Evaluation of electromyographic monitoring during insertion of thoracic pedicle screws

D. P. Reidy, D. Houlden, P. C. Nolan, M. Kim, J. A. Finkelstein

From Sunnybrook and Women's College Health Sciences Centre and the University of Toronto, Toronto, Canada

We prospectively studied the use of intercostal EMG monitoring as an indicator of the accuracy of the placement of pedicle screws in the thoracic spine.

We investigated 95 thoracic pedicles in 17 patients. Before insertion of the screw, the surgeon recorded his assessment of the integrity of the pedicle track. We then stimulated the track using a K-wire pedicle probe connected to a constant current stimulator. A compound muscle action potential (CMAP) was recorded from the appropriate intercostal or abdominal muscles. Postoperative CT was performed to establish the position of the screw. The stimulus intensity required to evoke a muscle response was correlated with the position of the screw on the CT scan.

There were eight unrecognised breaches of the pedicle. Using 7.0 mA as a threshold, the sensitivity of EMG was 0.50 in detecting a breached pedicle and the specificity was 0.83.

Thoracic pedicle screws were accurately placed in more than 90% of patients. EMG monitoring did not significantly improve the reliability of placement of the screw.

J Bone Joint Surg [Br] 2001;83-B:1009-14.

Received 22 December 2000; Accepted 8 March 2001

Pedicle screws are commonly used in the thoracic spine since they provide rigid three-column fixation. They also have a theoretical advantage over hooks or sublaminar

wires by avoiding the placement of instrumentation within the spinal canal.

The technique has not been universally accepted, however, particularly at higher levels of the spine, and reports in the literature remain inconclusive. Vaccaro et al,¹ in a cadaver study, observed that the risk of misplacement of the screw in the thoracic spine was 41%. Even with careful probing of the pedicular walls by experienced surgeons misplacement occurred. They argued that thoracic pedicle screws should only be used in specific circumstances when alternative methods of fixation are inappropriate.

Cinotti et al,² again in a cadaver study, suggested that the pedicles at T4 to T8 may be too small to accommodate screws. At the T6 level, a transverse diameter of less than 4.3 mm was noted in 68% of specimens and 40% of 126 screws violated the wall of the pedicle.

Xu et al^{3,4} suggested that thoracic placement of pedicle screws was a considerable technical challenge and that a partial laminectomy should be routinely performed in order to reduce the incidence of violation of the pedicle. The technique of Roy-Camille, Saillant and Mazel⁵ without visualisation of the medial pedicular wall, resulted in misplacement of the screw in 54.7% of cases.

Because of the difficulties associated with placement of the pedicle screw in both the thoracic and lumbar spines, a variety of techniques has been used to increase accuracy. In particular, the EMG response to stimulation of the pedicle has been extensively reported.⁶⁻¹² An intact pedicle gives a high level of electrical resistance so that a greater stimulus is required to evoke an EMG response. The electrical parameters which indicate a violated pedicle have been clearly defined in the lumbar spine.¹³

To our knowledge the value of EMG monitoring during the insertion of pedicle screws has not been assessed in the thoracic spine. Our primary aim was to determine if intra-operative EMG responses would predict the accuracy of placement of the screw when compared with postoperative CT. Our secondary objective was to determine the optimal threshold stimulus for predicting violation of the pedicle.

Patients and Methods

We studied 17 adults (95 thoracic pedicles) with fractures of the thoracic or thoracolumbar spine who had required

D. P. Reidy, FRCS (Tr & Orth), Spine Fellow

D. Houlden, PhD, Assistant Professor

Division of Neurosurgery

J. A. Finkelstein, MD, Assistant Professor

Division of Orthopaedic Surgery

Sunnybrook and Women's College Health Sciences Centre and the University of Toronto, Room MG 361, 2075 Bayview Avenue, Toronto, Ontario, Canada M4N 3M5.

