Ability of electromyographic monitoring to determine the presence of malpositioned pedicle screws in the lumbosacral spine: analysis of 2450 consecutively placed screws

Clinical article

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Object. Pedicle screws provide efficient stabilization along all 3 columns of the spine, but they can be technically demanding to place, with malposition rates ranging from 5% to 10%. Intraoperative electromyographic (EMG) monitoring has the capacity to objectively identify a screw breaching the medial pedicle cortex that is in proximity to a nerve root. The purpose of this study is to describe and evaluate the authors’ 7-year institutional experience with intraoperative EMG monitoring during placement of lumbar pedicle screws and to determine the clinical utility of intraoperative EMG monitoring.

Methods. The authors retrospectively studied 2450 consecutive lumbar pedicle screws placed in 418 patients from June 2002 through June 2009. All screws were inserted using a free-hand technique and anatomical landmarks, stimulated at 10.0 mA, and evaluated with CT scanning within 48 hours postoperatively. Medial pedicle screw breach was defined as having greater than 25% of the screw diameter extend outside of the pedicle, as confirmed on CT scanning or intraoperatively by a positive EMG response indicating a medial breach. The sensitivity and specificity of intraoperative EMG monitoring in detecting the presence of a medial screw breach was evaluated based on the following definitions: 1) true positive (a positive response to EMG stimulation confirmed as a breach intraoperatively or on postoperative CT scans); 2) false positive (positive response to EMG stimulation confirmed as a correctly positioned screw on postoperative CT scans); 3) true negative (no response to EMG stimulation confirmed as a correctly positioned screw on postoperative CT scans); or 4) false negative (no response to EMG stimulation but confirmed as a breach on postoperative CT scans).

Results. One hundred fifteen pedicle screws (4.7%) showed positive stimulation during intraoperative EMG monitoring. At stimulation thresholds less than 5.0, 5.0–8.0, and > 8.0 mA, the specificity of a positive response was 99.9%, 97.9%, and 95.9%, respectively. The sensitivity of a positive response at these thresholds was only 43.4%, 69.6%, and 69.6%, respectively. At a threshold less than 5.0 mA, 91% of screws with a positive EMG response were confirmed as true medial breaches. However, at thresholds of 5.0–8.0 mA or greater than 8.0 mA, a positive EMG response was associated with 89% and 100% false positives (no breaches), respectively.

Conclusions. When using intraoperative EMG monitoring, a positive response at screw stimulation thresholds less than 5.0 mA was highly specific for a medial pedicle screw breach but was poorly sensitive. A positive response to stimulation thresholds greater 5.0 mA was associated with a very high rate of false positives. The authors’ experience suggests that pedicle screws showing positive stimulation below 5.0 mA warrants intraoperative investigation for malpositioning while responses at higher thresholds are less reliable at accurately representing a medial breach.

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KEY WORDS • pedicle screw • electromyography • EMG • lumbar spine

Pedicle screws have been used in posterior spinal fixation constructs since the 1960s. Their placement was first reported by Boucher in 1959 and later popularized by Roy-Camille et al. in the 1960s. Today, pedicle screws represent an established and accepted form of instrumentation fixation because of their ability to provide efficient stabilization along all 3 columns of the spine. However, pedicle screws are technically demanding to place, with the rates of malposition ranging from 5% to 10%. Complications associated with mis-
placed pedicle screws include new-onset postoperative neuropathies, pseudarthrosis, and construct failure. In light of these difficulties, multiple assistive techniques have been devised to facilitate the accurate placement of pedicle screws such as fluoroscopic guidance,\textsuperscript{16} stereotactic guidance,\textsuperscript{18} and direct visualization of the medial wall after laminotomy.\textsuperscript{5,17} However, these techniques are coupled with increased radiation exposure, extended operating time, expensive equipment, and increased associated health care costs.

Intraoperative EMG monitoring was first reported by Calancie et al.\textsuperscript{5} in 1992. This technique is used for its theoretical ability to objectively monitor the accurate placement of pedicle screws and notify the surgeon of a screw in contact with a nerve root when breaching the medial pedicle cortex. This is accomplished by applying voltage pulses of desired magnitude through an inserted pedicle screw and recording the resultant evoked EMG responses in myotomes corresponding to the spinal levels being instrumented. A malpositioned screw breaching the pedicle reduces the impedance and allows current to flow more freely through neural tissue and produce a compound muscle action potential in the monitored myotome. However, an intact pedicle wall will prevent voltages of similar magnitude from reaching the myotomes being monitored. As a result, the accuracy of pedicle screw insertion can theoretically be judged based on the presence or absence of evoked electromyographic responses. The purpose of this study is to describe and evaluate our 7-year institutional experience with EMG monitoring of L1–S1 pedicle screws.

