



Correlation Between Single-Pulse and Pulse-Train Stimulation During Neuromonitoring of Thoracic Pedicle Screws in Scoliosis Surgery

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■ BACKGROUND: The use of thoracic pedicle screws (TPSs) during scoliosis surgery entails an inherent risk of neurological deficit. Triggered electromyography (t-EMG) is an accurate neuromonitoring test for detection of malpositioned TPSs. However, single-pulse (SP) t-EMG stimulation has shown variable capability for detecting medial pedicle breaches, while pulse-train (PT) t-EMG could be more accurate. The aim of this study was to analyze the correlation between SP t-EMG and PT t-EMG.

■ METHODS: This retrospective study included 20 patients who underwent scoliosis correction with 294 TPSs placed. A total of 588 tests with both SP t-EMG and PT t-EMG were performed, analyzed, and compared. The results of both t-EMG techniques were stratified into 3 different groups according to threshold obtained: group 1 (≤ 6 mA), group 2 (6.1–11.9 mA), and group 3 (12 mA). A generalized linear model was used to analyze the correlation between the methods.

■ RESULTS: SP t-EMG elicited response in 5 screws (1.7%) at ≤ 6 mA, 28 screws (9.5%) at 6.1–11.9 mA, and 261 screws (88.8%) at 12 mA. PT t-EMG elicited response in 16 screws (5.4%) at ≤ 6 mA, 30 screws (10.2%) at 6.1–11.9 mA, and 248 screws (84.4%) at 12 mA. There is a strong positive and significant association between SP t-EMG and PT t-EMG with a decrease ratio of 2% (95% confidence interval 1% to 3%).

■ CONCLUSIONS: SP t-EMG and PT t-EMG stimulation techniques had similar results when the stimuli were applied to TPSs, but PT t-EMG may have better efficacy in low-threshold group.

INTRODUCTION

Posterior all-screw construction is the most common method of instrumentation in scoliosis correction surgery.¹ Because of the increased incidence of pedicle dysplasia, vertebral rotation, and spinal cord concave proximity in patients who undergo scoliosis correction surgery, the use of thoracic pedicle screws (TPSs) entails an inherent risk of neurological deficit or spinal canal stenosis if a screw breaches the medial wall of any thoracic pedicle.^{2–4} Correct positioning of the screw in the thoracic pedicle is dependent on tract palpation, screw placement, image control, and intraoperative multimodal neuro-monitoring (IONM) when available.

Intraoperative imaging employing fluoroscopy or computed tomography scanning and navigation enables detection of malpositioned TPSs, but the accuracy is quite variable.^{5–8} IONM encompasses several modalities. These include transcranial motor evoked potentials (TcMEPs), which are both sensitive and specific for diagnosing spinal cord injury; somatosensory evoked potentials (SSEPs), which have a high specificity for detecting spinal cord injury, but are not considered a real-time method of

Key words

- Neuromonitoring
- Pulse-train
- Scoliosis
- Single-pulse
- t-EMG
- Thoracic pedicle screws

Abbreviations and Acronyms

IONM: Intraoperative multimodal neuromonitoring
PT: Pulse-train
SP: Single-pulse
SSEP: Somatosensory evoked potential
t-EMG: Triggered electromyography
TcMEP: Transcranial motor evoked potential
TPS: Thoracic pedicle screw

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neuromonitoring, as it only alerts the surgeon of an injury that occurred some minutes earlier; and triggered electromyography (t-EMG), which generally offers an accurate and real-time detection of a malpositioned TPS.^{9,10}

Electrical stimulation of TPSSs for evaluation of safe placement using single-pulse (SP) t-EMG stimulation has shown variable effectiveness for detecting pedicle breaches.¹¹ Traditionally, the electromyography response is recorded from the intercostal and abdominal effector muscles of each level of the spine, and lower t-EMG thresholds suggest that the cortical bone of the pedicle has been breached or that the TPS is near neurological structures. Previous studies have shown that SP t-EMG stimulation is reliable in detecting medially displaced pedicular screws in the lumbosacral region, but findings from studies evaluating SP t-EMG stimulation neuromonitoring during instrumentation in the thoracic spine are less consistent.^{3,9,12-14} Therefore, another method that has been described for detecting medially displaced TPSSs is t-EMG using a brief high-frequency 4-pulse train or pulse-train (PT) stimulation, which, in contrast to SP t-EMG, may more accurately detect medially malpositioned TPSSs using t-EMG of lower limb muscles.¹⁵⁻¹⁸ The aim of this study was to correlate the responses to SP t-EMG stimulation and PT t-EMG stimulation during scoliosis surgery.

MATERIALS AND METHODS

Study Design and Data Collection

Following institutional review board approval, a retrospective cohort study of 20 patients who underwent scoliosis correction with posterior spinal instrumentation and IONM from 2016 to 2019 at National Institute of Traumatology and Orthopaedics and Spine Institute of Rio de Janeiro was carried out. A total of 294 TPSSs were evaluated with both SP and PT t-EMG methods. Thus, 588 t-EMG stimulation tests were performed and compared. Intraoperative data were collected from 17 female and 3 male patients with a mean age of 18.1 years (range, 10–44 years); 12 patients were ≤ 18 years old. The etiologies of scoliosis included 16 idiopathic, 2 syndromic, 1 neuromuscular, and 1 thoracogenic. The mean preoperative Cobb angle was 67.7° (range, 47°–109°).