P. C. Nolan, MD, Consultant Orthopaedic Surgeon

Belfast City Hospital, Lisburn Road, Belfast BT9 7AB, Northern Ireland.

M. Kim, MD, Attending Orthopaedic Surgeon

2114 Rose Creek Boulevard, Fargo, North Dakota, USA.

Correspondence should be sent to Dr J. A. Finkelstein.

©2001 British Editorial Society of Bone and Joint Surgery
0301-620X/01/712017 \$2.00

operative fixation by posterior pedicle screws carried out by, or under the supervision of, the senior author (JAF) using the Universal Spine System (Synthes USA, Paoli, Pennsylvania). Written informed consent was obtained from all patients. We excluded these with primary or metastatic spinal tumours or spinal infection since their pedicles may have been deficient. We included only instrumented thoracic pedicles. We recorded the motor score index (Medical Research Council) and pinprick sensory score before and after surgery, and three months later. Routine preoperative imaging included plain radiography and CT. We gave all the patients opiates and short-acting muscle relaxants to simplify intubation and maintained anaesthesia with inhalational agents (0.5 to 1.0% isoflurane, 55 to 65% nitrous oxide). We did not use muscle relaxants during surgery when recording the EMG responses.

Operative procedure. After routine exposure of the posterior thoracic spine, we carried out intraoperative lateral radiography to identify levels and to assess the sagittal alignment of the thoracic spine. We did not use any other image-guidance system during insertion of the pedicle screw. We identified pedicle landmarks as described by Chapman and Anderson¹⁴ and Vaccaro et al¹ and made our entry points with a high-speed burr. We used a probe to enter the pedicle which was then palpated to ensure that bone was felt on all four walls and on the floor of the track. This was recorded. If it was thought that the pedicle had been breached, repositioning of the screw was attempted to achieve correct placement. We used the surgeon's assessment as the definitive intraoperative measure of the integrity of the pedicle regardless of the EMG value. Screws of a diameter 5 mm were routinely used above T7 and of 6 mm below this level.

Neurophysiological studies. We performed stimulation of the pedicle before insertion of the screw once the surgeon was satisfied with the pedicle track. The stimulating probe was a 0.18 gauge K-wire insulated with Teflon shrink-wrap except at its distal and proximal ends. One end was placed in the pedicle track and the other was connected to the cathode of the Cadwell constant current stimulator (Cadwell Laboratories Inc, Kennewick, Washington) using an alligator clip.¹³ The anode was a Grass needle electrode (Grass Instruments, Quincy, Massachusetts) placed laterally in the wound. Monophasic square stimulus pulses of duration 200 s were delivered at a rate of three per second. We obtained compound muscle action potentials (CMAPs) from Grass (EEG) electrode pairs placed 3 to 5 cm apart over the intercostal muscle which corresponded to the level and side being stimulated. We simultaneously monitored CMAPs from up to eight intercostal levels on one side to compare each intercostal response with those adjacent. This ensured that CMAPs were truly obtained from activation of the nerve root at the level of the pedicle being tested. When we undertook instrumentation below T8 we obtained abdominal CMAPs from electrodes placed 6 cm lateral to the umbilicus. Electrode impedance was kept below 5

kohms and an earth electrode was placed on the shoulder. We used an amplifier gain of 100 V per division and a recording bandpass of 10 to 2000 Hz with a sweep duration of 50 msec. During stimulation the surgeon carefully probed the walls and bottom of the pedicle track. The stimulus intensity started at 0 mA and was gradually increased in 0.1 mA increments to 20 mA. If no response was noted at 20 mA stimulation was discontinued. Based on experience in the lumbar spine, we used 7 mA to suggest violation of the pedicle.⁶⁻¹² A response consisted of a CMAP with a peak-to-trough amplitude of greater than 20 V and we recorded the stimulus at which the CMAP was

Fig. 1

CT scan showing inadvertent lateral placement of one screw and correct placement of the contralateral screw.

