In virtually all spine surgeries in which the “freehand” technique (Lenke) is used for pedicle screw placement, assessing the integrity of the established pedicle track using a ball-tipped probe is a crucial stage. The freehand technique involves using a midline incision and exposing the spine to the tips of the transverse processes bilaterally. For thoracic levels, a cortical bur can be used to initiate a posterior starting point. Once the cortical bone has been removed by the bur, a pedicle finder, or “gearshift,” is inserted into the cancellous bone of the pedicle to create the “track” along which the screw will ultimately be placed. Before placing the screw, the surgeon attempts to evaluate the integrity of the created track with a ball-tipped probe by moving the probe along the medial, superior, lateral, and inferior margins of the pedicle; this constitutes the “manual palpation” of the pedicle.

Manual palpation of a pedicle track is one of the most widely accepted methods for determining whether a screw should be placed in a particular track. If the surgeon deems the track to be acceptable, it is then ready for insertion of a pedicle screw, although some surgeons may further prepare the track with a threaded “tap” before placing the screw. On the other hand, if the surgeon detects a breach during manual palpation, he or she may opt to 1) place a screw with a diameter smaller than originally planned, 2) revise the track by using the gearshift to create a secondary track along an alternate trajectory within the pedicle, or 3) abandon placing a screw in that particular pedicle altogether.

Despite widespread use of this method, few studies have focused on the accuracy of manual palpation for thoracic pedicle screw placement. Authors of the present novel study assessed the accuracy of manual palpation for the detection of medial and lateral pedicle breaches during thoracic spine surgery in living adult humans.

Methods. Pedicle tracks were created freehand and manually palpated using a ball-tipped probe. Postoperative CT scans of all implanted thoracic and L-1 screws were evaluated with respect to screw position and the pedicle wall.

Results. Five hundred twenty-five pedicle track/screw placements were compared. There were 21 pedicles with medial breaches measuring ≥ 2 mm. The surgeon correctly identified only 4 of these pedicle tracks as having a medial breach. The surgeon correctly identified 17 of 128 pedicles with a significant (≥ 2 mm) lateral breach. One hundred two screw placements had no measurable breach in any direction (medial, lateral, or foraminal). The surgeon correctly identified 98% of these ideally placed screws.

Conclusions. In this real-time study of thoracic pedicle screw placement, the accuracy of manual palpation for detecting medial or lateral breaches that were ≥ 2 mm was disturbingly low. These findings are consistent with those in recent cadaveric evaluations of palpation accuracy and point to the critical need for more reliable alternative methods to assess pedicle integrity during the placement of thoracic pedicle screws for spine instrumentation surgery.
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manual palpation in detecting pedicle defects in the cadaveric thoracic spine varied from 50% to 81%, depending on the surgeon. Authors of these studies looked at the validity of probing pedicle tracks in cadaveric vertebrae; that is, palpation was done in the confines of a laboratory setting. To our knowledge, no author has conducted a prospective blinded study to evaluate real-time intraoperative accuracy of manual palpation of thoracic pedicle tracks in living adults. The present study is part of a larger study to develop a novel method to guide and assess pedicle screw placement using an electrophysiological approach.

Methods

The institutional review boards of both Upstate Medical University and Crouse Hospital approved the study protocol, and all patients provided informed consent. Subjects were primarily included in this analysis for deformities (thoracolumbar instrumentation and fusion) or cervical myelopathy (C3–T3 instrumentation and fusion), although tumors were not excluded. No emergent traumas were included since patient consent was required at least 24 hours prior to the surgical procedure. A board-certified and fellowship-trained (spine) attending neurosurgeon was common to both sites, and 8 neurosurgical residents were involved in screw placement at the Upstate Medical University site.

This analysis was part of a larger study that included electrophysiological testing of the pedicle track following manual palpation. Surgeons were blinded to the results of electrophysiology; that is, they were generally not told any results nor given any feedback based on experimental intraoperative testing, with one important exception. If intraoperative electrophysiological testing suggested that a screw placed in that pedicle track would be directly touching neural tissue, the blind was “broken” and the surgeon was alerted. The surgeon could then opt to place a smaller-diameter screw in that track, redirect the pedicle track, or abandon that pedicle.