Methods

Data Collection

We retrospectively reviewed the records obtained in all patients in whom pedicle screws were place with EMG monitoring involving spinal levels L1–S1 at The Johns Hopkins Hospital from June 2002 through June 2009. All pedicle screws included in this study were inserted using a free-hand technique in which anatomical landmarks are used to guide screw placement. The screws were placed by 5 neurosurgeons. Patient demographics, clinical presentation, indications for hardware placement, radiological studies, operative variables, and follow-up duration were reviewed for each case.

The accuracy of each pedicle screw placed was objectively evaluated using postoperative CT scanning within 48 hours of surgery in all patients. The presence and the extent of a cortical breach by any misplaced screw were determined by review of the axial postoperative CT scan and sagittal/coronal reconstructed images. Similar to previously reported studies on the accuracy of pedicle screw placement,\textsuperscript{18} a breach was defined as a screw with more than 25% of its diameter residing outside and medial, inferior, or superior to the pedicle. Screw malpositioning was measured between the pedicle cortex and inner margin of the screw. Additional note was made of intraoperatively identified pedicle-breached screws that required intraoperative repositioning. Because EMG monitoring was not designed to reliably alert the surgeon to a lateral breach, these screw breaches were not included in the statistical analysis.

Surgical Technique

Free-hand pedicle screw placement is performed using anatomical landmarks and intraoperative localizing lateral radiographs to establish the regional sagittal alignment of the spine. Pilot holes are fashioned using a high-speed air drill or an awl. In the lumbar spine the pilot hole is placed at the junction of the pars interarticularis, with the transverse process and the mammillary process/superior articular process of the segment of interest. This entry site is often located very close to the accessory process. Occasionally, in patients with severe degenerative joint disease, a medial entry site is selected by moving the entry site to the inferior portion of the superior articular process or the mammillary process. In these instances, a small piece of the inferior portion of the superior articular process/mammillary process is removed using a small rongeur, and the noted cancellous bone serves as the entry site. For S-1 screw placement, the pilot hole is selected over a rectangular segment of bone superior to the S-1 posterior foramen and the inferior portion of the superior articular process of S-1.

A mediolateral and superoinferior trajectory is selected based on the surgeon’s experience as well as the pre- and intraoperative imaging. We attempt to place screws with a rostrocaudal trajectory that parallels the superior endplate of the segment of interest. A mediolateral trajectory is followed in an attempt to triangulate screw placement from lateral to medial.

A pedicle probe is used to sound the pedicle, and a pedicle feeler is used to assess for a breach. Once it is determined that a pedicle breach has not occurred, pedicle markers are placed. If a breach is detected, then the trajectory is revised using the pedicle probe. An intraoperative lateral radiograph is used to image the pedicle markers. If the rostrocaudal trajectory is not satisfactory, the pedicle probe may be used to make the desired adjustment. Holes are tapped with an undersized tap, and screws are then placed. The screw size is selected based on pre- and intraoperative images. Typically screw sizes range from 6 to 7.5 mm in diameter and 40 to 55 mm in length in the lumbar spine.

Electrophysiological Monitoring

After screw insertion, the absence of neuromuscular blockade is confirmed by stimulation of the tibial nerve in the popliteal fossa with recording in the gastrocnemius muscle. A nasopharyngeal EMG monitoring probe with a ground inserted into the patient’s paraspinal musculature is used for stimulation of pedicle screws. Each screw is stimulated at 10 mA. A positive control is documented by applying stimulation close to a nerve root, if the dura is exposed, using a low-amplitude current (2 mA). Screws that provoke a negative response at 10 mA are assumed to be accurately positioned and without medial pedicle breach. However, this technique does not exclude lateral breach of the pedicle or bony breach in which the screw is not proximal to nerve tissue. A positive response at 10
mA necessitates obtaining an EMG threshold of stimulation. If the threshold for stimulation is noted to be greater than or equal to 7 mA, the screw is still considered to be adequately positioned. The 7-mA cutoff is based on our own anecdotal experience and the published literature.\(^4\) However, a threshold of less than 7 mA alerts the surgeon to attempt to visualize the medial pedicle intraoperatively and/or revise the screw positioning. A final lateral radiograph is used to confirm screw placement. Occasionally, an intraoperative posteroanterior radiograph is obtained to assess screw placement, if the surgeon is concerned about the medial or lateral position of a screw.

