The numerous advantages of using pedicle screws in the thoracic spine for anchoring long constructs are well described, and these advantages have led to increasing numbers of procedures using this approach. The greater difficulty of placing pedicle screws in the thoracic versus lumbar spine has also been described. To this point, a neuromonitoring strategy that could reliably mitigate the risk to the spinal cord as associated with the implantation of thoracic pedicle screws has been lacking.

In Part 1 of this 2-part report, we describe a novel neuromonitoring technique designed specifically for pre-
dicting medially malpositioned thoracic pedicle screws. The technique effectively marries the techniques of transcranial motor evoked potential (MEP) testing, which relies upon a train of stimulus pulses to evoke motor responses,\textsuperscript{10,12} and testing of lumbar pedicle screw implantation, which relies upon a low-impedance current path between the point of stimulation and the nerve root to detect a breach in the cortical bone lining the pedicle.\textsuperscript{6,11,12} Common to both tests is that the minimum stimulus intensity needed to elicit a response—the threshold intensity—serves as the primary outcome measure of the technique, rather than properties of the evoked response itself (for example, amplitude or latency).

Whereas the preceding companion article shows that this novel technique is highly effective at predicting a medially malpositioned screw, it does not address whether the technique can prevent such a screw placement in the first place. In this manuscript, we show in a prospective, blinded, and controlled study that we can prevent the placement of thoracic pedicle screws that would encroach significantly into the spinal canal.

**Methods**

All patients provided informed consent at enrollment in this study, and the study was approved by the institutional review boards of both Upstate University Hospital and Crouse Hospital (both in Syracuse).

Details related to our novel neuromonitoring technique can be found in the companion article.\textsuperscript{9} From study onset, the results of all intraoperative testing were withheld from the surgical team; that is, the team was blinded to test results. Beginning with the third patient tested, we added a provision to provide feedback to the surgical team—to break the blind—but only if testing indicated a high probability that the stimulating probe was in physical contact with, or in close proximity to, the dura mater of the spinal cord; a screw placed under these circumstances could cause either immediate or delayed injury to the spinal cord, so this risk needed to be avoided. We refer to this portion of the study in which only one type of feedback (that is, break the blind) was used as Phase 1. In the final year of the study we entered Phase 2, during which we started providing feedback to the surgical team on a regular basis.

Testing was done in real time by one of the neuromonitorists, who adjusted the stimulus intensity being delivered through the ball-tipped probe while the surgeon was manipulating that probe within the pedicle track. To test each pedicle track, the stimulus intensity was preset to 15 mA, although the intensity was sometimes lowered to 10 mA when working around T-1 or T-2, to protect against sudden strong contractions in muscles of the forearm and hand when the probe first made contact around the pedicle track entrance point. Typically the neuromonitorist directed the surgeon as to where to position the probe, beginning with the pedicle-track entrance ("entry point"), shifting deeper to where the ball-tip was estimated to lie halfway along the pedicle ("midpoint"), and finally advancing the probe deeper still to the bottom of the pedicle track ("floor"). At each position the probe was held station-

ary for 1–2 seconds, allowing the neuromonitorist time to carefully examine the continually updating records (as many as 10 channels of electromyogram [EMG] updating 3 times per second) to look for time-locked evoked activity from leg muscles. In the absence of such activity, the stimulus intensity was increased until responses from leg muscles became apparent, or to a maximum of 20 mA. The surgeon was then directed to withdraw the probe to the midpoint. If there was still no leg EMG activity at this site with maximum (20-mA) stimulation, we stopped stimulation and moved to the next site.

Conversely, if EMG responses were noted in any of the leg muscles, the stimulation intensity was lowered until only a trace response from a leg muscle was apparent, and in parallel the surgeon was directed to adjust the position of the probe slightly. It was in this fine-tuning of probe position to establish the minimum threshold intensity that we often called for two additional sites for the probe to be held: midway between the entry-point and the midpoint (termed "entry+") and midway between the midpoint and the floor (termed "mid+"). Once the threshold to multi-pulse stimulation was established at the optimal stimulus site (that site giving rise to the lowest threshold) for each of the muscles being monitored (each muscle having its own threshold), we switched to delivery of single-stimulus pulses at the same rate, while the surgeon continued to hold the probe at the optimal site.

