Utility of intraoperative electromyography in placing C7 pedicle screws

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OBJECTIVE The C7 vertebral body is morphometrically unique; it represents the transition from the subaxial cervical spine to the upper thoracic spine. It has larger pedicles but relatively small lateral masses compared to other levels of the subaxial cervical spine. Although the biomechanical properties of C7 pedicle screws are superior to those of lateral mass screws, they are rarely placed due to increased risk of neurological injury. Although pedicle screw stimulation has been shown to be safe and effective in determining satisfactory screw placement in the thoracolumbar spine, there are few studies determining its utility in the cervical spine. Thus, the purpose of this study was to determine the feasibility, clinical reliability, and threshold characteristics of intraoperative evoked electromyographic (EMG) stimulation in determining satisfactory pedicle screw placement at C7.

METHODS The authors retrospectively reviewed a prospectively collected data set. All adult patients who underwent posterior cervical decompression and fusion with placement of C7 pedicle screws at the authors' institution between January 2015 and March 2019 were identified. Demographic, clinical, neurophysiological, operative, and radiographic data were gathered. All patients underwent postoperative CT scanning, and the position of C7 pedicle screws was compared to intraoperative neurophysiological data.

RESULTS Fifty-one consecutive C7 pedicle screws were stimulated and recorded intraoperatively in 25 consecutive patients. Based on EMG findings, 1 patient underwent intraoperative repositioning of a C7 pedicle screw, and 1 underwent removal of a C7 pedicle screw. CT scans demonstrated ideal placement of the C7 pedicle screw in 40 of 43 instances in which EMG stimulation thresholds were > 15 mA. In the remaining 3 cases the trajectories were suboptimal but safe. When the screw stimulation thresholds were between 11 and 15 mA, 5 of 6 screws were suboptimal but safe, and in 1 instance was potentially dangerous. In instances in which the screw stimulated at thresholds ≤ 10 mA, all trajectories were potentially dangerous with neural compression.

CONCLUSIONS Ideal C7 pedicle screw position strongly correlated with EMG stimulation thresholds > 15 mA. In instances, in which the screw stimulates at values between 11 and 15 mA, screw trajectory exploration is recommended. Screws with thresholds ≤ 10 mA should always be explored, and possibly repositioned or removed. In conjunction with other techniques, EMG threshold testing is a useful and safe modality in determining appropriate C7 pedicle screw placement.

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KEYWORDS posterior cervical fusion; pedicle screws; electromyography; intraoperative; safety; medial breach; cervicothoracic junction; surgical technique

INDICATIONS for posterior cervical decompression, instrumentation, and fusion are broad, and include cervical spondylotic myelopathy, multilevel stenosis, pseudarthrosis after anterior cervical fusion, ossification of the posterior longitudinal ligament (OPLL), and deformity.¹²

Surgeons typically use a combination of the patient's clinical examination results, findings on radiographic imaging, and biomechanical considerations in determining the number of levels that are ultimately decompressed and/or fused.^{1,2,10} Determining the most appropriate distal fix-

ABBREVIATIONS CMAPs = compound muscle action potentials; EMG = electromyographic; OPLL = ossification of the posterior longitudinal ligament; VA = vertebral artery.

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tion level is controversial when considering the cervicothoracic junction, with some surgeons choosing to extend the fusion to the proximal thoracic spine instead of ending at C7, in part due to the unique morphometric properties of the C7 vertebral body and the challenges that its fixation presents.^{1,2,5,6}

The C7 vertebral body represents the transition point from the subaxial cervical spine to the upper thoracic spine. It has the largest vertebral body, longest spinous processes, and a relatively small lateral mass compared to other subaxial cervical levels.^{1,5,7,10} The C7 pedicle is often highly cortical and the dorsal landmarks for free-hand placement can have significant variability.^{1,5,10,11,14} As compared to lateral mass and translaminar screws, studies have demonstrated the biomechanical superiority of pedicle screws, especially at the distal end of a construct.^{1,18,21,26} However, intraoperative evaluation of cervical pedicle screw placement can be difficult to assess using fluoroscopy alone.^{2,5–8,13} There are often numerous technical challenges in obtaining a satisfactory view of the pedicles, including a patient's body habitus, shoulders, and positioning.^{5,7,11,14} As a result, surgeons have to rely on other techniques to allow for safe pedicle screw placement.^{14–17,20} Some surgeons avoid fixation at C7 and favor extending the instrumented construct to the upper thoracic spine.^{19,26,27,30}

