Clinical Neurophysiology 130 (2019) 573–581

Contents lists available at ScienceDirect

Clinical Neurophysiology

journal homepage: www.elsevier.com/locate/clinph

Focal hole versus screw stimulation to prevent false negative results in detecting pedicle breaches during spinal instrumentation

Walter Troni [a,*], Carlo Alberto Benech [b], Rosa Perez [b], Stefano Tealdi [b], Maurizio Berardino [c], Franco Benech [b]

[a] Department of Neurology and Clinical Neurophysiology, Clinica Fornaca di Sessant, Corso Vittorio Emanuele II, 10128 Turin, Italy
[b] Department of Neurosurgery, Clinica Fornaca di Sessant, Corso Vittorio Emanuele II, 10128 Turin, Italy
[c] Department of Anesthesiology, CTO Hospital, Via Zuretti 29, 10126 Turin, Italy

See Editorial, pages 552–553

ARTICLE INFO

Article history:
Accepted 25 November 2018
Available online 26 December 2018

Keywords:
Intraoperative neuromonitoring
Stimulus-evoked EMG
Spinal fusion
Spinal instrumentation
Pedicle breakthrough
Pedicle screw

HIGHLIGHTS

- Triggered EMG to detect pedicle screw malposition is burdened with frequent false negative results.
- Focal nerve root stimulation within the hole prevents inadvertent leakage of stimulating current.
- The technique is simple and fast, provides unambiguous results and prevents false negative results.

ABSTRACT

Objective: We describe a stimulus-evoked EMG approach to minimize false negative results in detecting pedicle breaches during lumbosacral spinal instrumentation.
Methods: In 36 patients receiving 176 lumbosacral pedicle screws, EMG threshold to nerve root activation was determined using a focal probe inserted into the pilot hole at a depth, customized to the individual patients, suitable to position the stimulating tip at the point closest to the tested nerve root. Threshold to screw stimulation was also determined.
Results: Mean EMG thresholds in 161 correctly fashioned pedicle instrumentations were 7.5 mA ± 2.46 after focal hole stimulation and 21.8 mA ± 6.8 after screw stimulation. Direct comparison between both thresholds in individual pedicles showed that screw stimulation was always biased by an unpredictable leakage of the stimulating current ranging from 10 to 90%. False negative results were never observed with hole stimulation but this was not true with screw stimulation.
Conclusions: Focal hole stimulation, unlike screw stimulation, approaches absolute EMG threshold as shown by the lower normal limit (2.6 mA; $p < 0.05$) that borders the upper limit of threshold to direct activation of the exposed root.
Significance: The technique provides an early warning of a possible pedicle breakthrough before insertion of the more harmful, larger and threaded screw.

1. Introduction

In order to prevent injury to nerve roots caused by surgical procedures of lumbosacral transpedicular screw fixation, Calancie et al. (1992, 1994) pioneered a novel electrophysiological technique known as triggered electromyography (tEMG). This original approach was based on delivering electrical pulses through a surgical tool inserted in the pedicle hole or directly to the screw and determining the minimum amount of current (threshold) required to elicit barely discernible compound muscle action potentials

Abbreviations: tEMG, triggered electromyography; CMAP, compound muscle action potential; FHS, Focal Hole Stimulation; VM, Vastus Medialis; TA, Tibialis Anterior; PL, Peroneus Longus; SL, Soleus; FHB, Flexor Hallucis Brevis; Hole-*t*, threshold to hole stimulation; Screw-*t*, threshold to screw stimulation; HVES, high voltage electrical stimulation; OSS, optimal stimulus site; CDI, Current Dispersion Index.

* Corresponding author at: Viale dei Castagni 1, 10026 Revigliasco, Turin, Italy.
E-mail addresses: wtroni@yahoo.com (W. Troni), carloalbertobenech@hotmail.com (C.A. Benech), rossiperez@hotmail.com (R. Perez), stefanotealdi.nch@gmail.com (S. Tealdi), maurizio_berardino@fastwebnet.it (M. Berardino), franco.benech@unito.it (F. Benech).

https://doi.org/10.1016/j.clinph.2018.11.029
1388-2457/

(CMAPs) from myotomes innervated by the tested nerve root. Since intact cortical bone significantly increases impedance to current flow, any breach of the medial pedicle wall caused by hole formation or screw insertion, will result in a significant reduction of threshold, approaching the values observed after direct stimulation of exposed nerve roots, ranging from 1.2 to 3.8 mA (Calancie et al.,1994).

However, despite its robust rationale and the initial encouraging results (Calancie et al., 1992,1994; Clements et al., 1996), subsequent reports (Raynor et al., 2007; Alemo and Sayadipour, 2010; Parker et al., 2011; Kulik et al., 2013), pointed out that tEMG fails to detect misplaced pedicle screws more often than expected, sometimes unpredictably giving a reassuring but false high threshold in spite of a definite anatomical lesion of the medial pedicle wall.

Mikula et al. (2016) have recently performed a systematic meta-analysis to determine the actual capability of tEMG to detect misplaced pedicle screws. The Authors found that the technique, "has very high specificity but only fair sensitivity for detecting mispositioned pedicle screws". In other word, tEMG shows few false positive but many false negative results, the latter representing as much as 22% of pedicle instrumentations; moreover, considering that some papers evaluated the efficacy of tEMG only in relation to the reduction of post-operative neurological deficits, this percentage is likely to be even greater, given that not all misplaced screws cause neurological damage.

Any strategy to elucidate the current limits of tEMG must start from a basic consideration: a correct threshold must reflect the actual amount of current reaching the point of the hole closest to the examined nerve root (*root point*). This represents the true, *absolute* threshold to pedicle stimulation that does not necessarily coincide with the current strength supplied by the stimulator. Pedicle screws with high electrical resistance (>50 mA) have been reported and attributed to a poor quality of the contact between the screw shaft and the probe (Anderson et al., 2002). However, such implausible values are more likely to result from inadvertent leakage of the current stream towards surrounding tissues anywhere before reaching the proper stimulation site (Skelly et al., 1999).

The purpose of this paper is to determine the *absolute* tEMG thresholds through a strictly Focal Hole Stimulation (FHS) delivered within the pilot hole at the root point, previously located in the individual patient using pre-operatory CT scan images. In each pedicle instrumentation, threshold to FHS has been compared with that to conventional screw stimulation to quantify the leakage of the stimulating current occurring with screw stimulation. Essential aspects of the method have been recently presented elsewhere (Troni et al., 2018).

