Threshold-based Monitoring of Compound Muscle Action Potentials for Percutaneous Pedicle Screw Placement in the Lumbosacral Spine: Can We Rely on Stimulation of the Uninsulated Screw to Provide a Valid Safety Warning?

Yoichi Tani, MD[a], Takanori Saito, MD, PhD[a], Shinichiro Taniguchi, MD, PhD[a], Masayuki Ishihara, MD [a], Masaaki Paku, MD [a], Takashi Adachi, MD, PhD [a], Muneharu Ando, MD, PhD [a], Nobuo Kohara, MD, PhD [a,b], Jun Kimura, MD, PhD [c]

[a] *Department of Orthopaedic Surgery, Kansai Medical University, Osaka, Japan*
[b] *Department of Neurology, Kobe City Medical Center General Hospital, Kobe, Japan*
[c] *Division of Clinical Electrophysiology, Department of Neurology, University of Iowa Health Care, Iowa City, Iowa 52242 USA.*

Correspondence author:

Yoichi Tani. MD,
Department of Orthopaedic Surgery
Kansai Medical University
2-5-1 Shinmachi, Hirakata-city, Osaka 573-1010, Japan
E-mail: taniyoic@gmail.com
Tel: +81-72-804-2436 FAX: +81-72-804-2439

The device(s)/drug(s) is/are FDA-approved or approved by corresponding national agency for this indication.
No funds were received in support of this work.
No relevant financial activities outside the submitted work.

Abstract

Study Design: A prospective analysis.

Objective: To test if threshold-based monitoring of compound muscle action potentials (CMAPs) by stimulating the screw loaded to uninsulated extender sleeve provides a valid safety warning for percutaneous pedicle screw (PPS) placements in the lumbosacral spine.

Summary of Background Data: Utility of the CMAP monitoring to PPS procedures remains controversial.

Methods: A series of 202 patients underwent a total of 1664 lumbosacral PPS placements under CMAP monitoring without fluoroscopic guidance. The monitoring consisted of stimulating the PPS assembled to uninsulated extender sleeve and recording CMAPs from the vastus medialis, biceps femoris, tibialis anterior, and medial gastrocnemius. Automated steps of a threshold hunting algorithm using 0.2-ms duration pulses of increasing intensities delivered at 2/s allowed quick determination of a minimum stimulation current to evoke >100-μV amplitude CMAPs.

Results: At L2 through S1 spines, postoperative CT scans identified 51 medial or inferior pedicle wall breaches of 1536 screws (3.3%) without neurologic complications. The ROC curve analysis determined the critical cut-off threshold value of 27 mA (74% sensitivity and 95% specificity) for predicting 35 breaches of 627 screws (5.6%) at L2 and L3, and of 17 mA (100% sensitivity, 98% specificity) for 16 of 909 (1.8%) at L4 through S1. While advancing the screw, 3 breaches (5.9%) showed a particularly low threshold of ≤6-mA, allowing the surgeon to immediately redirect the screw and retest the new trajectory as safe.

Conclusion: Screw stimulation with threshold hunting algorithm has a distinct advantage over the time-consuming insulated pilot hole stimulation, allowing an uninterrupted flow of the surgery. The present findings have documented practical usefulness and reliability of CMAP monitoring using direct stimulation of the PPS assembled to uninsulated extender sleeve.

Key Words: Percutaneous pedicle screw, pedicle screw stimulation, CMAP monitoring, Lumbsoacral spine, Pedicle breach, Threshold hunting algorithm, ROC curve analysis, Sensitivity, Specificity, Critical cut-off current intensity, Uninsulated extender sleeve

Level of Evidence: 2

Key Points

#. We tested if threshold-based monitoring of the lower limb CMAPs by stimulating the screw loaded to uninsulated extender sleeve provides a valid safety warning for lumbosacral PPS placements without fluoroscopic guidance.

#. Automated steps of a threshold hunting algorithm with increasing stimulus current delivered to PPS allowed quick determination of a minimum current intensity to evoke >100-μV amplitude CMAPs.

#. At L2 through S1 spines, postoperative CT scans identified 51 medial or inferior pedicle wall breaches of 1536 screws (3.3%) without neurologic complications.

#. The ROC curve analysis determined the critical cut-off threshold value of 27 mA (74% sensitivity and 95% specificity) for predicting 35 breaches of 627 screws (5.6%) at L2 and L3, and of 17 mA (100% sensitivity, 98% specificity) for 16 of 909 (1.8%) at L4 through S1.

#. The present findings have documented practical usefulness and reliability of CMAP monitoring using direct stimulation of the PPS assembled to uninsulated extender sleeve.

Mini Abstract

We monitored threshold-based compound muscle action potentials during 1664 lumbosacral percutaneous pedicle screw (PPS) placements without fluoroscopic guidance. Direct stimulation of the PPS assembled to uninsulated extender sleeve provided a valid safety warning in predicting medial or inferior pedicle breaches, particularly at L4 through S1 level.

Introduction

The pedicle screw (PS) placements in the lumbosacral spine, intended to lie entirely within the bone, may pass through the pedicle wall to irritate the nerve roots postoperatively. As shown in previous studies[1-9] and reviews,[10,11] which confirmed the original work by Calancie et al. (1994),[12] the threshold-based monitoring of compound muscle action potentials (CMAPs) provides valuable intraoperative safety measure during conventional open PS placement. This strategy consists of electrically stimulating either the pilot hole created in the pedicle for subsequent screwing or the screw itself and recording CMAPs from the lower-limb muscles. The technique relies on the principle that the pedicle presents an insulative barrier to low levels of current unless its wall breaches medially or inferiorly. The current flow would then take the path of least resistance at the insulation breakdown and excites the adjacent nerve roots evoking CMAPs with a low-level stimulation.

Recent emphasis on minimal invasiveness in spinal stabilization surgery has prompted spine surgeons to increasingly employ percutaneous pedicle screw (PPS) placement. In this approach, unlike open PS placement, the surgeon can rely on neither anatomic landmark nor tactile feedback when advancing the blunt-tipped probe into the vertebral body. Instead, widely used PPS instrumentation systems utilize fluoroscopyassisted guidewire insertion, followed by cannulated screw placements through minimal incisions. Threshold-based CMAP monitoring, therefore, should play a more important role for safe screw placement in PPS procedures than in the conventional open techniques. Only a limited number of PPS studies[13-19] and reviews[20,21] have, however, dealt with this type of neuromonitoring, probably for two reasons. First, percutaneous surgical techniques inevitably rely on fluoroscopy at the expense of radiation exposure. Second, minimal incisions call for the necessity of insulating the metallic instruments from the surrounding wet tissues to avoid the spread of current during stimulation.

We previously reported a lumbosacral PPS placement technique with a newly developed device named LICAP (Less Imaging Cannulated Awl and Probe) system, which requires neither fluoroscopy nor computer-aided navigations.[22,23] This technique helps eliminate the potential cumulative risk of repeated, low-dose radiation exposure to surgical teams. To further improve the technical precision, we have introduced threshold-based CMAP monitoring into the LICAP-assisted PPS technique,[24] resulting in a better result with no PPS-related nerve root compromise. The present study attempts to determine the critical cut-off values of threshold stimulus intensity for predicting medially or inferiorly misplaced PPSs identified by postoperative CT scans.