Intraoperative electromyographic (EMG) threshold testing is widely used to assist in determining the safety and accuracy of pedicle screws in the thoracolumbar spine.^{3,4,9,15,22,24,25} Although this modality has been shown to be safe and reliable in evaluating thoracolumbar pedicle screw placement, its generalizability to cervical pedicle screw placement is relatively unknown.¹⁵ Therefore the purpose of this study was 2-fold: first, to determine whether intraoperative neurophysiological monitoring may be useful for C7 pedicle screw fixation; and second, to establish the minimum EMG thresholds required to confirm adequate screw position.

Methods

After obtaining institutional review board approval, a retrospective review of prospectively collected data was undertaken. All adult patients who underwent posterior cervical decompression and fusion with placement of C7 pedicle screws at our institution between January 2015 and March 2019 were identified. The intraoperative neurophysiological records of these patients were obtained. Demographic variables included age, sex, BMI, and preoperative diagnosis/indication for surgery. Preoperative MRI and/or CT scans were carefully reviewed for the presence of a vertebral artery (VA) within the foramen transversarium at C7. When this artery was present, C7 pedicle screws were not placed because of increased risk of vascular injury or stroke. Operative variables collected included levels decompressed, levels fused, and intraoperative EMG data from all C7 pedicle screw stimulations. Postoperative variables included all complications from surgery (i.e., acute or late postoperative infection, adjacent segment disease, and pseudarthrosis); need for revision (patients who have been offered additional surgery as well

as those who have had additional surgery); and reason for revision.

Postoperatively, all patients underwent fine-cut (2-mm slice thickness) CT scanning with sagittal and coronal reconstructions from the occiput to T2. All CT scans were reviewed by a neuroradiologist who was unaware of intraoperative findings or EMG data, as well as by the operating surgeon. C7 pedicle screw position was analyzed and modeled according to the technique of Holdefer and colleagues.¹⁵ Screws were assigned a grade depending on position: 1) ideal, 2) suboptimal but safe, or 3) potentially dangerous (Fig. 1).

Patients were seen postoperatively at 3 weeks, 3 months, 6 months, 1 year, and yearly thereafter. Standard cervical radiographs were obtained at those intervals. All clinical notes were reviewed and any need for revision or further surgery was recorded.

Operative Procedure

All patients underwent surgery in the prone position with the head maintained in 20–25 pounds of traction by using Gardner-Wells tongs. Standard subperiosteal exposure was performed at the intended levels. Laminectomy was typically performed using the trough technique at the junction of the lamina and lateral mass. Subaxial lateral mass screws were placed using slightly modified An and Anderson techniques. When appropriate, thoracic pedicle screws were placed in a standard fashion. At T1, bicortical screws were placed intentionally; we put sufficiently long screws at T1 to attain purchase at the distal cortex. At C2, either pars or pedicle screws were placed.

Pedicle screws were placed at C7 by using one of several techniques. Typically, a high-speed burr was used to penetrate the outer cortex, often exposing a blush of pedicular bleeding at the intended starting point. The cranio-caudal entry point is 2–3 mm below and at the mediolateral midline of the C6–7 joint. Once the outer cortex had been breached, the pedicle was cannulated by using either a 3.5-mm tap, or a power drill with guard set to 20 mm. Our experience was that wider pedicles with cancellous bone were easily cannulated with a 3.5-mm tap or power drill that would “suck” the bit down the pedicle. Thinner or more corticated pedicles required the use of a power drill.