Anesthesia Protocol

The anesthesia protocol for scoliosis surgery with IONM was performed in a conventional fashion. In our protocol, anesthetic induction in adults is performed with 15-second bolus infusions of propofol and fentanyl with target plasmatic concentrations of 4 $\mu\text{g/mL}$ and 5 $\mu\text{g/mL}$, respectively, and induction doses of rocuronium 0.6 mg/kg and lidocaine 1.5 mg/kg. Rocuronium is reversed with sugammadex 2 mg/kg when necessary, and halogenated agents are avoided. Anesthetic maintenance is achieved by total intravenous anesthesia, with propofol at a target plasmatic concentration of 2–4 ng/mL, varying according to a bispectral index of 40–60, and continuous infusion of remifentanyl at 0.1–0.3 $\mu\text{g/kg/minute}$. In children < 12 years old, induction is performed with sevoflurane and nitrous oxide, followed by venoclysis and continuous infusion of propofol with immediate suspension of inhalation agents. All patients are kept normothermic with a warming blanket.

Surgical Technique

Following a standard posterior approach for scoliosis correction, pedicle instrumentation is done by the freehand technique, which consists of pedicle pilot hole preparation with either a curved awl or a drill bit. Next, the surgical team palpates all 5 walls of the pedicle tract with a ball-tipped probe and then inserts the TPS.⁷ All screws were composed of a titanium alloy and ranged in diameter from 4.0 mm to 6.5 mm. If during the pilot hole preparation a significant disruption of any of the 5 walls of the pedicle occurs that compromises fixation of the screw in the bone or puts at risk neurological or vascular integrity, this pedicle is skipped and left without instrumentation. After all the TPSSs are inserted, imaging control is done with fluoroscopy, according to the criteria of Kim et al.¹⁹

Neuromonitoring Technique

Both SP t-EMG and PT t-EMG readings were obtained by stimulating the shaft of the screw. Any t-EMG stimulus value < 12 mA was considered an alarm criterion and the fluoroscopy was rechecked. If any one of the Kim criteria was not met, the screw was withdrawn, and the pedicle tract was examined with the ball-tipped probe. The screw could be reinserted into the same tract, redirected, or not reinserted. The medially displaced screws that were not reinserted remained in the statistical analysis.

The neuromonitoring team protocol for stimulation and recording involves the placement of bilateral pairs of subdermal needles in the following muscles: C8-T1, abductor digiti minimi; T2-T6, axillary chest wall midline; T6-T12, abdominis rectus; L1-L2, iliopsoas; L3, quadriceps; L4-L5, tibialis anterior; S1-S2, abductor hallucis; S4, external anal sphincter. Cadwell Elite (Kennewick, Washington, USA) 32-channel neuromonitoring equipment was used. Current was delivered via a handheld probe against the TPS and returned via electrodes in the ipsilateral paravertebral tissue. SP t-EMG stimulation was a monophasic constant current pulse with a maximum intensity of 12 mA at a rate of 3.1 Hz and 100 μs of pulse duration, while PT t-EMG stimulation consisted of 4 200- μs square-wave pulses, with interpulse intervals within each train of 2 ms and intertrain frequency of 3 Hz. The filter settings were different for each neuromonitoring modality, ranging from 3000 Hz to 30 Hz in t-EMG and TcMEPs; 2000 Hz to 30 Hz in SSEPs, and 70 Hz to 1 Hz in electroencephalography. Besides continuous monitoring of the spinal cord by SSEPs and TcMEPs, after each TPS placement, TcMEP monitoring was repeated, and if there were no changes, the screw was maintained in that position pending t-EMG.

Once all the TPSSs were placed, threshold electromyography responses from leg muscles during PT t-EMG or responses from abdominal and intercostal muscles during SP t-EMG were recorded. We elected a maximum searching stimulus intensity of 12 mA. If an electromyography response was noted, the intensity was gradually reduced to the lowest reading that still elicited a response. The results of t-EMG from both techniques were stratified into 3 different groups for comparison: group 1 (≤ 6 mA), alarm criterion for possible clinically significant breaches; group 2 (6.1–11.9 mA), alarm criterion to alert the surgeon for medial breach; and group 3 (12 mA), possibly well-positioned screws.

Statistical Analysis

The association analysis was performed using a generalized linear mixed model or multilevel modeling, referred to here as model 1, which consists of identifying fixed and random effects considering the t-EMG stimulus response from each TPS from different levels of the thoracic spine of the same patient. This analysis indicated that t-EMG responses in different TPSSs of the same patient are not dependent as initially assumed; thus, it was possible to apply parametric methods without violating the assumption of independence. Therefore, a generalized linear model, referred to here as model 2, was used; it was chosen respecting the principle of parsimony, without a substantial difference in the Akaike information criterion. All statistical analyses were performed using Excel (Microsoft Corporation, Redmond, Washington, USA) or R version 4.0.2 (R Foundation for Statistical Computing, Vienna, Austria). A *P* value < 0.05 was considered significant.

RESULTS

The mean postoperative Cobb angle was 22.3° (range, 7°–54°), which corresponds to a scoliosis correction of 68.4%. None of the 20 subjects had any alarm changes in SSEPs or TcMEPs at any time during their procedures. A total of 294 TPSSs were assessed separately by SP t-EMG stimulation and by PT t-EMG stimulation (Table 1). Most of the screws showed responses at similar threshold levels, and there were no major discrepancies.