Fig. 2

Histogram showing the number of instrumented pedicles at each level in the thoracic spine.

Fig. 3

Histogram of number of pedicle screws classified as 'in' or 'out' by CT relative to their current as measured by EMG.

obtained. We also recorded somatosensory evoked potentials (SSEPs) intraoperatively, using responses of the posterior tibial nerve to measure the function of the spinal cord.

Radiological assessment. We obtained postoperative CT scans using 3 mm cuts with sagittal reformatting through each instrumented pedicle. These were independently assessed by two musculoskeletal radiologists who were blinded to the intraoperative details. Breach of the pedicle was reported if bone could not be seen to be entirely surrounding the screw (Fig. 1)

Statistical analysis. For each unit increment of EMG threshold, the number of screws in or out of the pedicle as judged by CT was plotted.

The sensitivity, specificity and their respective confidence intervals based on the binomial distributions were calculated for the threshold of 7 mA as well as for each integral threshold from 1 to 20. A receiver operating characteristic (ROC) curve was plotted using the threshold level from 1 to 20.¹⁵ This is a plot of the sensitivity *versus* the false-positive rate (1 - specificity) calculated over the range of possible thresholds.

A 2×2 table was constructed with EMG cut-off of 7 mA (less than or equal to, greater than) against the result on the CT scan (in/out) (Table I). Analysis of the data were performed using SAS 6.12 (SAS Institute, Cary, North Carolina) and the PEPI 2.0 (Stone Mountain, Georgia) statistical packages.

Results

Five screws were judged to have clearly violated the walls of the pedicle. These were redirected to obtain a satisfactory placement and were not included since it was not possible to obtain immediate CT confirmation of the initial position of the probe. This left 90 pedicles in the study. The distribution of vertebral levels is shown in Figure 2.

Table I. Comparison of the 'in/out' results for both EMG and CT

	CT 'out'	CT 'in'	Total
EMG 'out'	4	14	18
EMG 'in'	4	68	72
Total	8	82	90

Table II. Sensitivity and specificity (95% CI) for EMG calculated at cut-off values of 4 mA, 7 mA and 14 mA

	< 14 mA	< 7 mA	< 4 mA
Sensitivity	1.0 (0.79 to 1.0)	0.5 (0.18 to 0.82)	0.25 (0.04 to 0.61)
Specificity	0.6 (0.49 to 0.7)	0.83 (0.74 to 0.90)	0.98 (0.90 to 0.99)

Figure 3 shows the number of pedicles which were classified as either in or out by CT relative to the current. There were 18 pedicles with an EMG value of 7 mA or lower (EMG out) and 72 with a value greater than 7 mA (EMG in) (Table I). Of the 18 pedicles with a value of 7 mA or less, four had breached the walls but 14 were contained in bone. These were false-positive results since the CT scan had confirmed that there was accurate placement of the screw. Of the 72 pedicles with values of greater than 7 mA, four screws were out on the CT scan. These were false-negative results and included those outside the pedicle laterally and away from contact with the nerve root.

Overall, CT showed that eight of 90 screws (8.8%) had violated the walls of the pedicle. There were no cases of gross malposition of a screw. We noted malposition when threads projected beyond any of the cortical walls. Screws penetrated laterally in five, inferiorly in two and medially in one. All had been recorded as being contained in bone; therefore the surgeon accurately placed 82 of 90 screws (91.2%) (Fig. 3).

Using the cut-off value of 7 mA, the sensitivity of EMG for predicting malposition of the screw was 0.5 (95% confidence interval (CI) 0.18 to 0.82) and the specificity was 0.83 (95% CI 0.74 to 0.90). The effect of choosing alternative values of 4 mA or 14 mA on the accuracy of the EMG is presented in Table II. The values 4 mA and 14 mA were chosen to determine if increasing or decreasing the cut-off value of 7 mA by a factor of two would beneficially alter the sensitivity or specificity.