2. Materials and methods

2.1. Patient population

The study was performed on 36 consecutive patients undergoing vertebral stabilization for degenerative lumbosacral spinal disease. They were 24 males and 12 females, ranging in age from 43 to 73 years (mean: 58 ± 9). The study was conducted after approval by the local Ethics Committee. Written informed consent was obtained from all patients.

In all patients, the most common clinical complaints and the most frequent reason of surgical choice, were chronic or recurrent back pain and/or unilateral or bilateral radicular pain due to degenerative spondylosis or spondylolisthesis, iatrogenic instability secondary to decompression for herniated nucleus pulposus and/or spinal stenosis, trauma, as well as a variable combination of the above conditions.

All levels of spinal instrumentation in individual patients are listed in Supplementary Table S1.

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.clinph.2018.11.029.

2.2. Surgical procedure

Pedicle instrumentations were assembled according the shared procedure (Masferrer et al., 1998; Gaines, 2000). A free-hand pilot hole was first fashioned by means of pedicle bone probe according the conventional anatomical landmarks. The pilot hole was checked for pedicle breaches using a pedicle feeler and the screw was finally inserted. Standard titanium polyaxial pedicle screws have been used in all patients. Focal Hole Stimulation (FHS) was always performed immediately after removal of the pedicle feeler.

2.3. Recording

Compound muscle action potentials (CMAPs) were bilaterally recorded (Brain-AmpExG, Brain Product GmbH, Germany) using uninsulated subcutaneous stainless-steel needle electrode pairs from muscle districts representing all myotomes innervated by lumbosacral nerve roots involved in surgical procedure: Vastus Medialis (VM; L2-L4), Tibialis Anterior (TA; L4-L5), Peroneus Longus (PL; L5-S1), Soleus and Flexor Hallucis Brevis (SL, FHB; L5-S1-S2), with an inter-electrode distance of about 4 cm. The same sites were used to record maximal CMAPs to supramaximal trans-abdominal high voltage stimulation (HVES; Troni et al. 2013).

2.4. Focal Hole Stimulation (FHS)

Modified ball-type stimulating probes (EMS Medical®), fully insulated until the tip, were used to determine the EMG threshold (Hole-*t*) to nerve root activation through a focal stimulation within the just fashioned pilot hole (FHS) in a static condition (Fig. 1A). The distance between the origin of the planned hole (O) and the point of the hole trajectory intercepting the tested nerve root (R point) was previously measured on preoperative CT scan images (Fig. 2A). This measure determined in each patient the precise depth of probe insertion to position the stimulating tip at the point closest to the tested nerve root.

In a preliminary study carried out in 20 subjects of variable height and body constitution, OR distances ranged from 10 to 18 mm (Fig. 2A). Three types of stimulating probes, equipped with

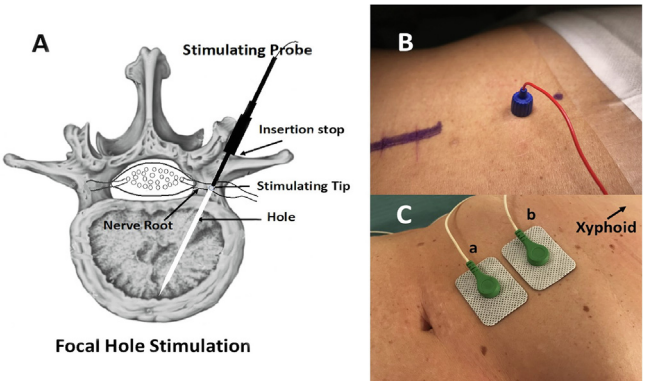

Fig. 1. A: schematic representation of FHS methodology: a modified ball type stimulating probe (EMS Medical®), fully insulated until the tip, was inserted into the hole at a depth, customized to the individual patients and dictated by the mechanical stop inserted in the probe, suitable to locate the stimulating tip as close as possible to the tested nerve root. B: a cork screw stimulating cathode was positioned at the proper vertebral level (Fig. 3) to perform supramaximal HVES of lumbosacral roots using the trans-abdominal stimulating montage. The ventral surface return electrodes for HVES (a) and FHS (b) are shown in C.

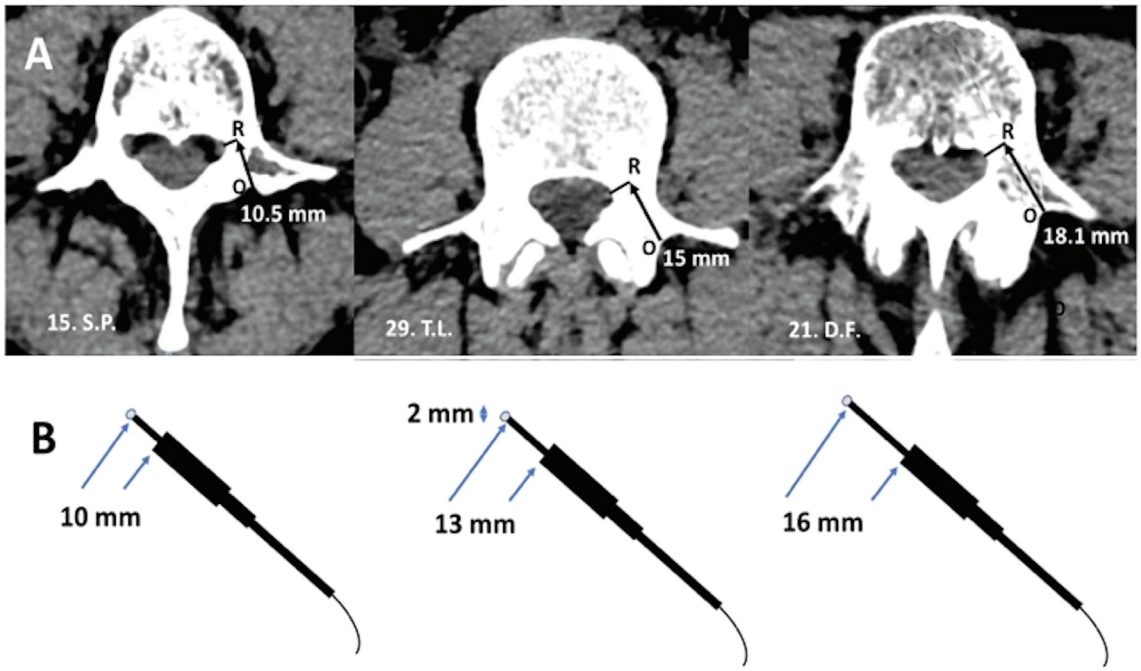

Fig. 2. A: The distance between the origin of the planned hole (O) and the point of the hole trajectory closest to the tested nerve root (R: root point), is shown on CT scan of 3 subjects well representing the whole range of OR intervals in normal population. B: three types of stimulating probes with increasing distances of 10, 13 and 16 mm from the terminal ball tip to the mechanical stop, were used to cover the whole range of OR variability.

a fixed mechanical stop placed 10, 13 and 16 mm away from the stimulating ball (Fig. 2B) were designed to cover the whole range of OR distances in our patient population. EMG threshold to FHS (Hole-*t*), as well as to screw stimulation, was the current intensity (mA) suitable to evoke muscle CMAPs of amplitude ranging between 50 and 100 μV in muscle districts innervated by the proper myotome. Constant current stimuli (0.2 ms) were delivered (Digitimer DS7A) at a rate of 1/sec.