Table 1. Single-Pulse and Pulse-Train Triggered Electromyography According to Threshold Groups

SP t-EMG	PT t-EMG			Total
	≤6 mA	6.1–11.9 mA	12 mA	
≤6mA	3	2	0	5
	60.00%	40.00%		100%
	18.75%	6.67%		—
	1.02%	0.68%		1.70%
6.1–11.9 mA	13	12	3	28
	46.43%	42.86%	10.71%	100%
	81.25%	40.00%	1.21%	—
	4.42%	4.08%	1.02%	9.52%
=12 mA	0	16	245	261
		6.13%	93.87%	100%
		53.33%	98.79%	—
		5.44%	83.33%	88.78%
Total	16	30	248	294
	—	—	—	—
	100%	100%	100%	—
	5.44%	10.20%	84.35%	100%

SP, single-pulse; t-EMG, triggered electromyography; PT, pulse-train.

Among the 294 TPSSs tested using the 2 techniques across thoracic levels, SP t-EMG elicited response in 5 screws (1.7%) at ≤6 mA, in 28 screws (9.5%) at 6.1–11.9 mA, and in 261 screws (88.8%) at 12 mA. PT t-EMG elicited response in 16 screws (5.4%) at ≤6 mA, in 30 screws (10.2%) at 6.1–11.9 mA, and in 248 screws (84.4%) at 12 mA (Table 1). Only 34 TPSSs had a response on threshold in a different group (Figure 1). Of these 34 screws, 29 (85.3%) showed response on SP t-EMG in a higher threshold group compared with PT t-EMG (Figure 2). The most common SP t-EMG and PT t-EMG values were 12 mA (Figure 3), observed in 245 TPSSs, and a positive and linear relationship between SP t-EMG and PT t-EMG of the 294 TPSSs was observed (Figure 4).

Three TPSSs were removed and not replaced after a lower threshold in the t-EMG stimulation tests when fluoroscopic findings and track palpation indicated a medially misdirected screw. We elected to maintain the results of SP t-EMG and PT t-EMG for these 3 screws in the statistical analysis. No postoperative neurological deficit was observed. One adolescent patient experienced transient chest wall pain, which could indicate thoracic nerve root irritation owing to a misdirected TPS despite a normal t-EMG result with both techniques.

Because of possible variability of pedicle and spinal canal diameters and spinal cord location at different levels of the thoracic spine, there may not be a single ideal threshold stimulus intensity for all thoracic levels, and thus multiple generalized linear mixed models were used.¹⁴ Other unusual possibilities of the t-EMG response are bilateral abnormal responses in the case of misplaced screws, when the TPS is near the spinal cord, which is known as the diffusion phenomenon, or when the TPS is breaching the ipsilateral foraminal area.^{15,20}

We chose to present the model that best summarizes the main findings. Although the SP t-EMG (value and dichotomic) responses were significant, model 1 did not have a significant intercept (Table 2). In addition, it did not adjust the data well for SP t-EMG values 12 mA (Figure 5). As for the random effects of model 1, the patient effect (random intercept) was significant for only 4 (20% of 20) patients, and little significance was observed for specific t-EMG response per patient (Figure 6). Thus, model 1 was not sufficiently well adjusted to be used as a

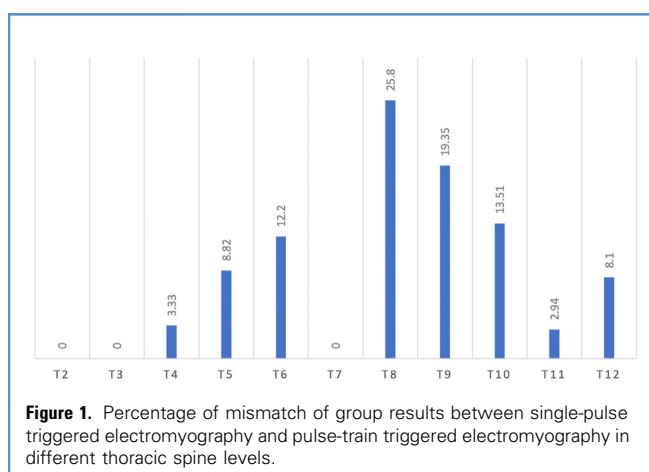


Figure 1. Percentage of mismatch of group results between single-pulse triggered electromyography and pulse-train triggered electromyography in different thoracic spine levels.