The ROC curve is shown in Figure 4. The area under the curve was 81.9% (95% CI 70.4 to 93.4) indicating that the EMG is a test of moderate overall diagnostic accuracy.¹⁶

There were no changes in the SSEPs for any patient and no patient had any postoperative neurological deterioration or significant complication.

Discussion

This appears to be the first study to use the EMG response of the intercostal muscles to determine the integrity of pedicles in the thoracic spine. There have been many reports which have examined the EMG response in the lumbar spine and electrical thresholds which indicated a breach of the pedicle have been clearly determined at this level.⁶⁻¹²

Calancie et al¹³ demonstrated that electrophysiological assessment of the position of the screw in a pig model was 100% accurate in detecting perforations in either the pedi-

cle or the anterior vertebral body. In a more recent human study¹⁷ these authors used both electrophysiological monitoring and palpation to achieve satisfactory placement of the screw in 68% of patients.

Holland et al¹¹ reviewed the limitations of EMG when determining the integrity of the pedicle in the thoracolumbar spine and emphasised that EMG responses must be recorded from the appropriate muscle groups. Chronically compressed nerve roots may require higher stimulating currents because of Wallerian degeneration. This should not affect our study as all cases were acute injuries. In the thoracic spine identification of intercostal levels is straightforward so that levels above and below the level of study can also be monitored.

We found that EMG monitoring of thoracic pedicles gave a percentage area under the ROC curve of 81.9%. By the criteria of Swets¹⁶ this indicates a test of moderate diagnostic accuracy since areas of 50% to 70% suggest low test accuracy, 70% to 90% moderate accuracy and greater than 90% high accuracy. There were two cases in which EMG, using a cut-off value of 7 mA, wrongly predicted the CT results.

In four pedicles, the intensity of the EMG stimulus was

Fig. 4

ROC curve. Cut-off values of 4 mA, 7 mA and 14 mA are indicated. The optimum threshold value will minimise the number of false-positive and false-negative results. This point will most closely approach the upper left-hand corner of the graph. The percentage area under the ROC curve is commonly used in a test of diagnostic accuracy.

high suggesting that the pedicle was intact, but the CT scan subsequently showed that the screws were malpositioned giving a false-negative result (5.6%, EMG in and CT out). It is possible that we did not place the stimulating probe near the part of the vertebra which had been breached before insertion of the screw, despite the surgeon's best intention to probe the entire hole in the pedicle. Raiszadeh et al¹⁸ in a goat model showed that false-negative results occur if the surgical field is 'wet' with either blood or saline compared with a 'dry' field.

False-negative results may also be explained by plastic deformation. This occurs when the ratio of the screw-to-pedicle diameter exceeds 80%.^{19,20} Impaction of cancellous bone against the wall of the pedicle during insertion of the screw leads to a tight interference fit, subjecting the cortical wall to microfracture and expansion. Since the dimensions of the pedicle are often less than 5 mm in the mid-thoracic spine^{3,13} plastic deformation will occur (Fig. 5). Although these screws have breached the pedicle they may still provide reliable fixation, but this can only be confirmed by mechanical testing. Belmont et al²¹ have suggested that well-positioned screws may have cortical penetration of 2 mm with cortical expansion and fracture of the medial wall.

It may be argued that direct stimulation of the screw may have produced an EMG response which reflects the CT scan more closely. Our protocol required stimulation of the probe tract before insertion of the screw. This is of greater clinical value since it identifies a safe pedicle track before placement of the screw. The pedicle may deform after insertion which could account for the poor sensitivity of the

test. Nevertheless, this was not associated with any adverse consequences since there were no changes in the function of the spinal cord as seen by monitoring of the SSEP and no postoperative motor or sensory changes.

