Neurophysiological Assessment of Thoracic and Cervical Pedicle Screw Integrity

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Summary: Transpedicular instrumentation of the thoracic and cervical spine is technically more difficult than at lumbar levels because of narrower pedicles and less sensitive intraoperative fluoroscopic assessment. Furthermore, the potential implications of a misplaced screw are greater because of the close proximity of the spinal cord and vertebral artery. Real-time confirmation of correct pedicle screw placement in the operating room is therefore considered even more important, and this article reviews the availability, utility, and limitations of electrophysiologic testing techniques that can be used for this purpose.

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Pedicle screws are used to anchor hardware directly to the vertebral bodies and facilitate spinal fusion and correction of deformity (Gaines, 2000; Yahiro, 1994). However, pedicle screws are placed without direct visualization, and more than 15% are found to be misplaced on postoperative computed tomography scans (Hicks et al., 2010), with potential for injury to the adjacent nerve roots as well as other complications including pseudoarthrosis and construct failure. An ongoing concern with these potential complications has led to the use of a number of precautionary techniques in the operating room to ensure accurate screw placement, including laminectomy with direct pedicle wall inspection (Xu et al., 1998), fluoroscopy (Choi et al., 2000), and computer-assisted navigation systems (Scheufler et al., 2011). There are also electrophysiologic pedicle screw testing techniques that take advantage of the high impedance to the passage of electric current that is provided by an intact layer of cortical bone. A correctly positioned pedicle screw or hole lies completely inside a layer of cortical bone, whereas a misdirected hole or screw that has perforated the medial wall of the pedicle will lie adjacent to the nerve root at that level without an intervening layer of bone. Therefore, electrical stimulation of a misplaced pedicle hole or screw will activate the adjacent nerve root and evoke a compound muscle action potential in the innervated muscle at lower stimulus threshold intensity than one that is correctly positioned within the body pedicle. The actual stimulus threshold cutoff value that is used to indicate a pedicle wall breech is based on statistical analysis—ideally, the level selected will correctly identify most pedicle wall perforations (i.e., high specificity) and any threshold above that level should indicate correct placement within the pedicle wall (i.e., high negative predictive value). This technique of intraoperative triggered electromyographic (EMG) testing with recordings made from appropriate lower extremity muscles and a stimulus intensity cutoff of 6–10 mA has been become well established for detecting medially misplaced lumbar pedicle screws (Skinner and Rippe, 2012) because it provides real-time data in the operating room without subjecting the patients to radiation exposure and increased operating time associated with the other techniques. However, false-negative results can occur in the presence of excessive pharmacologic neuromuscular blockade, chronically compressed and degenerated nerve roots, and when there is no monitored muscle available from the appropriate myotome (Holland, 2002).

Thoracic and cervical pedicles are smaller than their lumbar counterparts with an increased propensity for screw misplacement and pedicle wall breach (O'Brien et al., 2000; Parker et al., 2011). Moreover, the implications of a pedicle wall breach are potentially more severe at these levels because of the close proximity of the spinal cord and vertebral arteries (Fig. 1). This has led to reluctance to consider pedicular instrumentation at thoracic and cervical levels in favor of wires and hooks, and, of course, when screws are required, real-time confirmation of correct pedicle screw placement is considered even more important.

TESTING THORACIC PEDICLE SCREWS

The placement of thoracic pedicle screws complicated by the narrow pedicle and changes in anatomy and vertebral morphology in the scoliotic spine, with as many as 43% of screws misplaced (Belmont et al., 2002), and clinical complication rates as high as 16% (Li et al., 2010). Furthermore, intraoperative fluoroscopy is less reliable for detecting thoracic than lumbar pedicle wall breaches (Guzey et al., 2006). Stimulus-triggered EMG techniques have been used at thoracic levels but are limited by the paucity of segmentally innervated muscles available for recording responses. Many