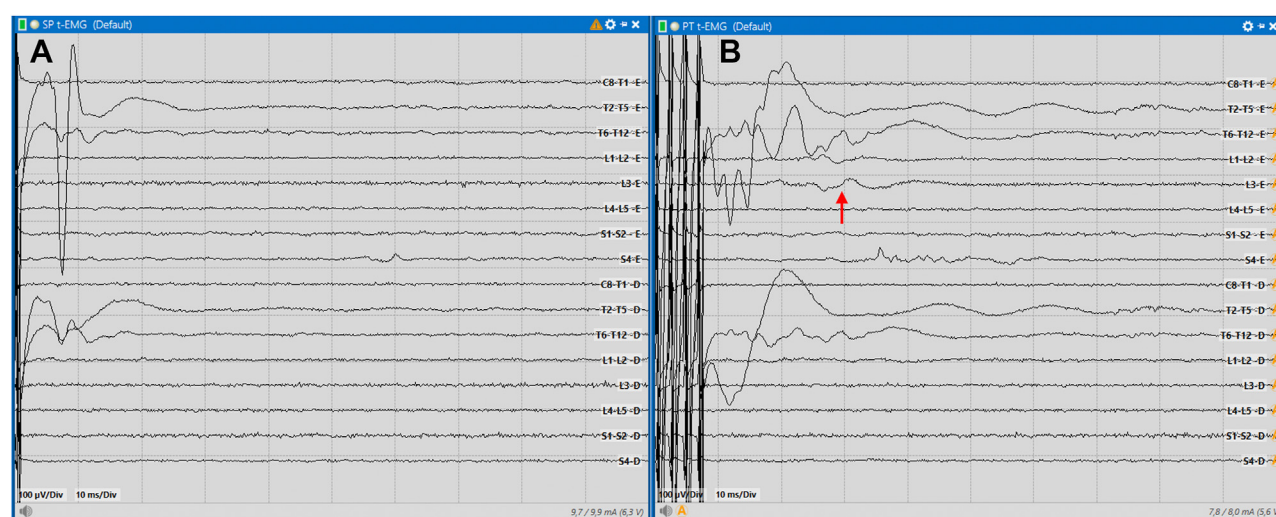


Figure 2. Thoracic pedicle screws at T5 level on the left side. (A) Single-pulse triggered electromyography showing response with 10 mA. (B) Pulse-train triggered electromyography with response using 8 mA,

demonstrating activation of further muscles (red arrow). SP, single-pulse; t-EMG, triggered electromyography; PT, pulse-train.

predictor, but owing to the random results, it is possible to assume the independence of the data, even if they come from the same patient.

Given the assumption that t-EMG measures are independent, multiple generalized linear models were used. A simple model without intercept was chosen, using only information the SP t-

EMG to predict PT t-EMG response. This model demonstrated good adjustment with a significant factor and high determination coefficient (R^2) (Table 3). Therefore, model 2 was chosen using the results of the residual analysis (Figure 7), and because it is more parsimonious, it required the fewest parameters. Thus, PT t-EMG can be obtained using the

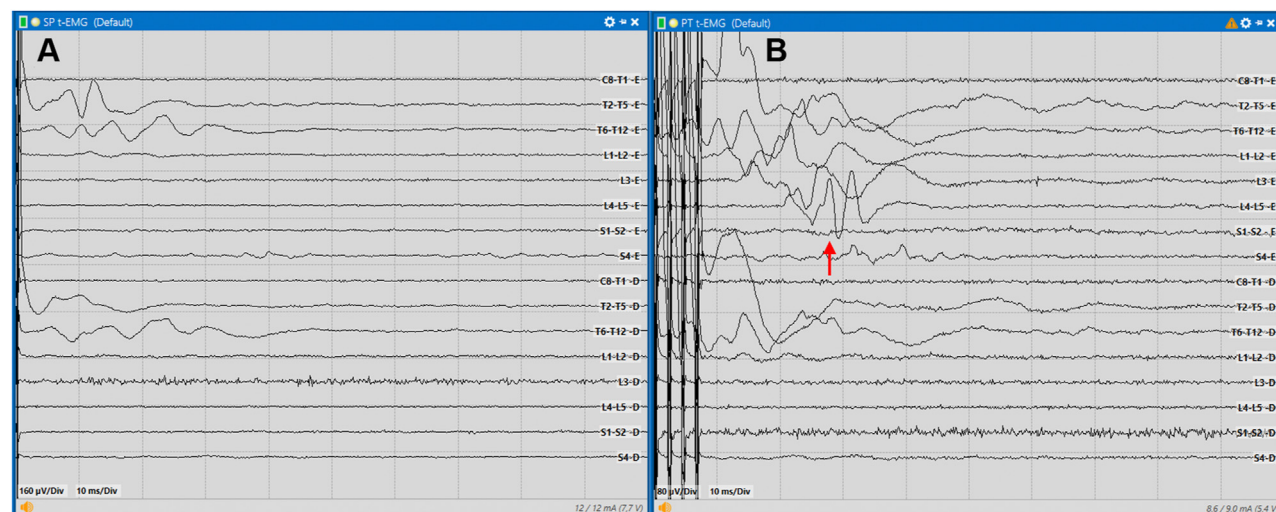


Figure 3. Thoracic pedicle screws at T11 level on the left side. (A) Single-pulse triggered electromyography evincing response with 12 mA. (B) Pulse-train triggered electromyography showing response with 9 mA

and additional muscle responses (red arrow). SP, single-pulse; t-EMG, triggered electromyography; PT, pulse-train.

