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Correlating Evoked Electromyography and Anatomic Factors During Spinal Cord Stimulation Implantation With Short-Term Outcomes

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ABSTRACT

Introduction: We examine ways intraoperative neuromonitoring during spinal cord stimulation (SCS) varies between a high-resolution investigational SCS (HR-SCS) paddle and a commercial paddle. Furthermore, the presence of evoked motor responses (eg, electromyography [EMG]) in painful regions during surgery is correlated to outcomes.

Materials and Methods: We used HR-SCS to assess EMG response from 18 patients (NCT05459324). Maximum percentage change in root mean squared (maxRMS) EMG values was determined. Correlations were performed with magnetic resonance imaging measurements and patient outcomes collected preoperatively and at three months (numerical rating scale [NRS], McGill Pain, Beck Depression Inventory, Oswestry Disability Index [ODI], and Pain Catastrophizing Score).

Results: Of the 18 patients (12 women to six men; mean age 56 years; eight with neuropathic pain, eight with persistent spinal pain syndrome, two with complex regional pain syndrome), nine had a response at three months based on 50% reduction in NRS, 14 by achieving minimal clinically important difference (MCID) on NRS, and 11 by reaching MCID on ≥three outcome metrics. The anterior posterior diameter (APD) of the spinal column at level of testing correlated with all three responses ($p < 0.05$). We examined RMS at muscles correlating with individual patient pain distributions and found correlations between RMS and MCID NRS and MCID ODI ($p < 0.05$). maxRMS in abductor hallucis correlated with improvement in NRS and ODI across the group ($p < 0.05$).

Conclusions: We found that eliciting EMGs over the painful areas during surgery caused alleviation of pain intensity and disability. Obtaining stimulation of abductor hallucis (AH) was more predictive of pain improvement than any other muscle group, and APD alone correlated with improvements in pain intensity and holistic outcomes. These pilot data suggest that implanters should consider APD and EMG responses from painful regions and AH during surgery.

Keywords: Chronic pain, evoked EMG, intraoperative neuromonitoring, minimum clinically important difference, spinal cord stimulation

INTRODUCTION

Chronic pain is a pervasive condition affecting millions of individuals worldwide, significantly burdening patients and healthcare systems.[1–4] Chronic pain often compromises the quality of life, particularly in those resistant to standard therapeutic interventions, leading to physical and psychologic distress and generating economic consequences.[3–5] Spinal cord stimulation (SCS) is an

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effective intervention for conditions such as persistent spinal pain syndrome (PSPS), neuropathic pain, and complex regional pain syndrome (CRPS).[6–10] SCS offers pain relief of varying degrees to many patients; however, there are some who do not achieve adequate relief in specific areas.[6,7] Such variability in outcomes underscores the need for more personalized and targeted stimulation techniques.[11] Evoked motor responses have emerged as a potentially transformative tool for enhancing the precision of SCS targeting.[12,13] However, it remains unclear how targeting specific areas of the dorsal column relieves pain in particular sites.[12,14–16]

Given the effectiveness of SCS therapy depends on correct placement to align with the regions of pain, there is a need for objective measures. Some have postulated that evoked motor response during intraoperative neuromonitoring (IONM) may provide a surrogate for dermatomal pain coverage. Recording electromyography (EMG) signals has been shown to accurately locate the physiological midline of the spinal cord during SCS placement, causing effective pain reduction in patients.[17] In a recent systematic review, the authors found that the use of IONM during SCS surgery produces better pain relief, fewer neurologic deficits, and shorter operation times.[18] We also have shown that dorsal cerebrospinal fluid (CSF) and CSF thickness affected the amplitudes needed to obtain a motor response.[19]

Here, we use a high-resolution investigational SCS paddle (HR-SCS) to assess evoked motor responses from 18 patients (NCT05459324). In this study, we evaluate the ways patient-specific factors, including root mean square (RMS) of signals in muscle groups affected by pain and anatomic factors, influence outcomes.

MATERIALS AND METHODS

Patients were recruited to this investigational device exemption (IDE) study (Food and Drug Administration IDE code: G210346) if they were experiencing ongoing leg and back pain, had a positive trial result with SCS showing >50% improvement on the numerical rating scale (NRS), had passed a psychologic evaluation, and had undergone presurgery magnetic resonance imaging (MRI). In our practice, pain specialists performed a percutaneous trial, and we recruited patients who were subsequently referred for paddle placement. The study was registered on ClinicalTrials.gov (Identifier: NCT05459324). Every patient gave their written consent before participating in this institutional review board (IRB)-approved study (Albany Medical College IRB, #5151 and #6426).

Surgical Workflow

Once patients provided consent, they completed baseline outcome measures for pain, disability, and depression. These assessments included the numerical rating scale (NRS), Beck Depression Inventory (BDI), McGill Pain Questionnaire (MPQ), Oswestry Disability Index (ODI), Pain Catastrophizing Scale (PCS), and a drawing illustrating their areas of pain. All these questionnaires were completed in the clinic and/or with a study coordinator/medical team available for questions. Demographic information including sex, age, diagnosis, and duration of illness was documented (Table 1). Patients then underwent a standard-of-care laminotomy with IONM as previously described.[12] Patients completed patient-reported outcomes (PROs) again at three months.