Materials and Methods

1. Patients

From August 2017 to August 2020, 202 patients (82 men), aged 44 to 89 (mean, 72) years, underwent a total of 1664 lumbosacral LICAP-assisted PPS placements with threshold-based CMAP monitoring at our institution. All agreed in writing to participate in the study after reading an informed consent form approved by the IRB. The indications for PPS instrumentation included spinal stenosis (106), spondylolisthesis (51), deformity (38), pyogenic spondylitis (4) and metastatic spinal tumor (3). We employed the LICAP-assisted PPS placement with CMAP monitoring even for spinal deformities unless they required vertebral osteotomies with wider opening of the surgical field.

2. Threshold-based CMAP monitoring

2.1. Surgical technique

As previously reported, we conducted lumbosacral PPS placements by using a set of newly developed devices without C-arm guidance or computer-aided navigation.[22,23] In brief, our equipment consisted of a pedicle targeting tool designed to identify and escort the cannulated awl to the correct starting point for cortical bone perforation, a guidewire that served to maintain the optimal position throughout the subsequent surgical steps and a cannulated, blunt-tipped probe, an equivalent of the "gearshift" used in conventional open PS placements. The surgeon could then advance the blunt-tipped probe searching for the cancellous bone track within the pedicle using tactile feedback as experienced in open techniques (Fig. 1-A, B). Through the pilot hole thus created in the pedicle, we finally inserted the cannulated self-tapping screw, which was loaded to extender sleeve, over the guidewire. The neuromonitoring then began using the NVM5® system (NuVasive, Inc., San Diego, California, USA) while advancing the screw through the pedicle.

2.2. Stimulation

A short-acting neuromuscular blockade, used only at induction of general anesthesia and not during surgery, usually left only a slight suppressive effect. Otherwise, we used a fast-acting reversal agent for immediate reversal of residual blockade effects. Prior to pedicle integrity testing, we delivered a train-of-four successive supramaximal stimulations to the fibular nerve at the knee and recorded CMAPs from the tibialis anterior muscle to confirm the muscle relaxation clearance.[10,21]

A clip (Reusable NV Clip) attached to the screwdriver served as the cathode with a pair of self-adhesive semicircular dual surface electrodes, each 32 mm in diameter, as anodes, mounted 2 cm apart (NVM5 Dual Gel Electrode) on the right or left buttock. Electrical stimulation consisted of a square wave, 0.2 ms in duration and up to 40 mA in intensity, delivered at a rate of 2/s. Over the course of rotating the handle on the screwdriver to advance the screw through the pedicle, the automated steps of a threshold hunting algorithm quickly found a threshold current intensity.

2.3. Recording

A pair of self-adhesive surface electrodes, placed bilaterally over the vastus medialis (L2, L3, L4), tibialis anterior (L4, L5), biceps femoris (L5, S1) and medial gastrocnemius (L5, S1, S2), allowed monitoring of L2 through S2 nerve roots with some overlap of myotomes.[25]An eight channel NVM5 system simultaneously registered evoked CMAPs from all sets of electrodes with oscilloscope settings for sensitivity at 100 μV/div and for bandpass filters at 10 Hz to 10 KHz. Another dual surface electrode,32 mm in diameter, served as the ground.

2.4. The multi-channel threshold hunting algorithm[26]

We used a NVM5® software for a patented rapid threshold hunting algorithm, which controlled stimulation and recording to quickly find the minimum current intensity that evokes >100-μV peak-to-peak amplitude CMAPs. It utilizes a combination of a bracketing method to find a range (bracket) and a bisection method to narrow the bracket. The process continued until the bracket width reached 0.1 mA. The display of the threshold current, thus determined, accompanied a color code; "red", "yellow" and "green" to indicate unsafe (≤ 6 mA), intermediate (7-10 mA) and safe (≥ 11 mA) levels.

3. Postoperative CT scan analysis

Using the postoperative CT scans, we identified the location of the pedicle screw breach as medial, lateral, superior or inferior and related it to the presence or absence of clinical symptoms. The amount of breach was quantified with a simple classification modified from Zdichavsky's grading system[27] as follows: Grade 0, no breach; Grade 1, breach less than half of screw diameter out of pedicle wall and Grade 2, breach more than half of screw diameter out of pedicle wall.

4. Receiver operating characteristic (ROC) curve analysis

We used ROC curve analysis to determine the critical cut-off threshold value for predicting medial or inferior pedicular breaches identified by postoperative CT scans. The analysis was conducted separately for the upper (L2 and L3) and lower (L4 through S1) spine groups of 627 and 909 screws. We excluded lateral and superior pedicular breaches from this analysis because PS-related nerve root compromise primarily involved medial or inferior pedicle wall with its proximity to the nerve root.[28] We also excluded the screws placed at L1, which innervates none of the muscles used in the current study.

5. Statistical analysis

We used t-test for comparing the threshold current intensities between correctly placed and medially or inferiorly misplaced PPSs for the screws at L2 through S1 as a whole and, for those in the subgroups of the upper and the lower spine groups, with $p < 0.05$

considered significant. The values represent mean ± standard error (SE) and corresponding 95% confidence intervals (CIs). For various cut-off threshold values, the graphical ROC curve was produced by plotting the calculated sensitivity (i.e., true positive rate) on the y-axis against 1−specificity (i.e., false positive rate) on the x-axis. We computed the area under the ROC curve (AUC) as a measure of an overall accuracy of the test and chose the point nearest to the upper left corner of the curves as a critical cut-off value. For all these analyses, we used SAS JMP software (SAS Institute Inc, Cary, NC, USA).

Results

Postoperative CT scans revealed the evidence of pedicle wall breaches for 120 of 1664 screws (7.2%) as shown in Table 1: 61 located medially, 53 laterally, 5 superiorly and one inferiorly. Postoperatively, all these patients remained clinically asymptomatic, despite identified breaches, with no signs of nerve root irritation or sensory/motor deficits, thus requiring no revision surgery for the misplaced screws.

The upper (L2 and L3) and lower (L4 through S1) spines combined, 51 of 1536 screws (3.3%) breached medially (50) or inferiorly (1) with 38 classified as grade 1 and 13 as grade 2. The incidence of PPS misplacement varied depending on the spinal level (Table

2). Analyzing all 1536 screws, the threshold current intensities showed significantly ($p < 0.001$) smaller values (mean ± SE) of 19.2 ± 0.9 mA for 51 displaced compared to 36.8 ± 0.2 mA for 1485 correctly placed screws. The corresponding scores in the upper spine group consisted of 22.2 ± 0.9 mA for 35 displaced and 38.5 ± 0.2 mA for 592 correctly placed screws ($p < 0.001$) (Fig. 2-A and Table 3), and in the lower spine group, 12.6 ± 1.7 mA for 16 displaced and 35.7 ± 0.2 mA for 893 correctly placed screws ($p < 0.001$) (Fig. 2-B and Table 3). Figures 1-A and B show distribution of the threshold current intensities for individual screws, combining those with 40 mA and any scores higher together, as shown on top of the scatterplots, in calculating mean thresholds.

Of the 51 displaced screws, 3 (5.9%) in 3 patients triggered a “red” color warning with particularly low threshold values, 3.5 mA, 5.0 mA and 5.0 mA, when advancing the screw at L3, L5 and L5. This alarm prompted the surgeon to withdraw both the screw and the guidewire and redirect the blunt-tipped probe to reposition the screw in a more lateral orientation. Stimulating the realigned screw yielded a higher threshold value of 40 mA, 40 mA and 31mA, indicating the pedicle integrity by color “green” in all 3 cases. Postoperative CT scans showed the correctly placed screws with the trajectory traces left by prior medial misplacement (Fig. 3), consistent with grade 1 breach for 2 and grade 2 for 1.

