A Biomechanical Study of Intrapeduncular Screw Fixation in the Lumbosacral Spine

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This laboratory experiment was undertaken to identify factors contributing to intrapeduncular screw fixation in the vertebra. Testing was performed in axial pull-out and cyclic loading modes using multiple screw designs inserted to various depths into fresh human lumbosacral vertebrae. The degree of osteoporosis played a major role in pull-out strength. Larger diameter, full-threaded screws inserted deep enough to engage the anterior vertebral cortex resulted in the most secure fixation. In the sacrum, the second sacral pedicle was the weakest location of insertion. Screws aimed laterally into the ala at 45° or medially into the first sacral pedicle resisted larger axial pull-out loads than those inserted straight anteriorly into the ala. Methyl methacrylate was found to restore secure fixation in previously-loosened screws and pressurization of cement doubled the pull-out force. In cyclic load tests, deeper-inserted screws were found to withstand a greater number of cycles before loosening. Measurements of pedicle outer cortical diameters were found in many specimens to be smaller than both the 4.5-mm and 6.5-mm diameter screws.

Intrapeduncular screw fixation of the spine is enjoying increasing world-wide popularity. At present there are several internal fixation systems available attached through pedicles utilizing plates and screws,18,19,29-32,38,39 wires and screws,20 rods and screws,6,11,13,14 and external fixation devices purchasing the vertebral body using intrapeduncular threaded pins.22-25 All of these systems depend upon the ability of a screw to obtain and maintain purchase in the vertebral body through the pedicle until solid fusion occurs. This laboratory experiment was undertaken to investigate the factors that contribute to the ability of a screw to hold the vertebra from within the pedicle.

MATERIALS AND METHODS

Twenty-nine fresh, human lumbosacral spinal specimens obtained at autopsy were used in this study. Specimen age averaged 74.5 years (range, 49–95). Disarticulated vertebral bodies were cleaned of all soft tissue. Individual vertebra underwent roentgenographic examination. There were no specimens with bony abnormalities demonstrated on roentgenogram or history of metastatic disease used in the study. Screw designs tested include: Steffee 6.5-mm pedicle screw, 6.5-mm standard cancellous
screw with a 32-mm thread length, a full-length threaded 6.5-mm cancellous screw, a 4.5-mm standard cortical screw, and a 4.5-mm Louis pedicle screw. The thread design of the Louis screw is intermediate between that of the cancellous and cortical types. Screws were inserted into pedicles after predrilling. A 3.2-mm drill was utilized for the 4.5-mm cortical screws and 6.5-mm cancellous and Steffee screw designs. A 2.7-mm drill was used for the Louis pedicle screw (Table 1). The proximal aspects of the pedicle screw hole were tapped for non-self-tapping screws to facilitate insertion. For testing, specimens were mounted into an Instron model 1122 (Instron Corp., Canton, Massachusetts) testing machine in specially-designed jigs. In pull-out, testing loads were applied along the long axis of the screw. Cyclic loading was done by toggling the proximal aspect of the screws in the medial-lateral and cephalad-caudal directions.

Axial pull-out testing was performed in numerous configurations, comparing screw designs, depth of insertion, the effect of methyl methacrylate augmentation, and various locations of screw placement in the sacrum. Failure was defined in axial pull-out testing as visible screw movement. To eliminate the large variation noted among specimens, the opposite pedicle of the same vertebra was used for comparison in all tests, except in sacral insertion site comparisons and methyl methacrylate augmentation studies.

Six different types of tests were performed on the disarticulated vertebral specimen.

(1) The effect of thread location within the pedicle and vertebra was tested using partially-threaded screw designs. The Steffee screw was inserted to the anterior cortex so the narrower, machine-threaded portion of the screw was positioned within the pedicle. This was compared to the Steffee screw inserted to 50% of the vertebral body, (at this level) only the larger, 6.5-mm cancellous-threaded portion of the screw was in pedicle, Fig. 1A). In another test, the standard 6.5-mm cancellous screw threaded only in the distal 32-mm aspect was compared to a 6.5-mm cancellous screw threaded throughout its full length. Both screws were inserted to the anterior cortex. This left the smooth, unthreaded shank of the partially-threaded screw within the pedicle (Fig. 1B).

(2) The effect of depth of insertion was tested using full-threaded screw designs. A standard 4.5-mm cortical and the full-threaded 6.5-mm cancellous screw were individually tested, comparing insertion depths of 50%, to anterior cortex and through and engaging anterior vertebral cortex (Fig. 1C).