We applied single-pulse stimulation for 3 reasons. First, as described in the companion manuscript,\textsuperscript{9} testing both pulse trains and single pulses helped us determine whether EMG activity from leg muscles was being evoked by direct stimulation of lower motor neuron axons, or if instead the response was being mediated by upper motor neuron axons (that is, being stimulated within the spinal cord) that were then, through temporal summation, trans-synaptically recruiting lower motor neurons to discharge. Second, single-pulse stimulation helped us identify the rare patient with a hyperexcitable spinal cord, alerting us to modify our alarm criteria for predicting an inappropriate (that is, medially biased) pedicle track.\textsuperscript{9}

The third and final benefit to testing single-pulse stimulation was that it helped us keep the surgical team blinded to our findings. That is, using both pulse-train and single-pulse stimulation to test all pedicle tracks that gave a positive response to stimulation, even at thresholds well above the alarm criteria we adopted (see below), made it more difficult for the surgical team to “read” the neuromonitoring investigators and guess the results of testing.

We initiated Phase 2 of the study after interim analysis of our data showed that pedicle-track pulse-train stimulation leading to leg responses at an intensity of 10 mA or lower was highly predictive of a medially breached screw. Thus for planned feedback we used this 10-mA value as our cutoff, warning the surgical team that when pedicle-track testing revealed leg responses at thresholds of 10 mA or lower, a screw placed along that pedicle track would probably breach the pedicle’s medial wall. This feedback was provided for 50% of the pedicle tracks being formed during Phase 2, and was block-randomized. In other words, we randomized by pedicle site, and not by patient. The decision whether to provide feedback for
the first pedicle track being tested in a given patient was made randomly, and the feedback status for the second pedicle being instrumented was the opposite of that for the first. Feedback consisted of a verbal report of the lowest threshold for eliciting EMG activity from the leg muscles, and whether responses at low thresholds were seen unilaterally or were bilateral. If the threshold for one or more leg muscles was 10 mA or lower, this information was accompanied with a statement that a screw placed along that pedicle track would probably result in a medial breach of the pedicle.

During Phase 2 of the study, we still maintained the provision to break the blind of the surgeon. Thus, if a pedicle track randomized to the “no feedback” category tested with a threshold of 4 mA or lower, we warned the surgical team just as we had done during Phase 1 of the study. As a consequence, the total number of pedicle tracks for which feedback was provided (either from breaking the blind or as planned) during Phase 2 of the study was slightly more than half the number of pedicles instrumented in this phase of the study.

Results

The companion article provides details of patient demographic characteristics and the overall methodology of our study and shows that our neuromonitoring method can accurately detect pedicle tracks that will—if not modified—lead to a medially malpositioned screw. In the present article we report the effect that providing feedback results to the surgical team had on the incidence of screw placements with significant encroachment on the spinal canal.

All screws were placed using the freehand method, which includes manual palpation of the pedicle’s margins with a ball-tipped probe. In our entire sample (n = 820 screws), after creating a pedicle track (cannulating the pedicle) with the pedicle finder and then manually palpating that pedicle track, the surgeon opted to revise the pedicle track 32 times, in each case without knowing the results of any stimulus-based testing that might have already been carried out. For all but one of these 32 cases of surgeon-choice revision, the pedicle finder was redirected, a new pedicle track with a slightly different trajectory was created, and the threshold of the revised pedicle track was then tested (in the one exception, the pedicle was abandoned altogether). For this population of surgeon-choice revised pedicle tracks, the average threshold to evoke an EMG response from one or more leg muscles was 15.2 ± 5.4 mA. Six of these revised pedicle tracks led to thresholds with the stimulating probe that were 10 mA or lower (suggesting an overly medial trajectory). Four of the screws placed along these tracks encroached upon the spinal canal by more than 2 mm.

Figure 1 shows an example where the surgeon decided to redirect the pedicle trajectory after palpating the T-5 pedicle track with the stimulating ball-tipped probe, but without knowledge of the test results. A 15-mA stimulus intensity failed to elicit EMG activity from any leg muscles (Fig. 1A), although responses were seen in the intercostal muscles (ICs) and abdominal muscles (Abs).

Detecting a lateral breach, the surgeon decided to redirect the pedicle finder medially and was satisfied with palpation of that revised pedicle track. Our testing of this revised pedicle track now showed low-threshold responses from multiple leg muscles, with the lowest threshold (in the abductor hallucis [AbH]) being 5.3 mA. Figure 1B shows responses (arrows) in all 3 leg muscles to a stimulus intensity of 8 mA. The upper CT scan of Fig. 1 shows the original pedicle track (what we call the “ghost track,” indicated by a black arrow) extending ventrally into the vertebral body. One can see how with palpation the surgeon might have detected a lateral breach of the pedicle track, particularly if the ball tip failed to enter the anterior body more ventrally. However, as shown in the lower CT in Fig. 1, the revised pedicle track now caused the screw to encroach upon the canal medially, as predicted by the stimulus-based testing.