C7 pedicle screws were directed in the sagittal plane perpendicular to the inclination of the C7 superior facet, and 20°–30° medially. If there was difficulty in placing the screw or anatomical landmarks were distorted, a partial laminotomy and foraminotomy was performed at the superior aspect of the C7 lamina, exposing the medial and superior edges of the pedicle. These trajectories were palpated with a ball-tipped probe, and if not done already, were tapped with a 3.5-mm tap. Placement of maximal-length screws was always performed, with the intent of being completely embedded in bone. Careful preoperative imaging review is useful in approximating the length and width of planned C7 pedicle screws. Typically, 4.0-mm screws of 24–30 mm length or 4.35-mm screws of 25- or 30-mm length were placed.

In cases in which the distal instrumented level was C7, such as in patients undergoing C3–7 decompression and

instrumented fusion, great care was taken not to expose the C7–T1 joint and to preserve the C7–T1 interspinous ligaments. Laminectomy was performed at C3–6, and the cranial aspect of the C7 lamina was resected with a 3-mm Kerrison rongeur, down to the C7 pedicle level, ensuring decompression past the C6–7 disc space (Fig. 2). In our experience, doing so may obviate the need to cross the cervicothoracic junction.

Intraoperative fluoroscopy was performed preoperatively to plan the incision and intraoperatively for level localization prior to laminectomy. Fluoroscopy was not typically used to place C7 or thoracic pedicle screws, or for any lateral mass screws. Intraoperative radiographs were taken once all screws were in place, in the lateral and true anteroposterior projections. The C7 level is often difficult to see on the lateral view, but appropriate true anteroposterior imaging is usually achievable.

Neurophysiological Testing

All posterior cervical surgeries were performed with neurophysiological monitoring. Somatosensory evoked potentials and EMG signals were monitored in all cases. If there was evidence of severe cord compression, especially with presence of T2 hyperintensity within the spinal cord consistent with contusion or myelomalacia, motor evoked potentials were monitored as well.

A Cadwell Cascade Pro was used to stimulate screws and record compound muscle action potentials (CMAPs) in the upper extremity. CMAPs were checked in the deltoid (C5); biceps (C5, C6); triceps (C6, C7); extensor digitorum (C7, C8); and abductor pollicis brevis (C8, T1) with needle electrodes. The parameters used were as follows: pulse width 200 μ sec, gain 200 μ V/division, HiCut filter of 3000, and LoCut filter of 10. The screws were electrically stimulated at 2-Hz monophasic pulses by using a monopolar probe. Once C7 pedicle screws were placed, they were electrically stimulated using a Cadwell Multi-Stage Clip, and thresholds were determined by gradually increasing the stimulus from 0 to 20 mA. Muscle relaxants were reversed or allowed to dissipate prior to stimulation and confirmed by a train-of-four response in the patient's hand.

Anesthesia

General endotracheal anesthesia is induced with propofol, lidocaine, fentanyl, midazolam, and succinylcholine. Baseline neurophysiological potentials data are then obtained, and confirmed once positioning is completed. At skin incision, we request supplementation of neuromuscular relaxation with rocuronium. Total intravenous anesthesia is typically maintained with remifentanyl and propofol infusion, as neuromuscular blockade is allowed to dissipate. If necessary, neuromuscular blockade may be pharmacologically reversed prior to screw stimulation. The mean arterial pressures are maintained above 65 mm Hg, and within 20% of a patient's baseline.

Results

Twenty-five patients undergoing posterior cervical decompression and fusion with placement of C7 pedicle

FIG. 1. **A:** Axial CT at the level of the C7 pedicle shows ideal placement of the pedicle screws; both screws stimulated at thresholds > 15 mA. **B:** Axial CT at the level of the C7 pedicle shows suboptimal placement of the left pedicle screw, with infringement on the foramen transversarium (red arrow); this screw stimulated at 14 mA. **C:** Coronal CT reconstruction shows cranial breach of the left C7 pedicle screw, which stimulated at 12 mA. Screw stimulation parameters are listed below each screw in red lettering. Figure is available in color online only.