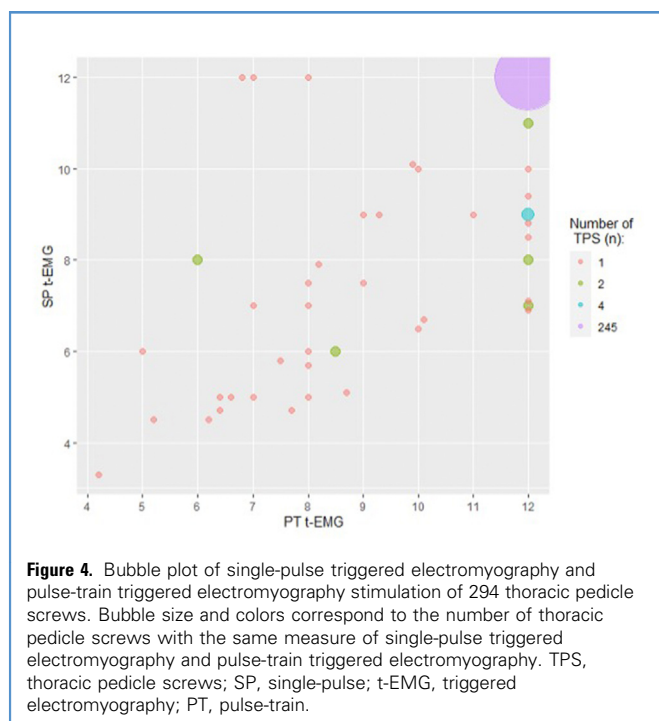


Figure 4. Bubble plot of single-pulse triggered electromyography and pulse-train triggered electromyography stimulation of 294 thoracic pedicle screws. Bubble size and colors correspond to the number of thoracic pedicle screws with the same measure of single-pulse triggered electromyography and pulse-train triggered electromyography. TPS, thoracic pedicle screws; SP, single-pulse; t-EMG, triggered electromyography; PT, pulse-train.

following equation: $PT\ t-EMG = 0.98 \times SP\ t-EMG$. We found a strong positive and statistically significant correlation between SP t-EMG and the PT t-EMG with a decreased ratio of only 2% (95% confidence interval 1% to 3%) (Table 3).

Table 2. Generalized Linear Mixed Models for Single-Pulse Triggered Electromyography (Model 1)

Fixed Effects	Estimates	CI	P Value
Intercept	2.83	−0.10 to 5.76	0.058
SP t-EMG (value)	0.55	0.24 to 0.87	0.001
SP t-EMG (dichotomic)	2.31	1.16 to 3.45	<0.001
Random Effects			
σ^2		0.94	
$\tau_{00Patient}$		9.47	
$\tau_{11Patient.SP\ t-EMG}$		0.06	
$\rho_{01Patient}$		−1.00	
$N_{Patient}$		20	
Observations		294	
Marginal R^2 /conditional R^2		0.662/0.724	
AIC		856.4083	
SP t-EMG (dichotomic): assumes 1 when t-EMG result is 12 mA and 0.			
CI, confidence interval; SP, single-pulse; t-EMG, triggered electromyography; AIC, Akaike information criterion.			

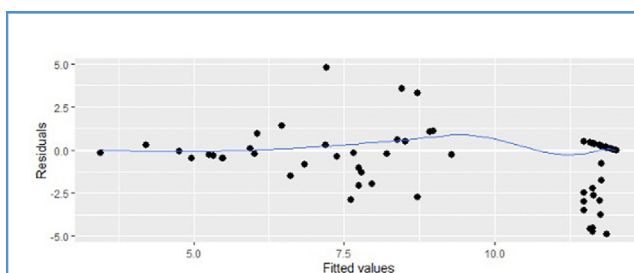


Figure 5. Homoscedasticity (constant variance of residues) of model 1.

DISCUSSION

Calancie et al.^{16,17} showed in a 2-part prospective blinded randomized study including multiple pathologies in a predominantly adult population that PT stimulation within the pedicle tract using a ball-tipped probe and electromyography of lower limb muscles correctly predicted all (100%) of the medially malpositioned screws. In their study, 802 screws were analyzed, and 32 screws were medially displaced at least 2 mm. The authors concluded that this novel neuromonitoring approach accurately predicts medially malpositioned TPSS, while lateral breach was unlikely to elicit a lower limb response when stimulated after direct depolarization of the corticospinal tract.^{16,17} However, the exact mechanism of the response is still debated, with some authors proposing a centrally activated H-reflex mechanism.²¹

In some studies, malpositioned TPSS were screws with any cortical pedicle breach, whereas in other studies, authors only considered pedicle breach exceeding 2 mm or half of the screw diameter inside the spinal canal as incorrect placement, usually with low t-EMG values.^{16,22,23} Other authors found 7 mA as the mean threshold for clinically significant breaches; thus, we chose ≤ 6 mA in our study. Intraoperative detection of such

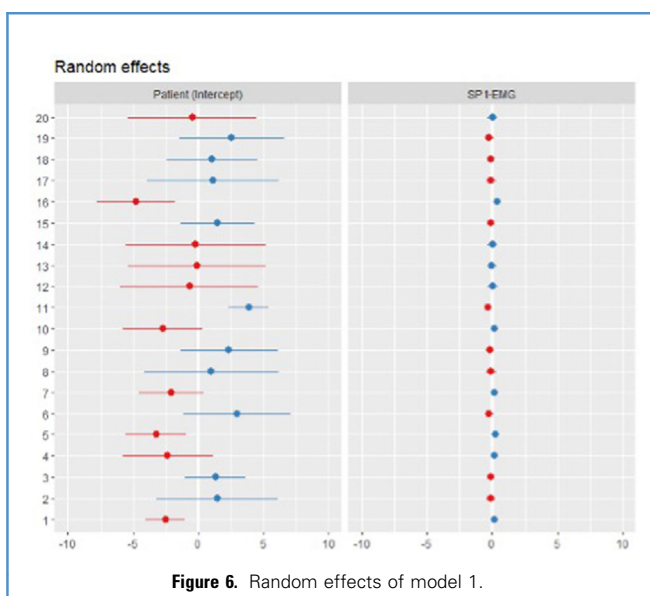


Figure 6. Random effects of model 1.

