Cortex of the pedicle of the vertebral arch. Part I: deformation characteristics during screw insertion

SERKAN İNCEOĞLU, PH.D.,1 CUMHUR KİLİNÇER, M.D.,2 ANDREA TAMI, PH.D.,3 AND ROBERT F. MCCLAIN, M.D.4

1Spine Research Laboratory, 1,4The Cleveland Clinic Spine Institute; 1Department of Orthopedic Surgery, Lerner College of Medicine; 1,4The Cleveland Clinic Foundation, Cleveland; 3Musculoskeletal Mechanics and Materials Laboratories, Department of Mechanical and Aerospace Engineering, Case Western Reserve University, Cleveland, Ohio; and 1Department of Neurosurgery, Medical School of Trakya University, Edirne, Turkey

Object. Elastic deformation has been proposed as a mechanism by which vertebral pedicles can maintain pullout strength when conical screws are backed out from full insertion. The response to the insertion technique may influence both the extent of deformation and the risk of acute fracture during screw placement. The aim of this study was to determine the deformation characteristics of the lumbar pedicle cortex during screw placement.

Methods. Lumbar pedicles with linear strain gauges attached at the lateral and medial cortices were instrumented using 7.5-mm pedicle screws with or without preconditioning by insertion and removal of 6.5-mm screws. The strains and elastic recoveries of the medial and lateral cortices were determined.

Results. Mean medial wall strains tended to be lower than mean lateral wall strains when the 6.5-mm and 7.5-mm screw data were pooled (p = 0.07). After the screws had been removed, 71 to 79% of the deformation at the lateral cortex and 70 to 96% of the deformation at the medial cortex recovered. When inserted first, the 7.5-mm screw caused more plastic deformation at the cortex than it did when inserted after the 6.5-mm screw. Occasional idiosyncratic strain patterns were observed. No gross fracture was observed during screw placement.

Conclusions. Screw insertion generated plastic deformation at the pedicle cortex even though the screw did not directly contact the cortex. The lateral and medial cortices responded differently to screw insertion. The technique of screw insertion affected the deformation behavior of the lumbar pedicles. With myriad options for screw selection and placement available, further study is needed before optimal placement parameters can be verified.

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KEY WORDS • cortical bone • pedicle cortex • pedicle expansion • pedicle screw • strain gauge

Despite the importance of the lumbar pedicle as an anatomical structure and a point of surgical fixation, most research has focused on anatomical descriptions of pedicle dimensions2,4,12,19,20,22 and biomechanical studies of pedicle screw pullout strength.3,15,21 The pedicle’s ability to expand to accommodate large implants, to rebound to maintain pullout strength when conical implants are drawn back, and to deform without acute failure has been observed but has not been quantified or explained. Although the results of some biomechanical studies suggest that increasing the screw’s diameter provides greater fixation strength,3,21 the insertion of overly large screws into the pedicle may cause deformation in the pedicle cortex or weakening or fracturing of the pedicle wall.16 Wall fracture or deformation may in turn increase the risks for fixation failure and neurological injury.11 An understanding of the mechanisms of pedicle wall deformation as well as the limits to elastic deformation would influence both screw design and selection.

Information regarding the effects of screw insertion on the mechanics of the pedicle cortex is limited. McLain et al.14 found that pedicles in the midthoracic region in older adults are often so narrow that the smallest standard pedicle screw would penetrate the pedicle cortex during a transpedicular insertion. Investigators reporting on large numbers of thoracic screw placements have suggested that, at least in younger patients, the pedicle expands to accommodate the larger screw (SI Suk, personal communication, 2002). In vitro studies have shown that when the screw diameter exceeded 75 to 80% of the inner diameter of the pedicle cortex, it caused permanent damage at the cortical bone.6,16 In these studies investigators examined gross deformation or disruption in the cortical wall, and there is still little information on the behavior of the cortex during insertion of a standard-sized screw into the lumbar pedicle. It is unknown whether the volume effect of a centrally placed screw can cause deformation without direct contact between the screw and cortex. It is also unknown whether the medial and lateral cortices are equally susceptible to deformation during screw placement or to what extent deformation during screw placement is elastic or plastic.

In this pilot study we tested the following hypothesis: the
insertion of a pedicle screw produces variable degrees of elastic and plastic deformation at the pedicle cortex, depending on the technique used for screw insertion and on the screw size, and the extent of this deformation would differ in the medial and lateral cortical walls.

Materials and Methods

Nine lumbar human vertebrae (L-3 and L-4) were obtained from six different cadavers. The cadavers were all male, ranged in age from 20 to 68 years at the time of death, and had no known bone or spinal disease. Bone mineral density measurements were taken via a DEXA scanner (QDR 4500A, Hologic) (Table 1). The specimens were stripped of soft tissue, wrapped in saline-soaked gauze, and kept frozen until the day of the test.

