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Clinical Study

Electromyography stimulation compared with intraoperative O-arm imaging for evaluating pedicle screw breaches in lumbar spine surgery: a prospective analysis of 1006 screws in 164 patients

Vijay M. Ravindra, MD, MSPH[1], Ricky R. Kalra, MD[1], Andrew T. Dailey, MD*

Department of Neurosurgery, Clinical Neurosciences Center and Huntsman Cancer Institute, University of Utah, 175 N. Medical Drive East, Salt Lake City, 84132 UT, United States

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Abstract

BACKGROUND CONTEXT: Lumbar pedicle screw placement can be technically challenging. Malpositioned screws occur in up to 15% of patients and could result in radiculopathy or instrumentation failure.

PURPOSE: To compare intraoperative electromyography (EMG) and image guidance using an O-arm for identifying pedicle breach during elective lumbar fusion.

STUDY DESIGN: Prospective observational study.

PATIENT SAMPLE: All adult patients undergoing elective lumbar spinal fusion operations for degenerative spine disorders (including adjacent segment degeneration, degenerative scoliosis, and symptomatic spondylosis and spondylolisthesis) at a single institution from July 1, 2014, to December 1, 2015, were prospectively tracked.

OUTCOME MEASURES: Pedicle breach.

METHODS: Pedicle screws from L2−S1 were placed using C-arm assisted freehand technique. All screws were stimulated with EMG and evaluated using the O-arm intraoperative imaging system. Electromyography data were compared with intraoperative images to assess the accuracy of identifying pedicle breaches. No funding was received for this work.

RESULTS: One thousand six lumbar pedicles screws were placed from L2 to S1 in 164 consecutive cases. The mean patient age was 59.2 years. Thirty-five breaches (15 lateral and 20 medial) were visualized with O-arm imaging and confirmed by palpation (3.5% of screws placed). Of the breaches, 14 screws stimulated below the 12-mA threshold, nine screws stimulated between 12 and 20 mA, and 12 screws did not generate an EMG response. Forty screws stimulated below a 12-mA threshold but showed no breach on imaging. Using the 12-mA threshold, the sensitivity of EMG was 40%, specificity was 96%, positive predictive value was 26%, and negative predictive value was 98%. All 35 breached screws were corrected during surgery. There were no postoperative symptoms caused by breached screws and no patients required reoperation.

CONCLUSIONS: Our findings indicate that EMG may not be a highly reliable tool in determining an anatomical breach during placement of lumbar pedicle screws. O-arm may be better for

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* Corresponding author. Department of Neurosurgery, Clinical Neurosciences Center, University of Utah, 175 N. Medical Drive East, Salt Lake City, 84132 UT, United States. Tel.: 801-581-6908; fax: 801-581-4385

E-mail address: neuropub@hsc.utah.edu (A.T. Dailey).

[1] Both authors contributed equally to this manuscript.

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detecting either medial or lateral breaches than EMG stimulation if there are concerns about screw placement or for confirmation of placement before leaving the operating room.

Keywords: Breach; Computed tomography; Degenerative spine disease; Electromyography; Intraoperative; Lumbar fusion; O-arm; Spine; Pedicle screw; Screw position

Introduction

Safe placement of lumbar pedicle screws is of obvious importance to patients and physicians [1]. A meta-analysis of studies published from 1966 to 2006 demonstrated the median malposition rates for non-navigated and navigated pedicle screws were 9.7% and 4.8%, respectively [2]. One series reported a malposition rate of 18% [3]. Malpositioned screws can result in postoperative radiculopathy secondary to medial breaches, pseudarthrosis due to poor screw purchase, and instrumentation failure. Although most breaches of the pedicle wall are clinically asymptomatic, in the era of litigation and readily available imaging, constructs with poorly positioned screws are suboptimal.