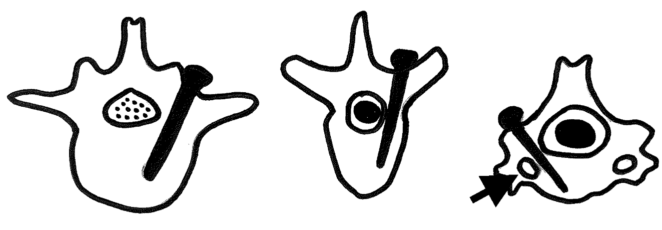

FIG. 1. Schematic representation of pedicular instrumentation at different spinal levels, demonstrating the narrower pedicles with closer proximity to the spinal canal at cervical and thoracic levels, and also the close proximity to the vertebral artery (arrow) at cervical levels.

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investigators have reported consistently lowered stimulus thresholds for medially misplaced pedicle screws from the lower thoracic levels (T8 through T12) using triggered EMG responses recorded from the rectus abdominus muscle (Table 1) (Duffy et al., 2010; Min et al., 2011; Norton and Heddon, 2009; Raynor et al., 2002; Reidy et al., 2001; Samdani et al., 2011; Shi et al., 2003). Finding a reliable recording muscle to confirm accurate placement of upper thoracic pedicle screws has been more problematic. Recordings made from exposed paraspinal muscles (Silverstein and Mermelstein, 2010) and intercostal muscles (Duffy et al., 2010; Norton and Heddon, 2009; Regidor et al., 2001; Rodriguez-Olaverri et al., 2008) have correctly identified upper thoracic pedicle screw perforations in some series. However, the sensitivity of triggered EMG recordings made from these muscles is much lower for detecting misplaced upper thoracic pedicle screws (Duffy et al., 2010; Regidor et al., 2001; Samdani et al., 2011). Furthermore, stimulus thresholds recorded from intercostal muscles in an animal model were not significantly lower for thoracic medial pedicle wall breach unless the screw was lying directly against the nerve root (de Blas et al., 2009, Montes et al., 2012). For these reasons, it appears that stimulus-triggered EMG is less reliable for detecting misplaced upper than lower thoracic pedicle screws (Table 1), and non-neurophysiologic techniques, such as the PediGuard device (Bai et al., 2012; Bolger et al., 2007; Ovadia et al., 2011) or computer-assisted navigation systems (Scheufler et al., 2011), may be more appropriate during these cases.

This situation is further complicated by the displacement of the spinal cord within the spal canal toward the concave side at the apex of the scoliosis curve (de Blas et al., 2012). Animal studies have shown that thoracic pedicle screw stimulus thresholds are affected by the distance of the screw from neural structures (Montes

TABLE 1. The Sensitivities and Suggested Threshold Cutoff Values for Studies That Have Used Triggered Electromyography to Detect Medial Thoracic Wall Perforations by Pedicle Screws

Study	Levels	Screws	Medial Perforation	Detection Method	Proposed EMG Threshold (mA)	Recording Muscle	Number detected (Sensitivity)	Negative Predictive Value (%)	Complications
Reidy et al., 2001	T1–12	90	8	Post-op CT	7	IC, RA	4 (50%)	94	0
Raynor et al., 2002	T6–T12	677	6 (0.8%)	Manual medial wall palpation	6*	RA	6 (100%)	96	0
Shi et al., 2003	T1–T12	87	5 (5.7%), All at T9-T12	Post-op CT	11	FCU, IC, RA	3 (60%)	98	0
Duffy et al., 2010	T1–T12	95	41	Post-op CT	6	IC, RA	11.8%	91.2	0†
Min et al., 2011	T5–T12	80	9 (11%)	Post-op CT	6	RA	0‡	95	0
Regidor et al., 2001	T2–T6	248	24 (10%)	Post-op CT	12	Axillary chest wall	10 (41%)	87.9	0
Samdani	T2–T12	937	47 (5%)	Post-op CT	6*	IC, RA	13 (28%)		0
et al., 2011	T10–T12	282	7 (2%)	Post-op CT	6*	RA	6 (86%)		0

*Proposed criteria either threshold <6 mA or ≥65% lower than "average" threshold.
†Two patients were taken back to the operating room to have radiographically misplaced screws replaced, but there were no clinical complications.
‡Three screws had stimulus thresholds <6 mA, but these were reinserted during surgery, and thus were not counted in the final numbers.
CT, computed tomography; FCU, flexor carpi ulnaris; IC = intercostals; Post-op, postoperative; RA = rectus abdominus.