FIG. 2. **A:** Sagittal CT reconstruction showing extensive anterior osteophyte formation and OPLL precluding an anterior approach. **B:** Preoperative sagittal T2-weighted MRI shows cord compression and T2 hyperintensity, with stenosis extending to the C6–7 disc space. **C:** Two-year follow-up sagittal T2-weighted MRI shows cord decompression with preservation of the cervicothoracic junction.

screws during the stated time period were identified. Primary indications for surgery included multilevel stenosis with or without myelopathy, including OPLL ($n = 13$), pseudarthrosis after prior anterior cervical discectomy and fusion with or without adjacent level stenosis ($n = 5$), central cord syndrome ($n = 4$), and deformity ($n = 3$). Multiple patients carried more than one diagnosis, such as OPLL, congenital stenosis, and central cord syndrome. The mean age was 61 years with a range from 45 to 79 years. Of these 25 patients, 19 had constructs terminating at C7 (Table 1).

Each patient had intraoperative recordings of CMAPs, and neurophysiological data are summarized in Table 2. Forty-three of 51 (84.3%) C7 pedicle screws stimulated at thresholds > 15 mA. Six of 51 (11.8%) C7 pedicle screws stimulated at thresholds between 11 and 15 mA, and 2 of 51 (3.9%) stimulated at thresholds ≤ 10 mA.

In the patient in case 3, the C7 pedicle screws stimulated at 11 and 14 mA, respectively. Postoperative CT demonstrated lateral breach bilaterally, but there was no immediate clinical consequence (Fig. 3A). In the patient in case 16, the right C7 pedicle screw stimulated at 13 mA, but the left stimulated at > 20 mA (Fig. 4A and B). The right screw was removed, the trajectory explored, and an early lateral breach was identified. A new more medial screw was placed that then stimulated at a threshold of > 20 mA (Fig. 4C and D). In the patient in case 19, the right C7 pedicle screw stimulated at 10 mA, was removed, and the trajectory explored. An obvious breach was not identified, and the screw was replaced in the same trajectory. This patient awoke with a severe right C7 radiculopathy, and postoperative CT demonstrated a superior breach (Fig. 3B). He was returned to the operating room, and the C7 screw was stimulated, again at the 10-mA threshold. A superior breach was confirmed after screw removal, and a generous C6–7 foraminotomy was performed to maximally decompress the C7 nerve root. A screw was not replaced, because there were pedicle screws placed at T1 and T2. Of note, the same patient's left C7 pedicle

screw stimulated at 14 mA, and was found to be laterally positioned on postoperative CT, but safe. Finally, in the patient in case 23, the right C7 pedicle screw stimulated at 8 mA. It was removed, and a medial breach was identified. Another pedicle screw could not be placed, and a lateral mass screw was placed instead. Other than the patient mentioned above who suffered a radiculopathy requiring revision, there were no neurological or in-hospital complications.

Postoperative CT was obtained in all patients, and all screw trajectories were scrutinized by the senior author and by a neuroradiologist who was unaware of intraoperative findings or EMG data. CT demonstrated ideal placement of the C7 pedicle screw in 40 of 43 instances in which EMG stimulation thresholds were > 15 mA. In the remaining 3 cases, the trajectories were lateral (encroaching on the foramen transversarium) but safe because preoperative imaging confirmed absence of a VA. When the screw stimulation thresholds were between 11 and 15 mA, 5 of 6 screws were lateral but safe, and in 1 instance showed a cranial breach, which was deemed potentially dangerous (Fig. 1C). In instances in which the screw stimulated at thresholds ≤ 10 mA, all trajectories were potentially dangerous with neural compression.