In a separate report originating from this study,15 we found poor agreement between the in vivo accuracy of manual palpation of a pedicle wall and the position of the screw placed within that pedicle track. One reason for this poor agreement is that in some cases the original pedicle track was contained within the bony margins of the pedicle, but the larger-diameter screw placed along that track breached the medial wall of the pedicle. Figure 2 shows a case in which we believe this happened, illustrating small evoked responses in hand and foot (AbH) muscles to strong (20-mA) stimulation through the ball-tipped probe of the initial left T-4 pedicle track. As discussed in the companion manuscript,9 such high thresholds to probe stimulation were not a cause for concern. After implanting a screw along that pedicle track, the threshold to screw stimulation (12 mA; response to 18 mA shown in Fig. 2B) was found to be much lower than what we had just seen testing the pedicle track with the ball-tipped probe (20 mA). Figure 2 from the companion manuscript9 shows just how rare it is for a screw threshold to be less than that of its pedicle track. We asked the surgeon to remove the screw and recheck the pedicle track with probe stimulation, and lower-limb EMG activity was now evoked at a threshold of only 5.1 mA when stimulating at the pedicle’s midpoint (response to 8 mA stimulation shown in Fig. 2C). With the stimulating probe positioned at this site within the pedicle track, the surgeon was now able to discern a medial breach in the pedicle. He revised the pedicle track by redirecting the pedicle finder laterally, leading to a satisfactory screw placement.

After manually palpating the initial pedicle track, the surgeon re-palpated the track, this time while stimulating pulse trains were delivered through the ball tip of the insulated probe. In this way we tested a total of 820 pedicle tracks, leading to 780 screw placements that were evaluated by postoperative CT scan. The difference in number between pedicle tracks and screw placements is largely because some pedicle tracks were tested twice due to revision.

The majority (n = 684) of these pedicle tracks were tested without providing any form of feedback (FB) of test results to the surgical team. When FB was provided, it was for one of two reasons. First, if testing revealed an especially low threshold (≤ 4.0 mA) to evoke EMG
activity from one or more leg muscles, suggesting direct contact between the ball-tipped probe and the spinal cord dura mater, we broke the blind and provided feedback (BB-FB), informing the surgeon of our findings and giving him the opportunity to take action. We broke the blind at 29 pedicle sites. Second, in Phase 2 of this study we began providing planned feedback (PL-FB) for 50% of the pedicle tracks tested. Planned feedback was provided for 107 of the pedicle tracks tested, using an alarm threshold cutoff of 10 mA (that is, thresholds < 10 mA led to a warning to the surgical team of a probable medial breach should a screw be placed along that track).

Upon receiving a warning from our testing (either BB-FB or PL-FB), the surgeon could take one of 4 actions: 1) revise the pedicle track, typically by redirecting the pedicle finder laterally and creating a new pedicle track, either from the same starting point or from a slightly different entry point; 2) keep that pedicle track and place a screw as originally planned; 3) keep that pedicle track and place a screw of smaller diameter than originally planned; or 4) abandon that pedicle altogether.

Figure 3 summarizes the average thresholds of pedicle tracks before (pre-revision) and after (post-revision) feedback-based revision, presenting feedback after breaking the blind (BB-FB; n = 29 sites) separately from that arising from planned feedback (PL-FB) triggering an alarm (n = 15 sites). Figure 3 also includes average pedicle track thresholds for the 6 instances in which the surgeon was provided feedback (either BB-FB or PL-FB) of low thresholds to evoke leg EMG responses during pedicle track palpation but chose to place a screw along that pedicle track anyway. In these cases, since there was no revision, only the pre-revision average is plotted in Fig. 3. Finally, Fig. 3 provides for reference two additional data points: 1) the average thresholds of the 32 pedicle tracks associated with screws that encroached medially upon the spinal canal by 2 mm or more (from the companion manuscript); and 2) the average threshold of all pedicle tracks that were not subject to revision in some way (that is, they were “clean”).

Several points stand out from Fig. 3. First, the average threshold of pedicle tracks from the BB-FB group was much higher (14.0 mA) after revision than before (3.6 mA). This was also true for pedicle tracks revised within the PL-FB category, shifting from 8.5 mA (on average) to 17.7 mA. The thresholds for these revised pedicle tracks were much closer to the average of all pedicle tracks examined that neither triggered an alarm (from monitoring).
nor were revised at the surgeon’s discretion in the absence of feedback (Fig. 3, “all ‘clean’ sites”).