Multiple methods of reducing malposition rates have been described in the literature. Clinical and cadaveric studies have demonstrated that the use of intraoperative x-rays to assess pedicle screw placement does not accurately detect malpositioned screws [4−6]. Neurophysiologic monitoring, specifically electromyography (EMG), was introduced as a supplement to imaging techniques in identifying malpositioned screws that may be impinging on transiting neural structures [1]. Specifically, the use of EMG monitoring with stimulation of the pedicle screw and subsequent measurement of the compound muscle action potential (CMAP) in the lower extremity has been proposed and reported [7−10]. Previous studies have demonstrated the potential utility of EMG in helping establish adequate placement of pedicle screws [8,9]. However, the availability of intraoperative computed tomography (CT) to assess the placement of pedicle screws has brought the utility of EMG assessment into question at our institution.

There have been no reports comparing the reliability of EMG with that of intraoperative imaging. The purpose of this study was to compare EMG and O-arm intraoperative CT imaging for pedicle screw placement in identifying anatomical pedicle breach during elective lumbar fusion. The hypothesis is that EMG stimulation will compare poorly with intraoperative imaging techniques in identifying anatomical breaches during placement of lumbar pedicle screws.

Methods

This prospective observational study was performed at a single institution from July 1, 2014, to December 1, 2015, following institutional review board approval. During this 18-month period, all adult patients undergoing elective lumbar spinal fusion operations for degenerative spine disorders, including adjacent segment degeneration, degenerative scoliosis, and symptomatic spondylosis and spondylolisthesis, were prospectively enrolled and tracked. Pedicle screws were placed from L2 to S1 using C-arm-assisted freehand technique with anatomic landmarks. All screws were stimulated with EMG and then evaluated using the O-arm intraoperative imaging system. Electromyography data and intraoperative images were used to assess pedicle breaches, which were confirmed by palpation. All corrections were performed at the time of initial surgery. All suspected breaches identified by EMG or imaging were evaluated by removing the screw, palpating the entire screw trajectory, and repositioning the screw using anteroposterior and lateral radiographs in cases of confirmed pedicle breaches.

Technique of placing pedicle screws

After completing a subperiosteal dissection in all patients, pedicle fixation was performed using anterior or posterior and lateral fluoroscopy to establish regional alignment. The pedicle entry point was identified using a triangulation technique, using the facet joint and the transverse process as landmarks. After the starting point was identified with anatomic landmarks, a high-speed drill is used to make a pilot hole, with the trajectory of the tract identified using a Lenke pedicle finder. The screw trajectory was palpated using a ball-point probe. After confirming four walls and a floor of the pedicle, the pedicle trajectory was tapped with an undersized tap. The trajectory was reprobed to confirm no breaches after tapping. The pedicle screw was placed down the tapped trajectory manually.

Technique of stimulus evoked EMG

Induction and administration of anesthesia throughout the case was coordinated for the proper collection of EMG, somatosensory evoked potential (SSEP), and motor evoked potential (MEP) data. This consisted of sedation without paralytics using continuous infusions of propofol and fentanyl. After placement of all screws and before stimulation, a train of four tests was conducted to ensure that there was minimal or no neuromuscular blockade. In cases where MEPs were used, an MEP was also obtained to confirm no neuromuscular junction blockade.

The technique for stimulation was based on the initial report by Calancie et al. [7]. Briefly, constant-current pulses

(0−20 mA in amplitude and 200 millisecond in duration) were applied at a rate of 5 Hz through the inserted pedicle screw to evaluate each screw trajectory. Evoked EMG from the muscles monitored at the levels of L2−S1 warned of perforation of the cortical bone and close apposition of the screw with motor nerve fibers (Table 1). Compound muscle action potentials were recorded using needle electrodes placed bilaterally into the rectus femoris, tibialis anterior, medial gastrocnemius, and peroneus longus muscles. Pedicle screws placed above L2 level were not included because of the difficulty in recording an appropriate CMAP for thoracolumbar stimulation [1]. With the presence of an EMG response, the thresholds were decreased until there was no response. The constant-current pulses were then gradually increased until a response was re-elicited. This was recorded as the stimulus threshold for each screw. The minimum stimulus amplitude needed to evoke EMG when stimulating through the pedicle screw was determined. When screws stimulated at a threshold of ≤12 mA, the screw was removed and the tract was palpated in search of breach in the medial, lateral, superior, and inferior quadrants.