After the lateral and medial cortices of each pedicle had been thawed to room temperature, they were meticulously cleaned of all adherent tissue. After the surfaces of the cortices had been deactivated and defatted, linear strain gauges (350 V, Thermo BLH Inc.) were mounted to the lateral and medial surfaces of the pedicle isthmus, in circumferential orientation, and affixed with cyanoacrylic glue.

The vertebral specimens were embedded in a polyester resin (Bondo, Mar-Hyde Corp.), leaving the posterior elements exposed (Fig. 1). The strain gauges were routed through an analog-to-digital board to data-acquisition software (Strain Smart version 2.2.3, MicroMeasurements Group).

The pedicle screws were inserted according to a standard technique and the senior author (R.F.M.) placed all screws for testing. The optimal starting point and the orientation for screw insertion was defined with respect to the pedicle in all planes. A starter awl was used to create the entry point, and a blunt-tip pedicle probe was passed manually through the central axis of the pedicle into the vertebral body. The laminar cortex of the pilot hole was then tapped using an undersized 5.5-mm tap, which had the same pitch as the selected screw, to facilitate the start of screwing in a consistent manner.

Nine vertebrae yielding eighteen pedicles were instrumented using pedicle screws in a paired testing array. One pedicle of each vertebra received a primary 6.5-mm screw, which was placed and removed. This procedure was followed by insertion of a secondary 7.5-mm screw, which was placed and removed in the same fashion. The opposite side received a primary 7.5-mm screw without any placement of a 6.5-mm screw. This instrumentation scheme was switched between the left and right pedicles of each vertebra in consecutive insertions.

The 6.5-mm conical pedicle screws (Osteonics, Stryker) were inserted first in the indicated pedicle. After each turn of the screw, the surgeon paused a few seconds to eliminate noise in the strain data. Once testing had been completed, the pedicles were cut transversely at the isthmus (narrowest region) by using a reciprocal saw.

Results

Three pedicles were excluded from the comparative analysis of medial and lateral strain. One medial and two lateral strain gauges were excluded from the analysis when they produced negative strain during screw insertion. Because the pedicle expansion was expected to produce tensile (positive) strain, negative strains were considered idiosyncratic and were excluded from the study. To maintain the paired testing array for analysis of the screw insertion technique, we excluded the one lateral and two medial strain gauges that were paired with the strain gauges that produced negative strain. Hence, the analyses on the lateral and medial cortices were conducted using seven and eight pedicles, respectively.

Strain data during a typical screw insertion is presented in Fig. 2. The insertion of the 6.5-mm primary screw generated a mean value of 2234 ± 2556 με at the lateral cortex and 618 ± 562 με at the medial cortex (p > 0.05) as shown in Fig. 3. The insertion of the 7.5-mm secondary screw produced 4533 ± 4660 με at the lateral cortex and 1376 ± 926 με at the medial cortex (p > 0.05). The difference in values between the lateral and medial cortices was close to being significant when both screws were pooled (p = 0.07). The difference in strain measurements between the 6.5-mm and 7.5-mm secondary screws was significant only with respect to the medial cortex (p < 0.05). When inserted into the intact pedicle without preplacement of the 6.5-mm screw, the 7.5-mm primary screw produced 2319 ± 2812 με at the lateral cortex and 4593 ± 7686 με at the medial cortex (p > 0.05).

The deformation seen in each insertion was predominantly elastic. After the 6.5-mm screw had been placed and removed, 78.93 ± 13.35% of the deformation at the lateral wall and 95.65 ± 8.08% of the deformation at the medial wall recovered (p < 0.05) (Fig. 4). After the 7.5-mm secondary screw had been similarly placed and removed, 78.71 ± 11.39% and 91.87 ± 8.70% of the deformations at the lateral and medial walls, respectively, recovered (p < 0.01). The difference between elastic recoveries following removal of the 6.5-mm and 7.5-mm secondary screws was significant only with respect to the medial cortex (p = 0.05). When placed into the pedicle without preplacement

<table>
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<th>Specimen No.</th>
<th>Age (yrs),†</th>
<th>Sex</th>
<th>Level</th>
<th>BMD (g/cm²)</th>
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* BMD = bone mineral density.
† At time of death.

Mean values are presented ± standard deviations.
of a smaller screw, the 7.5-mm primary screw tended to cause more plastic deformation, with recovery of only 70.66 ± 18.94% at the lateral cortex and 69.78 ± 32.0% at the medial cortex (p > 0.05). The difference between the elastic recoveries seen after removals of the 7.5-mm secondary and primary screws was only significant when data from the lateral and medial cortices were pooled (p < 0.05) and not when separate analyses were made of the lateral (p > 0.05) and medial (p > 0.05) walls.