The ROC curve analysis determined the critical cut-off for the threshold current intensity of 27 mA (74% sensitivity, 95% specificity and 0.855 AUC) for the upper spines (Fig. 4-A) and of 17 mA (100% sensitivity, 98% specificity and 0.995 AUC) for the lower spines (Fig. 4-B).

Discussion

Accumulated evidence indicates that the threshold-based CMAP monitoring helps quickly verify correct PS placement during traditional open surgery.[1-12] Some surgeons, however, still question its true clinical value as the test yields few false positive but many false negative results or high specificity with low sensitivity[29-36] based on a recent meta-analysis of up to 22% of misplaced screws.[11] When applying this technique to PPS procedures, one of the main methodological concerns relates to an unintended current leakage to the surrounding wet tissues through the metallic instruments. The stimulus current, if delivered with a monopolar arrangement using the uninsulated PPS as the cathode and a needle or surface electrode as the anode placed nearby or remotely, would take multiple parallel pathways from one electrode to the other. To minimize this spread of current, some investigators use either a plastic tube or apply a surface insulative treatment on the pedicle access probe.[13-20] They then test the pilot hole by continuously stimulating a moving focal probe before PPS placement. Screw stimulation, as a final test, however, must employ the uninsulated metallic instruments because insulating the screw/extender sleeve assembly poses a practical difficulty. Such exhaustive preparation improves the accuracy of monitoring at the expense of an additional operative time, a major drawback not widely accepted by spine surgeons. We, therefore, conducted the CMAP monitoring only when advancing the screw through the pedicle, which may have possibly increased the threshold readings by a leakage of the stimulus current through uninsulated extender sleeve.

The present study has demonstrated that PPS stimulation even with a widely-used set of uninsulated metallic instruments serves well for monitoring purposes particularly for the L4, L5, and S1 roots. At these lower spine levels, categorical scatterplots for the breach (−) and breach (+) groups showed clearly different distributions without any outlier points (Fig. 2-B). Based on the ROC curve analysis for predicting postoperative medial or inferior pedicle breach at these levels (Fig. 4-B), we identified the critical cut-off for the current intensity of 17 mA (100% sensitivity, 98% specificity, and 0.995 AUC). This higher cut-off value than the specific searching intensities of 4 to 11 mA used in most previous studies[1-5,12,32] probably resulted from the leakage of the PS stimulus current towards surrounding tissues before reaching the site of pedicle wall breach. Others reported in open surgeries, that screw stimulation, even after carefully cleaning the surgical field and retracting soft tissue from the stud of the screw, still showed higher thresholds than pilot hole stimulation with various insulated pedicle access probes.[12,18]

The amount of current leakage, as a biasing factor with screw stimulation, theoretically should show unpredictable values. In practice, however, it remained nearly constant in the same intraoperative settings, resulting in only a small threshold variability in detecting pedicle breaches. The use of relatively large surface anodes located remotely from the surgical wound may account for this observation. With such a distant surface anode, unlike a needle inserted nearby, the stimulating current spreads more widely to render its effective fraction reaching the nerve root under study relatively constant irrespective of anodal position, which varies slightly from one patient to another.

In contrast to the lower spine group, the upper group showed a much greater threshold variability for pedicle breaches, making the monitoring less effective (Fig. 2-A). The ROC curve analysis (Fig. 4-A) revealed a reduced sensitivity of 74% for the critical cut-off of 27 mA, possibly reflecting the use of the vastus lateralis (L2 and L3) as the sole target muscle. Additional CMAP assessments from proximal lower-limb muscles such as the obturator-innervated adductor longus (L2, L3 and L4) and adductor magnus (L2, L3, L4 and L5) might have increased the test accuracy.

In the present series, we experienced a particularly low threshold of ≤ 6 mA breaches in 3 patients, necessitating prompt removal and repositioning of the screw in a more lateral orientation (Fig. 3). The automated system used in this study provided the surgical team with real-time identification of the low threshold intensity both visually and audibly. This nearly instantaneous feedback allowed the surgeon to immediately redirect the screw and retest the new trajectory as safe, avoiding nerve root compromise in all cases.

Threshold-based CMAP monitoring with PS stimulation plays a particularly important role in our LICAP-assisted PPS procedure, which relies on fluoroscopy only when pen marking the lateral border of each pedicle on the skin after positioning the patients prone with general anesthesia. Without further use of fluoroscopy, our threshold monitoring provides a useful addition to the surgeon's tactile feedback in avoiding nerve root irritation. The present data have indicated that the warning criterion of 17 mA will provide reliable safety feedback for PPS placements in the lower lumbosacral spines in preventing not only neurologic complications but also asymptomatic medial or inferior pedicle wall breaches. Screw stimulation with rapid threshold hunting algorithm has a distinct advantage over the time-consuming insulated pilot hole stimulation, allowing an uninterrupted flow of the surgery.

In PPS procedures without CMAP monitoring, lateral pedicle wall breach tends to occur more frequently than medial breach, as previously reported.[37,38] The pattern reversed to a medial breach preponderance by using the CMAP monitoring as experienced in this study. This interesting change in orientation may reflect the surgeons' mental effort to place the PPS more obliquely for better stability, if guided by this type of monitoring. The present findings have documented practical usefulness and reliability of CMAP monitoring using direct stimulation of the PPS assembled to uninsulated extender sleeve.

References

1. Maguire J, Wallace S, Madiga R, et al. Evaluation of intrapedicular screw position using intraoperative evoked electromyography. *Spine* 1995; 20:1068-74.

2. Glassman SD, Dimar JR, Puno RM, et al. A prospective analysis of intraoperative electromyographic monitoring of pedicle screw placement with computed tomographic scan confirmation. *Spine* 1995; 20:1375-9.

3. Lenke LG, Padberg AM, Russo MH, et al. Triggered electromyographic threshold for accuracy of pedicle screw placement: An animal model and clinical correlation. *Spine* 1995; 29:1585-91.

4. Clements DH, Morledge DE, Martin WH, et al. Evoked and spontaneous electromyography to evaluate lumbosacral pedicle screw placement. *Spine* 1996; 21:600-4.

5. Toleikis JR, Skelly JP, Calvin AO, et al. The usefulness of electrical stimulation for

assessing pedicle screw placement. *J Spinal Disord* 2000; 13:283-9.

6. Bose B, Wierzbowski LR, Sestokas AK. Neurophysiologic monitoring of spinal root function during instrumented posterior lumbar spine surgery. *Spine* 2002; 27:1444-50.

7. Raynor BL, Lenke LG, Bridwell KH, et al. Correlation between low triggered electromyographic thresholds and lumbar pedicle screw malposition: Analysis of 4857 screws. *Spine* 2007; 32:2673-8.

8. Pajewski TN, Arlet V, Phillips LH. Current approach on spinal cord monitoring: the point of view of the neurologist, the anesthesiologist, and the spine surgeon. Eur *Spine J* 2007; 16 (Suppl 2):S115-29.

9. Kaliya-Perumal AK, Charng JR, Niu CC, et al. Intraoperative electromyographic monitoring to optimize safe lumbar pedicle screw placement – a retrospective analysis. *BMC Musculoskelet Disord* 2017; 30;18(1):229. doi:10.1186/s12891-017-1594-1.