Preoperative MRI images were obtained for every patient. The preoperative axial spinal MRI of each patient was assessed to measure the CSF area at the level of the stimulated contacts. CSF thickness was then measured using a tracing tool available on the iSite radiology program (Philips Healthcare Informatics, Foster City, CA), as described previously. Anterior posterior diameter (APD) was measured on the axial plane, from the middle of the posterior vertebral body to the anterior aspect of the lamina, at the level of relevant contacts.

Compound motor action potentials, evoked motor responses (termed "EMG" for remainder of manuscript), and somatosensory evoked potentials were used during surgery as standard of care. In the study, we see whether EMG responses differ with the experimental lead and commercial lead. We use IONM so we can perform the cases under general anesthesia and ensure laterality and patient safety with paddle leads.[20] A cascade PRO IONM system (Cadwell Inc, Kennewick, WA) was used to monitor and record EMG data. Testing was conducted on nine muscle groups bilaterally. From distal to proximal, we assessed the abductor hallucis (AH), tibialis anterior (TA), medial gastrocnemius (MG), quadriceps (QUAD), bicep femoris (BF), adductor magnus (ADD), gluteus maximus (GLUT), and lower and upper rectus abdominis (Fig. 1). After standard-of-care laminotomy, HR-SCS (Micro-Leads Inc, Somerville, MA) was first placed, and EMGs were monitored when the device was stimulated. After testing, it was removed, and the commercial SCS paddle (model type and company based on lead used in trial) was placed, EMG responses documented, and the paddle implanted. Placement of paddles was confirmed with C-arm fluoroscopic imaging. We aligned commercial and HR-SCS leads on the basis of anatomic placement on these images. In 16 of 18 patients, anatomic midline overlapped with the physiological midline. In the two remaining patients, the evoked responses observed in the muscles on the right body were smaller than the responses on the left body. In these cases, physiological midline was inconclusive.

A longitudinal tripole (+/-/+) at both the top and bottom of the commercial and HR-SCS paddles was tested in nine patients. In the initial nine patients, the HR-SCS only allowed testing of the bottom tripole. Stimulation was administered at a frequency of 60 Hz with a pulse duration of 300 μs through a hand-held programmer. Amplitudes were progressively raised by a 0.5-mA step size until reaching either a motor threshold or maximum threshold (10 mA). The minimum stimulation amplitude was defined as motor threshold on the basis of EMG changes. Maximal stimulation amplitude was the highest amplitude used for stimulation in the operating room.

Signal Processing

All EMG signals were processed offline in MATLAB R2022b (MathWorks, Natick, MA). EMG signals were denoised using a previously developed algorithm, which involved applying a 10% threshold and removing values exceeding the threshold.[13] The RMS of signals were computed at each amplitude (stimulation-ON) for all patients and normalized with respect to baseline (stimulation-OFF) as previously described.[21] At the individual level, maximum percentage change in RMS (maxRMS) was determined for amplitudes ≤10mA across all eight mediolateral contacts.

Individual patient motor heatmaps were created in GraphPad Prism-10 (GraphPad Software, Inc, San Diego, CA) for all nine muscle groups at the corresponding spine level(s) (Fig. 2). Based on maxRMS, the patients were then divided into responders (values ≥50% RMS change regarding baseline) and nonresponders (values

Table 1. Subject Demographics.

Patient	Age (y)	Sex	Diagnosis	Duration of illness (y)	Pain distribution	Responder at 3-mo follow-up based on 50% NRS	Responder at 3-mo follow-up based on MCID NRS	Responder at 3-mo follow-up based on MCID ≥3	Minimum stimulation amplitude (mA)	Maximum stimulation amplitude (mA)	Commerical paddle type	MRI-obtained measurement: APD (mm)	MRI-obtained measurement: IPD (mm)	MRI-obtained measurement: dCSF (mm)	Likert scores
2	60	M	PSPS	8	B/L— low back		X	X	5	7.5	Medtronic Specify™ 5-6-5 lead	15.8	20	4	7: complete coverage of the back
3	46	M	NP	5	B/L—low back, glutes, hamstrings, calves	X	X	X	1	2	Boston Scientific Cover-Edge™ 32	11.3	14.8	2.5	3: coverage of the back and right calf, no glute or hamstring coverage
4	29	M	PSPS	4	R—glutes, hamstring, calf		X	X	10	10	Nevro Surpass™ Surgical Lead	15.2	19.5	5	2: coverage of right low back, no right leg coverage
5	43	F	CRPS	4	B/L—full back, low back (above glutes), glutes, posterior shoulder. L—calf, knee, shin. R—knee	X	X	X	7.5	10	Nevro Surpass™ Surgical lead	14.8	19.6	5	4: coverage of the low back and calf, no glute coverage
6	40	F	NP	18	L—low back (above glute), glute, hamstring, calf	X	X		5	10	Medtronic Specify™ 5-6-5 lead	17	21.5	4.8	6: coverage of the low back, left glute, and hamstring, minimal calf coverage
7	52	F	NP	10	Upper and lower back				10	10	Medtronic Specify™ 5-6-5 lead	17.6	18.8	3.9	2: minimal low back coverage
8	67	M	NP	15	B/L—low back. R—knee		X		10	10	Abbott Penta™ Paddle lead	19	19.3	5.3	5: coverage of low back, no knee coverage
9	57	F	NP	7	B/L—low back (above glute). L—glute, hamstring, calf				10	10	Boston Scientific Cover-Edge™ 32	18.1	20	5.4	1: no coverage
12	78	F	NP	7	B/L—low back and abdominals				3	10	Boston Scientific Cover-Edge™ 32	18	21.5	4.7	5: coverage of low back
21	57	F	CRPS	>4	B/L—full back, low back (above glutes), posterior leg (glutes, calf, hamstring)	X	X	X	7.5	10	Boston Scientific Cover-Edge™ 32	ND	ND	ND	4: minimal coverage of back and left leg
22	60	F	NP	19	B/L—low back (above glutes), anterior and posterior leg (quads, calf, hamstrings, shins)	X	X	X	10	10	Boston Scientific Cover-Edge™ 32	15	17.6	4.3	4: minimal coverage of back
23	67	F	PSPS	12	B/L—low back (above glutes). R—quad and hamstring	X	X	X	2.5	10	Boston Scientific Cover-Edge™ 32	14.1	17.3	3.1	5: good coverage of the left side