The median clinical follow-up was 22.7 months (range 4–57 months). No patients were lost to follow-up. The patient in case 15 has suffered from pseudarthrosis at C6–7, with radiographic evidence of C7 screw loosening, and failure to form bridging bone at the C6–7 facet. Anterior cervical discectomy and fusion at C6–7 has been offered, but the patient has yet to undergo surgery. The patient in case 3, who had undergone C2–T1 decompression and fusion for central cord syndrome/OPLL, suffered from broken T1 pedicle screws bilaterally, but ultimately went on to fuse the C7–T1 facets successfully, and is clinically asymptomatic. Of the patients reaching 12-month follow-up, 22/23 have achieved solid fusion. No other patient has required or been offered revision surgery. There has not been any clinically apparent C7–T1 degeneration requir-

TABLE 1. Patient demographics and results summary

Case No.	Age (yrs)	Sex	Diagnosis	Levels	Rt C7 Threshold (mA)	Lt C7 Threshold (mA)	Rt C7 Position*	Lt C7 Position*
1	49	M	CCS	C3–7	20	20	1	1
2	58	F	Deformity	C2–7	20	18	1	1
3	66	M	CCS, OPLL	C2–T1	14	11	2	2
4	52	M	CSM	C3–7	20	20	1	1
5	79	M	CSM, OPLL	C3–7	18	20	1	1
6	64	M	CSM	C3–7	20	20	1	1
7	72	F	CSM	C3–7	18	18	1	1
8	57	M	CSM, CS	C3–7	20	20	1	1
9	61	M	CSM, OPLL	C4–7	19	18	1	2
10	60	M	Deformity	C2–T2	18	16	1	1
11	71	M	PA, ASD	C4–7	18	17	1	2
12	60	M	CSM	C3–7	16	12	1	3
13	50	F	CSM	C4–7	20	20	1	1
14	74	M	CSM	C5–T1	16	20	2	1
15	59	M	CSM, OPLL	C3–7	20	18	1	1
16	57	M	PA, ASD	C4–7	13, 20	20	2, 1	1
17	55	M	Deformity	C2–T4	18	20	1	1
18	72	M	Synovial cyst	C7–T1	16	17	1	1
19	59	M	PA, ASD	C5–T2	10	14	3	2
20	63	M	CSM	C3–7	20	18	1	1
21	66	F	CCS	C3–7	17	19	1	1
22	52	M	CSM	C3–7	20	20	1	1
23	45	M	PA, ASD	C5–7	8	20	3	1
24	54	M	CCS	C3–7	20	18	1	1
25	59	F	PA, ASD	C4–7	17	14	1	2

ASD = adult spinal deformity; CCS = central cord syndrome; CS = congenital stenosis; CSM = cervical spondylotic myelopathy; PA = pseudarthrosis.

* Screws were assigned a grade depending on position: 1, ideal; 2, suboptimal but safe; or 3, potentially dangerous (as described by Holdefer et al.).

ing extension of instrumentation to the thoracic spine in any patients whose construct terminated at C7 (n = 19), with follow-up extending nearly 60 months.

Discussion

The C7 vertebral body is morphometrically unique, because it represents the transition point from the subaxial cervical spine to the upper thoracic spine.¹ It has the largest pedicles but relatively small lateral masses compared to other subaxial cervical levels. Studies have demonstrated biomechanical superiority of pedicle screws as compared to lateral mass or translamina screws.^{1,17,18,20,21,26} If C7 is the lowest instrumented vertebra, pedicle screw fixation is preferred—especially if the construct spans multiple levels, has no anterior fixation, or is in an osteoporotic individual—to avoid instrumentation failure.^{17,18,21,26} However, placing C7 pedicle screws is technically demanding, and places multiple neural structures at risk.^{14,17,21} C7 pedicle screws are smaller and may be more cortical than proximal thoracic pedicle screws.^{17,21} Medial breach may lead to cord or C8 nerve root injury. Superior breach may result in C7 nerve root injury. Lateral breach may lead to VA injury or stroke in the 0.3%–18.4% of patients in whom the artery enters at C7.³⁰

In light of this, all efforts must be given to maximize the safety of inserting C7 pedicle screws. First, careful preoperative review of imaging studies is crucial. Important considerations in preoperative planning include assessing the fundamental need to extend the construct to C7, estimating the length and diameter of C7 pedicle screws, and scrutinizing for the presence of a VA in the foramen transversarium (and in those instances possibly electing not to place a C7 pedicle screw).