TABLE 2. Stimulus Thresholds for Correctly and Incorrectly Placed Thoracic Pedicle Screws Assessed by Postoperative CT Scans Placed on the Concave Versus Convex Sides in 23 Pediatric Scoliosis Spine Cases (de Blas et al., 2012)

	Concavity		Convexity	
Pedicle Screw Placement	Number	EMG threshold	Number	EMG threshold
Intact wall	141	21.1 ± 8.2	150	23.9 ± 7.7
Medial breach	13	12.9 ± 3.2	16	13.8 ± 3.6
Inside spinal canal	5	9.7 ± 3.2	6	12.1 ± 3.4

CT, computed tomography; EMG, electromyography.

TABLE 3. Stimulus Thresholds for Spinal Cord Activation Using High-Frequency Pulse Train Stimulation of Correctly Placed and Misplaced Thoracic Pedicle Holes and Screws Based on Postoperative Computed Tomography Scan (Donohue et al., 2008)

	Complete Medial Wall Perforation		Close to Medial Wall		Correctly Placed	
	Hole	Screw	Hole	Screw	Hole	Screw
Number	19	19	38	42	3	3
Thresholds	7.9 mA ± 4.6	19.8 ± 5.3	13 ± 5.7	24.1 ± 6.2	>30 mA	>30 mA

TABLE 4. Stimulus Thresholds of Cervical Screws Versus Postoperative CT findings (Djurasovic et al., 2005)

Stimulus Threshold (mA)	CT Findings	
	Acceptable	Unacceptable
>15	124	1
10–15	13	2
<10	2	5

CT, computed tomography.

TABLE 5. Sensitivity and Negative Predictive Value for Identifying Misplaced Pedicle Screws on Postoperative Computed Tomography Scan Using Stimulus Threshold Cutoffs of 15 and 10 mA (Djurasovic et al., 2005)

Stimulus Threshold (mA)	Correctly identified (Sensitivity)	Negative Predictive Value (%)
15	7/8 (88%)	99
10	5/8 (62%)	98

et al., 2012). Hence thoracic pedicle screws placed on the concave side of the scoliotic spine have lower stimulus thresholds than those placed on the convex side, and this needs to be taken into account when using this technique to determine the likelihood of a medical pedicle wall breach (Table 2) (de Blas et al., 2012).

Medial thoracic wall breaches, including those at upper thoracic levels, have been detected by activation of the corticospinal tracts with recordings made from leg muscles using a high-frequency four-pulse stimulus train via an insulated ball-tipped probe, a stimulus protocol similar to that used for eliciting transcranial motor-evoked potentials. The stimulus thresholds for medially misplaced holes were much lower than those for correctly based holes based on postoperative computed tomography scan results (Table 3). Using a stimulus threshold cutoff of 15 mA, this technique correctly identified 18 of 19 medial pedicle wall breaches for a sensitivity of 95% and a negative predictive value of 60%. Once instrumented with a screw, the sensitivity of this technique fell to 58% (Donohue et al., 2008), underscoring the importance of testing both pedicle holes and screws in all cases.