Table 3. Generalized Linear Model for Pulse-Train Triggered Electromyography (Model 2)

Parameters	Estimates	CI	P Value
PT t-EMG	0.98	0.97 to 0.99	<0.001*
Observations		294	
R^2 /Adjusted R^2		0.990/0.990	
AIC		901.5098	

CI, confidence interval; PT, pulse-train; t-EMG, triggered electromyography; AIC, Akaike information criterion.
*Statistically significant.

medial misplacement ensured that no patient needed to return to the operating room for TPS revision.^{15,17}

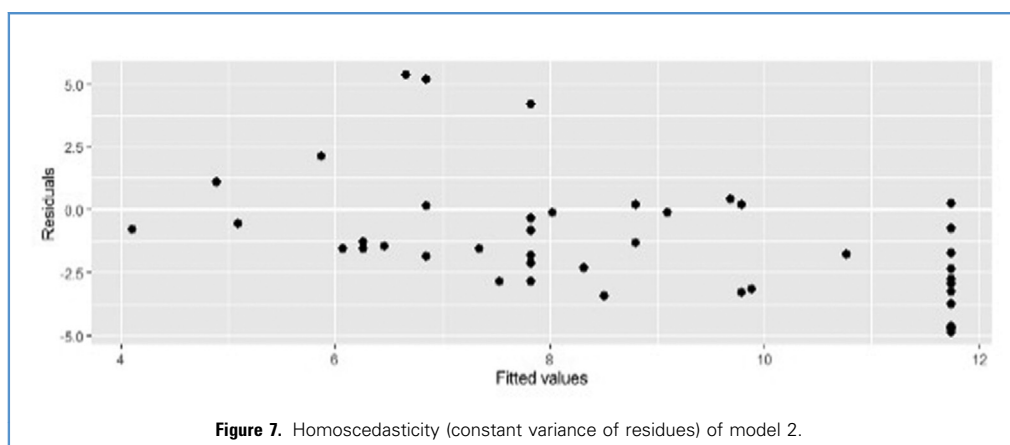
We restricted the maximum stimulus delivered on the TPS to 12 mA for both SP and PT t-EMG to avoid local contractions of the arm or hand (when testing T1–T3 pedicles) and to avoid back or abdominal muscle contractions at high stimulus intensity.¹⁵ While some authors increased threshold cutoffs to 15 mA and even 25 mA to minimize false-negative screws, we believe that a t-EMG current threshold of 6–11 mA provided the most accurate testing parameters while minimizing the likelihood of missing a medially malpositioned TPS.^{14,16,24,25} Again, the focus of our study was to examine the correlation of SP t-EMG and PT t-EMG, not the accuracy of TPS placement itself.

Correlation between t-EMG with SP and PT stimulation found excellent concordance in T11, T12, and L1 pedicle tracts in a study that considered pedicle screw insertion in L1 as part of the thoracic spine because of its close relationship to the end of the thoracic spinal cord.¹⁶ In our study, we found high agreement between both tests at T2, T3, T4, and T11, with more discrepancy observed at T8 and T9, possibly related to the degree of pedicle dysplasia. Some authors observed that independent of TPS position, in scoliotic curves the convex side has a higher threshold than the concave side (Figure 1).^{4,26}

In some instances, when the patient has a high number of dysplastic pedicles where insertion of the TPSs is challenging, disruption of the pedicle wall can be expected. The surgeon may choose to skip pedicles, inserting the TPSs at alternating levels. This strategy of lower screw density was used in several patients in our study; it minimizes the neurological risk without biomechanical compromise as well as reduces the cost of the surgery.^{15,27,28} Anatomical particularities at the upper levels of thoracic spine make correct TPS insertion more demanding.^{29,30} Intercostal muscles in the same region have been reported to be unreliable owing to overlap of the innervation of these muscles. To increase the accuracy of upper thoracic t-EMG, we use axillary electrodes between T2 and T6.²⁴

Because thoracic nerve roots are nonspecifically innervated, it is difficult to truly define a threshold value. Sometimes an intrinsic or anatomical characteristic of a patient does not allow a standard threshold value of t-EMG, as some patients are more hyperexcitable or hypoexcitable when stimulated, or they have a different bone tissue impedance because of osteoporosis or other associated factors. Other options to detect a medially misdirected screw placement are to evaluate a reduction of 60%–65% from the mean in t-EMG or to decrease the alarm criterion cutoff by 2 mA.^{16,29,31}