2.5. Screw stimulation

EMG threshold to screw stimulation (Screw-*t*) was determined according to conventional approach (Calancie et al., 1994): the head of the screw was stimulated by direct contact of the same stimulating probe, after carefully cleaning from biological fluids. Care was taken to apply stimulation through the shaft and not the mobile crown of the screw.

2.6. Return stimulating electrodes

For both hole and screw stimulation, to prevent the risk of current shunt we avoided, as predicted by the current protocol, the use of a needle anode, usually inserted each time by the surgeon in the nearby paravertebral muscles. A large surface return electrode was placed on the abdominal wall approximately between umbilicus and xifoid process. (Fig. 1Cb). It was contiguous to the surface anode used for nerve root HVES (Fig. 1Ca).

2.7. High voltage electrical stimulation (HVES) of lumbosacral roots

Nerve root HVES (Fig. 1B, Ca), according to the trans-abdominal technique (Troni et al., 1996), was performed throughout surgery (Troni et al., 2013) to complement tEMG after insertion of each screw and at the end of surgery as a final survey of functional integrity of all lumbosacral nerve roots.

The first step was identification of the optimal stimulating site (OSS) over the vertebral column, that is the site providing a simultaneous and balanced supramaximal stimulation of all involved lumbosacral nerve roots. Since, in MRI studies, the imaginary line joining the OSS, located by neurophysiological mapping, to the ventral anode intersected in most subjects the middle one third of the lumbar enlargement of the spinal cord (Troni et al., 2011), the inverse procedure was adopted to locate the vertebral OSS in our patients exploiting the preoperative MRI images, as exemplified in Fig. 3.

Baseline maximal CMAPs from all recording sites were obtained as soon after complete wash-out of the initial dose of muscle relaxant was reached.

2.8. Neuromuscular blocking agents

Patients did not usually receive neuromuscular blocking agents, other than the initial dose at the beginning of surgical session for intubation; otherwise, when further doses were occasionally requested by surgeons to increase neuromuscular relaxation, nerve root HVES proved to be a sensitive tool to monitor the degree of neuromuscular blockade. In the rare cases in which a supplementation of neuromuscular blocking agent was given shortly before tEMG procedures, Sugammadex®, a fast-acting neuromuscular blockade reversal drug, was given 4 to 6 minutes before neurophysiological evaluation.

2.9. Evaluation of pedicle screw positioning

Postoperative CT scan was used to assess the location of pedicle screws and to detect possible pedicle breaches. Moreover, the distance between the cortical bone of medial pedicle and the inner margin of the screw was measured in each instrumentation.

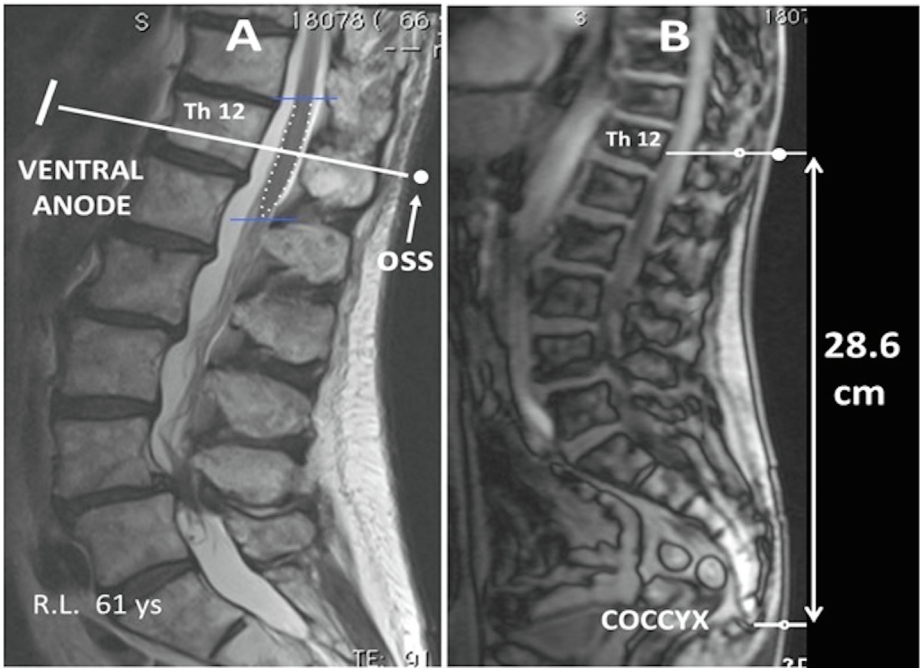

Fig. 3. A: A line was drawn on a T2 weighted MRI image of lumbar spine, joining the middle one third of the lumbar enlargement of the spinal cord to the planned position of the ventral surface anode. The dorsal end of the line was chosen as the optimal stimulus site (OSS) for lumbosacral HVES. B: the distance between OSS and the Coccyx, chosen as the only unambiguous anatomical reference, was measured. This distance was reproduced on the patient in prone position to locate OSS.

3. Results

3.1. Feasibility of FHS

Hole-*t* values could be obtained from all pedicle instrumentations (176). FHS was approved by surgeons who found it fast and convenient, mainly because they had to manage only the stimulating probe. The use of a fixed ventral surface anode avoided the need to insert and remove each time the needle anode, as provided for by conventional screw stimulation. Moreover, the correct depth of focal stimulation within the hole was automatically dictated by the stop included in the probe. All results are listed in Supplementary Table S1.

3.2. Definition of normal values

We considered normal all Hole-*t* and Screw-*t* values recorded from pedicle instrumentations which met the following criteria: 1. Normal intraoperative X ray fluoroscopy; 2. Apparent integrity of the medial pedicle wall through pedicle feeler check and absence of anatomical conflict between screw and nerve root at visual inspection after laminectomy (when performed); 3. Unchanged amplitudes and area of maximal CMAPs to nerve roots HVES throughout surgery; 4. Demonstration in the postoperative CT scan of a correct screw position with integrity of the medial pedicle wall; 5. Unchanged or improved clinical findings in postoperative evaluation.