10. Holland NR. Lumbosacral surgery. In: Husain AM, ed. *Practical Approach to Neurophysiologic Intraoperative Monitoring*. Demos Medical Publishing Llc, New York: Demos, 2008: 139-54.

11. 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; 24:624-38.

12. Calancie B, Madsen P, Lebwohl N. Stimulus-evoked EMG monitoring during transpedicular lumbosacral spine instrumentation: Initial clinical results. *Spine* 1994; 19:2780-6.

13. Ozgur BM, Berta S, Khiatani V, et al. Automated intraoperative EMG testing during percutaneous pedicle screw placement. *Spine J* 2006; 6:708-13.

14. Bindal RK, Ghosh S. Intraoperative electromyography monitoring in minimally invasive transforaminal lumbar interbody fusion. *J Neurosug Spine* 2007; 6:126-32.

15. Wood MJ, Mannion RJ. Improving accuracy and reducing radiation exposure in minimally invasive lumbar interbody fusion. *J Neurosurg Spine* 2010; 12:533-9.

16. Wang MY, Pineiro G, Mummaneni PV. Stimulus-evoked electromyography testing of percutaneous pedicle screws for the detection of pedicle breaches: a clinical study of 409 screws in 93 patients. *J Neurosurg Spine* 2010; 13:600-5.

17. Malham GM, Goss B, Blecher C. Percutaneous pedicle screw accuracy with dynamic electromyography: The early experience of a traditionally open spine surgeon. *J Neurol Surg A* 2015; 76:303-8.

18. Troni W, Benech CA, Perez R, et al. Focal hole versus screw stimulation to prevent false negative results in detecting pedicle breaches during spinal instrumentation. *Clin Neurophysiol* 2019; 130:573-81.

19. Wu Y, Cohen D, Tellez M, et al. Application of different thresholds for instrumentation device testing in minimally invasive lumbosacral spine fixation. *J Clin Neurosci* 2020; 72:224-8.

20. Isley MR, Zhang XF, Balzer JR, et al. Current trends in pedicle screw stimulation techniques: Lumbosacral, thoracic, and cervical levels. *Neuordiagn J* 2012; 52:100-75.

21. Taylor WR, O'Brien RA, Cornwall GB, et al. The role of integrated neurophysiologic monitoring in XLIF. In: Ggdrich JA, Volcan IJ, eds. *Extreme Lateral Interbody Fusion*. 2nd ed. Quality Medical Publishing Inc, St. Louis; 2013:45–57.

22. Saito T. A new pedicle screw insertion technique for MIS-TLIF as a measure in reducing radiation exposure. In: Baba H, ed. OS NOW Instruction, No. 18: *Lumbar spine surgery.* Tokyo: Medical View Co., Ltd; 2011;85-93 (in Japanese).

23. Tani Y, Saito T, Taniguchi S, et al. A new technique useful for lumbosacral percutaneous pedicle screw placement without fluoroscopy or computer-aided navigation systems. *J Orthop Sci* 2021 (in press).

24. Tani Y, Saito T, Taniguchi S. Direct electrical stimulation of the pedicle screw as a

useful measure for successful percutaneous pedicle screw placement. *Clin Neurophysiol* 2019;130: e194-195.

25. Delagi EF, Perotto AO, Iazzetti J, et al. *Anatomic guide for the electromyographer: The limbs and trunk*, *5th ed*. Springfield, Illinois: CC Thomas; 1996.

26. Farquhar A. Multi-channel stimulation threshold detection algorithm for use in neurophysiology monitoring. *US patent 8*, 206, 312 B2. 2012.

27. Zdichavsky M, Blauth M, Knop C, et al. Accuracy of pedicle screw placement in thoracic spine fractures. *Eur J Trauma* 2004; 30:234-240.

28. Söyüncü Y, Yıldırım FB, Sekban H, et al. Anatomic evaluation and relationship between the lumbar pedicle and adjacent neural structures: An anatomic study. *J Spinal Disord Tech* 2005; 18:243-6.

29. Holland NR, Lukaczyk TA, Riley LH, et al. Higher electrical stimulus intensities are required to activate chronically compressed nerve roots. *Spine* 1998; 23:224-7.

30. Alemo S, Sayadipour A. Role of intraoperative neurophysiologic monitoring in lumbosacral spine fusion and instrumentation: a retrospective study. *World Neurosurg* 2010; 73:72-6.

31. Duffy MF, Phillips JH, Knapp DR, et al. Usefulness of electromyography compared to computed tomography scans in pedicle screw placement. *Spine* 2010; 35:E43-8.

32. Parker SL, Amin AG, Farber HF, et al. Ability of electromyographic monitoring to determine the presence of malpositioned pedicle screws in lumbosacral spine: analysis of 2450 consecutively placed screws. *J Neurosurg Spine* 2011; 15:130-5.

33. Skinner SA, Rippe DM. Threshold testing of lumbosacral pedicle screws: A reappraisal. *J Clin Neurophysiol* 2012; 29:493-501.

34. Kulik G, Pralong E, McManus J, et al. A CT-based study investigating the relationship between pedicle screw placement and stimulation threshold of compound muscle action potentials measured by intraoperative neurophysiological monitoring. *Eur*

Spine J 2013; 22:2062-8.

35. Sharan A, Groff MW, Dailey AT, et al. Guideline update for the performance of fusion procedures for degenerative disease of the lumbar spine. Part 15: Electrophysiological monitoring and lumbar fusion. *J Neurosurg Spine* 2014; 21:102-5.

36. Lee CH, Kim HW, Kim HR, et al. Can triggered electromyography thresholds assure accurate pedicle screw placements? A systematic review and meta-analysis of diagnostic test accuracy. *Clin Neurophysiol* 2015; 126:2019-25.

37. Gelalis ID, Paschos NK, Pakos EE, et al. Accuracy of pedicle screw placement: a systematic review of prospective in vivo studies comparing free hand, fluoroscopy guidance and navigation techniques. *Eur Sine J* 2012; 21:247-255.

38. Raley DA, Mobbs RJ. Retrospective computed tomography scan analysis of percutaneously inserted pedicle screws for posterior transpedicular stabilization of the thoracic and lumbar spine. *Spine* 2012; 37:1092-1100.

Table1. Distribution of pedicle breaches of all directions for PPSs placed at L1 through S1 spines

Vertebral level	No of screws	Breach(+)	%
L1	128	23	18
L2	289	43	15
L3	338	24	7
L4	372	17	5
L5	381	12	3
S1	156	1	1
Total	1664	120	7.2

PPS, percutaneous pedicle screw

Table2. Distribution of medial or inferior pedicle breaches for PPSs placed at L2 through S1 spines

Vertebral level	No of screws	Breach(+)	%
L2	289	21	7
L3	338	14	4
L4	372	9	2
L5	381	7	2
S1	156	0	0
Total	1536	51	3.3

PPS, percutaneous pedicle screw

Table3. Comparison of threshold current intensities between PPS stimulation with and without medial or inferior pedicle breach

	All screws (L2 through S1)			Upper spines (L2 and L3)			Lower spines (L4 through S1)		
	Breach(+)	Breach(-)	p-value*	Breach(+)	Breach(-)	p-value*	Breach(+)	Breach(-)	p-value*
Number of screws	51	1485	NA	35	592	NA	16	893	NA
Threshold current intensity (mA)									
Mean ± SE	19.2 ± 0.9	36.8 ± 0.2	< 0.001	22.2 ± 0.9	38.5 ± 0.2	< 0.001	12.6 ± 1.7	35.7 ± 0.2	< 0.001
[95% CI]	[17.5 - 20.9]	[36.5 - 37.1]		[20.5 - 23.9]	[38.0 - 38.9]		[9.3 - 15.8]	[35.3 - 36.1]	

*Calculated according to t-test

NA, not applicable; PPS, percutaneous pedicle screw; CI, confidence interval

Figure 1-A

Blunt finger dissection to locate the transverse process (TP) and the facet (left), followed by PTT insertion so that its bifid hook grips and straddles the base of the TP (right).