To illustrate the role of feedback, Fig. 4 shows an example in which the surgeon—after creating a pedicle track with the pedicle finder—did not detect a breach in this left T-6 pedicle using manual palpation. Testing of the pedicle track revealed low thresholds in leg muscles (7.3, 5.9, and 6.1 mA in the quadriceps, tibialis anterior [TA], and AbH, respectively) when the ball-tipped probe was positioned at the midpoint of the pedicle track (Fig. 4 stimulation intensity = 7.4 mA). These thresholds would not have reached the alarm threshold to break the blind (none was ≤ 4.0 mA), but as this example occurred late in our series and was randomized to the planned-feedback group, the results of testing were shared with the surgeon and he redirected the pedicle finder to create a revised pedicle track. Testing of this revised pedicle track (results not illustrated) revealed much higher thresholds in the TA and AbH muscles (17.1 and 19.6 mA), with no response in the quadriceps to a maximum of 20 mA, and a screw was placed along this revised pedicle track. Above the waveform scans of Fig. 4 are 5 adjacent axial CT scans. The middle 3 scans reveal a defect in the medial wall of the left pedicle (to the right in each image) that we believe represents the “ghost track” where the pedicle finder first passed, a defect that was revealed with testing but missed by manual palpation alone. We propose that a screw placed along this pedicle track would have encroached upon the medial canal by 2 or more mm, since the finder had already itself breached the pedicle’s medial wall, and the screw diameter typically used at this level was 4.5 mm. Instead, the screw placed along the revised pedicle track clearly was lateral to the pedicle’s medial wall (right-most CT scan of Fig. 4). (Note that the CT scans shown in Fig. 4 were deliberately made “bright” to better visualize the defect in the pedicle’s medial wall; for quantifying screw position, the brightness would normally be scaled down considerably.)

In sharp contrast to the improved (that is, increased) thresholds associated with revision of suspect pedicle tracks shown in the 2 left-most groups of Fig. 3, there were 6 pedicle tracks that testing showed had very low thresholds (4.3 mA on average; middle single bar of Fig. 3)—results that were shared with the surgeon—yet for a variety of reasons a screw was placed along each of these pedicle tracks “as is.” Since these pedicle tracks were not revised, only a pre-revision value is shown. The very low average (4.3 mA) is not much different from that of the BB-FB group (3.6 mA), and it is considerably lower...
than the average of pedicle tracks associated with screws proven to have significant (≥ 2 mm) medial encroachment of the spinal canal (second bar from the right of Fig. 3).

Figure 5 shows an example of one of these 6 screws whose pedicle track testing triggered a “break the blind” feedback alarm, but into which a screw was placed anyway. After making an initial pedicle track in the right T-3 pedicle, the surgeon did not detect a pedicle defect using manual palpation, while testing revealed responses in multiple leg muscles at a stimulus intensity of less than 4.0 mA (we had not yet established the exact thresholds before the surgeon withdrew the probe). We broke the blind and informed the surgeon, and he revised the trajectory of the pedicle finder laterally, creating a new pedicle track. Retesting that pedicle track revealed responses in multiple leg muscles, including AbH muscles bilaterally as shown in Fig. 5, at thresholds as low as 2.2 mA (right AbH). The surgeon stated, with reference to this revised pedicle track, “It’s clearly a lateral breach,” and suggested that the stimulus current from the ball-tipped probe might be shunting through a “window” into the spinal canal (and acting on the spinal cord) from the preexisting (that is, initial) pedicle track. As the axial (Fig. 5A) and sagittal (Fig. 5B) CT scans show, however, the screw placed in the right pedicle violated the canal space.

The very low average threshold for the alarm-triggering pedicle tracks that were not revised—4.3 mA from the middle bar of Fig. 3—would suggest that at least some of the screws placed along these tracks, such as the example shown in Fig. 5, would have breached medially into the spinal canal. In fact, all 6 of these screws showed a medial breach on CT scans, ranging from 1.3 to 3.2 mm in magnitude (mean breach magnitude 2.0 ± 0.7 mm).

Besides revising (or keeping) the original pedicle track in response to feedback, our surgeons placed a smaller-diameter screw than originally planned a total of 3 times: once in the BB-FB group, and twice in the PL-FB group. The other option was to abandon a pedicle track altogether. This option was used 5 times: twice each for the BB-FB and PL-FB groups and (as mentioned above) once when the surgeon chose to revise a pedicle track in the absence of feedback and ultimately abandoned that pedicle altogether.