(Continues)

Table 1. *Continued*

Patient	Age (y)	Sex	Diagnosis	Duration of illness (y)	Pain distribution	Responder at 3-mo follow-up based on 50% NRS	Responder at 3-mo follow-up based on MCID NRS	Responder at 3-mo follow-up based on MCID ≥3	Minimum stimulation amplitude (mA)	Maximum stimulation amplitude (mA)	Commerical paddle type	MRI-obtained measurement: APD (mm)	MRI-obtained measurement: IPD (mm)	MRI-obtained measurement: dCSF (mm)	Likert scores
24	51	F	PSPS	5	B/L—low back, glutes, quads and hamstrings		X		10	10	Boston Scientific Cover-Edge™ 32	14.4	17.5	4.8	5: coverage of the back, no right leg coverage
25	78	F	PSPS	1.5	B/L—glutes and hamstrings				5	9	Nevro Surpass™ Surgical Lead	15.2	19.3	4.9	3: only right quad coverage, no left or right hamstring coverage
26	75	M	PSPS	>20	B/L—low back (above glutes). R — pelvis	X	X	X	5.5	7.5	Nevro Surpass™ Surgical Lead	12.2	18	4.7	6: low to mid coverage of back
27	34	F	PSPS	>4	B/L—mid back (around spine), low back. L—hamstring, calf, knee. R—posterior shoulder, hip, hamstring		X	X	4.5	7	Nevro Surpass™ Surgical Lead	14.4	17.2	3.6	7: coverage of all muscle groups involved at high levels
28	71	M	NP	20	B/L—upper and lower back, posterior neck, dorsal arms (shoulders to fingertips), glutes, hamstrings, calves	X	X	X	10	10	Boston Scientific Cover-Edge™ 32	12.3	21.4	5.6	4: some coverage of low back and right calf, no hamstrings, gluts, or left calf coverage
29	49	F	PSPS	15	B/L—glutes, quads, anterior lower leg	X	X	X	10	10	Nevro Surpass™ Surgical Lead	14.8	18.7	6.2	4: coverage of quads, front of leg, no coverage of gluts

Likert scale: 1, no areas covered; 2, low response of some painful areas; 3, low response of all painful areas or most areas uncovered with low/mid response in those covered; 4, coverage of some painful areas as a midresponder; 5, coverage of most areas as a midresponder; 6, most painful areas covered robustly as a mid-to-high responder; 7, all painful areas covered mid-to-high response.
B/L, bilateral;.F, female; IPD, interpedicular distance; L, left; M, male; mA, milliampere; ND, no data; NP, neuropathic pain; R, right; X, "yes" for responder.

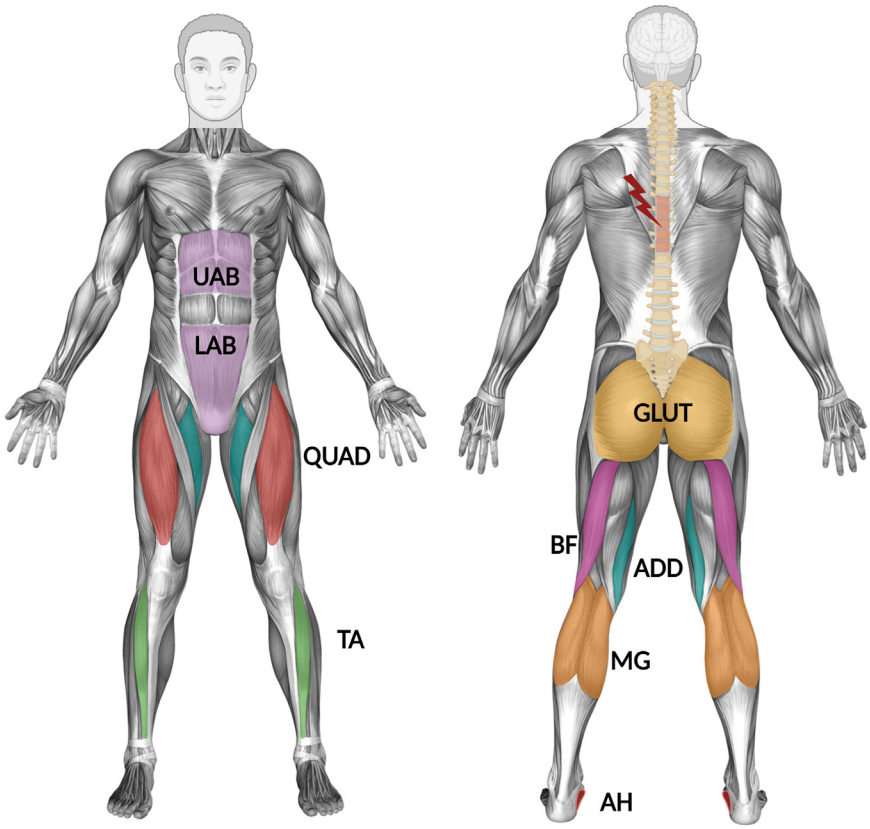

Figure 1. This panel indicates nine muscle groups whose data were recorded to investigate their responses at applied stimulation. Thoracic spinal levels T6–T10 where HR-SCS paddles were placed to investigate muscle responses are shown (red lightning bolt). LAB, lower abdominis; UAB, upper abdominis.