Figure 1-B

Cannulate awl with stylet escorted by the PTT perforates cortical bone (left). Then, blunt-tipped probe was advanced within the pedicle over a guidewire (right).

Figure 2-A

Threshold current for 592 correctly placed and 35 misplaced PPSs at L2 and L3. As we used "40" for thresholds of ≥40 mA, the dots line up together on top of the scatterplots.

Figure 2-B

The same arrangement as in Fig. 1-A for 893 correctly placed and 16 misplaced screws at L4 through S1. Note the dots lined up together at 40 mA for the same reason as in the Fig. 1-A.

Figure 3

A postoperative CT at L5 in a 57-year-old patient shows the correctly repositioned PPS with a trajectory trace of grade 2 breach (arrows) left by the medially misplaced prior PPS.

Figure 4-A

An ROC curve drawn by plotting the true positive rate of medial or inferior pedicle wall breaches as a function of the false positive rate for different cut-off values at L2 and L3.

Figure 4-B

An ROC curve computed in the same way as Fig. 3-A for L4 through S1 spines, showing "0.995" AUC and the critical cut-off value of 17 mA with 100% sensitivity and 98% specificity.

Figure1-A

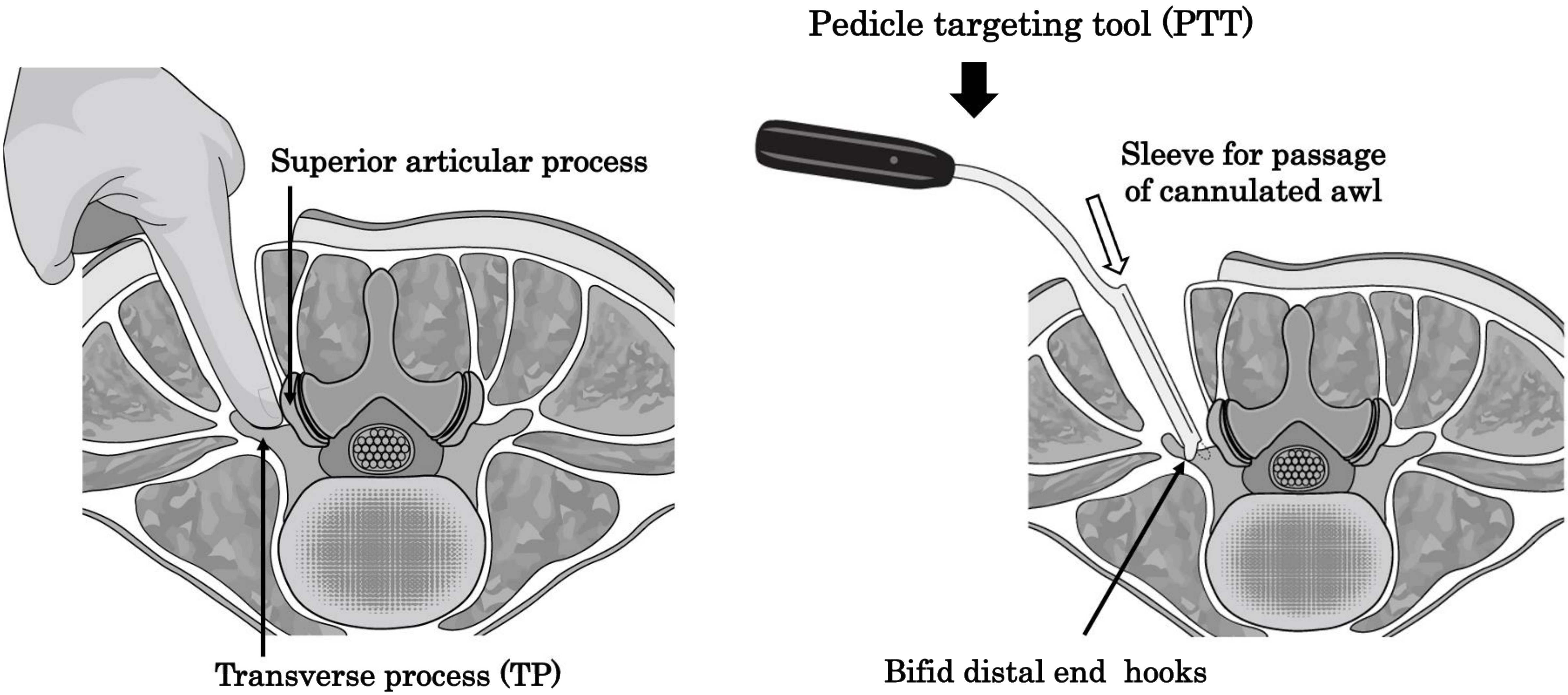

Superior articular process
Transverse process (TP)
Pedicle targeting tool (PTT)
Sleeve for passage of cannulated awl
Bifid distal end hooks