(3) Different screw designs were compared at a constant depth of insertion. The 4.5-mm cortical screw and the 6.5-mm full-threaded cancellous screw were compared at two depths of insertion: to the cortex (Fig. 1D) and through the cortex. In addition, the 4.5-mm Louis pedicle screw was compared to the 4.5-mm cortical (Fig. 1E), and the 6.5-mm full-threaded cancellous design, each screw was inserted to a depth of 50% of the vertebral body in these tests.

(4) The strength of five different sacral insertion sites was investigated using the 6.5-mm full-threaded cancellous screw: (a) into the first sacral pedicle engaging the anterior cortex; (b) straight anteriorly into the second sacral pedicle between the first and second dorsal sacral foramen engaging the anterior cortex; (c) the sacral ala through the dorsal cortex at a point cephalad to the first dorsal sacral foramen directed straight anteriorly engaging the anterior cortex; (d) angled laterally 45° into the sacral ala at the level of the first sacral pedicle; and (e) similarly to the previous method but more caudally at the level of the second sacral pedicle (Fig. 2). Absolute pull-out values are presented for this group.

(5) The effect of methyl methacrylate augmentation was tested after inserting screws into the pedicle and loading them to failure. Screws were then reinserted into the same stripped screw hole after 2 cm³ of liquid methyl methacrylate had been inserted either with or without pressurization. Pressurization was accomplished using a 0.5-cm³ bolus of methyl methacrylate inserted into the screw hole anterior to the level of the pedicle with a catheter-tipped syringe. This bolus was then allowed to partially harden. Two cubic centimeters of liquid cement were then inserted with a catheter-tipped syringe to a level just posterior to the first bolt but anterior to the pedicle. The catheter tip was inserted deep enough into the pedicle to seal against the pedicle wall, preventing back flow of cement. Injected cement was forced into the surrounding cancellous bone in the posterior aspect of the vertebral body anterior to the pedicle. Cement was allowed to harden with the screw in place and pull-out testing was performed.

(6) Cyclic loading was performed using 6.5-mm full-threaded cancellous screws, comparing the effect of depth of insertion upon screw loosening. Screws were loaded from a point just posterior to pedicle entry and toggled in either the medial-lateral or cephalad-caudal directions. Specimens were embedded in methyl methacrylate and mounted into a specially-designed jig. Screws were repetitively loaded in the appropriate orientation, 3 mm in each direction from the initial placement position. Testing was terminated when the force required to toggle the proximal end of the screw through the constant 6-mm distance decreased to 50% of the force required in the first complete cycle. Three insertion
FIGS. 1A–1E. (A) Steffee 6.5-mm pedicle screws inserted to the anterior cortex with machine-threaded segment in pedicle (left) and with 6.5-mm threads filling pedicle (right), test 2, Table 2. (B) Full-threaded 6.5-mm screw inserted to anterior cortex (left) and 6.5-mm standard cancellous screw inserted to anterior cortex with the smooth shank of the screw filling the pedicle (right), test 3, Table 2.

(C) Full-threaded 6.5-mm screw inserted to the anterior cortex (left) and to a depth of 50% of the vertebral body diameter, (right), test 6, Table 2. (D) 4.5-mm standard cortical screw inserted to the anterior cortex (left) and 6.5-mm full-threaded screw inserted to the anterior cortex, (right), test 8, Table 2. (E) 4.5-mm standard cortical screw (left) and 4.5-mm Louis pedicle screw (right), both inserted to a depth of 50% of the vertebral body diameter, test 10, Table 2.

Depths were tested: (a) 50% of the vertebral body; (b) to the anterior cortex; and (c) through the anterior cortex. Tests were performed comparing two depths of insertion within the two pedicles of the same vertebra.

The medial–lateral width of the narrowest portion of the pedicle was measured both from roentgenograms of individual vertebrae in the axial plane and from computerized tomographic spine examinations in 601 pedicles. Individual disarticulated vertebra specimens obtained at autopsy and from preserved cadavers were placed directly upon a radiographic plate and roentgenograms were obtained. Measurements were then obtained directly from radiographic film. There was no detectable magnification using this technique. Direct outer
RESULTS

PULL-OUT TESTS

Failure in pull-out testing typically occurred in younger specimens by fracturing of the pedicle at the site of screw insertion, while failure in older osteoporotic specimens tended to occur without fracture of the pedicle.