One hundred and sixty-one Hole- and Screw-*t* values met these criteria (all values reported in Supplementary Table S1 except figures in bold Italics). Since no significant differences were observed, for both Hole- and Screw-*t*, between values obtained at different vertebral levels, all data were pulled together. The resulting mean values were 7.52 mA ± 2.46 (range 2.9–13) for Hole-*t* and 21.8 mA ± 6.8 (range 8,6–44) for Screw-*t*. The lower normal limits (mean – 2SD; $P < 0.05$) were 2.6 and 8.2 mA for Hole-*t* and Screw-*t*, respectively.

Individual pairs of Hole- and Screw-*t* values from single pedicle instrumentations were poorly correlated (r: 0.23). In each pair, the ratio between Hole-*t*, as index of the *absolute* EMG threshold (see Discussion), and the corresponding Screw-*t*, was calculated according to the following formula: 100 – 100 (Hole-*t*/Screw-*t*). The resulting value was assumed as index of the amount (%) of current dispersion (CDI: Current Dispersion Index) from the screw towards surrounding tissues before reaching the root point. Mean CDI was 63.3% ± 13.8 (range: 11–90 %). An outstanding difference between the two stimulation techniques was the focal recording area resulting from FHS compared to Screw stimulation (Fig. 4). With FHS of L3 an threshold motor response limited to VM was the most constant finding. The same was true for individual stimulation of L4, L5 and S1, that elicited threshold responses usually restricted to TA and PL (L4, L5) or Soleus and FHB (S1).

3.3. Abnormal findings

Twelve values (9 Hole- and 3 Screw-*t*) were significantly reduced (all figures typed in bold italic in Supplementary Table S1).

3.3.1. Abnormal findings with proven breakthrough of medial pedicle wall

In 4 cases, (No 2, 5, 15, 19) the abnormal Hole-*t* (<2.6 mA) was associated with a defined breakthrough of pedicle wall, confirmed by postoperative CT scan. In cases 2 and 5, due to a reassuring intraoperative X ray fluoroscopy and pedicle feeler check, the low threshold was suspected to be a false positive result and the screw was inserted in the prepared hole. However, direct inspection after laminectomy revealed in both cases a clear anatomical conflict between root and screw. Note that in case 2 a concomitant Screw-*t* alteration was found (6.2 mA), while in case 5, Screw-*t* was within the normal range (12 mA), as evidence of a false negative result. In case 2 a new, more divergent hole was performed (Fig. 5); Screw-*t* value was normal after stimulation of the redirected screw (12.6 mA); in case 5 the screw was removed but

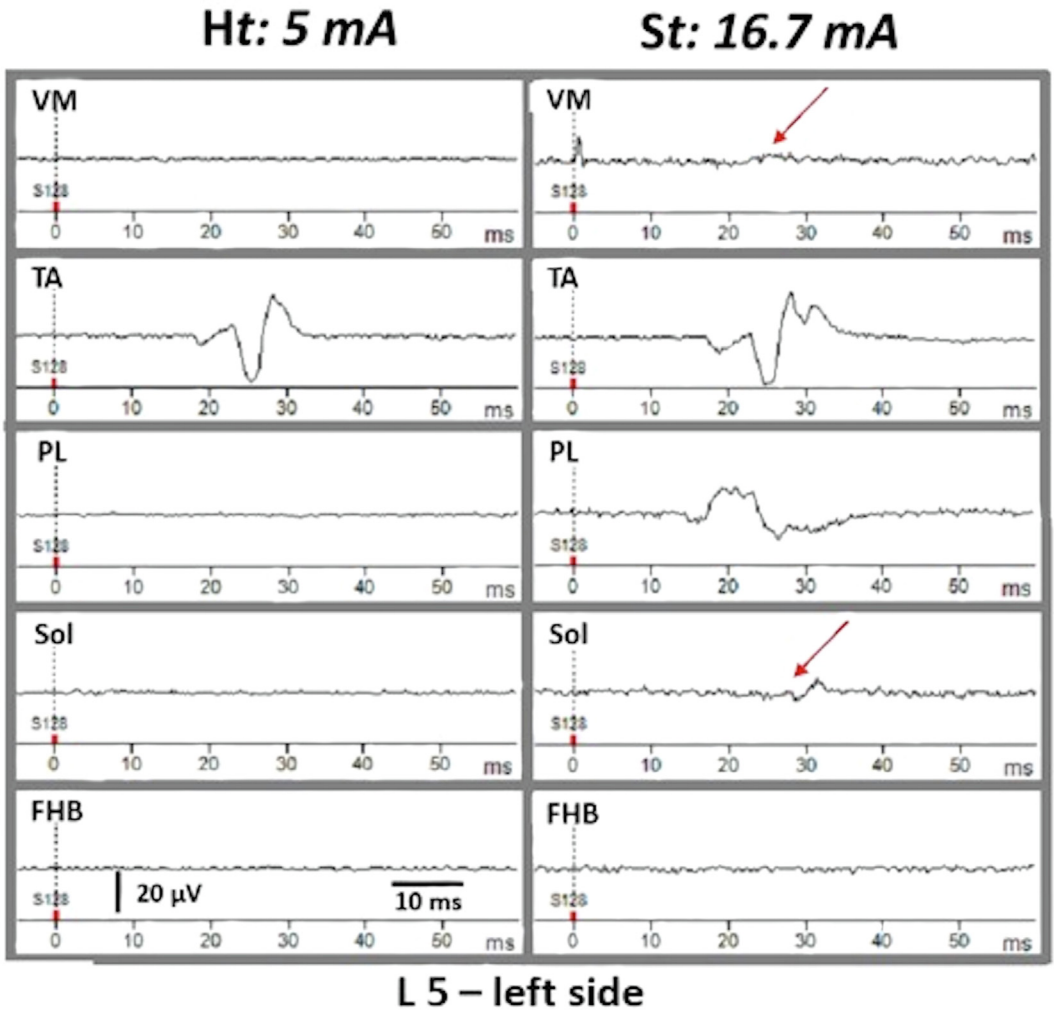

Fig. 4. Comparison between CMAPs recorded at threshold stimulus intensity after focal hole and screw stimulation at the same vertebral level (left L5) in a single patient (No 3). Hole-*t* was lower (5 mA) than Screw-*t* (16.7 mA) and a threshold CMAP was recorded only from TA muscle. With screw stimulation, CMAPs were also recorded from PL and, although of very small amplitude, from VM and Soleus muscles (arrows). VM: Vastus Medialis; TA: Tibialis Anterior; PL: Peroneus Longus; Sol: Soleus; FHB: Flexor Hallucis Brevis.

not replaced (Fig. 6). In the other two cases (No 15, 19), on the basis of the experience provided by cases 2 and 5, screw insertion was avoided, and new properly redirected holes were fashioned. Threshold for screw inserted in the new hole was still reduced in case 15 (7.5 mA), despite a post-operative CT scan showing a properly positioned screw, and within the normal range (15 mA) in case 19 (Fig. 7).