**Statistical Definitions**

The accuracy of EMG monitoring at detecting the presence of a medial, superior, or inferior screw breach was evaluated based on the following definitions: 1) a true-positive finding is defined as positive EMG stimulation of a pedicle screw that was immediately evaluated intraoperatively and determined to be malpositioned or confirmed as a breach on postoperative CT; 2) a false-positive finding is defined as positive EMG stimulation of a pedicle screw that was immediately evaluated intraoperatively and determined to be correctly positioned and confirmed to be accurately placed on postoperative CT; 3) a true-negative finding is defined as no EMG stimulation of a pedicle screw at 10.0 mA that is confirmed to be accurately placed on postoperative CT; and 4) a false-negative finding is defined as no EMG stimulation of a pedicle screw at 10.0 mA that is determined to be medi ally malpositioned on postoperative CT. Sensitivity is defined as the number of true positives divided by the sum of true positives and false negatives. Specificity is defined as the number of true negatives divided by the sum of true negatives and false positives.

**Results**

In 418 patients, 2450 pedicle screws were inserted at the L1–S1 levels. All screws were inserted using a free-hand technique and EMG monitoring was used throughout the procedure. Overall, the mean (± SD) age of patients at the time of surgery was 54.9 ± 14.5 years. The indications for hardware placement included spondylolisthesis (42.6%), degenerative disease (35.1%), tumor (9.6%), trauma (9.1%), and infection (3.6%). Screw distribution at each spinal level was as follows: 112 screws (4.6%) at L-1, 228 (9.3%) at L-2, 400 (16.3%) at L-3, 641 (26.2%) at L-4, 651 (26.6%) at L-5, and 418 (17.0%) at S-1. Twenty-three screws (0.9%) were identified that breached the medial pedicle cortex. Eighteen screws breached the lateral pedicle cortex, and no superior or inferior breaches were identified. These findings were established either intraoperatively or postoperatively on CT scans. One hundred fifteen pedicle screws (4.7%) exhibited a positive stimulation during intraoperative EMG monitoring. The threshold of positive stimulation ranged from 2.5 to 10.0 mA. Of the 115 pedicle screws with a positive EMG response at any threshold (range 2.5–10.0 mA), only 16 (13.9%) were confirmed to have breached the medial pedicle cortex (true-positive finding) based on intraoperative revision or postoperative CT evidence.

The vast majority (95.0%) of pedicle screws were correctly positioned and elicited no stimulation below 10.0 mA (true negatives). The false-negative rate was 0.3% (7 of 2335 screws). This represents screws that showed no stimulation at or below a threshold of 10.0 mA but were identified as breaching the medial pedicle cortex on postoperative CT scans. With respect to the 115 screws that provoked a positive response during EMG monitoring, 50 had a stimulation threshold of 8.0–10.0 mA, none (0%) of which represented a confirmed breach. Fifty-four screws had a stimulation threshold between 5.0 and 7.9 mA, only 6 (11.1%) of which represented a confirmed breach (Fig. 1). Eleven screws had a stimulation threshold less than 5.0 mA, 10 (90.9%) of which represented a confirmed breach (Table 1). The specificity of EMG monitoring is inversely proportional to the stimulation threshold, whereas the sensitivity is directly proportional to the stimulation threshold. At a stimulation threshold of 5.0 mA, the sensitivity and specificity were 43.4% and 99.9%, respectively. At a stimulation threshold of 8.0 mA, the sensitivity and specificity were 69.6% and 97.9%, respectively. At a stimulation threshold of 10.0 mA, the sensitivity and specificity were 69.6% and 95.9%, respectively (Table 2).

**Discussion**

Pedicle screw instrumentation is technically demanding\(^2\) and is increasingly implemented because of its ability to provide stabilization along all 3 columns of the spine. Malposition rates of up to 20% have been reported, even in the hands of experienced surgeons.\(^6\) Although many assistive techniques have been developed, they are associated with significant drawbacks: increased operative time with use of navigational systems, increased radiation exposure with modalities such as fluoroscopy, and increased morbidity with laminectomy.\(^4\),\(^6\),\(^17\),\(^18\) As a result, the ability to consistently confirm accurate pedicle screw placement intraoperatively would be extremely beneficial. We have used a free-hand pedicle screw placement technique in conjunction with EMG stimulation of the pedicle screws. With these techniques, our screw breach rates and revision rates in the lumbosacral spine have been acceptable compared with those published in the literature.\(^9\),\(^11\)

Since Calancie and colleagues\(^3\) first proposed intra-
Monitoring for malpositioned lumbosacral screws