O-arm

The clinical standard for evaluating screw position is CT scan [11], but this equipment is not readily available in most operating rooms. Additionally, once a malpositioned screw is seen on postoperative CT [12,13], the decision to re-operate or not becomes the question. Intraoperative CT imaging (O-arm; Medtronic Navigation, Louisville, Colorado) provides 3-D imaging information and has become widely available for use [14]. Additionally, the O-arm has been shown to be highly accurate in identifying screw malposition [15]. The use of this information during surgery can allow for screw revision without having to return to the operating room, subjecting the patient to additional operating room time, anesthetic risks, etc. In comparison with postoperative CT imaging, the O-arm allows for real-time gantry adjustment to allow for complete visualization of screw placement along the axis of the pedicle. Intraoperative CT images were interpreted by the attending spine surgeon.

Statistical analysis

We compared EMG data and intraoperative CT findings obtained with the O-arm. Electromyographic data were grouped based on stimulation threshold, as <12 mA or ≥12 mA; these values were derived from previous reports of EMG thresholds used. Stimulation threshold data were compared with screw location on CT scan. Presence or absence of pedicle breach was determined by an attending spine surgeon at the time of surgery. A comparison of EMG and intraoperative CT scan findings was made for all screws as a group.

Using intraoperative O-arm imaging as the gold standard for comparison, we calculated sensitivity, specificity, positive predictive value, and negative predictive value of EMG at detecting pedicle breach.

Table 1
Nerve root distributions and the corresponding muscle groups

Muscle groups	Nerve root
Quadriceps	L2, L3, and L4
Hamstring	L4 and L5
Tibialis anterior	L4 and L5
Gastrocnemius	S1
Abductor hallucis	S1

Table 2
Baseline demographic information for patients enrolled

Variable	Total number of patients (n=164)
Female	90/164 (55%)
Mean age (years)	59.2
Obese (BMI>30)	41%
Number of vertebral levels fused	
2	67
3	52
4	12
5+	33

Results

Over 18 months, a total of 1,006 lumbar pedicles screws were placed from L2 to S1 using a freehand technique with anatomic landmarks observed on lateral radiographs to establish regional sagittal alignment. The mean age of the patients in these 164 consecutive cases was 59.2 years (Table 2). The majority of the screws were placed at L5 (33%), L4 (31%), and S1 (23%) (Table 3).

Thirty-five anatomical breaches (15 lateral and 20 medial) were visualized during surgery with O-arm imaging, and all were confirmed by palpation (3.5% of all L2−S1 screws placed). With EMG, 14 screws stimulated below the 12-mA threshold, nine screws stimulated ≥12 and ≤20 mA, and 12 breached screws did not generate an EMG response. Forty screws stimulated below a 12-mA threshold but showed no breach on imaging or direct palpation and were left in place. Using the 12-mA threshold for our analysis, the sensitivity of EMG was 40%, specificity was 96%, positive predictive value was

Table 3
Frequency of screw placement by vertebral level

Screw location	# of screws (%)
L2	52 (5.2%)
L3	82 (8.1%)
L4	308 (30.6%)
L5	330 (32.8%)
S1	234 (23.3%)
Total	**1,006**

Table 4
Contingency table comparing the standard (O-arm) with EMG with a cut-off of 12 mA

		O-Arm (gold standard)		
		Positive breach	Negative breach	Total
Stimulation threshold (EMG)	<12 mA (positive)	14	40	**54**
	≥12 mA (negative)	21	931	**952**
	Total	**35**	**971**	**1,006**

Sensitivity: 40%; specificity: 96%; positive predictive value: 26%; negative predictive value: 98%.
EMG, electromyography.

