimulator with desired midline placement. Upper-extremity, median nerve SSEPs generated by stimulation of the right and left median nerves demonstrated significant bilateral amplitude decreases *(asterisks)* in response to SCS at 2–4 V providing electrophysiological confirmation of sufficient (midline) electrode placement.

Discussion

Despite its proven clinical efficacy in reducing pain and improving quality of life for patients suffering from various intractable pain syndromes, SCS remains technically demanding and constrained by the high cost and technological limitations of current hardware. Revision surgery remains common due to infection, initial misplacement, and various types of hardware failure.[19,39,41,42] Moreover, cost effectiveness studies have shown that the financial impact of SCS is strongly influenced by perioperative complications and the need for revision surgery.[2,18,25] Inadequate pain coverage may result from poor lateralization during initial placement of the SCS electrode and can be particularly problematic during placement of cervicomedullary and cervical stimulators where patient verification of pain coverage is lost due to general anesthesia. A recent review of hardware failure modes in 289 patients undergoing SCS identified poor pain relief coverage as the most common indication for revision surgery.[33] Moreover, even if painful areas are adequately covered by stimulation, stimulation-induced paresthesias in regions not involved in the pain syndrome, such as the contralateral face or extremity, may lead to patient discomfort and dissatisfaction with SCS.[13,27] Thus, efforts directed at optimizing initial SCS electrode placement during surgery may reduce the cost and improve the efficacy of this therapy.

Although it does not guarantee patient pain relief and satisfaction, the fundamental doctrine governing SCS therapy involves steering stimulation-induced paresthesias to cover a patient's perceived spatial distribution of pain.[24] Since patients undergoing general anesthesia during cervical and cervicomedullary SCS cannot participate in confirming good overlap of paresthesias and pain, an objective lateralizing strategy is desirable to prevent poor electrode placement and subsequent revision. Relying on radiological assessments of midline (intraoperative radiography and fluoroscopy) and the surgeon's visual estimate alone for placement of lateralized electrodes may lead to poor coverage since it has been observed that anatomical midline may differ from the more clinically relevant physiological midline.[8]

Our technique of median nerve SSEP modulation with SCS is based on the neurophysiological concept of electrical collision. By primarily acting on the dorsal column pathways in the spinal cord, SCS has been shown to generate both orthodromic and antidromic sensory responses.[43] Antidromic activation of peripheral nerve fibers is one of the hypothesized pain relief mechanisms behind SCS.[17] When antidromic and orthodromic responses within the same conduction pathways meet or collide, they can ultimately cancel each other out by negative interference. This phenomenon of collision is increasingly being explored during intraoperative physiological monitoring of the spinal cord since it may hold the potential to more specifically detect injury to descending motor tracts.[20,29] Yingling and Hosobuchi[44] reported that antidromic impulses triggered by SCS can be measured at peripheral nerves and used to assist in placement of dorsal column spinal cord stimulation systems. We extended their findings to develop a technique that lateralizes electrode placement during cervical and

cervicomedullary SCS by using antidromic impulses to collide with orthodromic impulses evoked by unilateral median nerve SSEPs. Thus, in our patients, collision of orthodromic sensory responses generated by peripheral stimulation of the median nerve with antidromic sensory responses generated by SCS led to lateralized modulation and eventual extinguishment of SSEPs measured at the scalp. Moreover, after successful lateralization, the electrode was repositioned in 15 patients so that collision phenomenon would generate the greatest SSEP amplitude reduction with the lowest stimulation intensity of the spinal cord stimulator.

This technique, which utilizes well-established routine SSEP recording, did not require additional training of our neurophysiology staff nor did it add significant time to the procedure. Continued advancements in SCS lead technology may obviate the need for lateralization by placing multiple parallel leads or wider paddle leads with multiple rows of embedded electrode contacts. However, in the cervical spine, where the potential for postlaminectomy instability is greater than in the thoracic spine, we believe that a minimal exposure with small laminotomy and limited ligamentous disruption is prudent. Moreover, added cost and risk of infection aside, placing more hardware into the cervical epidural space to treat predominantly unilateral pain syndromes arguably exposes the patient to added neurological risk. Future studies will help determine whether such neurophysiological optimization of electrode location can improve pain control outcomes in SCS by helping surgeons localize the electrode for optimal pain management.

Conclusions

Somatosensory evoked potentials can safely, easily, and successfully predict the lateralization of an epidural electrode and corresponding stimulation-induced paresthesias in a patient undergoing cervical or cervicomedullary spinal cord stimulation. Moreover, continuous SSEP monitoring can be used to provide neurophysiological surveillance of final electrode position by alerting the surgical team to an unintended movement of the electrode during anchoring and closing steps. Further studies performed prospectively are needed to determine whether intraoperative SSEP monitoring during SCS surgery can improve pain control outcomes.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: Tomycz, Balzer, Crammond, Habeych, Thirumala, Moossy. Acquisition of data: Tomycz, Balzer, Crammond, Habeych, Urgo, Moossy. Analysis and interpretation of data: Tomycz, Balzer, Crammond, Habeych, Thirumala, Moossy. Drafting the article: Tomycz, Balzer, Crammond, Thirumala, Moossy. Critically revising the article: Tomycz, Balzer, Crammond, Habeych, Urgo, Moossy. Reviewed final version of the manuscript and approved it for submission: Tomycz, Balzer, Crammond, Habeych, Thirumala, Moossy. Statistical analysis: Balzer. Administrative/technical/material support: Balzer, Moossy. Study supervision: Moossy.

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