TABLE 1: Summary of results of 115 pedicle screws identified by intraoperative EMG monitoring as exhibiting a positive response to stimulation*

<table>
<thead>
<tr>
<th>Lowest Current of EMG-Positive Response (mA)</th>
<th>No. of Pedicle Screws w/ Positive Response</th>
<th>Pedicle Breach (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.0–10.0</td>
<td>50</td>
<td>0 (0)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50 (100.0)</td>
</tr>
<tr>
<td>5.0–7.9</td>
<td>54</td>
<td>6 (11.1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>48 (88.9)</td>
</tr>
<tr>
<td>2.0–4.9</td>
<td>11</td>
<td>10 (90.9)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 (9.1)</td>
</tr>
<tr>
<td>total</td>
<td>115</td>
<td>16 (13.9)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>99 (86.1)</td>
</tr>
</tbody>
</table>

* When a positive response was evoked, the spinal level was assessed for pedicle breach. Screws modified intraoperatively and breaches identified on postoperative CT scans together comprise the true-positive stimulations. False-positive results represent screws, intraoperatively identified by EMG monitoring as provoking a positive response, that were confirmed to be accurately placed on postoperative CT scans.

Intraoperative EMG monitoring as a technique to objectively determine a medial pedicle cortex breach, several institutions have incorporated its use in their routine surgical practice. This intraoperative technique involves stimulating an inserted pedicle screw and recording the evoked EMG response in the myotome corresponding to the instrumented spinal level. A malpositioned screw breaching the pedicle will have the stimulating current flow through the neural tissue and will result in a compound muscle action potential in the corresponding myotome. In contrast, a properly positioned screw will not affect the spinal bone integrity and the stimulating current will be relatively insulated from the nerve root and will not result in an electrophysiological change in the corresponding myotome. This technique allows immediate assessment of pedicle screw placement, but the utility of intraoperative EMG monitoring is still questionable because research has shown large variance in its accuracy of distinguishing malpositioned screws.

Our institution’s experience with 2450 lumbar pedicle screws placed with intraoperative EMG monitoring resulted in 115 (4.7%) positively stimulated screws. Of these, only 16 (13.9%) were confirmed to have actually breached the medial pedicle cortex, representing true positives. There were an additional 18 pedicle screws that were found to breach the lateral pedicle wall on postoperative CT, but EMG monitoring was not designed to reliably detect such breaches. Consistent with previously published studies assessing EMG monitoring, we classified these screws as true negatives for the purposes of the statistical analysis. There were no inferior or superior breaches in the study population. The minimum screw diameter used in this study was 6 mm. When the pedicle was deemed too small to accept this size screw, an “in-out-in” technique was used. This technique was occasionally used at the L-1 or L-2 level when small pedicles (< 6 mm in diameter) were encountered. Nonetheless, a breach was still defined to have occurred if more than 25% of the screw was outside the medial pedicle. Although a screw breach may be the result of either improper placement trajectory or a pedicle being too small to accept the full diameter of the screw, all breaches identified in the present series were a consequence of improperly aligned screw trajectory.

An additional 7 screws showed no stimulation below a threshold of 10.0 mA, but subsequently were also confirmed to have breached the cortex on postoperative CT, thus representing false negatives. As such, the sensitivity of EMG monitoring decreases and its specificity increases with lowered thresholds of stimulation. At threshold values of 10.0, 8.0, and 5.0 mA, the sensitivity was 69.6%, 69.6%, and 43.4%, whereas the specificity was 95.9%, 97.9%, and 99.9%, respectively. Our experience confirms that lower threshold values are more accurate at revealing the presence of a medially malpositioned screw. Using a threshold value of 5.0 mA will result in misidentification of approximately one-half of all medial breaches. With a specificity of 99.9%, however, any stimulation below this threshold must be immediately evaluated, because it most likely represents a misplaced screw. Because of its poor sensitivity, even at high thresholds, EMG monitoring should not be used as a screening tool to detect potential breaches.