The specific methods for manual palpation and intraoperative electrophysiological testing were described in detail in a previous paper. Briefly, the surgeon made a track in a pedicle using the freehand method and then palpated the track with a ball-tipped probe, announcing his determination of an intact or breached track to us for later comparison with both neuromonitoring- and CT-based evaluations of screw positioning.

For this study, surgeons routinely took fluoroscopic images once all of the screws had been implanted to assess positioning from a lateral view. Stealth navigation and an O-arm were used during 5 cases. Although the freehand method was not used for the subset of screws placed with the navigation system, the surgeon still palpated the resultant pedicle track with the ball-tipped probe. This manual palpation was entirely consistent with the freehand method; hence, these screw placements were included in the overall sample.

Screw position was assessed via CT scanning, typically within 2 days after surgery. To determine the accuracy and reproducibility of our CT evaluation, two blinded reviewers (a neurophysiologist and a neurosurgical resident) reviewed the scans twice, with a minimum of 4 weeks between viewings. Classifying the screw position by analyzing CT scans is inherently subjective. That is, two different persons might assign different “scores” to the same screw (that is, interobserver reliability), or the same person might assign different scores to the same screw during repeated scoring sessions (that is, intraobserver reliability). To evaluate surgeon accuracy with manual palpation, interobserver and intraobserver reliability kappa scores were calculated independently for medial and lateral breaches. These kappa scores were restricted to screw placements determined to have at least 2 mm of their diameter either medial or lateral to the pedicle. Breaches < 2 mm were not included in this analysis given the limitations of CT resolution in determining whether pedicle wall plasticity or fracture had occurred in these placements. Scans were viewed exclusively on the OsiriX DICOM viewer, with measurements taken using OsiriX digital calipers. Contrast was adjusted to minimize artifact and flare, but no filters were applied.

Screw position was measured in the medial, lateral, and foraminal directions, relative to the associated pedicle. Although some screws were intentionally placed via an extrapedicular (or an “in-out-in”) approach, any breaches in such cases were still counted and measured as lateral, as the surgeon was still able to manually palpate and judge whether the desired placement had been achieved.

By dealing with medial and lateral breaches independently of one another, it may seem possible for some breaches to be “double counted,” that is, if the screw breached in both the medial and lateral orientations, relative to the pedicle. However, by restricting our analysis to those screws that were either ideally positioned (no measurable breach in any orientation) or breached by ≥ 2 mm medially or laterally, relative to the pedicle, no breaches were double counted; that is, no breaches were ≥ 2 mm out of the pedicle both medially and laterally.

Occasionally, based on feedback from manual palpation and/or electrophysiological testing, pedicle tracks were revised intraoperatively. For these instances, we cannot address the accuracy of manual palpation for the original track since no CT image was obtained until after the track had already been revised. Thus, the accuracy of manual palpation for revised tracks was established based on the surgeon’s final track, once manual palpation revealed adequate positioning.

Results

The accuracy of manual palpation using a stainless steel ball-tipped probe was assessed on the basis of 525 pedicle screws implanted in 43 patients. Screws were implanted in every level of the thoracic spine as well as L-1 (note that L-1 is included in this thoracic study, as the caudal tip of the spinal cord is typically still present at that level). The distribution of screws by level is shown in Table 1. Of the 525 implanted screws, 339 were prepared and manually palpated by the attending neurosurgeon, while 186 were prepared and manually palpated by one of the 8 neurosurgical residents involved in this study. Our
analysis is primarily based on a subset of 251 of those 525 screws, which includes (as determined on CT analysis) 21 screws with medial breaches $\geq 2$ mm, 128 screws with lateral breaches $\geq 2$ mm, and 102 screws with no measurable breach (medial, lateral, or foraminal). None of these breaches resulted in postoperative neurological or vascular complications.

**Medial Breaches**

Of the 21 medial breaches $\geq 2$ mm, the surgeon correctly identified the breach in 4 cases, failed to identify any breach in 16, and declared 1 to be an in-out-in (that is, lateral) breach. An example of one of these misidentified medial breaches is shown in Fig. 1, with a screw extending 4.4 mm into the canal space, yet its pedicle track was determined via manual palpation to have no breach.