TESTING CERVICAL PEDICLE SCREWS

Despite a 6% malposition rate, there is a <2% incidence of postoperative radiculopathy and only a single case of vertebral arterial injury from cervical pedicle screw insertions (Abumi et al., 2000; Deen et al., 2003; Graham et al., 1996; Heller et al., 1995). Misplaced screws are most common at C4, because of the narrow pedicle wall, and at C7, because of the difficulty with fluoroscopic evaluation at that level from shoulder positioning (Abumi et al., 2000). The widespread myotomal innervation from the cervical cord expansion more readily lends itself to the application of intraoperative EMG detection of misplaced pedicle screws. A 15 mA stimulus threshold had a sensitivity of 88% and a negative predictive value of 99% for correctly identifying a pedicle screw misplaced outside the pedicle or lateral cervical mass (Tables 4 and 5). Furthermore, intraoperative EMG testing detected 7 of 11 misplaced screws that were missed on plain radiographs (Djurasovic et al., 2005). Obviously, a potential disadvantage of stimulus-triggered EMG compared with non-neurophysiologic techniques, such as the PediGuard device (Koller et al., 2009; Zeller et al., 2009) or computer-assisted navigation systems (Scheufler et al., 2011), is the potential failure to identify lateral wall perforations that could potentially compromise the vertebral arteries (Fig. 1).

SUMMARY

Thoracic and cervical pedicle screws are becoming increasingly used for spinal stabilization. Transpedicular instrumentation is technically more difficult at these levels than in the lumbar spine because of narrower pedicles and more limited intraoperate fluoroscopic assessment. Furthermore, although the incidence of postoperative complications has been low, the potential implications of a misplaced screw are much higher because of the close proximity of the spinal cord and vertebral artery. The same triggered EMG techniques that have been successfully used to identify misplaced lumbar pedicle screws can easily be applied to cervical pedicle screws, using similar stimulus intensities and recordings made from arm muscles. Triggered EMG is less useful for identifying misplaced thoracic pedicle screws primarily because of the lack of available recording sites. While lower thoracic pedicular instrumentation can be assessed using recordings made from rectus abdominus, assessment at higher thoracic levels is less reliable and potentially further complicated by scoliosis curves. Application of the same stimulus parameters used to elicit transcranial motor-evoked potentials can be used to detect medial thoracic wall perforations even at higher levels from activation of the corticospinal tracts in the spinal cord with recordings made from leg muscles. Nonphysiologic techniques, such as the PediGuard device or computer-assisted navigation systems, may be more useful for detecting pedicle wall perforations in the upper thoracic spine or lateral pedicular perforations in the cervical spine that could potentially compromise the closely adjacent vertebral arteries. Finally, and perhaps most importantly, it

TABLE 6. Key Points

1. Cervical pedicle holes and screws can be tested for medial pedicle wall perforation using triggered EMG recordings made from appropriate myotomal muscles. Using a stimulus threshold of 15 mA will identify 88% of the medial pedicle wall breeches with a 99% negative predictive value.
2. Lower thoracic pedicle screws can also be tested for medial pedicle wall perforation using stimulus-triggered EMG with recordings made from the rectus abdominus muscle. Using a stimulus threshold of 6 mA, or ≤65% of the average threshold value for that case, will identify 85%–100% of the medial pedicle wall breeches with a >90% negative predictive value.
3. Confirming correct placement of pedicular hardware is more problematic in the upper thoracic spine, particularly in the presence of a scoliosis curve, and these are cases where multiple complimentary monitoring techniques should probably be available, including triggered EMG recordings made from the intercostal muscles, pulse train stimulation with recordings made from the lumbar myotomes, and/or nonphysiologic techniques, such as the PediGuard device or computer-assisted navigation systems.
4. Although these data indicate that positive intraoperative neurophysiologic testing will identify misplaced hardware (sensitivity) and negative testing can confirm correctly placed hardware (negative predictive value), there is no published prospective outcome data that show this has reduced postoperative neurologic complications or improved outcome.

should be noted that none of the misplaced pedicle holes or screws that were detected in any of the studies quoted here were associated with postoperative neurologic deficit. In fact, there is yet to be any published outcome data showing reduced postoperative neurologic deficit from using these intraoperative electrophysiologic techniques to confirm satisfactory placement of pedicle screws at any spinal level to justify the additional time, effort, and expense involved (Table 6).

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