Figure1-B

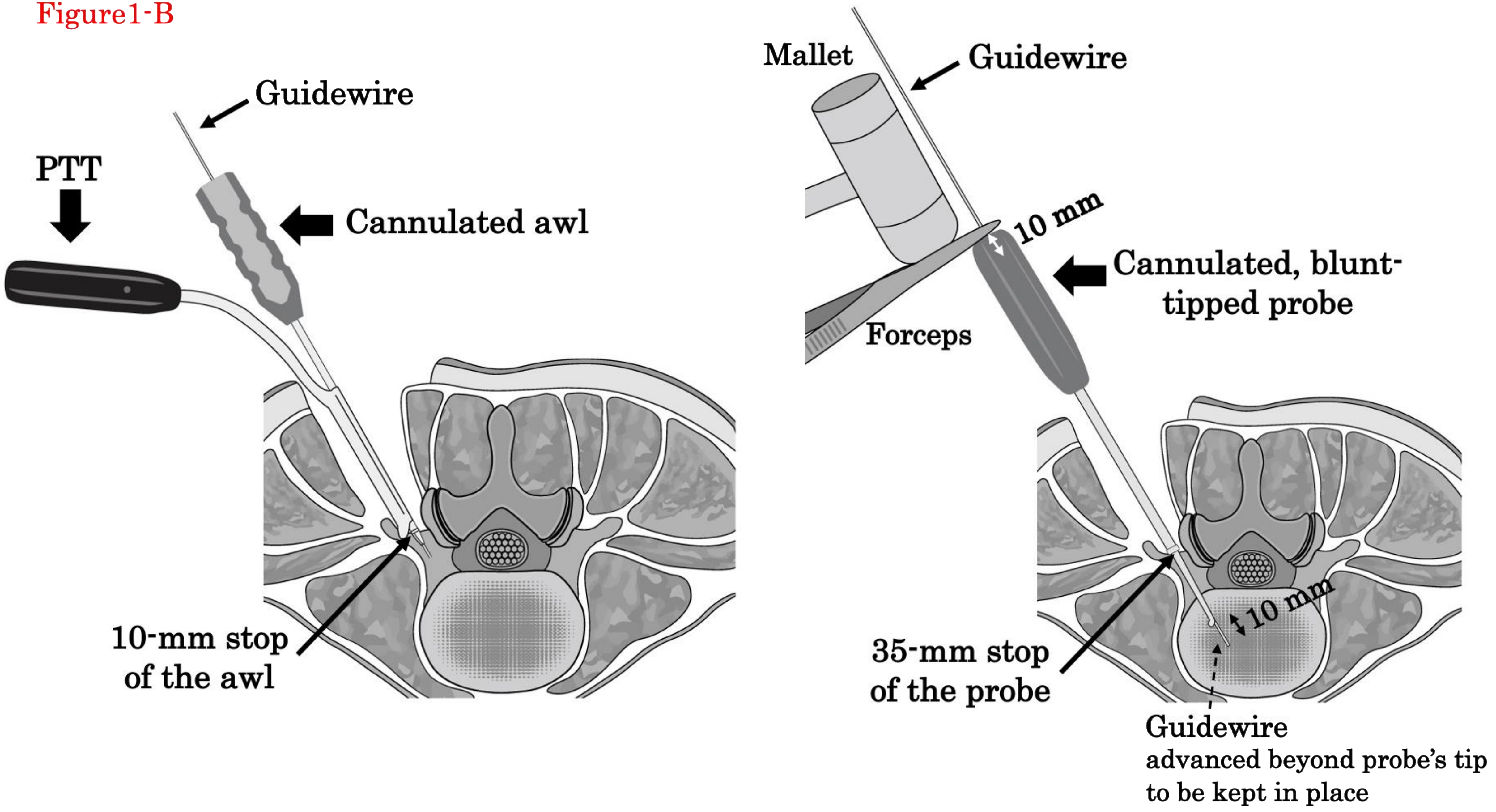

Guidewire
PTT
Cannulated awl
10-mm stop
of the awl
Mallet
Guidewire
10 mm
Cannulated, blunt-
tipped probe
Forceps
10 mm
35-mm stop
of the probe
Guidewire
advanced beyond probe's tip
to be kept in place

Figure2-A

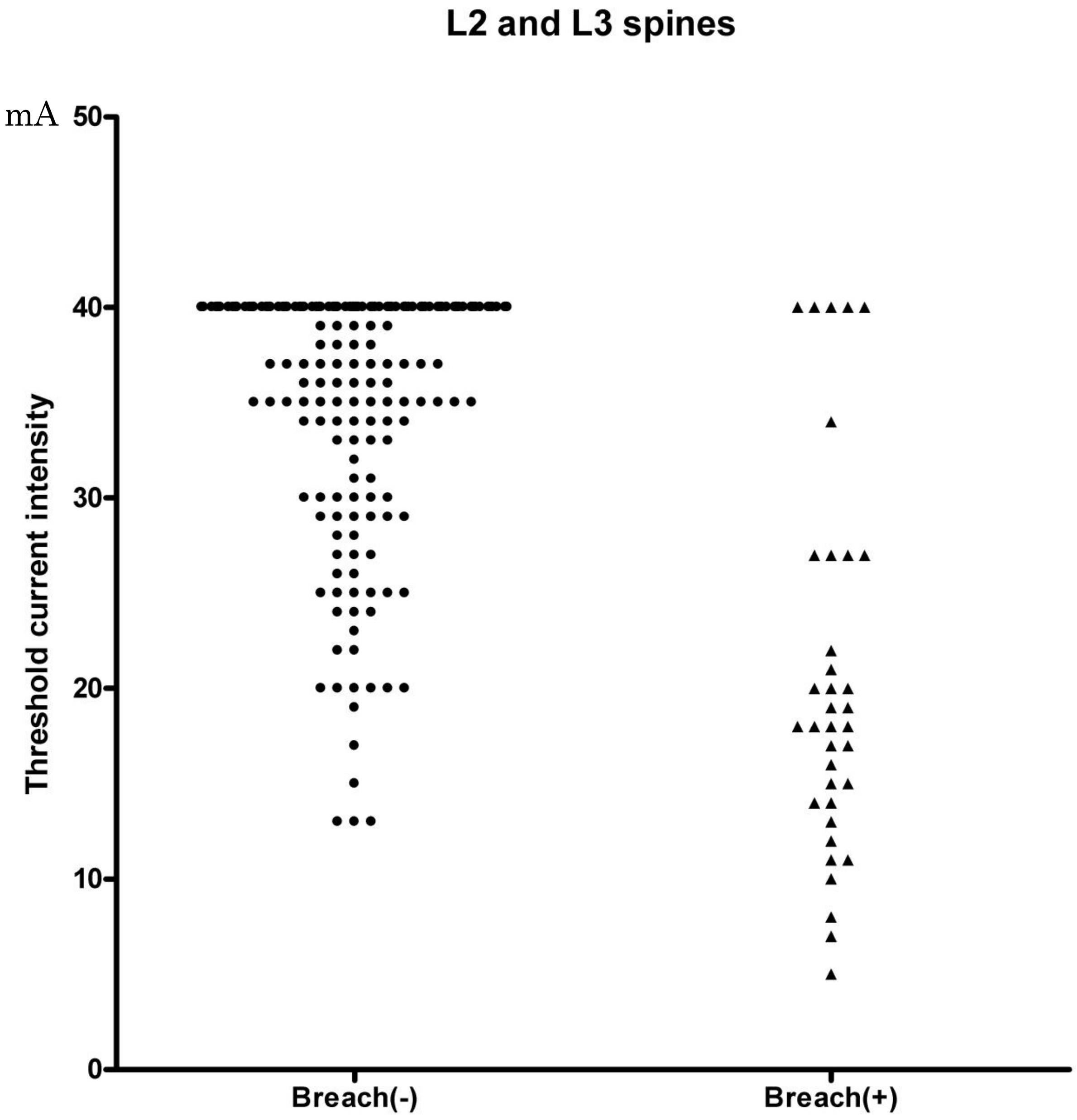

L2 and L3 spines
mA
50
40
30
20
10
0
Threshold current intensity
Breach(-)
Breach(+)