RIGHT-LEFT SYMMETRY

Pairs of screws of the same design were inserted to the same depth in the right and the left pedicle of eight vertebra. The mean percent difference in pull-out force between the two pedicles of the same vertebra was 1%, ranging from −29% to 18%. This difference was not statistically significant (Table 2, test 1), showing right versus left symmetry.

EFFECT OF THREAD LOCATION WITHIN THE VERTEBRA

There was a mean increase of 77% (range, 21%–176%) seen in force required in pull-out tests of Steffee screws inserted to a depth with the cancellous threaded portion of the screw still in the pedicle, as compared with Steffee screws inserted to the anterior cortex (Table 2, test 2). The increased pull-out force of the shallower inserted screw was statistically significant (p < 0.05).

The mean pull-out force was 109% (range, 26%–152%) greater for the 6.5-mm full-

<table>
<thead>
<tr>
<th>Screw</th>
<th>Minor Diameter (mm)</th>
<th>Major Diameter (mm)</th>
<th>Thread Pitch (mm)</th>
<th>Length of Screw Threaded (mm)</th>
<th>Drill Size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steffee</td>
<td>3.0</td>
<td>6.5</td>
<td>2.75</td>
<td>32</td>
<td>3.2</td>
</tr>
<tr>
<td>6.5-mm cancellous</td>
<td>3.0</td>
<td>6.5</td>
<td>2.75</td>
<td>32</td>
<td>3.2</td>
</tr>
<tr>
<td>6.5-mm cancellous</td>
<td>3.2</td>
<td>6.5</td>
<td>2.75</td>
<td>Full length</td>
<td>3.2</td>
</tr>
<tr>
<td>4.5-mm cortical</td>
<td>3.0</td>
<td>4.5</td>
<td>1.75</td>
<td>Full length</td>
<td>3.2</td>
</tr>
<tr>
<td>4.5-mm Louis</td>
<td>3.0</td>
<td>4.5</td>
<td>2.25</td>
<td>Full length</td>
<td>2.7</td>
</tr>
<tr>
<td>Test</td>
<td>Screw Type</td>
<td>Depth of Insertion</td>
<td>Number (N)</td>
<td>Mean Pull-out Force (Newtons)</td>
<td>Standard Error (SE) of Mean Pull-out Force (Newtons)</td>
</tr>
<tr>
<td>------</td>
<td>------------</td>
<td>-------------------</td>
<td>------------</td>
<td>-----------------------------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>1.</td>
<td>constant</td>
<td>constant</td>
<td>8</td>
<td>624 (167–1156)</td>
<td>124</td>
</tr>
<tr>
<td>2.</td>
<td>Steffee 6.5 mm</td>
<td>large threads in pedicle vs. to cortex</td>
<td>7</td>
<td>518 (323–1078)</td>
<td>116</td>
</tr>
<tr>
<td>3.</td>
<td>6.5-mm cancellous threaded 32 mm vs. 6.5 mm full-threaded cancellous</td>
<td>to cortex</td>
<td>6</td>
<td>366 (167–1049)</td>
<td>137</td>
</tr>
<tr>
<td>4.</td>
<td>4.5-mm cortical</td>
<td>50% vertebral body vs. to cortex</td>
<td>6</td>
<td>725 (137–1039)</td>
<td>142</td>
</tr>
<tr>
<td>5.</td>
<td>4.5-mm cortical</td>
<td>to cortex vs. engaging cortex</td>
<td>6</td>
<td>719 (118–1793)</td>
<td>205</td>
</tr>
<tr>
<td>6.</td>
<td>6.5-mm full-threaded cancellous</td>
<td>50% vertebral body vs. to cortex</td>
<td>8</td>
<td>513 (205–725)</td>
<td>83</td>
</tr>
<tr>
<td>7.</td>
<td>6.5-mm full-threaded cancellous</td>
<td>to cortex vs. engaging cortex</td>
<td>11</td>
<td>947 (500–1676)</td>
<td>76</td>
</tr>
<tr>
<td>8.</td>
<td>4.5-mm cortical vs. 6.5-mm full-threaded cancellous</td>
<td>to cortex</td>
<td>9</td>
<td>396 (176–725)</td>
<td>63</td>
</tr>
<tr>
<td>9.</td>
<td>4.5-mm cortical vs. 6.5-mm full-threaded cancellous</td>
<td>engaging cortex</td>
<td>7</td>
<td>930 (216–2352)</td>
<td>289</td>
</tr>
<tr>
<td>10.</td>
<td>4.5-mm cortical vs. 4.5-mm Louis</td>
<td>50% vertebral body</td>
<td>8</td>
<td>561 (245–892)</td>
<td>83</td>
</tr>
<tr>
<td>11.</td>
<td>4.5-mm Louis vs. 6.5-mm full-threaded cancellous</td>
<td>50% vertebral body</td>
<td>6</td>
<td>443 (245–608)</td>
<td>55</td>
</tr>
</tbody>
</table>
threaded cancellous screw, as compared with a 6.5-mm partial-threaded cancellous screw (both screw types inserted to cortex). This increase was significant (p < 0.05, Table 2, test 3).