What were the practical consequences of the feedback—either planned or when breaking the study blind—we provided to the surgical team? Did we reduce the number of clinically relevant medially malpositioned screws in our study population? If “yes,” we would prove that applying this novel monitoring technique improved patient safety, by reducing the incidence of a known and documented risk to neurological function—a pedicle screw encroaching on the spinal cord. To answer this question, we used chi-square and Fisher exact tests to compare the number of screws found to breach the pedicle medially and encroach on the spinal canal by 2 mm or more to all other screw placements, as a function of whether
feedback was provided and acted upon to revise a pedicle track. This chi-square contingency table is illustrated in Table 1, and Fisher exact testing revealed a $p$ value of 0.02, proving that provision of appropriate feedback of test results—and acting on that feedback—led to a significant reduction in the numbers of screws with clinically relevant medial malpositioning.

Traditional somatosensory evoked potential (SSEP) and transcranial MEP monitoring was performed throughout each patient’s surgical procedure. There were no significant changes in SSEP parameters or MEP thresholds that could be attributed to screw placement, and none of the patients awoke with a worsening of their neurologic status. Two patients—one with a left-side T-9 screw and transcranial MEP monitoring was performed through T-5, 4.0–5.0 mm for T-2 through T-4, and 4.0 mm for T-1. There was a trend toward the use of larger screw diameters in the present study were 5.5–6.5 mm for L-1 through T-10, 4.5–5.5 mm for T-9 through T-5, 4.0–5.0 mm for T-2 through T-4, and 4.0 mm for T-1. There was a trend toward the use of larger screw whose threads encroached 4.8 mm into the canal and one with a right-side T-6 screw with threads extending 3.2 mm into the canal—were brought back to the operating room within several days of their initial surgery for revision of these 2 screw placements. The revisions were completed without complication. Both of these screws were at sites for which pedicle track feedback was withheld from the surgical team, either because the “break the blind” option had not yet been implemented (in the first case) or because the screw placement occurred within Phase 2 of the study but was randomized to not receive feedback (in the second). In this second case, lower-limb thresholds (8.2 and 9.0 mA for TA and AbH muscles, respectively) did not trip the “break the blind” alarm cutoff of 4.0 mA that we had adopted, but would have caused us to warn the team of a probable medial malpositioning, had we provided feedback for this site, because at least one lower-limb muscle threshold to pulse-train stimulation was less than 10 mA.

**Discussion**

The original goal of this study was to develop and validate a novel intraoperative neuromonitoring method for detecting pedicle tracks that, if populated with a pedicle screw in the thoracic spine, would result in a breach of the pedicle’s medial wall and stenosis of the spinal canal. A unique feature of the study design was that during Phase 1 the great majority (> 96%) of screws were placed without providing feedback of testing to the surgical team: the surgeons were blinded to test results. The companion manuscript (Part 1)” shows that the original goal was achieved, with our novel method delivering a level of accuracy for predicting screw medial malpositioning unsurpassed by other neuromonitoring or imaging technologies currently in use.

Phase 2 of the study was marked by a revision to the protocol by which we began providing feedback of test results for 50% of the screw placements. In the present article, we showed, by combining results of suspect pedicle sites in which we broke the blind with cases including planned feedback, that we significantly reduced the number of thoracic pedicle screws with clinically relevant (> 2 mm) medial malpositioning.

**What Constitutes a Clinically Relevant Medial Breach?**

In the literature, the incidence of thoracic-level screw medial malpositioning ranges from 1.5% to 18.3% (mean 7.1% ± 4.9%). However, many of these reports did not include the criteria by which a malpositioning was determined, making direct comparisons between these studies problematic.

Of those studies that do specify the magnitude of breach, most use either a 2-mm value, or one-half the diameter of the screw, as the basis for inclusion of that screw in their count of malpositionings. **TABLE 1: Chi-square contingency table showing numbers of screws with medial encroachment of 2 mm or more as a function of feedback status and action taken***

<table>
<thead>
<tr>
<th>Feedback/Revision</th>
<th>Medial Encroachment</th>
<th>$\geq$ 2 mm</th>
<th>&lt; 2 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>no/no</td>
<td>32</td>
<td>653</td>
<td></td>
</tr>
<tr>
<td>yes/yes</td>
<td>0</td>
<td>95</td>
<td></td>
</tr>
</tbody>
</table>

* If an alarm was given, but no action was taken, it was treated as if there was no feedback.
Is Neuromonitoring for Pedicle Screw Placement Necessary?