There were 14 cases in which the EMG indicated violation of the pedicle, but the CT scan confirmed accurate placement of the screw, a high rate of false-positive results (78%, EMG out/CT in). None of these patients had new neurological deficits. These findings are probably due to leakage of current from the pedicle. Loss of electrical impedance may be caused either by inadvertent violation of the cortex but with correct placement of the screw, loss of bone density in osteoporotic patients, or to a small diameter of the pedicle. The initial choice of a 7 mA threshold as the best electrical cut-off point is derived from previous experience in the lumbar spine.⁶⁻¹² Our ROC results indicate that the threshold of 7 mA is also suitable for the thoracic spine giving the least number of false-positive and false-negative results. A cut-off of 14 mA would make the test more sensitive but less specific. A lower cut-off of 4 mA would increase specificity but reduce sensitivity.

The use of EMG monitoring for the insertion of pedicle screws appears to be of limited value in the thoracic spine. The operating surgeons were able to determine correctly if the screw was entirely within the pedicle in more than 90% of insertions by using standard anatomical landmarks and radiography on the operating table. Regardless of the cut-off level used, EMG would not improve this accuracy. Although eight screws (9%) were inadvertently placed outside the pedicle in spite of the surgeon believing they were within it, none caused problems. Many cadaver studies have shown a high incidence of violation of the wall of the pedicle during insertion of thoracic screws, although without clinical implication. Liljenqvist, Halm and Link²² reviewed the use of thoracic and lumbar pedicle screws in idiopathic scoliosis. Although 25% of screws violated either the pedicle or vertebral cortex there were no neurological complications and only one screw required removal. On re-exploration the authors found the pedicle track to be intact and suggested that the CT appearance may have been due to plastic deformation.

Faraj and Webb²³ in a review of the position of 140 thoracic and 508 lumbar pedicle screws reported that the risk of neurological injury or misplacement of the screw was extremely low. Only three of 648 thoracic and lumbar screws were misplaced. They did not analyse the position by CT and the accuracy of relying only on plain radiographs is controversial.^{24,25}

Accurate placement of screws will provide optimal bio-mechanical strength. It is also desirable to avoid injury to thoracic nerve roots during the positioning of the screw. EMG monitoring of the placement of the pedicle probe in the thoracic spine does not add to the surgeon's ability to position the screws correctly. In the hands of experienced spinal surgeons thoracic pedicle screws give reliable fixation in thoracolumbar trauma. Given the deficiencies asso-

Fig. 5

CT scan showing plastic deformation. The normally concave medial wall of the pedicle has expanded to develop a convex contour.

ciated with this test in the thoracic spine, EMG monitoring cannot improve the accuracy of placement of the screw using well-described anatomical landmarks.

While our study does not support EMG monitoring of pedicle tracks, we still attach considerable importance to the monitoring of the long tracts of the spinal cord using monitoring of SSEP or motor-evoked potentials or both. These techniques may quickly detect and perhaps prevent iatrogenic injury to the spinal cord caused by a medially misplaced screw and are part of our standard practice.