The screw placements were similarly distant to each strain gauge, with a center-to-gauge distance for the lateral cortex of 6.6 ± 1.7 mm and one for the medial cortex of 6.0 ± 1.8 mm (p > 0.05). Regression analysis showed weak relations between the strain and the center-to-gauge distance for the 6.5-mm (R² = 0.09, p > 0.05), 7.5-mm secondary (R² = 0.03, p > 0.05), and 7.5-mm primary (R² = 0.34, p = 0.01) screws when the lateral and medial gauge data were pooled. Regression analysis also showed weak

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**Fig. 1.** Photographs showing screws implanted into the pedicles with strain gauges attached at the lateral and medial cortices.

**Fig. 2.** Representative graph illustrating the change in strain at the lateral and medial cortices of the pedicle during insertion and removal of screws. The long plateau at the end of the stepwise increments indicate the strain at full insertion; the sharp drops that follow indicate the removal of the screws.
relations between the elastic recovery and the center-to-gauge distance for the 6.5-mm ($R^2 = 0.002, p > 0.05$), 7.5-mm secondary ($R^2 = 0.003, p > 0.05$), and 7.5-mm primary ($R^2 = 0.03, p > 0.05$) screws when the lateral and medial gauge data were pooled.

The analysis showed insignificant ($p > 0.05$) and weak regressions between the maximum strain data obtained from insertion of each screw and bone density for the 6.5-mm primary ($R^2 = 0.06$ for lateral, $R^2 = 0.28$ for medial), 7.5-mm secondary ($R^2 = 0.06$ for lateral, $R^2 = 0.08$ for medial), and 7.5-mm primary ($R^2 = 0.05$ for lateral, $R^2 = 0.11$ for medial) screws. Similarly, regressions between bone density and elastic recovery were weak and insignificant ($p > 0.05$) for the 6.5-mm ($R^2 = 0.00$ for lateral, $R^2 = 0.06$ for medial), 7.5-mm secondary ($R^2 = 0.18$ for lateral, $R^2 = 0.13$ for medial), and 7.5-mm primary ($R^2 = 0.08$ for lateral, $R^2 = 0.06$ for medial) screws.

**Discussion**

The role of pedicle expansion in fixation strength, pull-out resistance, and failure behavior is not well understood. The effect of pedicle fracture—the final outcome of progressive expansion—is believed to be important to construct viability and strength as well as to potential nerve injury. The present study was designed to assess the deformation characteristics of the pedicle cortex during pedicle screw insertion, selecting a few easily defined variables from among the many that might be suggested, in order to determine whether insertion technique may play a role in outcome.

The results show that the pedicle cortex expanded in a ductile manner to accommodate the screw during insertion and that the deformation recovered to some degree on removal of the screw. This observation was in agreement with those by Abshire et al. who found that the pedicle was able to maintain the holding power of the screw even when the conical screw was backed out, a finding suggestive of an elastic recovery of deformation of trabecular and cortical bone.

The residual strains observed after removal of the screws confirmed a degree of plastic deformation at the pedicle cortex. Residual strains were observed even at the low strain levels generated during the insertion of the 6.5-mm screw. In our study the strains generated by insertion of the 6.5-mm screw at the pedicle cortex were lower than ultimate failure strain values for other tubular cortical bones. The ultimate tensile strain of human femoral cortical bone in the transverse direction has been reported in the literature to be 7200 με. Wachter et al. reported that the tensile yield strain of human femoral cortical bone in the transverse direction was 6600 με (approximated from a yield stress of 11.64 MPa and an elastic modulus of 1.76 GPa by using Hooke’s Law). The strains recorded over the pedicle cortex during the insertion of the 7.5-mm screw were sometimes higher than those values, yet no fractures were observed in these pedicles. Therefore, one can speculate that the cortical bone of the pedicle is more ductile than typical cortical bone in other long bones with a lower yield strain and a greater capacity for plastic deformation than the cortical bone of the femur. This could be due to differences in the microstructure of the cortical bone from the two different anatomical regions (see our companion article in this issue).