Both surveys\(^8,13,50\) and historical controls\(^56,67\) suggest that neuromonitoring can be useful for certain types of cases.\(^4,21,23,34,43,51,78\) But one case-control series pointed out the low rates of neural injury, even when no neuromonitoring was used.\(^79\) In the present study we encountered a 4% incidence of medially malpositioned screws encroaching on the spinal canal by 2 mm or more. This compares favorably to the mean 7.1% malpositioning rate derived from the literature (from the previous section). Nevertheless, the fact that none of our subjects awoke with a neurological deficit caused by a screw malpositioning cannot be used to argue that neuromonitoring for these types of cases is unnecessary. As a reminder, there were dozens of pedicle tracks that were not populated with a screw due to our warnings, any one of which could have led to acute neural injury. Immediate neurological injury following a screw malpositioning is a known risk of this procedure, and acute rates of injury ranging from 0.31% to 8.3% have been reported.\(^14,25,30,81\) What has been lacking is a clear indication of the degree to which a medially malpositioned screw might cause neurological symptoms over the long term. Several case reports of delayed neurological symptoms (including weakness, paresthesia, pain, and headache) associated with a screw in the canal space have appeared.\(^2,53,57\) In addition, a recent paper describes multiple subjects with delayed paralysis or other neurological symptoms following scoliosis surgery, in which the authors attribute morbidity to pedicle screws inadvertently placed into the spinal canal by 2 mm. In reference to pedicle screws, these authors concluded: “In the absence of direct neural injury, this explains the clinical finding of medial perforation of up to 4 mm without neurologic compromise.”\(^56\) The authors of another study agreed that up to a 4 mm encroachment by a pedicle screw into the thoracic spinal canal would be clinically acceptable.\(^26\) However, the assumption that the spinal canal can sustain an immediate stenosis of 4 mm or more (or as much as 8 mm, since screws are often placed bilaterally at the same level) without risk to the spinal cord has been disputed.\(^5,72\)

Is a Blinded Study Necessary?

When discussing the evidence supporting the use of intraoperative neuromonitoring for preventing neurological injury, a number of authors have pointed out the absence of controlled studies (that is, Class I evidence) addressing this topic.\(^3,22,30,33,51,52,63,66\) With rare exceptions,\(^4\) in the absence of such evidence, the argument goes, the justification for neuromonitoring is weak at best,\(^24\) and professional organizations representing spine and cranial surgeons typically leave the decision of whether to use neuromonitoring up to the surgeon. These organizations have refrained from making any statements suggesting that neuromonitoring should be considered a “standard” procedure.\(^4,17,74\) Thus while there are many advocates for the use of neuromonitoring for preventing patient injury during spine surgery, there are also skeptics who will not be satisfied with anything less than Class I evidence supporting neuromonitoring’s benefit to patient welfare. For these reasons, we believed a blinded and controlled study of this novel monitoring approach was necessary to improve the probability that surgeons and monitoring teams would at least give this approach a fair trial, if warranted by our results.

Is a Blinded Study Ethical?

Some of the same individuals pointing out an absence of Class I evidence to support the use of neuromonitoring question the ethics of carrying out such a study.\(^19,33,77\) For example, Francesco Sala, a neurosurgeon who publishes frequently in the field wrote “It is very unlikely that Class I studies will ever occur in the field of IN” (intraoperative neuromonitoring), because: 1) “... a controlled study where patients are randomly assigned to a control group or a monitored group would be unethical and unacceptable to patient and surgeon alike;” and 2) sample sizes would be prohibitive, given the historically low incidence of severe injury.\(^66\) A spirited discussion on this topic appeared recently in a series of letters to the editor,\(^28\) with most respondents taking the position of Sala in the preceding quotation.

We believe our study meets the standards for Class I evidence (control group of patients who are effectively not monitored due to withholding of feedback; blinding of surgeons and CT interpreters to test results; randomization), and in practice we did not withhold information

The companion paper showed that our patient population was diverse, with a broad variety of surgical indications.\(^9\) However, none of our data were derived from children, who make up a sizeable cohort of patients undergoing thoracolumbar spinal instrumentation and fusion for the treatment of idiopathic or neuromuscular scoliosis. Thus we must acknowledge that while the monitoring approach we have described in these two articles should—in principle—be as effective in this pediatric population as we have found it to be in adults for minimizing the incidence of medially malpositioned thoracic pedicle screws, the absolute numbers defining effective alarm criteria might differ slightly from those that we have recommended in these papers (10 and 15 mA for lower and upper bounds).
that had clearly been shown to be predictive of screw position. That is, we broke the study blind when it looked like a screw, if placed, would be very close to or touching the thecal sac. Standard SSEP and MEP monitoring was carried out and was of no benefit in detecting screws with significant medial malpositioning.