Figure2-B

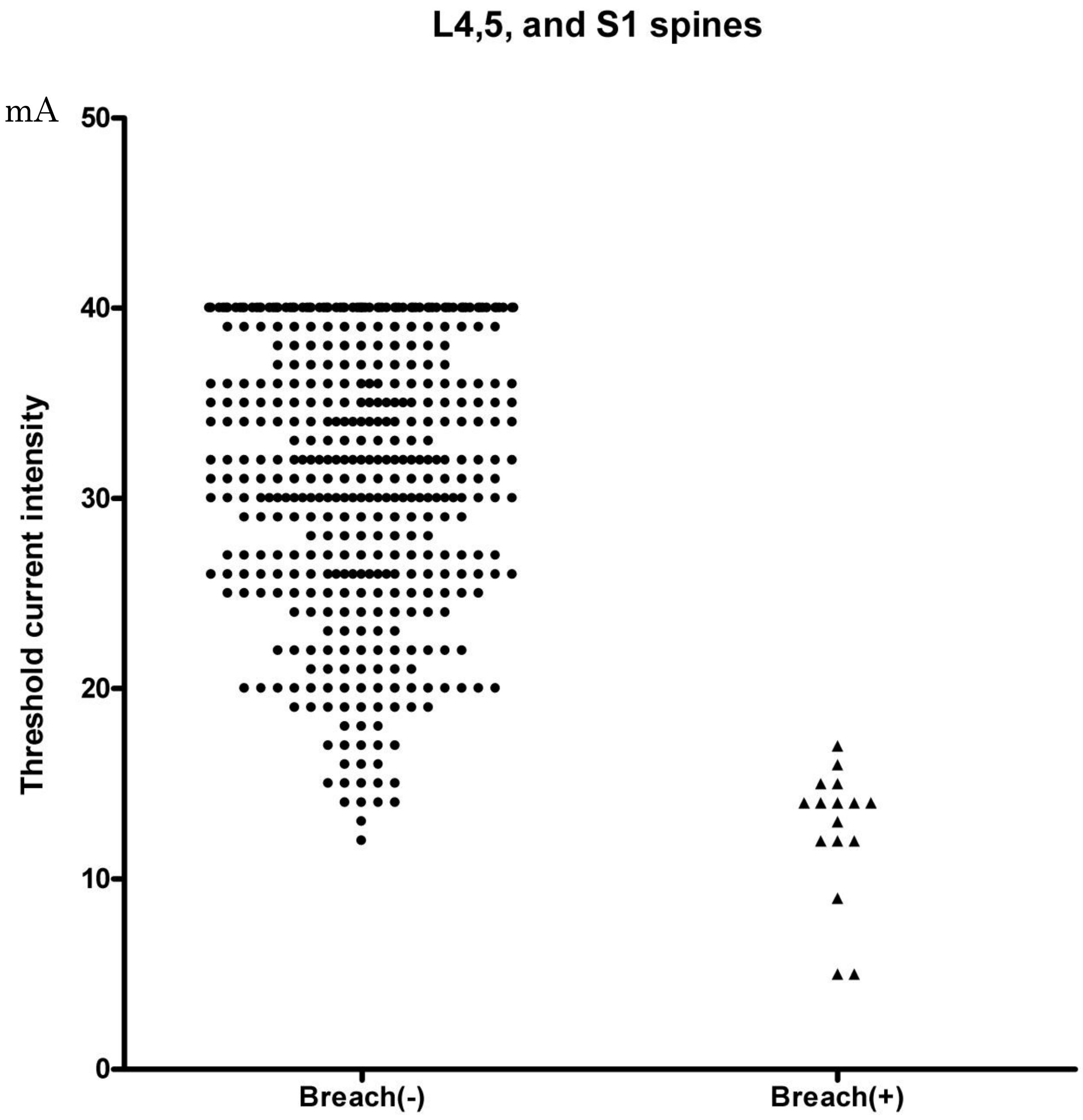

L4,5, and S1 spines
mA
Threshold current intensity
50
40
30
20
10
0
Breach(-)
Breach(+)

Figure3.