**EFFECT OF DEPTH OF INSERTION**

There was no significant difference (p > 0.05) between "50% depth" and "to cortex" insertions for either the 4.5-mm cortical or the 6.5-mm full-threaded screws. The mean percent change was −4% (range, −54%–50%) for the 4.5-mm cortical screw tests and 16% (range, −47%–129%) for the 6.5-mm full-threaded screw tests (Table 2, tests 4 and 6). The “through cortex” insertion were significantly stronger than the “to cortex” insertions for both the 4.5-mm cortical and 6.5-mm full-threaded screws (p < 0.05). The mean increase was 120% (range, −24%–533%) for the 4.5-mm full-threaded screw and 31% (range, −30%–101%) for the 6.5-mm cortical screw (Table 2, tests 5 and 7).

**EFFECT OF SCREW DESIGN**

The 6.5-mm full-threaded cancellous screw was significantly stronger than the 4.5-mm standard cortical screws (p = 0.05) for the “to cortex” insertion. The mean difference was 65% (range, −47%–178%) (Table 2, test 8). When using the “through cortex” insertion, there was a 32% mean increase in pull-out force in the larger screw (range, −40%–127%), but this was not statistically significant (Table 2, test 9).

The 4.5-mm Louis pedicle screw demonstrated pull-out forces on an average of 89% (range, −29%–232%) less than the 6.5-mm full-threaded screw design. This difference was statistically significant (Table 2, test 11).

Though not significant, the Louis pedicle screw withstood an average 12% (range, −42%–92%) greater pull-out force before failure when compared to the 4.5-mm cortical screw inserted to similar depths of 50% of the vertebral body (Table 2, test 10).

**METHYL METHACRYLATE AUGMENTATION**

Nonpressurized methacrylate placement restored the screws’ ability to withstand pull-out loading to within 5% (range, −64%–72%) of the original value. The mean pull-out force was 1029 N (range, 559–1441 N) without methyl methacrylate and 892 N (519–1470 N) with methyl methacrylate. This 5% difference was not statistically significant.

In contrast, pressurized methyl methacrylate caused a 96% (range, 24%–133%) increase in mean pull-out force compared to the original value. The mean pull-out was 982 N (range, 539–1372) for the original and 1933 N (1097–2793 N) for the pressurized methacrylate group. This difference was statistically significant (p < 0.05, Table 3).

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**TABLE 3. Methyl Methacrylate Augmentation**

<table>
<thead>
<tr>
<th>N</th>
<th>Mean and Range Pull-out Force (Newtons)</th>
<th>SE Mean Pull-out Force (Newtons)</th>
<th>Mean and Range % Difference</th>
<th>SE Mean % Difference</th>
<th>P Value</th>
<th>0.05 or Less</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>1029 (559–1441)</td>
<td>135.0</td>
<td>127.4</td>
<td>−5 (−64–72)</td>
<td>17</td>
<td>*</td>
</tr>
<tr>
<td>5</td>
<td>982 (539–1372)</td>
<td>139.5</td>
<td>356.3</td>
<td>96 (24–133)</td>
<td>19</td>
<td>*</td>
</tr>
</tbody>
</table>

vs. 2 cm

methacrylate augmentation

vs. 2 cm

pressurized methacrylate augmentation
TABLE 4. Sacral Pull-out Tests

<table>
<thead>
<tr>
<th>Location of Screw Insertion</th>
<th>N</th>
<th>Mean Pull-out Force (Newtons)</th>
<th>Range (Newtons)</th>
<th>SE Mean Pull-out Force (Newtons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ala 0°</td>
<td>10</td>
<td>668</td>
<td>421-1166</td>
<td>86</td>
</tr>
<tr>
<td>Ala 45° lateral</td>
<td>13</td>
<td>1007</td>
<td>510-1646</td>
<td>95</td>
</tr>
<tr>
<td>S1 pedicle</td>
<td>13</td>
<td>185</td>
<td>78-519</td>
<td>33</td>
</tr>
<tr>
<td>S2 pedicle</td>
<td>12</td>
<td>870</td>
<td>363-1764</td>
<td>117</td>
</tr>
</tbody>
</table>