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

References

1. Vaccaro AR, Rizzolo SJ, Allardyce TJ, et al. Placement of pedicle screws in the thoracic spine. *J Bone Joint Surg [Am]* 1995;77-A:1193-206.
2. Cinotti G, Gumina S, Ripani M, Postacchini F. Pedicle instrumentation in the thoracic spine: a morphometric and cadaveric study for placement of screws. *Spine* 1999;24:114-9.
3. Xu R, Ebraheim NA, Ou Y, Yeasting RA. Anatomic considerations of pedicle screw placement in the thoracic spine: Roy-Camille technique versus open lamina technique. *Spine* 1998;23:1065-8.
4. Xu R, Ebraheim NA, Shepherd ME, Yeasting RA. Thoracic pedicle screw placement guided by computed tomographic measurements. *J Spine Disord* 1999;12:222-6.
5. Roy-Camille R, Saillant G, Mazel C. Plating of thoracic, thoracolumbar and lumbar injuries with pedicle screw plates. *Orthop Clin North Am* 1986;17:147-59.
6. Clements DH, Morledge DE, Martin WH, Betz RR. Evoked and spontaneous electromyography to evaluate lumbosacral pedicle screw placement. *Spine* 1996;21:600-4.
7. Darden BV, Wood KE, Hatley MK, Owen JH, Kostuik J. Evaluation of pedicle screw insertion monitored by intraoperative evoked electromyography. *J Spinal Disord* 1996;9:8-16.
8. Glassman SD, Dimar JR, Puno RM, et al. A prospective analysis of intraoperative electromyographic monitoring of pedicle screw placement with computed tomographic scan confirmation. *Spine* 1995;20:1375-9.
9. Holland NR. Intraoperative electromyography during thoracolumbar spinal surgery. *Spine* 1998;23:1915-22.
10. Holland NR, Kostuik JP. Continuous electromyographic monitoring to detect nerve root injury during thoracolumbar scoliosis surgery. *Spine* 1997;22:2547-50.
11. Holland NR, Lukaczky TA, Riley LH, Kostuik JP. Higher electrical stimulus intensities are required to activate chronically compressed nerve roots. *Spine* 1998;23:224-7.
12. Welch WC, Rose RD, Balzer JR, Jacobs GB. Evaluation with evoked and spontaneous electromyography during lumbar instrumentation: a prospective study. *J Neurosurg* 1997;87:397-402.
13. Calancie B, Lebowitz N, Madsen P, Klose KJ. Intraoperative evoked EMG monitoring in an animal model: a new technique for evaluating pedicle screw placement. *Spine* 1992;17:1229-35.
14. Chapman JR, Anderson PA. Posterior plate fixation of the cervicothoracic junction. *Techniques in Orthopaedics* 1994;9:80-5.
15. Henderson AR. Assessing test accuracy and its clinical consequences: a primer for receiver operating characteristic curve analysis. *Ann Clin Biochem* 1993;30:521-39.
16. Swets J. Measuring the accuracy of diagnostic systems. *Science* 1988;240:1285-93.
17. Calancie B, Madsen P, Lebowitz N. Stimulus-evoked EMG monitoring during transpedicular lumbosacral spine instrumentation: initial clinical results. *Spine* 1994;19:2780-6.
18. Raiszadeh K, Devlin V, Vaughan RH, Maissie J, Akbarnia BA. Triggered-EMG (T-EMG) use for intact, redirected and dangerously placed pedicle screws. *Procs North American Spine Society New Orleans*, 2000:131-2.
19. Misenhimer GR, Peek RD, Wiltse LL, Rothman SLG, Widell EH Jr. Anatomic analysis of pedicle cortical and cancellous diameters as related to screw size. *Spine* 1989;14:367-72.
20. Sjoström L, Jacobsson O, Karlström G, Pech P, Rauschnig W. CT analysis of pedicles and screw tracts after implant removal in thoracolumbar fractures. *J Spinal Disord* 1993;6:225-31.
21. Belmont PJ, Klemme WR, Dhawan A, Polly DW. *The accuracy of transpedicular screw placement in vivo (abstract)*. *Procs North American Spine Society* 2000:130-1.
22. Liljenqvist UR, Halm HF, Link TM. Pedicle screw instrumentation of the thoracic spine in idiopathic scoliosis. *Spine* 1997;22:2239-45.
23. Faraj AA, Webb JK. Early complications of spinal pedicle screw. *Eur Spine J* 1997;6:324-6.
24. Sapkas GS, Papadakis SA, Stathakopoulos DP, et al. Evaluation of pedicle screw position in thoracic and lumbar spine fixation using plain radiographs and computed tomography: a prospective study of 35 patients. *Spine* 1999;24:1926-9.
25. Whitecloud TS, Skalley TC, Cook SD, Morgan EL. Roentgenographic measurement of pedicle screw penetration. *Clin Orthop* 1989;245:57-68.