26%, and negative predictive value was 98% (95% CI 15−40%) (Table 4). All 35 breached screws were corrected during surgery. There were no postoperative symptoms caused by breached screws and no patients required re-operation.

Discussion

The risks of pedicle screw fixation and breach, either lateral or medial, include nerve root irritation or permanent nerve injury [1]. Known factors that may reduce the incidence of violation and nerve injury include a thorough knowledge of anatomy, experience, and if possible via a laminectomy defect or decompression, exploration of the foramen and manual palpation of the canal itself. Electrophysiologic monitoring, which can be useful in avoiding neurological injury when treating spinal deformity [16], was advocated as an adjunct to assist with identifying breaches when placing pedicle screws in the lumbar spine. Somatosensory evoked potentials alone have been shown to be ineffective in detecting nerve root injuries [17,18]; however, dermatomal SSEPs may have improved accuracy [18,19] for direct nerve root compression over traditional SSEPs. Calancie et al. [20] first introduced evoked EMG monitoring with direct pedicle screw stimulation and distal CMAP recording as a method to identify pedicle violation.

Clinical studies have previously supported the use of pedicle screw stimulation for assessing or verifying placement into the pedicle [8−10]. Glassman et al. [1] found that stimulus EMG provided guidance in lumbar pedicle screw placement, which was confirmed using postoperative CT scanning. The reliability of this method was correlated as a function of stimulation threshold and postoperative neurological examination; however, this method of verification is subject to bias. In the current investigation, we compared intraoperative EMG findings with intraoperative O-arm imaging. We chose O-arm imaging for our comparison because of its availability and versatility as well as its ability to detect malposition during surgery and make corrections intraoperatively. Although there is metallic artifact, CT scanning has been established as a reasonable measure of pedicle screw position in relationship to the lumbar pedicle [21].

In a direct comparison between EMG and intraoperative CT imaging (O-arm) for identifying breaches after pedicle screw fixation and placement, we found that EMG is suboptimal (sensitivity 40%, positive predictive value 26%) for identification of anatomical pedicle breach and should not be used as the only method to identify pedicle violation if other methods of assessment are available. Although the sensitivity was low (40%), we found the specificity of stimulation <12 mA was 96%, indicating that stimulation below this threshold could be used to rule in a pedicle breach and subsequent nerve root irritation. Similarly, the high-negative predictive value (98%) can be used to infer that stimulation ≥12 mA is suggestive that there is no pedicle breach. The high false-positive rate, however, makes the sole use of EMG for this purpose difficult. Additionally, low sensitivity is not desirable for a screening test and did not compare well with O-arm imaging. Based on these findings, we would recommend that EMG should not be relied upon as the sole method of verification of lumbar pedicle screw placement and detection of a potential anatomical breach, in either the medial or the lateral direction, if other tools are available.

Similar to the findings of Parker et al. [22], we found a high specificity (>95%) with a low sensitivity for EMG findings. In addition, we found a high rate of false positives as they did. They used a lower threshold and concluded that stimulation below 5 mA warranted intraoperative investigation, whereas higher thresholds were less reliable. In our investigation, we used a threshold of 12 mA as cut-off point but still found an alarmingly high rate of false positives.

Raynor et al. [23] reported a failure of intraoperative monitoring (SSEPs, descending neurogenic-evoked potentials, transcranial MEPs, dermatomal SSEPs, and spontaneous and triggered EMG) to identify 45/12,375 (0.36%) patients with false-negative neurologic deficits; of those, eight had permanent neurologic deficits. The authors concluded that there is a risk of undetected neurologic deficit despite the proper use of intraoperative monitoring. In a subsequent publication using the same data, however, they identified 386 (3.1%) patients with degradation of EMG signal intraoperatively, but with intervention (repositioning of hardware) 93.3% had improved EMG signal and no neurological deficits [24]. This was a reduction from potential injury in 3.1% of patients to a permanent neurological deficit rate of 0.12%, confirming the use of intraoperative monitoring as an adjunct. Based on a series of 4857 pedicle screws placed, Raynor et al. [25] determined that a threshold of 2.8 mA had a specificity of 100% with sensitivity of 8.4% and that a threshold of 8.0 mA had a 94% specificity and 85% sensitivity. On the basis of this information, they concluded that triggered electromyographic stimulation should be used in conjunction with palpation and radiography to optimize safe pedicle screw placement; however, intraoperative CT imaging was not used as an adjunct in evaluating screw placement and compared with EMG in that study.