There is a growing body of evidence on the role of intraoperative EMG monitoring in determining lumbar pedicle screw malpositioning. Using an animal model, Lenke and coworkers established normative stimulation threshold ranges suggesting that stimulation between 4.0 and 8.0 mA indicated a possible pedicle wall defect and that stimulation at less than 4.0 mA indicated likely pedicle wall defect with possible nerve root irritation. In studies in humans, Glassman et al. determined that a stimulation threshold greater than 15 mA was associated with an intact pedicle with adequate screw instrumentation, which established an upper bound to stimulation levels. An evoked response at a stimulation current less than 6.0 mA, correlating with likely screw malposition, was proposed in clinical studies by Maguire et al. Although

TABLE 2: Statistical results of EMG monitoring at different threshold cutoffs*

<table>
<thead>
<tr>
<th>Threshold Cutoff</th>
<th>True Positive</th>
<th>True Negative</th>
<th>False Positive</th>
<th>False Negative</th>
<th>Sensitivity</th>
<th>Specificity</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.0 mA</td>
<td>16</td>
<td>2328</td>
<td>99</td>
<td>7</td>
<td>69.6%</td>
<td>95.9%</td>
</tr>
<tr>
<td>8.0 mA</td>
<td>16</td>
<td>2378</td>
<td>49</td>
<td>7</td>
<td>69.6%</td>
<td>97.9%</td>
</tr>
<tr>
<td>5.0 mA</td>
<td>10</td>
<td>2426</td>
<td>1</td>
<td>13</td>
<td>43.4%</td>
<td>99.9%</td>
</tr>
</tbody>
</table>

* The sensitivity of EMG monitoring in detecting medially misplaced screws is directly related to the threshold cutoff value, whereas the specificity is inversely related to the threshold cutoff value.
these studies established threshold ranges to determine pedicle breach, the reproducibility, sensitivity, and specificity of intraoperative EMG monitoring is continually being assessed to evaluate its efficacy.

The poor sensitivity of EMG monitoring precludes its use as a single modality to determine intraoperative pedicle screw breaches, but it is a valuable tool for determining the accuracy of screw placement when used in concert with intraoperative radiography and postoperative CT scanning. Further studies are warranted to establish if the utility of intraoperative EMG monitoring can be improved in specific clinical cases. For example, the type of spinal pathology could affect the sensitivity of EMG monitoring because nerve root dysfunction may involve wallerian degeneration. This degeneration would result in spinal roots that may not reliably stimulate the corresponding myotomes. Thus, the clinical presentation may determine the use of EMG monitoring in patients with preoperative motor radiculitic deficits because the standard stimulating thresholds may not elicit a response from these chronically damaged nerve roots. Other patient factors may also influence the main flaw in using EMG monitoring to determine the accuracy of pedicle placement, which is its high number of falsely stimulated screws that are in fact well within the medial pedicle cortex. The structural bone integrity of the preexisting spine can be taken into consideration when deciding to use EMG monitoring because degenerated bone, as in the case of patients with osteoporosis or the elderly population, will have minor bone defects that may be clinically insignificant but could lead to an increased susceptibility to pedicle screw stimulation. Adjunctive monitoring techniques would be helpful in such cases. In addition to these variations, it is possible that the minor differences in pedicle shapes and sizes among different spinal levels and among different age groups warrant distinct normative current threshold values for each spinal level and for each age group. With further studies determining the best situations in which to use intraoperative EMG monitoring, its utility to predict pedicle screw breaches may improve and potentially be associated with a foreseeable decrease in surgical complications in the future. However, we certainly do not believe that the results of this study suggest that EMG monitoring of lumbar pedicle screws should be adopted as standard of care. Nor was this study designed to assess the cost-effectiveness of EMG monitoring. Further studies will be needed to address these issues. What we can conclude from the results of this study is that EMG monitoring of lumbar pedicle screws is highly specific for medial breaches when a threshold of less than 5.0 mA elicits a positive response, and therefore, these screws warrant immediate intraoperative investigation to determine if they have been misplaced.

Conclusions

When utilizing intraoperative EMG monitoring, a positive response at screw stimulation thresholds less than 5.0 mA warrants immediate intraoperative investigation to determine if a breach has occurred. Raising the threshold value is associated with decreasing specificity and increasing sensitivity, but even at a stimulation threshold of 10.0 mA, the sensitivity of EMG monitoring is only 70%. As a result, EMG monitoring is a poor screening tool for detecting medial pedicle screw breaches. Its most useful application is as a warning tool for likely screw malpositioning in the presence of positive stimulation at thresholds of 5.0 mA or less.

Disclosure

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

Author contributions to the study and manuscript preparation include the following. Conception and design: Witham, Parker, McGirt. Acquisition of data: Parker, Amin, Farber. Analysis and interpretation of data: Witham, Parker, McGirt. Drafting the article: Parker, Amin. Critically revising the article: Witham, Parker, McGirt, Scuibba, Wolinsky, Bydon, Gokaslan. Approved the final version of the paper on behalf of all authors: Witham. Statistical analysis: Parker. Administrative/technical/material support: Witham, Bydon, Gokaslan.

References

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