Recent reports of thoracic pedicle screw monitoring using thoracic-innervated musculature and single-pulse stimulation have widely disparate conclusions about efficacy.18,47,62,64,70 These approaches were modeled after a lumbosacral monitoring test that we developed,11,12 but our original test was never intended for application to the thoracic spine. Most of the studies did not follow our recommendations of stimulating within the pedicle track via the ball-tipped probe,11,12 but instead restricted testing to screw stimulation only.18,32,52,60,64,75 One must question the wisdom of a modification in protocol that—while perhaps saving a few seconds per pedicle site—leads to results that simply cannot be trusted. The fact that most screws now being implanted are made of titanium alloys, whose semiconductor-like properties present their own unique problems when forced to serve as stimulating electrodes,16 further diminishes the reliability of thoracic pedicle screw monitoring techniques that rely upon screw stimulation and EMG activity evoked from thoracic-innervated musculature for detecting medial malpositioning of thoracic pedicle screws.

Therefore, at the study outset we were not withholding neuromonitoring test results already proven to predict pedicle screw position. Early in our study we incorporated a design modification that allowed us to break the study blind if very low thresholds indicative of direct contact between nerve root and ball-tipped probe were encountered.31,37 Once we began providing planned feedback (Phase 2), rather than randomly deciding what patients would and would not have neuromonitoring test results shared with the surgeon, we randomized feedback between screw sites within the same patient. Thus every patient in Phase 2 benefited to some degree from our novel but not yet proven monitoring technique, to the extent that feedback might be shown to lower the incidence of significant medial malpositioning of screws. And we have, in fact, now shown just this in the present article.

By extension, those patients in Phase 1 of the study for whom we broke the blind of pedicle site testing also benefited from their participation, since our data show convincingly that it reduced the incidence of screw placements encroaching upon the spinal cord by 2 mm or more. This is because although there is no way to know whether screws placed along the original pedicle tracks triggering the “break the blind” or planned feedback alarms would have breached medially (since nearly all of these pedicle tracks were revised), Fig. 3 shows that the average pedicle track threshold of the 32 screws known to have been medially malpositioned by 2 mm or more was 7.1 mA, a value considerably greater than the average of the pedicle tracks triggering “break the blind” feedback, and only slightly lower than the average of the planned-feedback pedicle tracks whose threshold triggered a warning alarm to the surgical team.

As a reminder, we broke the blind only in cases when we believed the patient could be at immediate risk of neural injury if a screw was placed along a particular pedicle track, based upon a very low (< 4 mA) threshold of leg muscle EMG to pedicle-track stimulation. When providing planned feedback during the study’s second phase, however, we were attempting to minimize medially placed screws altogether, rather than just avoiding those that were so far medial that a screw might be touching the dura. This caveat required use of an alarm threshold greater than the 4 mA value we had been using for breaking the blind.

Is Each Step of the Protocol Necessary?

The main innovations of this protocol are: 1) the use of a 4-pulse stimulus train to facilitate recruitment of lower motor neurons from stimulation of upper motor neuron axons in the spinal cord; 2) deliberate examination of multiple depths of the pedicle track with a ball-tipped probe while pulse trains are being delivered; and 3) targeting muscles in the legs for monitoring evoked responses. Innovations 1 and 3 will be immediately familiar to neuromonitoring teams who use transcranial electrical stimulation for monitoring MEPs. Many of the neuromonitoring devices now in use are already capable of generating repeated pulse trains, hence need little or no software upgrading. In the absence of misdirection, each pedicle track can be tested in less than 30 seconds, on average. And, there are no special anesthesia requirements for this protocol beyond those already in place for MEP monitoring. In other words, there will be almost no additional cost or time added when incorporating this protocol into the existing testing battery (typically SSEP and MEP monitoring) that is likely to already be in place for any case calling for implantation of thoracic pedicle screws.

Single-pulse stimulation appears to be adequate to detect medially biased pedicle tracks at spinal levels of T-11 through L-1 when stimulation recruits lower motor neuron axons that have already separated from the spinal cord and are shifting laterally within the thecal sac (for example, L-3 nerve root axons innervating the quadriceps). For more rostral levels in the spinal cord, pulse-train stimulation was much more effective for recruitment of lower-limb muscles. During this series (and for one patient studied subsequent to data analysis), we noted leg muscle responses to stimulation at levels rostral to T-10 for both pulse-train and single-pulse stimulation. Responses to single-pulse stimulation indicate a hyperexcitable lumbosacral spinal cord, and while we cannot recommend specific numbers, we suggest that when seen, one should effectively lower the alarm threshold levels by 1–2 mA. For example, suppose pedicle-track testing at T-6 revealed a response to pulse-train stimulation at a threshold of 9.8 mA in a leg muscle, but single-pulse stimulation at a threshold of 12 mA also evoked activity in leg muscles. Instead of warning the surgeon of a probable breach due to a threshold of less than 10 mA, one might consider issuing a warning only for pulse-train responses seen at thresholds of 8 mA or lower.