As a whole, the literature supporting the use of EMG has been sparse. In fact, the 2005 Guidelines for the Performance of Fusion Procedures for Degenerative Disease of the Lumbar Spine concluded there was no substantial evidence for the use of intraoperative monitoring to provide useful information to the surgeon [26]. Interestingly, the 2014 Guidelines gave the same recommendations stating: "There is no evidence that conflicts with the previous recommendations regarding electrophysiological monitoring published in the original version..." [27]. Thus, in the 9 years in between, there was no supporting evidence for the use of EMG. The current investigation not only provides evidence against the sole use of EMG for pedicle screw placement but also provides evidence for the use of intraoperative CT when available to verify and avoid placement of malpositioned screws.

Limitations

There are limitations to the current investigation. The primary limitation of this study is that we are only able to assess the ability of EMG to detect pedicle screw perforations in either the medial or the lateral direction. Because of our study methods, this is a purely anatomic finding, which is confirmed by O-arm imaging and direct palpation. Our methods limited us from determining the utility of EMG to detect clinically significant breaches. In this investigation, we did not grade the breaches, nor did we differentiate between medial and lateral breaches because all breaches may compromise the biomechanical integrity of lumbar constructs [28]. Although the use of CT is an accepted method of verifying lumbar pedicle screw placement [21], we used the O-arm imaging system as a comparison, which is not of the same quality as standard 64-slice CT. The diagnostic accuracy of EMG compared with O-arm as a gold standard must be considered in light of these limitations. O-arm was used as the standard in this investigation because of its widespread availability and accepted use [15,29], although it should be noted that O-arm imaging is not universally available, and EMG may be more accessible when compared with O-arm. This is further supported by the fact that no patients required postoperative CT imaging or reoperation for persistent neurological symptoms secondary to malpositioned instrumentation. In addition, EMG may not be reliable in identifying all breaches, particularly breaches that do not risk neurological injury, as may happen in a lateral breach. However, it is likely that screws that breach the pedicle in any position have suboptimal biomechanical integrity and may lead to construct failure, and thus merit identification. It may be that the 14 cases of true-positive EMG represented all cases in which there was actual contact or near approximation of malpositioned screw to a nerve root, in which case the clinical utility of EMG may have been more beneficial than suggested by our study methods. However, it is true that cortical breaches in general portend suboptimal placement of the pedicle screw and even those that do not risk nerve root injury or irritation may compromise biomechanical integrity. Lastly, it should be noted that our method to assess and correct every anatomic breach detected on O-arm imaging resulted in a 0% rate of clinically detected neurological harm. Therefore, it can be concluded from our data that O-arm more accurately detects cortical breaches and when O-arm findings are used intraoperatively to detect and correct malpositioned screws, the incidence of neurological symptoms or reoperation for screw malposition can be brought to zero. However, O-arm would not be able to provide real-time physiological information regarding nerve root injury occurring during the preparation and placement of pedicle screws, which could be detected by continuous EMG monitoring. Injury that could be detected by EMG could lead to permanent deficits that are not reversible by screw repositioning. Thus, the ultimate clinical utility of EMG in the setting of lumbar pedicle screw instrumentation may still be unresolved.

Conclusion

Our data suggest that the EMG modality for identifying anatomical pedicle breaches may be unreliable. In the modern era of intraoperative imaging, lumbar screws could be evaluated for anatomical breaches with O-arm rather than relying on EMG stimulation alone if there are doubts about the position. Direct visualization of the pedicle and palpation of the entire trajectory confirm that O-arm is highly accurate in assessing pedicle breaches.

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