Ongoing investigations of the cortical shell of the lumbar pedicle have shown that the osteonal structure of the pedicle cortex is laid down mainly, but not exclusively, in the anteroposterior (longitudinal) direction. Surprisingly, the surrounding lamellar bone, which is the subperiosteal layer seen in typical cortical bone, is absent in the lumbar pedicle. Considering that osteons in the pedicle cortex are laid down in the anteroposterior direction, the interstitial matrix between the osteons is most likely forced to stretch as the pedicle deforms and expands, allowing the osteons to separate without actually fracturing during screw insertion. The energy imposed during pedicle expansion may dissipate at the pedicle cortex through longitudinal microfractures, as with ductile deformation, as opposed to major transverse or comminuted fractures, as seen in long bones during the insertion of oversized intramedullary implants. This may allow a greater safety margin in the lumbar pedicle for expansion prior to gross fracture, but further studies are needed to prove this hypothesis.
Cortex deformation characteristics during screw insertion

The results show that the lateral cortex experienced more plastic deformation than the medial cortex. Concerns that this difference might have been due to asymmetric screw placement were allayed when the histological analysis showed that the screws were centrally placed within the pedicle. The plastic deformation at the pedicle cortices occurred even though the screw itself did not directly contact the cortex. Moreover, in our investigations, and consistent with previous reports,10 the lateral cortex appeared thinner than the medial cortex. This would explain much of the difference in deformation characteristics between the lateral and medial cortices and would support clinical findings regarding the higher frequency of fractures of the lateral cortex than of those of the medial cortex.10

Another interesting finding of this study was that insertion of the 7.5-mm screw into the pedicle caused more plastic deformation than insertion following placement and removal of the 6.5-mm screw. This was probably because incremental deformations in the trabecular bone allowed the stresses to be absorbed partially within the trabecular network before transmitting them to the cortical shell. Tapping the trabecular bone before screw insertion was shown to decrease the pullout strength.3 This probably occurred because the tap cuts the bone instead of compacting it. In a previous in vitro biomechanical study trabecular bone had a better grip on the implant when the implant compressed the bone rather than cut it during insertion.17 Hence, the use of a smaller sized screw instead of a tap may be a better technique because we know that it reduces plastic deformation at the cortex and prepares the hole without cutting the trabecular bone. The effects of this technique on pullout strength have not yet been proven.

During screw insertion, the trabecular bone within the pedicle was compacted toward the outer diameter. The strains measured at the cortex were due to stresses transmitted through the trabecular network to the outer cortex. The removal of the screw released the energy stored within the trabecular bone and cortex to some extent. Therefore, it is important to note that we do not know whether residual strains measured at the cortex are caused by plastic deformation in the cortical bone or by interlocking of the compacted trabecular bone. Further studies involving imaging and damage analysis are needed.

In our opinion, our strain gauge measurement method was adequate but not optimal to confirm the cortical changes associated with screw placement. The pedicle is a complex 3D structure. Transpedicular instrumentation causes a nonuniform deformation at the cortex that cannot be determined entirely by using a strain gauge. Similarly, there is an assumption that a centrally placed screw will impart deforming forces uniformly around the circumference of the pedicle wall. The pedicle fill cannot be precisely defined with a ratio at one cross-section because the pedicle diameter is variable along the pedicle axis and the elliptical or eccentric cross-section. Therefore, a more complete investigation of pedicle cortex deformation during screw insertion could be done by using noncontact measurement systems incorporating surface mapping of 3D anatomy.

Our specimens were harvested from spines with low-normal to low bone mineral density because we encountered difficulties in obtaining cadaveric spines from young individuals without systemic disease. Thus, we may speculate about the strain behavior of young pedicles from our data, but confirmation is not yet available. Nevertheless, our results showed that strain and deformation recovery had no relation to bone mineral density among the range of specimens available in this study, however. Furthermore, a recent study by Inceoglu et al.7 noted that bone density in the pedicle was not well represented by traditional DEXA measurements of the lumbar spine. Therefore, the trabecular bone mass within the pedicles in the present experiment may not have been well reflected in DEXA measurements and this may have influenced the regression analyses mentioned earlier.

Further studies should be conducted to confirm these initial observations, to advance our understanding of the mechanical properties of the pedicle cortex, and to construct an appropriate criterion for screw size selection and instrumentation techniques.

Conclusions

The deformation characteristics of the pedicle cortex during pedicle screw placement were characterized for a small population of relatively uniform specimens. Screw placement in the pedicle produced large strains and plastic deformation at the pedicle cortex, even though the screws did not directly contact the cortical bone. Coaxial screws, equidistant from the medial and lateral cortices, generated consistently higher strains in the lateral compared to medial cortices. The pedicle cortex recovered 70 to 90% of the maximum deformation after removal, a finding that suggests that the pedicle could accommodate the placement of large screws through progressive distortion rather than acute failure and fracture. The extent of plastic deformation was lessened by placement and removal of a smaller screw before a large screw was placed, suggesting that pilot hole preparation does affect pedicle biomechanics. Further study of larger numbers of individuals, focusing on specific variables of sex, age, extremes of bone density, and implant design, should be performed.

Disclosure

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References

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