<50% RMS change regarding baseline). The responder group was further divided into low (51%–100% RMS change), mid (101%–500% RMS change), and high (501%–maxRMS change) responders.

The patient heatmaps were scored with a Likert scale to assess whether evoked motor response correlated with the patient's individualized pain pattern. Specifically, on a seven-point scale: 1 (no areas covered), 2 (low response of some painful areas), 3 (low response of all painful areas or most areas uncovered with low/mid response in those covered), 4 (coverage of some painful areas as a midresponder), 5 (coverage of most areas as a midresponder), 6 (most painful areas covered robustly as a mid–high responder) to 7 (all painful areas covered, mid–high response) (Fig. 3). Robustness of coverage was based on percentage RMS change.

Statistical Analysis

Statistical analyses were performed in GraphPad Prism-10 (GraphPad Software, Inc). The difference in PRO scores between baseline and three months was documented. Percentage change (mean ± SEM) and raw score change between the three-month postoperative score and the preoperative baseline score were calculated. Previously established minimal clinically important difference (MCID) values for SCS treatment of pain, across all five outcome measures, were used. An improvement of ≥2.0 points on the NRS, 6.9 points on the BDI, 1 point on the MPQ, 8.2 points on the ODI, and 1.9 points on the PCS is clinically meaningful to the patient.[22–25] Responders were those who achieved 50% pain relief on NRS. We termed those with MCID on NRS as MCID NRS responders and those with MCID on ≥three outcome metrics as MCID >3 responders. Pearson's correlation analysis was performed to determine the correlation values between pain outcome measures and MRI parameters. The D'Agostino-Pearson test was used for testing normality. Some patients did not complete all PROs, and any missing data were omitted and not included in the analysis. Outliers were excluded and defined as ± >2 standard deviations away from the mean.

RESULTS

The mean (SEM) percentage change improvement in NRS score (n = 18) was −45.6 + 7.7%; MPQ (n = 15) was −6.6% + 26.4%; ODI (n = 15) was −30.2% + 8.3%; PCS (n = 14) was −41.8% + 10.5%, and BDI (n = 15) was −15.4% + 17.4% (Table 2). Nine of 18 patients were deemed responders based on 50% improvement in NRS at three months; 14 of 18 met MCID for NRS; 11 of 15 met MCID for MPQ, 10 of 15 on MCID for ODI, 11 of 14 on MCID for PCS, and 7 of 15 on MCID for BDI (Supplementary Data Table S1). Eleven of 18 patients achieved MCID on ≥three outcome metrics. We examined factors that correlated with whether patients were deemed a responder. Percentage change in NRS inversely correlated with duration of illness (r = −0.50, p = 0.03), with no other demographic correlations observed. The MRI measurement of APD correlated with response on all three primary end points (r = 0.52, p = 0.03 [percentage change NRS]; r = 0.52, p = 0.03 [MCID on NRS]; r = 0.71, p = 0.001 [MCID on three outcomes]).

Next, we examined ways patient IONM data correlated with patient outcomes and MRI measurements. Patients who reached