**Lateral Breaches**

Within the sample of 128 lateral breaches $\geq 2$ mm, the surgeon correctly identified the breach in 17 cases and failed to correctly identify it in 111. Of the 111 lateral breaches $\geq 2$ mm, 101 were classified by the surgeon as having no breach, 1 as medial, 5 as inferior, and 4 as superior to the pedicle.

**No Breach**

One hundred two screws had no measurable breach of the pedicle cortex in any direction (that is, medially, laterally, or foraminal). These were correctly identified by the surgeon in 98% (100) of the cases. In 2 instances (2%), the surgeon declared that there was a breach, yet no measurable breach was evident on the postoperative CT scan.

**Revised Tracks**

Among the 251 screw placements evaluated here, there were 14 revised tracks. Despite the revisions, 3 placements had medial breaches measuring $\geq 2$ mm inside the canal space, and 7 had lateral breaches $\geq 2$ mm outside the pedicle. As the breaches were $\geq 2$ mm, and yet were determined by the surgeon to be appropriate, we regarded them as having been “incorrectly identified” by manual palpation. Four revised placements had no measurable breach in any orientation.

**Accuracy of Manual Palpation for Breached and Nonbreached Placements**

Among the 251 evaluated placements, the unrevised and revised totals combined (21 medial, 128 lateral) were 149 breaches $\geq 2$ mm. Of these, 128 (17 medial, 111 lateral) were inaccurately considered to have no breach based on manual palpation. Additionally, 2 screw placements with no measurable breach were misidentified during manual palpation as having been breached. Thus, 130 misidentifications among the 251 palpated screw tracks were made by manual palpation (17 medial, 111 lateral, and 2 “no breach”), for an overall manual palpation accuracy of 48.2%.

**Accuracy of O-Arm–Assisted Screw Placements**

At the surgeon’s discretion, an O-arm navigation system was used during 5 cases (54 screws). In this subset of 54 screws, there were 2 medial breaches $\geq 2$ mm (3.7%), 17 lateral breaches $\geq 2$ mm (31.5%), and 11 screw placements with no measurable breach (20.4%). These percentages were virtually indistinguishable from those of the larger population (525 screws). In the larger cohort, which includes the 54-screw subset, there were 21 medial breaches $\geq 2$ mm (4%), 128 lateral breaches $\geq 2$ mm (24.4%), and 102 screw placements with no measurable breach (19.4%).

**Computed Tomography Inter- and Intraobserver Reliability Kappa Scores**

Both intra- and interobserver reliability kappa scores were calculated for the two blinded CT reviewers, and the individual kappa scores were averaged together to report a final, averaged intra- and interobserver kappa. The abil-
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ity to correctly identify—based on CT images—medial and lateral defects (which had not undergone revision) was assessed independently against the control group of 102 screws with no measurable breach in the medial, lateral, or foraminal directions.

For medial breaches ≥ 2 mm, the average intraobserver reliability kappa for CT assessment of thoracic pedicle screw placement was 0.67 (Observer 1 = 0.84, 95% CI 0.75–0.93; Observer 2 = 0.5, 95% CI 0.37–0.64). The average interobserver reliability kappa for these medial breaches was 0.53.

For lateral breaches ≥ 2 mm, the average intraobserver reliability kappa was 0.72 (Observer 1 = 0.77, 95% CI 0.69–0.85; Observer 2 = 0.66, 95% CI 0.57–0.75). The average interobserver kappa was 0.67.