Additionally, various intraoperative techniques have been described that potentially reduce the incidence of misplaced C7 pedicle screws, including intraoperative

TABLE 2. Intraoperative EMG threshold compared to postoperative C7 pedicle screw position

EMG Threshold	Screw Position Assessed on CT Scans		
	Ideal (grade 1)	Suboptimal, Safe (grade 2)	Suboptimal, Unacceptable (grade 3)
16–20 mA	40	3	0
11–15 mA	0	5	1
1–10 mA	0	0	2

FIG. 3. A: Axial noncontrast CT in the patient in case 3 demonstrating bilateral C7 pedicle screws that stimulated at 11 and 14 mA, respectively. Screw stimulation parameters are listed below each screw in red lettering. **B:** Sagittal noncontrast CT in the patient in case 19 demonstrating a superior pedicle breach with violation of the neuroforamen (red arrow). Figure is available in color online only.

fluoroscopy, 2D or 3D navigation, and screw stimulation.^{5–8,11,22} However, intraoperative fluoroscopy is challenging at the cervicothoracic junction, and stereotactic navigation, although accurate and helpful, can add to operating time and may not be readily available at some centers.^{5,14,16} Therefore, additional testing modalities such as C7 pedicle screw stimulation may be of benefit.^{8,11}

Intraoperative pedicle screw stimulation has been shown to be a valuable tool in improving the safety of screw placement, especially in cases in which intraoperative fluoroscopy is difficult to interpret due to complex anatomy or body habitus.^{1,2,18,21} The results of a recent meta-analysis determined that the most accurate threshold for safe pedicle screw placement in the lumbar spine was between 10 and 15 mA, and in fact, many centers have adopted a standard threshold of 12 mA.^{3,4,6,9,22–25,29} Similarly, in the thoracic spine, EMG thresholds < 12 mA were found to correlate highly with pedicle screw malposition.²⁵ Whereas EMG thresholds for thoracic and lumbar pedicle screws have been well defined, thresholds for the cervical spine have yet to be characterized.

To date, 2 studies have investigated the use of EMG stimulation thresholds in the cervical spine to evaluate pedicle screw placement, and these papers reached very different conclusions.^{8,15} Holdefer et al. performed triggered EMG thresholds at the deep edge of pilot holes drilled in 244 lateral masses and 113 pedicles (C7 and T1) in 32 patients.¹⁵ They determined that 5 mA was the critical threshold for potentially dangerous screw position. In contradistinction, in a study of 122 lateral mass screws and 25 C7 pedicle screws in 26 patients, Djurasovic and colleagues suggested that a screw stimulation threshold of > 15 mA predicted acceptable screw position, with a positive predictive value of > 99%.⁸ They furthermore found that

screw stimulation thresholds of < 10 mA were associated with screw malposition in the majority of cases, and recommended prompt exploration, repositioning, or removal. If the stimulation threshold was between 10 and 15 mA, they recommended exploration, although this threshold was usually associated with adequate screw placement.

Overall, our study confirms the findings of Djurasovic, in that stimulation thresholds of > 15 mA were predictive of satisfactory screw placement.⁸ Forty of 43 screws whose trajectories stimulated at the threshold of > 15 mA were found to be ideal on postoperative CT, whereas the remaining 3 were suboptimal but safe. Stimulation thresholds between 11 and 15 mA were associated with lateral trajectories that occasionally required revision. All screws with stimulation thresholds ≤ 10 mA were found to be potentially dangerous and/or required revision.

There are significant methodological differences between our study and those of Holdefer et al. and Djurasovic et al. that may explain the disparate threshold values reached by the authors. First, Holdefer and colleagues stimulated pilot holes rather than the actual screw. Pilot hole testing may detect an unsafe trajectory before inserting the pedicle screw and potentially harming the nerve roots. However, this method cannot detect pedicle screw breach. In addition, Holdefer et al. used longer pulse duration widths in their study than Djurasovic et al. (200 μsec vs 50 μsec). Prior literature has suggested that longer pulse widths (300 μsec) provide more accurate detection, but 200 μsec has a higher sensitivity.^{24,28,29}