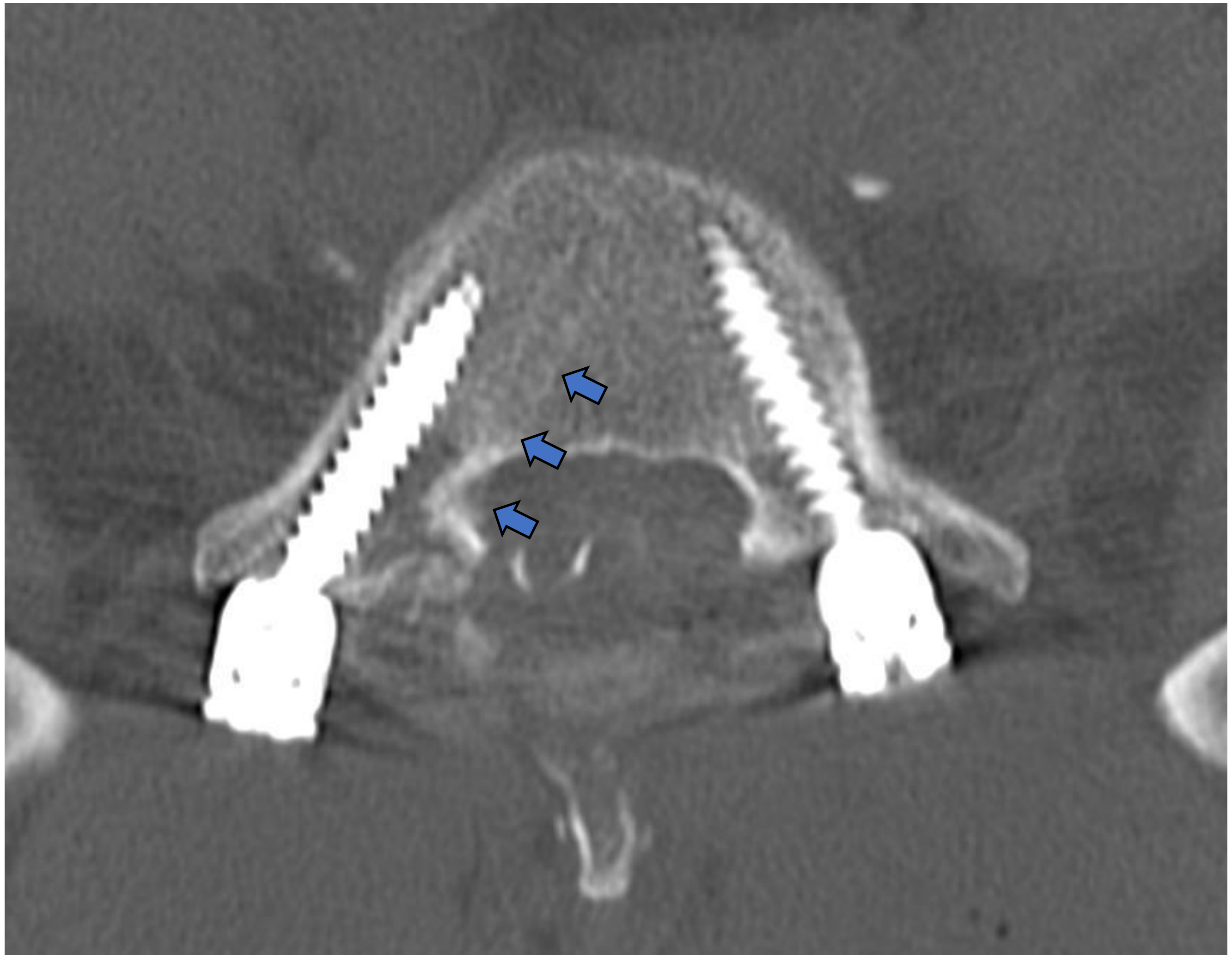


Figure4-A

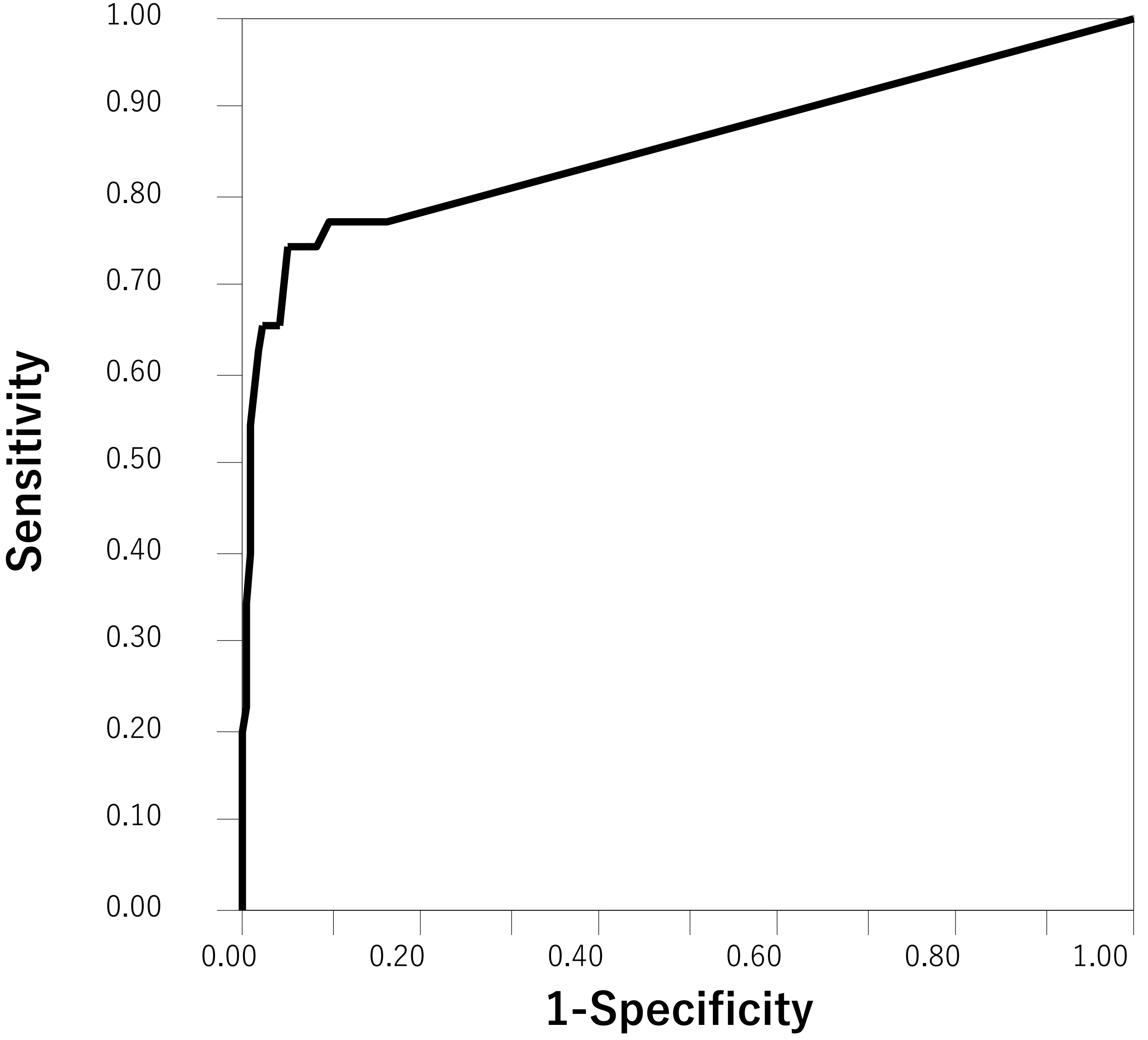
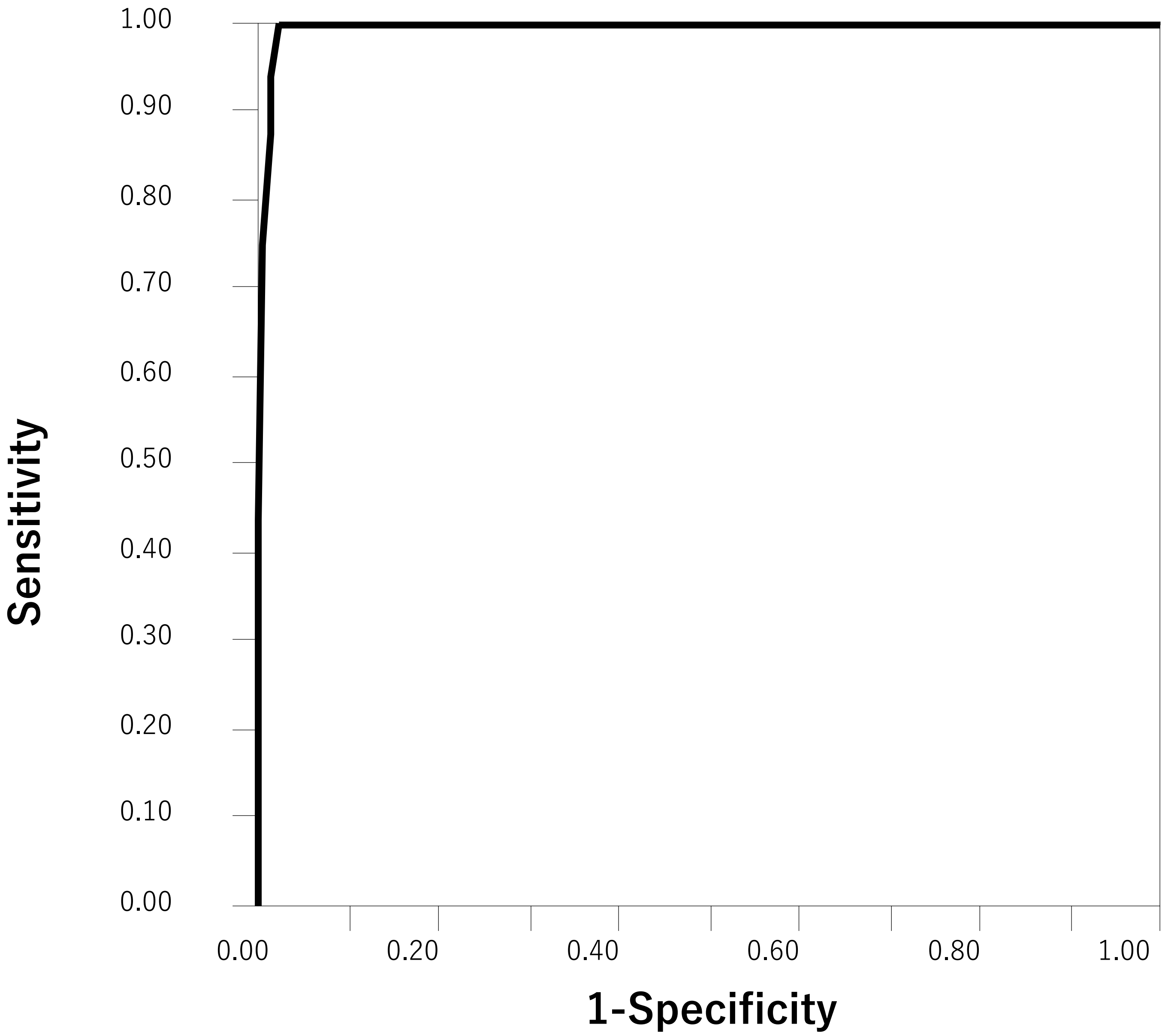

1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Sensitivity
0.00
0.20
0.40
0.60
0.80
1.00
1-Specificity

Figure4-B


1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Sensitivity
0.00
0.20
0.40
0.60
0.80
1.00
1-Specificity