3.3.2. Abnormal or borderline findings without proven evidence of pedicle breakthrough

In 9 pedicle instrumentations abnormal (<2.6 mA; No 6, 10, 21, 31a, 33) or borderline (2.6–3 mA; No 4, 13, 25, 31b) Hole-*t* values were found in absence of a proven pedicle breach. In the first 4 cases (No 4, 6, 10, 13), due to a normal intra-operative evaluation, including visual inspection after laminectomy (4, 13), abnormal or borderline Hole-*t* values were considered false positive results and the screws were left in place. However, postoperative CT scan in 3 of these 4 cases revealed a close proximity between the inner margin of the screw and the cortical bone of medial pedicle, further underlined by a marked asymmetry compared to the other side (Fig. 8). Such anatomical correlation is not available for the following 5 cases (Pat. n. 21, 25, 31a, 31b, 33) because the growing evidence about the capability of FHS to detect a dangerous proximity between hole and nerve root even in absence of a defined pedicle lesion, discouraged insertion of the screw and advised redirection of the pedicle route.

3.4. Comparison between diagnostic sensitivity of Hole- and Screw-t

Altogether, an abnormal Hole-*t* (<2.6 mA; $p < 0.05$) was observed in 9 pedicle instrumentations (5.1%) and in all of them but one, the reliability of this finding was confirmed by a breakthrough of medial pedicle wall or by a close proximity between the screw and the cortical pedicle bone.

A direct comparison between diagnostic sensitivity of Hole-*t* and Screw-*t* can be made only for cases in which Screw-*t* was evaluated in screws inserted in the same, misdirected hole in which Hole-*t* was determined.

Of the four cases meeting this condition (2, 5, 6, 10) only two (2, 6) showed a concomitant Screw-*t* alteration (<8.2 m). This means that in cases 5 and 10, Screw-*t* values represent false negative results. False negative results were never observed for Hole-*t*.

4. Discussion

Stimulation through the hole**,** always combined with screw stimulation, was an integral part of the original tEMG technique described by Calancie et al. in 1994. Repetitive stimulating pulses

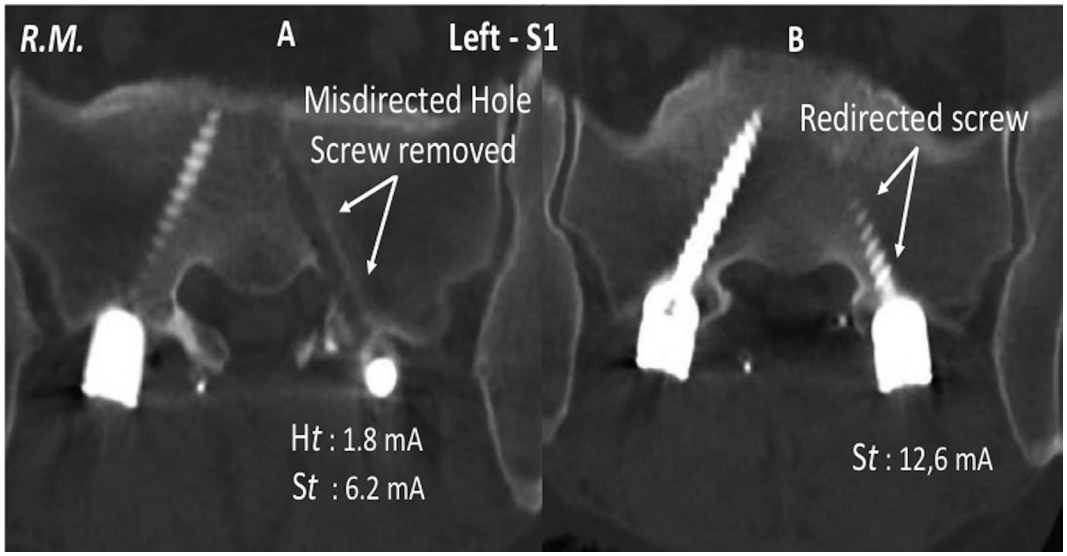

Fig. 5. Case No 2. Screw was inserted in the left S1 hole despite a reduced Hole-*t* (1.8 mA) with concordant reduction of Screw-*t* (6.2 mA) due to an apparently reassuring intraoperative pedicle feeler check. After visual inspection through laminectomy showed a definite anatomical conflict between nerve root and screw, the screw was removed and redirected. A: The shadow of the vacant, misdirected hole is evident with a possible, limited breach of medial pedicle wall. B: Screw-*t* of the redirected screw was normal (12.6 mA) in keeping with the correct location of the screw in the post-operative CT scan.