Regardless of the actual threshold, the results of this study complement those of Holdefer et al. and Djurasovic and colleagues, in that the addition of EMG threshold testing improved the safety and accuracy of cervical pedicle screw placement. Holdefer et al. concluded that,

FIG. 4. A: Screenshots taken from intraoperative right C7 pedicle screw stimulation. The right C7 pedicle screw initially stimulated at 13 mA, which replicated at 15 and 16 mA (red arrows), prompting exploration. **B:** Axial noncontrast CT demonstrating the initial trajectory of the right C7 pedicle screw, which was found to be lateral and subsequently revised (red arrow). **C:** An early lateral breach was identified and a new more medial screw was placed, which then stimulated at a threshold of > 20 mA. **D:** Axial non-contrast CT demonstrating final position of the right C7 pedicle screw. Screw stimulation parameters are listed below each screw in red lettering. Figure is available in color online only.

when comparing the control group where the surgeon was blinded to the EMG testing results to the test group where the surgeon was notified of the EMG results, 4.5% of the control group had misplaced screws whereas 0% had misplaced screws in the experimental group.¹⁵ In all 4 cases in the experimental group, the screws were removed and either left out or replaced in new trajectories. This reduction results in a number needed to treat of 22 to prevent a dangerous pedicle screw. Similarly, Djurasovic et al. concluded that the addition of screw stimulation provided a “valuable aid to surgeons in the accurate placement of posterior cervical instrumentation.”⁸

Limitations of this study include a relatively small sample size, low incidence of misplaced screws, and overall limitations of EMG testing. The small sample size decreases the power of the study. False-negative EMG thresholds may occur from the stimulation of the screw or pilot hole and the nerve root in chronic compression or neuropathy or in a “wet” environment.¹⁶ A false-positive EMG threshold may occur in the setting of a pedicle screw repositioned due to a prior medial breach, owing to the

existing violation of the medial cortex. In these situations, we have placed a small Gelfoam sponge in the more medial trajectory to mitigate current spread and replaced the screw to a more lateral trajectory. In cases in which the patient’s anatomy prevented the replacement of a pedicle screw, we converted to a lateral mass screw. Last, based on a meta-analysis of numerous studies, EMG testing is associated with low overall sensitivity, with up to 22% of misplaced screws not detectable by EMG methods.²⁸ These limitations notwithstanding, the major strength of this study is the homogeneity of the test subject: only C7 pedicle screws were stimulated. Previous studies had grouped lateral mass and pedicle screws, as well as C7 with T1 pedicle screws, and it was our intention to define the crucial threshold solely for the C7 pedicle.^{8,15}

Conclusions

EMG threshold testing is a useful addition to the surgeon’s armamentarium in placing safe C7 pedicle screws. It can alert the surgeon intraoperatively to the possibility of

a misplaced C7 pedicle screw, and potentially avoid neural injury or reduce the need for revision surgery. In our experience, EMG thresholds correlated well with postoperative CT findings. Stimulation thresholds > 15 mA were always associated with satisfactory pedicle screw placement. Stimulation thresholds between 11 and 15 mA mostly indicated suboptimal, but clinically acceptable, screw positions. For these values we recommend exploration of the trajectory. In our experience stimulation thresholds ≤ 10 mA were always associated with potentially dangerous screws, and in these situations we recommend prompt exploration, repositioning, or removal. We encourage future studies with larger sample sizes to confirm the results of this study.

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Disclosures

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

Conception and design: all authors. Acquisition of data: Gologorsky, Kennamer, Moore, Steinberger, Yao, Syed, Arginteanu. Analysis and interpretation of data: Gologorsky, Rasouli. Drafting the article: Gologorsky, Rasouli, Kennamer. Critically revising the article: Gologorsky, Rasouli, Kennamer. Reviewed submitted version of manuscript: Gologorsky, Rasouli, Kennamer.

Approved the final version of the manuscript on behalf of all authors: Gologorsky. Statistical analysis: Kennamer. Administrative/technical/material support: Gologorsky, Rasouli, Yao. Study supervision: Gologorsky, Rasouli, Moore, Steinberger, Yao, Syed, Arginteanu.

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