During pedicle tract preparation before inserting the TPSs, we performed careful palpation of the 5 walls of the pedicle to detect any breach. The accuracy of intraoperative pedicle tract palpation reported in the literature ranges from 40% to 85%.^{17,32} This suggests that this standard intraoperative step, which is designed to prevent misdirected TPS insertion, is less reliable than we would like to believe. Thus, IONM—specifically t-EMG—proved to be a more reliable modality to assess pedicle integrity. Although few publications presented findings of greater accuracy with pedicle tract t-EMG than screw stimulation (and pedicle tract t-EMG tends to have an average threshold lower than TPS stimulation), in our view, after creating the pedicle tract the TPSs can still be inserted in a skewed direction or false trajectory, or the wider diameter of TPSs (relative to the pedicle tract) may result in a clinically relevant breach of a pedicle wall. For all these reasons, many authors prefer screw stimulation in the operating room.^{14,29,30}

**Figure 7.** Homoscedasticity (constant variance of residues) of model 2.

In the literature, we encountered a description and comparison of SP and PT stimulation inside the pedicle tract, as was originally described for the lumbar spine,¹¹ showing lower thresholds using PT t-EMG except in patients with spinal cord hyperexcitability, and the assertion that PT t-EMG can cause false-positive alarm thresholds.¹⁶ When analyzing pedicle tract and TPS t-EMG neuromonitoring, we found only this comparison with PT t-EMG showing less stimulus intensity detected in the pedicle tract. In that study, there was no comparison between SP t-EMG and PT t-EMG after TPS insertion, and the target muscles chosen to analyze T1-T6 were assessed by intercostal electrodes instead of the axillary position, creating possible artifacts with the PT stimulus.^{16,17}

CONCLUSIONS

In this cohort of 20 mostly pediatric-age patients undergoing posterior spinal fusion and instrumentation for scoliosis correction under neuromonitoring with SP t-EMG and PT t-EMG, there was a strong, positive, and significant linear correlation between the 2 t-EMG methods with only a 2% difference when applied to TPSSs. Studies analyzing and comparing TPS t-EMG stimulation with SP and PT techniques have yet to yield a consensus. These findings suggest that the PT technique is at least equivalent to the conventional SP technique widely employed, and it may have superior efficacy in the low-threshold group.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Luis E. Carelli: Conceptualization, Methodology, Material preparation, Investigation, Formal analysis, Writing — original draft, Previous versions of the manuscript, Read and approved the final manuscript. **Luiz E. Almeida:** Conceptualization, Methodology, Material preparation, Investigation, Formal analysis, Writing — original draft, Previous versions of the manuscript, Read and approved the final manuscript. **Juan P. Cabrera:** Conceptualization, Methodology, Writing — original draft, Previous versions of the manuscript, Read and approved the final manuscript. **Ahsan Ali Khan:** Conceptualization, Methodology, Material preparation, Investigation, Formal analysis, Writing — original draft, Previous versions of the manuscript, Read and approved the final manuscript. **Maria L. Mendonça:** Conceptualization, Methodology, Previous versions of the manuscript, Read and approved the final manuscript. **Robson Teixeira Vital:** Conceptualization, Methodology, Previous versions of the manuscript, Read and approved the final manuscript. **Giuliana Vasconcelos de Souza Fonseca:** Conceptualization, Methodology, Material preparation, Investigation, Formal analysis, Previous versions of the manuscript, Read and approved the final manuscript. **Marcia M. Rodriguez Jardim:** Conceptualization, Methodology, Previous versions of the manuscript, Read and approved the final manuscript.