Discussion

Authors of previous cadaveric studies reported the accuracy of manual palpation in correctly identifying a breached pedicle within the thoracic or thoracolumbar spine in the range from 40% to 85%. In the current in vivo study, we found that manual palpation detected 48.2% of all breaches ≥ 2 mm, which is in line with previously reported rates. It is worth noting that correct identification of pedicle tracks having no breaches was the largest contributor to that 48.2% accuracy rate (98% of no-breath screws were correctly identified, whereas only 19% of medial and 13% of lateral breaches ≥ 2 mm were correctly identified). Our findings agree with the concluding statement made by Sedory et al.: “The standard ball-tipped probe was much less reliable than expected.” In fact, our results were on the low end of the accuracy range reported by Sedory et al. However, it must be remembered that our accuracies were determined via intraoperative palpation and postoperative CT analysis rather than via palpating segmentally separated cadaveric vertebrae and using direct visualization (via dissection) to determine breach rates. Manual palpation in an in vivo study is likely to be more difficult (that is, may have lower accuracy rates) than in a cadaveric study in which surrounding soft tissue and the ribs (which may act as confounding factors in an in vivo study) have been removed. Moreover, the time constraints in an operating room setting are absent in a lab setting, and while impossible to quantify, they likely have a further negative impact on palpation accuracy in the operating room.

One unavoidable consequence of our study design was the inclusion of cases in which a pedicle wall correctly identified as “intact” via palpation then fractured as the screw was placed. Both the pedicle finder used to create the initial track and the pedicle probe used to palpate it had a smaller diameter than the screw that was ultimately placed. Therefore, it is possible for the track to be intact when the surgeon palpates it and then for it to fracture when the larger-diameter screw is placed. We know of one such occurrence in our series (identified by electrophysiological testing), but there were almost certainly additional cases that went undetected, inflating the error rate associated with palpation. This risk has also been shown when undercutting a prepared pedicle track. After the creation of an initial track, a surgeon, in an attempt to reduce the risk of screw malpositioning, may opt to “tap” the hole by using a threaded tap that is typically 0.5–1 mm smaller in diameter than the screw that will be placed. Chin et al. reported that in the lumbar spine, the increased screw diameter relative to the diameter of the tap presents a “low but real risk of pedicle screw break-through” during insertion. We do not consider this to be a significant source of error in our study, as fractures from a larger-diameter screw being placed in a pedicle are unlikely to result in breaches ≥ 2 mm, and thus would not have been included in the breaches reported here.

Another potential source of error with respect to surgeon accuracy rates is the assumption that an inserted screw will follow the palpated, prepared trajectory. In a study using thoracic cadaveric spines, the screw did not always follow the prepared trajectory, specifically for untapped pilot holes. Erkan et al. found that a “pilot hole alone does not insure [sic] that the screw will follow the pilot hole.” These authors reported that only 80% of untapped screws followed the pilot holes, while 97% of the tapped screws did. Note also that our study included cases in a teaching hospital during which senior residents prepared and palpated the initial track, the attending surgeon checked the palpation, and then the senior residents inserted the screw. It has been well documented that there is a learning curve associated with the insertion of thoracic pedicle screws. As Joglekar et al. concluded, “There are no shortcuts.” In other words, an inexperienced surgeon, as compared with an experienced one, is going to have an increased breach rate. Since our senior surgeon does not typically tap the prepared pedicle track, it is possible that the initial track was palpated and reported—correctly—as intact, but then the resident, because of his or her inexperience, deviated from the prepared track while inserting the screw and created a breach at that point.

Finally, by including all breaches ≥ 2 mm in our analysis, we further inflated our surgeon’s “miss rate” relative to those in other in vivo studies of screw placement accuracy. Not all studies consider breaches (medial and/or lateral) that are 2–4 mm to be clinically significant. As regards manual palpation, however, a breach of the med-
Theoretical reasons, manual palpation using a ball-tipped probe was grossly insufficient for identifying pedicle tracks that would result in malpositioned screws, specifically those projecting medially into the thoracic spinal canal. Furthermore, it may be advantageous—particularly for inexperienced surgeons—to use a tap prior to inserting thoracic pedicle screws, as this step may increase the probability of accurate placement of the screw within the palpated pilot hole.

Acknowledgment

We thank Shilpa Agarwal for her help with analysis of this study.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper. Miriam L. Donohue, Ph.D., declares no conflict of interest. Ross R. Moquin, M.D., is a paid consultant for K2M. Amit Singla, M.B.B.S., M.S., declares no conflict of interest. Blair Calancie, Ph.D., received a research grant from the National Institutes of Health (NS063055; NINDS) in support of this study.

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

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Accepted January 21, 2014.

Please include this information when citing this paper: published online February 21, 2014; DOI: 10.3171/2014.1.SPINE13197.

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