In our first two patients we had several pedicle screw placements that showed significant (> 2 mm) medial canal

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encroachment, yet their thresholds to probe-based testing of the pedicle track were not that low (12–15 mA). We noted that the surgeons palpating the pedicle tracks were rapidly moving the probe along the pedicle track, almost “bouncing” the probe off the bottom of the track. Once we asked the surgeon to slow down the probe movement and be more deliberate in placing the probe—particularly emphasizing probing the pedicle’s midpoint and the “entry+” and “mid+” positions—we no longer encountered these big discrepancies between magnitude of screw medial malpositioning (large) and probe-based threshold (high). Thus it is essential to not only use the ball-tipped probe to test the pedicle track—which proponents of the freehand method advocate in any case—but to make slow and deliberate movements with that probe, allowing the neuromonitorist enough time to adequately interrogate the entire pedicle, given the 3-Hz rate of pulse-train delivery that we recommend.

As the companion paper shows, this technique is much less effective for predicting and preventing medi- ally malpositioned screws if the target muscles used for electromyography are intercostal and/or abdominal.9 We found many instances of very low-threshold responses from these muscle groups to probe-based stimulation even for pedicle tracks leading to screws far removed from the canal space. Thus while these responses might tell the surgeon about proximity of a probe or screw to a thoracic nerve root, they do little to warn of proximity to the spinal cord, at least in our hands. Moreover, our technique is of no use whatsoever in detecting lateral breaches, but this was never a goal of this study.

It is also worth repeating that stimulation of the screws alone will not work nearly as well as stimulating within the pedicle track, and we strongly advise against using this “time-saving” approach. That is, stimulating just the screw may save the 30 seconds or so that testing the screw’s pedicle track might require, but if detection of a significant malpositioning fails, as we predict will occur on a fairly regular basis when stimulating the screw alone, and the patient has to return to the operating room for revision surgery, or now has a new deficit, the time-savings quickly lose their appeal.

Finally, a few comments about training and experience are called for. First, we recently showed that manual palpation of the pedicle alone in an operating room setting—even by a fellowship-trained spine surgeon—often fails to detect misdirected pedicle tracks that will lead to a medially malpositioned screw.13 Similarly, we must emphasize that an inexperienced neuromonitoring team will probably not achieve the level of accuracy in preventing medially malpositioned screws that is possible with close adherence to the protocol described in these two companion papers. Of course, this concern applies across the spectrum of neuromonitoring techniques now employed in the operating room, as has been pointed out by numerous authors.29,48,49,82

Conclusions

In the companion report, we showed that when impl-anting thoracic pedicle screws, responses to low-thresh-old pedicle-track pulse-train stimulation from leg muscles can predict screw placements that will have an excessive medial bias.9 In this blinded and randomized study we proved, as shown in the present report, that acting on this information by revising the direction/trajectory of the pedicle finder within the pedicle track significantly reduced the probability of placing a screw with a clinically relevant amount of encroachment upon the spinal canal. Implementation of this approach for thoracic ped-icle screw placement should lead to a reduction in immediate or delayed spinal cord myelopathy caused by canal stenosis from a medially placed pedicle screw and a lower probability that a patient will require additional surgery to revise and/or remove the offending screw(s).

Acknowledgments

We wish to thank: 1) Evan Belanger, Margaret Fischer, and Catherine Murtagh-Schaffer for help with obtaining consent from patients; 2) John Smale of Digitimer Ltd. for providing us with a device to capture the voltage-equivalent magnitude of constant-current stimulation pulses delivered to subjects; 3) Chuck Hughes of SPS Medical (Rush, New York) for performing sterilization valida-tion of the ball-tipped probe we used in roughly half of our cases; and 4) the operating room staff of Crouse Hospital and Upstate University Hospital (both of Syracuse, New York) for squeezing our outsized instrumentation rack into their already-crowded domains.

Disclosure

This study was supported by a grant from the National Institutes of Health to B. Calancie (NS R01 NS063055). Digitimer Ltd. (Welwyn Garden City, UK) designed and provided a current/voltage adapter for recording voltage pulses calibrated to the intensity of current pulses being delivered. Dr. Moquin reports a consultant relationship with K2M.

Author contributions to the study and manuscript preparation include the following. Conception and design: Calancie, Moquin. Acquisition of data: all authors. Analysis and interpretation of data: Calancie, Donohue. Drafting the article: Calancie. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Calancie. Statistical analysis: Calancie, Donohue. Administrative/technical/material support: Calancie. Study supervision: Calancie.

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