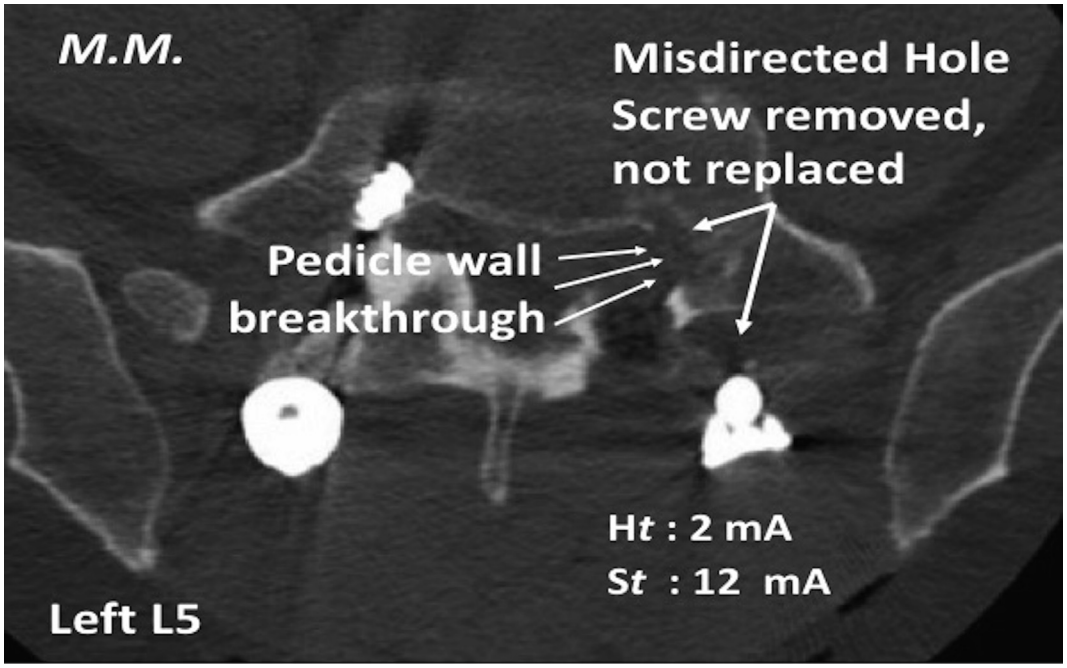

Fig. 6. Case No 5. False negative result with screw stimulation. Despite a reduced Hole-*t* value (2 mA), due to a reassuring intraoperative fluoroscopy and pedicle feeler check, the screw was inserted, and the false positive nature of the Hole-*t* seemed to be confirmed by the normal Screw-*t* (12 mA). However, visual inspection after laminectomy revealed a breach of medial pedicle and anatomical conflict with L5 nerve root. The screw was removed but not replaced.

of 7 mA intensity, used as a common cutoff value, were delivered using a probe electrified by connection with the alligator clip of the cathode as it was being advanced into the pedicle during hole formation. These authors first observed that threshold to hole stimulation was in average lower than that to screw stimulation.

Later, Calancie et al (2009) claimed that the use of fully insulated ball-tipped electrodes, where the current delivery is concentrated at the 2.0 to 3.0 mm tip of the probe, would allow for a better localization of a pedicle wall breach. This finding was challenged in the recent metanalysis by Mikula et al. (2016), as direct comparison between hole, at least as it was performed in the reviewed papers, and screw stimulation indicated the screw as a more accurate electrical conductor.

Many kinds of instruments have been used by surgeons to conduct current within the hole, including tap, awl, and any other purpose-made "electrified" pedicle probes, as recently reviewed by Isley et al. (2012), but not always paying the due attention to the electrical insulation of the stimulating devices. Dickerman and Guyer (2006) recommended to test also circumferentially within the pedicle to get a detailed check of the hole. Further

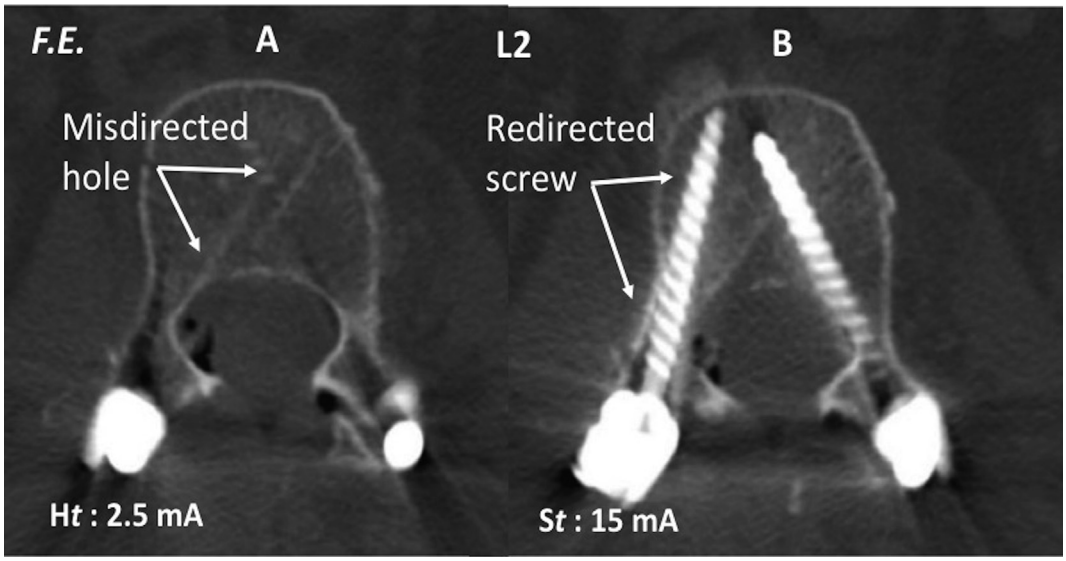

Fig. 7. Case No 19. In this case, at bone probe removal (right L2), a moderate CSF leakage was observed. Focal hole stimulation showed an abnormal Hole-*t* (2.5 mA). Based on the previous experience from cases 2 and 5, screw insertion was avoided, and a new redirected, more divergent hole was made. Postoperative CT scan showed the misdirected hole route (A) causing a dural breach. Threshold to stimulation of the screw inserted into the new hole (B) was normal (15 mA). No evidence of root damage was observed as shown by unchanged maximal CMAPs after nerve root HVES throughout surgery and by a normal neurological examination in postoperative course.

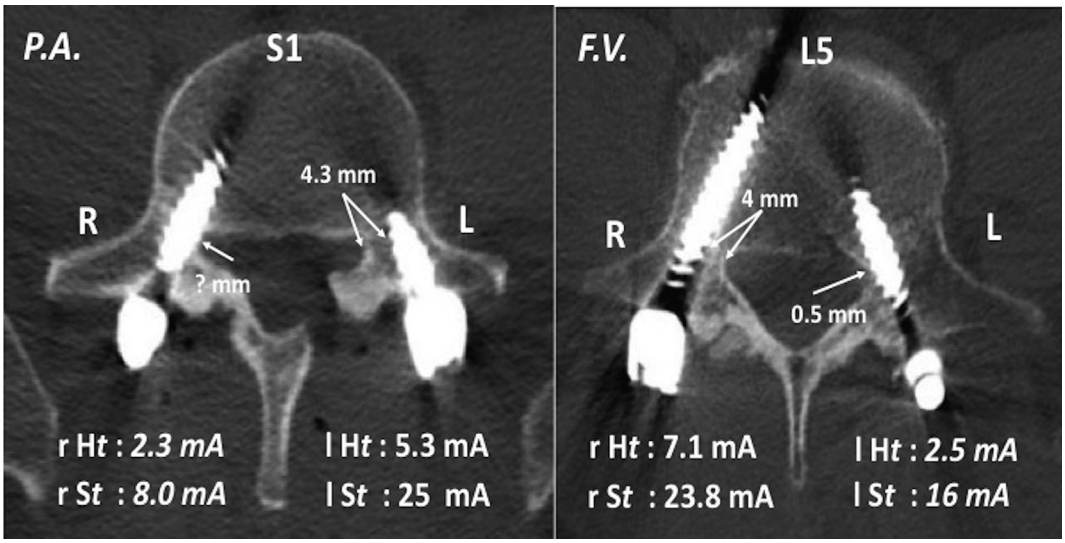

Fig. 8. Cases No 6 and 10. In both cases abnormal Hole-*t* values were observed on the side where postoperative CT scan showed a close proximity between the pedicle cortical bone and the medial margin of the screw, though in the absence of pedicle breakthrough. Note the marked difference with the contralateral sides, showing normal Hole- and Screw-*t* values. A concomitant, borderline (8 mA) Screw-*t* value was observed in the affected side in case 6, but not in case 10.

improvements according to this *dynamic* approach included the use of persistently electrified, purpose-made pedicle perforators to guide the formation of the pilot hole (Rose et al., 1997).