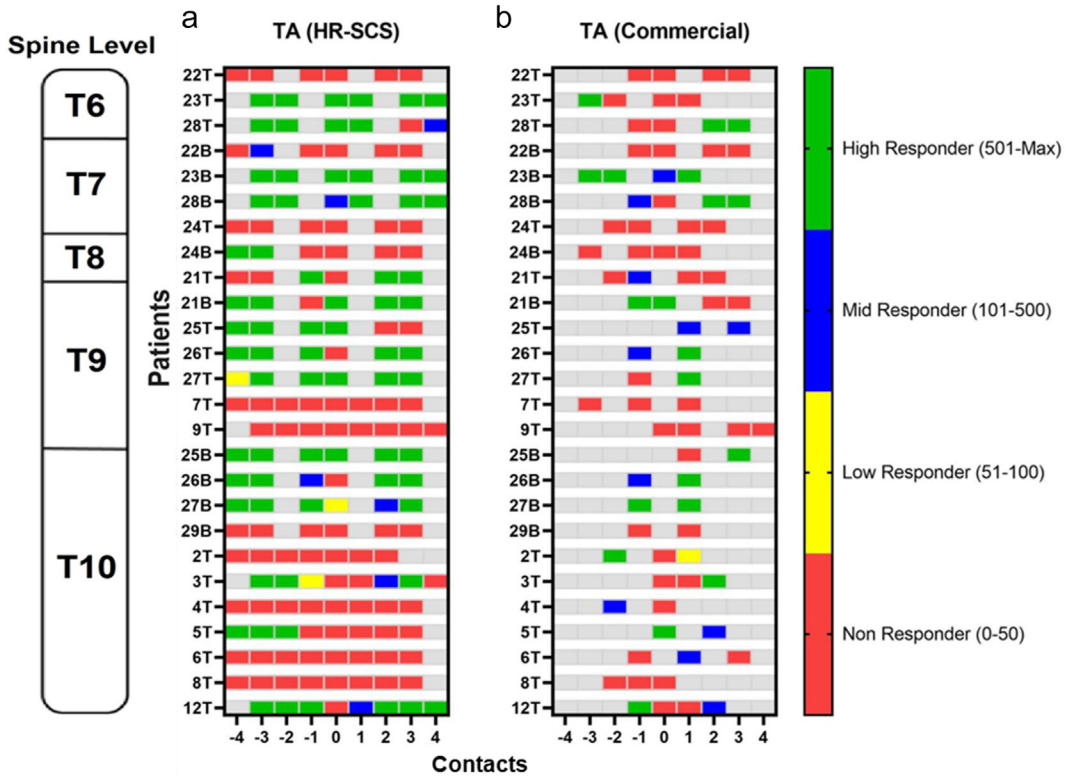

Figure 2. A characteristic motor recruitment heat map was created for each muscle. In this figure, we show an example for TA at 0.5 to 10 mA (a, b). Panel a depicts HR-SCS results whereas panel b depicts commercial paddles. Responders were determined on the basis of values >50% RMS change regarding baseline, and nonresponders were classified as values <50%. Responders were separated into low (51%–100% RMS change), mid (101%–500%), and high (501%–max%) responders. These values were decided on the basis of the change in percentage threshold.

MCID on NRS had significantly greater coverage of painful regions with the implanted paddle ($r = -0.50$, $p = 0.03$). Patients who reached MCID ODI had significantly more coverage of painful regions with both HR-SCS ($r = 0.55$, $p = 0.03$) and commercial paddles ($r = -0.64$, $p = 0.01$). Furthermore, in commercial paddles, less stimulation was needed to target these motor responses corresponding with patient dermatome ($r = -0.50$, $p = 0.03$). Activation of distal muscles with HR-SCS negatively correlated with percentage change in NRS ($r = -0.49$, $p = 0.04$) and ODI ($r = -0.58$, $p = 0.02$). The correlations of specific muscles with outcomes and patient specific data are listed in Table 3. APD ($r = 0.56$, $p = 0.02$) in addition to interpedicular distance ($r = 0.64$, $p = 0.006$) and dorsal CSF thickness ($r = 0.66$, $p = 0.004$) correlated with the maximum stimulation used. Dorsal CSF (dCSF) thickness also correlates with minimal stimulation amplitude required to obtain a response ($r = 0.69$, $p = 0.002$) and maximum stimulation amplitude ($r = 0.66$, $p = 0.004$).

DISCUSSION

In our study, comprising 18 patients who underwent SCS surgery with IONM, we looked at the intricate relationships among physiological factors, stimulation parameters, and clinical outcomes of the patients. To address the difference between commercial and HR-SCS paddles, we normalized our heatmaps and scaled with respect to the specific anatomic midline, considering contact and paddle dimensions. For the testing parameters, we only applied IONM stimulation at 60 Hz, which is most used for these types of recording. Although these devices are capable of various stimulation waveforms, we did not account for whether patients received burst or high-frequency stimulation in the three-month postoperative period. Instead, our focus remained on the outcome measures the patients reported, regardless of their specific programming parameters. The primary objective of our study was to investigate the correlation between patients who responded positively to the electrophysiological aspects of the stimulation, such as changes in muscle activity in their painful regions, and those who reported overall positive outcomes from SCS treatment.

We found that when evoked motor responses were obtained in muscles corresponding with the patient's painful dermatomes, there was an improvement at three months in both NRS and ODI. It stands to reason that if stimulation is reaching the patient's painful area, the intensity of pain and the patient's disability will be reduced.[26] Frankly, the question is why all outcome measures do not respond in kind. First, it must be considered that the Likert RMS score we provide is a global assessment, and although it may cover some painful areas well, it may not cover all of them. Many of our patients reported pain outside the area that SCS would be expected to cover, and despite instructions given by a member of our medical team to only consider the pain that is being treated by SCS, this remains difficult.

We next examined whether activation of a specific muscle during IONM led to better outcomes. We observed a negative correlation between maxRMS in AH on HR-SCS paddle and NRS pain score. This finding is interesting because it is rare that the pain in the