REFERENCES

- Crostell M, Mazza O, Mariani M, Mascello D. Treatment of severe scoliosis with posterior-only approach arthrodesis and all-pedicle screw instrumentation. *Eur Spine J*. 2013;22(Suppl 6): S808-S814.
- Parker SL, McGirt MJ, Farber SH, et al. Accuracy of free-hand pedicle screws in the thoracic and lumbar spine: analysis of 6816 consecutive screws. *Neurosurgery*. 2011;68:170-178.
- Reidy DP, Houlden D, Nolan PC, Kim M, Finkelstein JA. Evaluation of electromyographic monitoring during insertion of thoracic pedicle screws. *J Bone Joint Surg Br*. 2001;83:1009-1014.
- de Almeida LEPCA, da Silva LECT, de Castro CJ, de Souza Fonseca GV, Vital RT, Jardim MMR. Pedicle morphology in scoliosis: classification agreement for pre-operative evaluation. *Coluna/Columna*. 2020;19:176-179.
- Larson AN, Santos ERG, Polly DW, et al. Pediatric pedicle screw placement using intraoperative computed tomography and 3-dimensional image-guided navigation. *Spine (Phila Pa 1976)*. 2012;37: E188-E194.
- Santos ERG, Ledonio CG, Castro CA, Truong WH, Sembrano JN. The accuracy of intraoperative O-arm images for the assessment of pedicle screw position. *Spine (Phila Pa 1976)*. 2012;37: E119-E125.
- Ughwanogho E, Patel NM, Baldwin KD, Sampson NR, Flynn JM. Computed tomography-guided navigation of thoracic pedicle screws for adolescent idiopathic scoliosis results in more accurate placement and less screw removal. *Spine (Phila Pa 1976)*. 2012;37: E473-E478.
- Rampersaud YR, Pik JHT, Salonen D, Farooq S. Clinical accuracy of fluoroscopic computer-assisted pedicle screw fixation: a CT analysis. *Spine (Phila Pa 1976)*. 2005;30: E183-E190.
- Laratta JL, Ha A, Shillingford JN, et al. Neuromonitoring in spinal deformity surgery: a multimodality approach. *Global Spine J*. 2018;8:68-77.
- Schwartz DM, Auerbach JD, Dormans JP, et al. Neurophysiological detection of impending spinal cord injury during scoliosis surgery. *J Bone Joint Surg Am*. 2007;89:2440-2449.
- Calancie B, Leibold N, Madsen P, Klose K. Intraoperative evoked EMG monitoring in an animal model. A new technique for evaluating pedicle screw placement. *Spine (Phila Pa 1976)*. 1992;17: 1229-1235.
- Danesh-Clough T, Taylor P, Hodgson B, Walton M. The use of evoked EMG in detecting misplaced thoracolumbar pedicle screws. *Spine (Phila Pa 1976)*. 2001;26:1313-1316.
- Raynor BL, Lenke LG, Kim Y, et al. Can triggered electromyograph thresholds predict safe thoracic pedicle screw placement? *Spine (Phila Pa 1976)*. 2002;27:2030-2035.
- Mikula AL, Williams SK, Anderson PA. The use of intraoperative triggered electromyography to detect misplaced pedicle screws: a systematic review and meta-analysis. *J Neurosurg Spine*. 2016;24: 624-638.
- Donohue ML, Murtagh-Schaffer C, Basta J, Moquin RR, Bashir A, Calancie B. Pulse-train stimulation for detecting medial malpositioning of thoracic pedicle screws. *Spine (Phila Pa 1976)*. 2008;33:378-385.
- Calancie B, Donohue ML, Harris CB, et al. Implantation of thoracic pedicle screws: a blinded and randomized clinical study. Part 1. Methods and alarm criteria. *J Neurosurg Spine*. 2014;20: 675-691.
- Calancie B, Donohue ML, Moquin RR. Neuromonitoring with pulse-train stimulation for implantation of thoracic pedicle screws: a blinded and randomized clinical study. Part 2. The role of feedback. *J Neurosurg Spine*. 2014;20:692-704.
- Kozaki T, Tsutsui S, Yamada H. Transcranial motor evoked potentials electrically elicited by multi-train stimulation can reflect isolated nerve root injury more precisely than those by conventional multi-pulse stimulation: an experimental study in rats. *J Clin Monit Comput*. 2020;34:125-129.
- Kim YJ, Lenke LG, Cheh G, Riew KD. Evaluation of pedicle screw placement in the deformed spine using intraoperative plain radiographs: a comparison with computerized tomography. *Spine (Phila Pa 1976)*. 2005;30:2084-2088.
- de Blas G, Burgos J, Regidor I, et al. Recording diffusion responses from contralateral intercostal muscles after stimulus-triggered electromyography refining a tool for the assessment of thoracic pedicle screw placement in an experimental porcine model. *Spine (Phila Pa 1976)*. 2009;34:391-396.
- 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.

22. Duffy MF, Phillips JH, Knapp DR, Herrera-Soto JA. Usefulness of electromyography compared to computed tomography scans in pedicle screw placement. *Spine (Phila Pa 1976)*. 2010;35:43-48.
23. de Castro CJ, da Silva LECT, Almeida LE, et al. Intra- and interobserver analysis of pedicle screw placement in scoliosis correction. *Coluna/Columna*. 2020;19:172-175.
24. Regidor I, de Blas G, Barrios C, et al. Recording triggered EMG thresholds from axillary chest wall electrodes: a new refined technique for accurate upper thoracic (T2-T6) pedicle screw placement. *Eur Spine J*. 2011;20:1620-1625.
25. Barsotti CE, Gavassi BM, Prado FE, et al. Diagnostic accuracy of perioperative electromyography in the positioning of pedicle screws in adolescent idiopathic scoliosis treatment: a cross-sectional diagnostic study. *BMC Musculoskelet Disord*. 2020; 21:473.
26. de Blas G, Barrios C, Regidor I, et al. Safe pedicle screw placement in thoracic scoliotic curves using t-EMG: stimulation threshold variability at concavity and convexity in apex segments. *Spine (Phila Pa 1976)*. 2012;37:E387-E395.
27. Hwang CJ, Lee CK, Chang BS, Kim MS, Yeom JS, Choi JM. Minimum 5-year follow-up results of skipped pedicle screw fixation for flexible idiopathic scoliosis. *J Neurosurg Spine*. 2011;15:146-150.
28. Quan GMY, Gibson MJ. Correction of main thoracic adolescent idiopathic scoliosis using pedicle screw instrumentation: does higher implant density improve correction? *Spine (Phila Pa 1976)*. 2010;35:562-567.
29. Ugur HC, Attar A, Uz A, Tekdemir I, Egemen N, Genç Y. Thoracic pedicle: surgical anatomic evaluation and relations. *Clin Spine Surg*. 2001;14: 39-45.
30. Samdani AF, Tantorski M, Cahill PJ, et al. Triggered electromyography for placement of thoracic pedicle screws: is it reliable? *Eur Spine J*. 2011;20: 869-874.
31. Isley MR, Pearlman RC, Wadsworth JS. Recent advances in intraoperative neuromonitoring of spinal cord function: pedicle screw stimulation techniques. *Am J Electroneurodiagnostic Technol*. 1997; 37:93-126.
32. Donohue ML, Moquin RR, Singla A, Calancie B. Is in vivo manual palpation for thoracic pedicle screw instrumentation reliable? *J Neurosurg Spine*. 2014;20:492-496.

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