However, all these exhaustive techniques using continuous stimulation with a moving focal probe during formation of the pilot hole, are technically difficult, require an adequate training, a long experience and a good "team spirit" between well-motivated neurophysiologists and surgeons. This is probably why such comprehensive neuro-monitoring approaches remains the privilege of a few patients. In most cases, only screw stimulation is performed to get a final seal of a successful screw positioning, sometimes disappointed by the urgent need to remove and replace the screw.

Moreover, only specific cutoff values are usually tested, valid for both hole, when performed, and screw stimulation, avoiding defining the individual threshold and considering the test safe when no CMAPs are recorded at the chosen stimulus intensity. Many "caveat" stimulus strengths have been suggested for lumbosacral pedicle stimulation over the last 20 years: ≤7.0 mA (Calancie et al.,1994), ≤6.0 mA (Maguire et al 1995), ≤10 mA (Glassman et al., 1995), ≤4.0 mA (Lenke et al., 1995), ≤11.0 mA (Clements et al., 1996), ≤10.0 mA (Toleikis et al., 2000), ≤5.0 mA (Parker et al., 2011). The wide range of these *alarm thresholds* indicates that they are the result of empirical, personal experiences of the different authors rather than the expression of objective normative data.

Actually, normative EMG threshold values to selective stimulation of the hole to be compared to those to screw stimulation, obtained from correctly fashioned pedicle instrumentations, have been never reported.

The purpose of navigation within the hole is obviously to define the most effective site of stimulation. However, the latter is

necessarily represented by the point where the stimulating tip reaches the maximum proximity to the tested nerve root. This point can be located with good approximation in the individual patient in the preoperative CT scan, making navigation within the hole unnecessary. This enables a focal activation of a nerve root in a static condition, allowing a fine modulation of current intensity to reach a precise measure of the threshold. The obtained value defines the *absolute* EMG threshold to pedicle stimulation, that is the threshold almost exclusively dictated by the *distance* between the stimulating tip and the nerve root and the degree of *electrical impedance* provided by the pedicle wall. Our normative Hole-*t* values (mean: 7.6 mA ± 2.5) confirm this result since the lower normal limit (2.6 mA) borders the upper normal limits of the threshold to direct activation of the exposed nerve root (Calancie et al., 1994).

Our normative Screw-*t* values (mean 21.8 mA ± 6.8), agree with those reported in the literature and the lower normal limit (8.2 mA) coincides with that resulted to be the most reliable threshold cutoff (8 mA) in the meta-analysis by Lee et al. (2015). However, the upper limit (44 mA), similar to that reported by other authors (Calancie et al., 1994), is too high to be plausible whatever the degree of electrical impedance of the pedicle wall (Skelly et al.,1999). The only reasonable explanation is that a large part of the current stream delivered by the stimulator and read as the *formal* threshold on the display of the device, is lost by dispersion through the surrounding tissues before reaching the critical *root point* within the hole.

As observed by Davis et al. (2014) standard titanium screws, unlike hydroxyapatite-coated screws, are good electrical conductors and this justifies the significant current leakage we observed with screw stimulation.

This could not be a limit of screw stimulation in itself, provided that the biasing factor was constant, simply resulting in a change of reference values. Unfortunately, this was not the case because the current leakage proved to be extremely variable and totally unpredictable.

Since FHS provides the absolute threshold, a direct comparison between Hole- and Screw-*t* values, obtained from the same correctly fashioned pedicle instrumentation, provides a simple measure of the amount of current leakage after screw stimulation. A mean Current Dispersion Index (CDI) of 66% was calculated, ranging from 10 to 90%.

This is not surprising because when the stimulating tip of the probe contacts the head of the screw, these two components behaves as a single probe with a large part, the screw itself, totally uninsulated and in direct contact with the surrounding tissues.

In practice, a dispersion of 70% represents the boundary for a concordant behavior between hole and screw thresholds to detect pedicle lesion. When current dispersion is lower than 70% the Screw-*t* increasingly approaches that of Hole-*t* and both values almost coincide when current dispersion reaches the minimum value (10%). The opposite is true with a current dispersion greater than 70% which generates a Screw-*t* progressively diverging from Hole-*t*, resulting in a false negative result when Hole-*t* is abnormal. As a simple theoretical example, with a current dispersion of 80%, an abnormal Hole-*t* of 2.5 mA, corresponds to a Screw-*t* of 12.4 mA, that is a normal value. In our casuistry a CDI $\geq$ 70% was observed in 40 pedicle instrumentations (27%).

A further methodological concern is the stimulating montage which currently employs, as a return electrode (anode), a stainless-steel needle inserted somewhere distally and contralaterally to the cathode probe in the surgical wound. Since current always take the easiest pathway to the return electrode, the use of an anode with a very reduced section area such a needle, may generate a partial current shunt, bypassing the stimulus target, directed toward the needle that becomes an active electrode. This is demonstrated by the frequent occurrence of a local twitch in the paravertebral muscles where the needle is inserted, due to anodal stimulation. The use of a large, surface anode, located far away from the surgical wound, causing a rapid damping of the stimulating current after reaching the target, makes the anode a virtually inert electrode and prevents current shunts.

No false negative results were observed with FHS while the results with screw stimulation were in keeping with the well-known and shared limits of the technique. Moreover, it is doubtful that the abnormal or borderline Hole-*t* values, observed in cases without secure evidence of pedicle breach, represent convincing false positive results, because in most cases a remarkable proximity between the medial margin of the screw and the pedicle cortical bone was shown by CT scan. During formation of a handmade pedicle hole, the surgical probe generates, besides the main mechanical pressure along the long axis of the planned hole, also minor but unavoidable circumferential impacts. This inadvertent mechanical component, if it occurs in close proximity to the cortical bone, can cause microfractures that, although not detected by CT scan examination, are likely to induce a fall in electrical impedance of the pedicle wall (Toleikis et al., 2000).