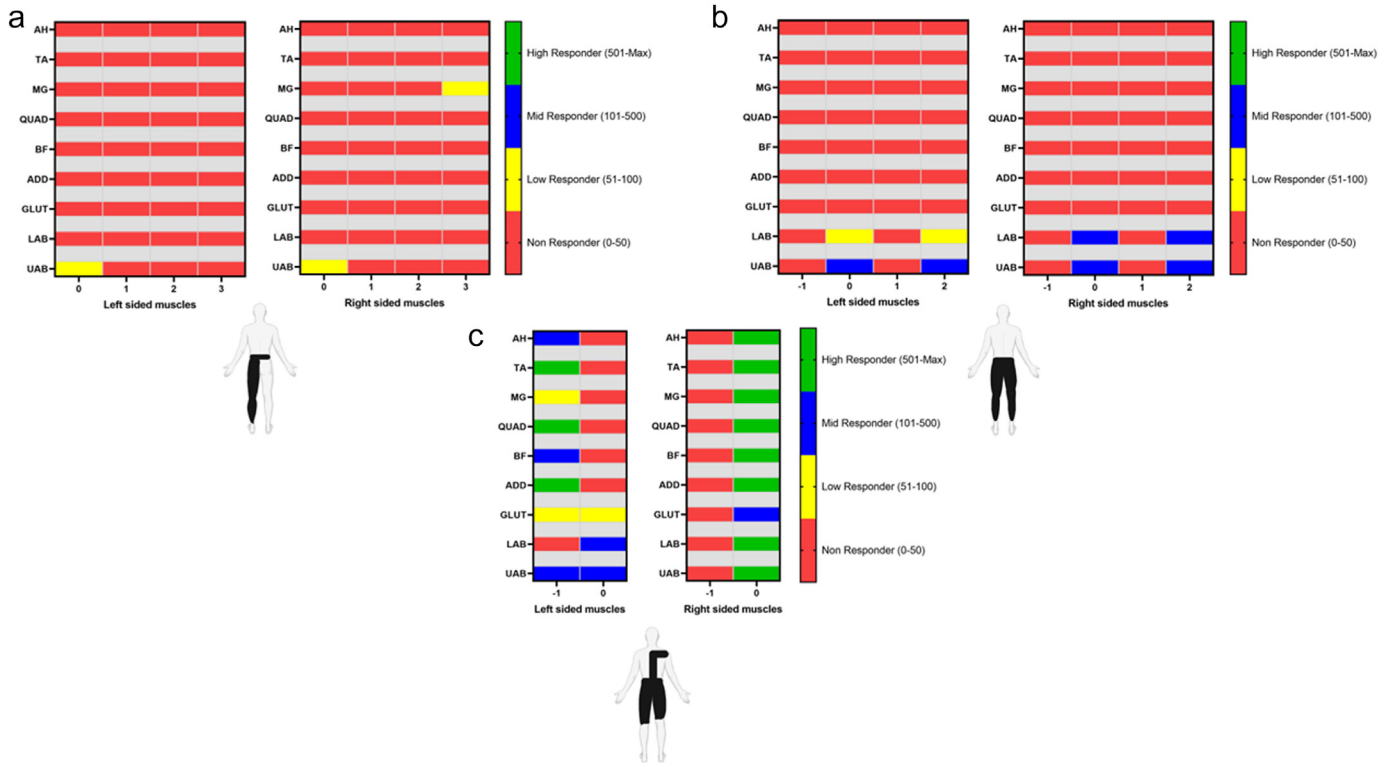

Figure 3. Likert scale determination. Likert scale scores were determined to assess the likelihood of pain relief based on extent of coverage. This seven-point Likert scale was scored as follows on the basis of the degree of response on heatmaps for each muscle: 1 (no areas covered), 2 (low response of some painful areas), 3 (low response of all painful areas or most areas uncovered with low–mid response in those covered), 4 (coverage of some painful areas as a midresponder), 5 (coverage of most areas as a midresponder), 6 (most painful areas covered robustly as a mid–high responder) to 7 (all painful areas covered, mid–high response). Robustness of coverage was based on percentage RMS change. The locations of preoperative pain reported by individual subjects are depicted by black-shaded areas on the human diagram. Panel a represents a subject with a Likert score of 1; panel b represents a subject with a Likert score of 4; and panel c represents a subject with a Likert score of 7.

distribution of the AH is the sole reason someone undergoes SCS. However, the AH is innervated by branches of the tibial nerve, which originates from the sciatic nerve. Also innervated by the sciatic nerve or its branches are the biceps femoris (BF), MG (tibial), and the TA (deep peroneal nerve). BF correlated with improvements in ODI, whereas no correlations were seen with MG or TA. Although significant, the correlations are somewhat modest, and we need to confirm them in a larger data set. Furthermore, it may be interesting in the future not only to ask patients where their pain is related to their feet but also to carefully inspect sensation and ask about numbness, paresthesia, and tingling if AH coverage is indeed shown in the future to be a biomarker in a larger sample size.

Table 2. Average Raw Score Change and Percentage Change for Each Pain Outcome at the Three-Month Follow-Up.

Outcome measure	Average raw score change ([preoperative score−postoperative score] ± SEM)	Average percentage change (% ± SEM)
NRS (n = 18)	3.4 ± 0.6	−45.6 ± 7.7
MPQ (n = 15)	3.3 ± 2.0	−6.6 ± 26.4
PCS (n = 14)	9.6 ± 2.6	−41.8 ± 10.5
ODI (n = 15)	15.7 ± 4.5	−30.2 ± 8.3
BDI (n = 15)	5.1 ± 2.2	−15.4 ± 17.4

In addition to evoked motor responses, we add to the literature on patient-specific MR findings and stimulation requirements. Patients with smaller APDs were likely to require less energy and have better outcomes on all three metrics at three months. Notably, APD considers dCSF thickness in its measurement. Previously, we have shown that dCSF thickness correlated with energy requirements on postoperative day 1 programming amplitude using tonic stimulation.[19] Others have shown supporting data that CSF thickness is a notable variable in amplitudes needed to evoke responses and potentially to treat patients.[27,28] Here, we show that dCSF thickness correlated with minimal and maximal amplitude to response and RMS scores in many muscle groups. Lempka et al found, with modeling, that the amplitude of evoked compound action potentials (ECAPs) correlated similarly with dorsal CSF thicknesses.[29] This is particularly interesting given ECAPs are a measure of therapy reaching the dorsal column as its target. Data have suggested that the more times the therapy elicits ECAPs, the higher the dose of therapy the patient receives.[30] Because dCSF thickness is a portion of APD, with the bony architecture constituting the remainder, it is not surprising that the closer the electrode is to the area it is targeting, the better the response. The correlation between outcomes and APD, but not between outcomes and CSF thickness, is not unexpected given dCSF thickness changes with posture, but bony distances do not.[31]

Table 3. Correlation Coefficients and *p* Values of maxRMS in Muscles Related to Patient-Specific Data.

Paddle	Muscle	Patient-specific data	Correlation coefficient (*r*)	*P* Value
HR-SCS	AH	50% NRS pain response	−0.49	0.04
	AH	% change in NRS	−-0.50	0.04
	AH	% change in ODI	−0.60	0.02
	BF	% change in ODI	−0.63	0.01
	TA	APD	−0.63	0.007
Commercial	AH	% change in NRS	−0.48	0.04
	TA	APD	−0.57	0.017

Intraoperatively, CSF thickness remains stable given the patient remains prone and the lead is not subject to forces of patient movement.

Our study has several limitations. Most notably, this was a National Institutes of Health-sponsored trial, and patient recruitment was limited to 18 patients. The number and heterogeneity of patients limit the statistics we can perform, especially given we assign patients to different subgroups. We show that motor evoked responses in painful regions correlated with outcomes. We acknowledge that APD may be a notable confounder of these data, and in a larger subset of data, it would be worth performing multivariate analysis. Our previous work showed that HR-SCS induced distinct patterns in lower extremities with higher precision.[13,32] Although we noted a clear medio-lateral selectivity over the dorsal column, which was mapped on the basis of these evoked muscle responses, we did not find a significant correlation between these clinical features and muscle responses. One reason might be the small number of subjects compared with the high dimensional EMG data set and high variance in pain location. Thus, these data should be considered preliminary findings for further exploration. Interestingly, patients who had pain for a longer duration showed more improvement in NRS than is shown in the literature. SCS has been shown to have a success rate of 85% if implantation occurs within two years of pain symptoms appearing.[33] It is important to note that this study only looked at short-term effects of SCS implantation, and NRS scores were assessed three months after surgery.

CONCLUSION

To our knowledge, this is the first study to discuss ways that coverage of a patient's painful dermatomes through evoked responses intraoperatively correlates with outcomes at three months.

Authorship Statements

Marisa DiMarzio, Tessa Harland, Steven Paniccioli, John Dalfino, Yohannes Iyassu, Bryan L. McLaughlin, and Julie G. Pilitsis performed the experiments; Deepak Berwal, Alejandra Quintero, and Marisa DiMarzio analyzed data; Ilknur Telkes, Alejandra Quintero, and Julie G. Pilitsis interpreted the results of the experiments; Deepak Berwal, Alejandra Quintero, Marisa DiMarzio, and Deborah R. Morris prepared the figures and tables; Deepak Berwal and Alejandra Quintero drafted the manuscript; Alejandra Quintero, Ilknur Telkes, Marisa DiMarzio, Deborah R. Morris, and Julie G. Pilitsis edited and revised the manuscript. All authors reviewed the final manuscript. Bryan L. McLaughlin and Julie G. Pilitsis approved the final version of the manuscript.

Conflict of Interest

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SUPPLEMENTARY DATA

To access the supplementary material accompanying this article, visit the online version of *Neuromodulation: Technology at the Neural Interface* at www.neuromodulationjournal.org and at https://doi.org/10.1016/j.neurom.2024.08.004.

REFERENCES

1. Cohen SP, Vase L, Hooten WM. Chronic pain: an update on burden, best practices, and new advances. *Lancet*. 2021;397:2082–2097.
2. Rojo E, Pérez Hernández C, Sánchez Martínez N, et al. Real-world cost-effectiveness analysis of spinal cord stimulation vs conventional therapy in the management of failed back surgery syndrome. *J Pain Res*. 2021;14:3025–3032.
3. Yang S, Zhong S, Fan Y, et al. Research hotspots and trends on spinal cord stimulation for pain treatment: a two-decade bibliometric analysis. *Front Neurosci*. 2023;17:1158712.