Our results provide a rational explanation of false negative results, the main complaint of t-EMG using screw stimulation, and explain why tEMG is unanimously considered a technique with high specificity (few false positive results) but low sensitivity (high number of negative results) with these two features inversely correlated: specificity increases adopting more severe cutoff values but at the expense of a further, proportionate reduction in sensitivity (Raynor et al., 2007).

FHS proved to be a fast procedure since no more that 10–15 s were usually needed by the neurophysiologist to determine the EMG threshold in a comfortable, static condition. The same time was enough also for Screw Stimulation.

FHS can be easily combined with lumbosacral HVES (Troni et al., 2013) which provides maximal CMAPs from the same muscle districts used to measure tEMG thresholds. Nerve root HVES quickly checks the functional integrity of individual nerve roots after each screw insertion and, at the end of surgery, provides a final, comprehensive survey of all lumbosacral nerve roots involved in surgical procedure.

5. Conclusions

FHS obviously does not help to guide formation of the pilot hole. So, as pointed out by Isley et al. (2012), it remains an "after the fact" observation. However, it provides an early warning of a misdirected hole, avoiding insertion of the more dangerous, larger and threated screw and promptly promoting, as occurred in several of our patients, a redirection of the screw. In the case represented in Fig. 7, considering the significant postoperative CT scan, avoiding screw insertion may have played a favorable role in preventing neurological deficits.

A fundamental role, as anatomical guide to hole formation, will be probably played by the incoming surgical robotics (Overley et al., 2017), that, if successful, will also define the future role, if any, of electrophysiological monitoring in spinal instrumentation.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of interest

None of the authors has competing interests to declare.

References

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

Anderson DG, Wierzbowski LR, Schwartz DM, Hilibrand AS, Vaccaro AR, Albert TJ. Pedicle screws with high electrical resistance: a potential source of error with stimulus-evoked EMG. Spine 2002;27:1577–81.

Calancie B, Lebwohl N, Madsen P, Klose KJ. Intraoperative evoked EMG monitoring in an animal model. A new technique for evaluating pedicle screw placement. Spine 1992;17:1229–35.

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

Calancie B. New techniques for thoracic pedicle screw testing. In: Paper presented at: 20th Annual Meeting of the American Society of Neurophysiological Monitoring; Vancouver, Canada. p. 352–9.

Clements DH, Morledge DE, Martin WH, Betz RR. Evoked and spontaneous electromyography to evaluate lumbosacral pedicle screw placement. Spine 1996;21:600–4.

Davis TT, Tadlock S, Bernbeck J, Fung DA, Molinares DM. Can triggered electromyography be used to evaluate pedicle screw placement in hydroxyapatite-coated screws: an electrical examination. J Clin Neurophysiol 2014;31:138–42.

Dickerman RD, Guyer R. Letter to the Editor: Intraoperative electromyography for pedicle screws: technique is the key! J Spinal Dis Tech 2006;19:463.

Gaines Jr RW. The use of pedicle-screw internal fixation for the operative treatment of spinal disorders. J Bone Joint Surg Am 2000;82:1458–76.

Glassman SD, Dimar JR, Puno RM, Johnson JR, Shields CB, Linden RD. A prospective analysis of intraoperative electromyographic monitoring of pedicle screw placement with computed tomographic scan confirmation. Spine 1995;20:1375–9.

Isley MR, Zhang XF, Balzer JR, Leppanen RE. Current trends in pedicle screw stimulation techniques: lumbosacral, thoracic, and cervical levels. Neurodiagn J 2012;52:100–75.

Kulik G, Pralong E, McManus J, Debatisse D, Schizas C. 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.

Lee CH, Kim HW, Kim HR, Lee CY, Kim JH, Sala F. 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.

Lenke LG, Padberg AM, Russo MH, Bridwell KH, Gelb DE. Triggered electromyographic threshold for accuracy of pedicle screw placement. An animal model and clinical correlation. Spine 1995;20:1585–91.

Maguire J, Wallace S, Madiga R, Leppanen R, Draper V. Evaluation of intrapedicular screw position using intraoperative evoked electromyography. Spine 1995;20:1068–74.

Masferrer R, Gomez CH, Karahalios DG, Sonntag VK. Efficacy of pedicle screw fixation in the treatment of spinal instability and failed back surgery: a 5-year review. J Neurosurg 1998;89:371–7.

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.

Overley SC, Cho SK, Mehta AI, Arnold PM. Navigation and robotics in spinal surgery: where are we now? Neurosurgery 2017;80:586–99.

Parker SL, Amin AG, Farber H, McGirt MJ, Sciubba DM, Wolinsky JP, Bydon A, Gokaslan ZL, Witham TF. Ability of electromyographic monitoring to determine the presence of malpositioned pedicle screws in the lumbosacral spine: analysis of 2450 consecutively placed screws. J Neurosurg Spine 2011;15:130–5.

Raynor BL, Lenke LG, Bridwell KH, Taylor BA, Padberg AM. Correlation between low triggered electromyographic thresholds and lumbar pedicle screw malposition: analysis of 4857 screws. Spine 2007;32:2673–8.

Rose RD, Welch WC, Balzer JR, Jacobs GB. Persistently electrified pedicle stimulation instruments in spinal instrumentation: technique and protocol technique. Spine 1997;22:334–43.

Skelly JP, Toleikis JR, Carlvin AO. Pedicle screw stimulation in a fluid environment. Paper presented at: 10th Annual Meeting of the American Society of Neurophysiological Monitoring; Denver, CO, 1999.

Toleikis JR, Skelly JP, Carlvin AO, Toleikis SC, Bernard TN, Burkus JK, et al. The usefulness of electrical stimulation for assessing pedicle screw placements. J Spinal Disord 2000;13:283–9.

Troni W, Bianco C, Coletti Moja M, Dotta M. Improved methodology for lumbosacral nerve root stimulation. Muscle Nerve 1996;19:595–604.

Troni W, Di Sapio A, Berra E, Duca S, Merola A, Sperli F, Bertolotto A. A methodological reappraisal of noninvasive high voltage electrical stimulation of lumbosacral nerve roots. Clin Neurophysiol 2011;122:2071–80.

Troni W, Benech CA, Perez R, Tealdi S, Berardino M, Benech F. Non-invasive high voltage electrical stimulation as a monitoring tool of nerve root function in lumbosacral surgery. Clin Neurophysiol 2013;124:809–18.

Troni W, Benech CA, Perez R, Tealdi S, Berardino M, Benech F. A methodological reappraisal of triggered electromyography for placement of pedicular screw. In: Paper presented at: 31st International Congress of Clinical Neurophysiology; Washington, DC. May 1–6, 2018. p. S118.