4. Zhou M, Zhong H, Xing C, et al. Comparison of clinical outcomes associated with spinal cord stimulation (SCS) or conventional medical management (CMM) for chronic pain: a systematic review and meta-analysis. *Eur Spine J*. 2023;32:2029–2041.
5. Zajacova A, Grol-Prokopczyk H, Zimmer Z. Pain trends among American adults, 2002–2018: patterns, disparities, and correlates. *Demography*. 2021;58:711–738.
6. Hoikkanen T, Nissen M, Ikäheimo TM, Jyrkkänen HK, Huttunen J, von Und Zu Fraunberg M. Long-term outcome of spinal cord stimulation in complex regional pain syndrome. *Neurosurgery*. 2021;89:597–609.
7. Maher C, Underwood M, Buchbinder R. Non-specific low back pain. *Lancet*. 2017;389:736–747.
8. Mekhail N, Levy RM, Deer TR, et al. Long-term safety and efficacy of closed-loop spinal cord stimulation to treat chronic back and leg pain (Evoke): a double-blind, randomised, controlled trial. *Lancet Neurol*. 2020;19:123–134.
9. Petersen EA, Schatman ME, Sayed D, Deer T. Persistent spinal pain syndrome: new terminology for a new era. *J Pain Res*. 2021;14:1627–1630.
10. Vallejo R, Gupta A, Cedeno DL, et al. Clinical effectiveness and mechanism of action of spinal cord stimulation for treating chronic low back and lower extremity pain: a systematic review. *Curr Pain Headache Rep*. 2020;24:70.
11. Kurt E, Noordhof RK, van Dongen R, Vissers K, Henssen D, Engels Y. Spinal cord stimulation in failed back surgery syndrome: an integrative review of quantitative and qualitative studies. *Neuromodulation*. 2022;25:657–670.
12. Hwang R, Field N, Kumar V, et al. Intraoperative neuromonitoring in percutaneous spinal cord stimulator placement. *Neuromodulation*. 2019;22:341–346.
13. Telkes I, Hadanny A, DiMarzio M, et al. High-resolution spinal motor mapping using thoracic spinal cord stimulation in patients with chronic pain. *Neurosurgery*. 2022;91:459–469.
14. Bryson N, Lombardi L, Hawthorn R, et al. Enhanced selectivity of transcutaneous spinal cord stimulation by multielectrode configuration. *J Neural Eng*. 2023;20:046015.
15. Hofstoetter US, Perret I, Bayart A, et al. Spinal motor mapping by epidural stimulation of lumbosacral posterior roots in humans. *iScience*. 2021;24:101930.
16. Howell B, Lad SP, Grill WM. Evaluation of intradural stimulation efficiency and selectivity in a computational model of spinal cord stimulation. *PLoS One*. 2014;9:e114938.
17. Shils JL, Arle JE. Intraoperative neurophysiologic methods for spinal cord stimulator placement under general anesthesia. *Neuromodulation*. 2012;15:560–571 [discussion: 571–562].
18. Schlaeppi JA, Schreen R, Seidel K, Pollo C. Intraoperative neurophysiological monitoring during spinal cord stimulation surgery: a systematic review. *Neuromodulation*. 2023;26:1319–1327.
19. 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.
20. 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.
21. Berwal D, Quintero A, Telkes I, et al. Improved selectivity in eliciting evoked electromyography responses with high-resolution spinal cord stimulation. *Neurosurgery*. 2024;95:322–329.
22. Paul AR, Kumar V, Roth S, Gooch MR, Pilitsis JG. Establishing minimal clinically important difference of spinal cord stimulation therapy in post-laminectomy syndrome. *Neurosurgery*. 2017;81:1011–1015.
23. Sabourin S, Tram J, Sheldon BL, Pilitsis JG. Defining minimal clinically important differences in pain and disability outcomes of patients with chronic pain treated with spinal cord stimulation. *J Neurosurg Spine*. 2021;35:243–250.
24. Mitchell B, Deckers K, De Smedt K, et al. Durability of the therapeutic effect of restorative neurostimulation for refractory chronic low back pain. *Neuromodulation*. 2021;24:1024–1032.
25. Deckers K, De Smedt K, Mitchell B, et al. New therapy for refractory chronic mechanical low back pain-restorative neurostimulation to activate the lumbar multifidus: one year results of a prospective multicenter clinical trial. *Neuromodulation*. 2018;21:48–55.
26. Maughan EF, Lewis JS. Outcome measures in chronic low back pain. *Eur Spine J*. 2010;19:1484–1494.
27. Anaya CJ, Zander HJ, Graham RD, Sankarasubramanian V, Lempka SF. Evoked potentials recorded from the spinal cord during neurostimulation for pain: a computational modeling study. *Neuromodulation*. 2020;23:64–73.
28. Barolat G. Epidural spinal cord stimulation: anatomical and electrical properties of the intraspinal structures relevant to spinal cord stimulation and clinical correlations. *Neuromodulation*. 1998;1:63–71.
29. Zander HJ, Graham RD, Anaya CJ, Lempka SF. Anatomical and technical factors affecting the neural response to epidural spinal cord stimulation. *J Neural Eng*. 2020;17:036019.
30. Costandi S, Kapural L, Mekhail NA, et al. Impact of long-term evoked compound action potential controlled closed-loop spinal cord stimulation on sleep quality in patients with chronic pain: an EVOKE randomized controlled trial study subanalysis. *Neuromodulation*. 2023;26:1030–1038.
31. Brucker-Hahn MK, Zander HJ, Will AJ, et al. Evoked compound action potentials during spinal cord stimulation: effects of posture and pulse width on signal features and neural activation within the spinal cord. *J Neural Eng*. 2023;20:046028.
32. Berwal D, Telkes I, Agarwal S, et al. Investigation of the intraoperative cortical responses to spinal motor mapping in a patient with chronic pain. *J Neurophysiol*. 2023;130:768–774.
33. Kumar K, Hunter G, Demeria D. Spinal cord stimulation in treatment of chronic benign pain: challenges in treatment planning and present status, a 22-year experience. *Neurosurgery*. 2006;58:481–496 [discussion: 481–496].

COMMENTS

Although this study reports on a relatively small number of patients, it will give the reader some insight into the use of EMGs in the perioperative assessment and targeting in patients presenting for SCS using surgical electrodes. It suggests that there is a correlation between muscle stimulation in the painful area and subsequent outcome at three months after SCS. It also supports other reports that anteroposterior spinal diameter and the associated size of the cerebrospinal fluid space correlates with the amount of postoperative energy required for stimulation and the clinical outcome. It provides a useful background that both the authors and other readers might wish to build on with further studies.

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In spinal cord stimulation, objective measurements to identify the "hot spot" still relied on anatomic features and in case of awake patients, implants based on the patient's cooperation. This study describes a potential tool that is objective to optimize the positioning and therefore the pain-reducing effect. I look forward to further studies with longer follow-up time and extended groups.

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