SACRAL FIXATION

The weakest sacral insertion site was the S2 pedicle; mean pull-out was 185 N (Table 4, range, 78–519 N) (Fig. 3). The next weakest location was the sacral ala inserted straight anteriorly; the mean pull-out force was 668 N (range, 421–1166 N). The S1 pedicle site failed at an average of 870 N (range, 363–1764 N). The 45° placement into the ala was the strongest with mean pull-out values of 1007 N (range, 510–1646 N). These high pull-out values were seen when screws were inserted laterally at 45° in the sacral ala in either the cephalad or caudal sites of insertion (Table 5). The S2 pedicle site was significantly weaker than any of the other sacral placement sites (Table 4).

The two angles of alar screw insertion were also significantly different from each other (Table 4).

CYCLIC LOADING

In medial–lateral cyclic loading, screws inserted “to cortex” required a 91% (2%–153%) mean increase in cycles to cause screw loosening, as compared with those screws inserted anteriorly to a “50% depth.” This increase was statistically significant (p < 0.05) (Table 6).

For cephalad–caudad loading a 1044% increase in cycles was needed to loosen those screws inserted “to cortex,” compared with those inserted to only a 50% depth. The increased number of cycles required to loosen the deeper-inserted screws was statistically significant to p < 0.05 (Table 5).

Comparisons of cyclic loading in the cephalad-caudal direction of screws inserted anteriorly securely engaging the anterior cortex and screws inserted just to the anterior cortex demonstrated a 194% (range, 49%–328%) increase in cycles to loosen the more-deeply inserted screws purchasing the anterior cortical vertebral bone (Table 6). The increased number of cycles was again statistically significant (p < 0.05, Table 6).

PEDICLE SIZE

The narrowest dimension of the pedicle isthmus is in the transverse plane. The average width in this plane was noted to range from 18 mm in the L3 vertebra to 4.5 mm in the fifth thoracic vertebra. The width then increased again in more cephalad vertebral levels averaging 7.9 at T1 (Table 7 and Fig. 4).

DISCUSSION

Insertion of screws into the spine to obtain stability is not a recent development. Multiple authors have described screw fixation of the facets and pedicles to aid in obtaining solid

TABLE 5. Lateral Alar Pull-out Tests

<table>
<thead>
<tr>
<th>Location of Laterally-inserted Screw</th>
<th>N</th>
<th>Mean Pull-out Force (Newtons)</th>
<th>Range Pull-out Force (Newtons)</th>
<th>SE Mean Pull-out Force (Newtons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1 pedicle level</td>
<td>6</td>
<td>906</td>
<td>510-1578</td>
<td>144</td>
</tr>
<tr>
<td>S2 pedicle level</td>
<td>7</td>
<td>1039</td>
<td>608-1646</td>
<td>134</td>
</tr>
</tbody>
</table>
fusion in single or multiple levels. Many authors have described extensive clinical experience with intrapeduncular spine stabilization with posterior fixation devices. All of these designs ultimately depend upon the quality of purchase obtained by threads in the pedicle and vertebral body.

Although many studies have addressed the biomechanical properties of bone screws in cortical bone, little laboratory data are available concerning the multiple factors that may contribute to screw purchase in the vertebral pedicles. Lavaste tested multiple screw designs, while Krag et al. tested varied pitch, minor diameter, and major diameter in 6-mm and 7-mm screws. Currently, multiple screw sizes and thread designs are being used clinically. In this study the authors have attempted to evaluate some of the factors contributing to screw purchase in the pedicles and vertebra, using currently-available screw designs and a 6.5-mm cancellous screw threaded throughout its full length.

To compensate for tremendous individual

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**TABLE 6.**

<table>
<thead>
<tr>
<th>Direction of Loading</th>
<th>N</th>
<th>Depth of Insertion</th>
<th>Mean and Range Number of Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medial/Lateral</td>
<td>6</td>
<td>50% of vertebral body vs. to cortex</td>
<td>165 (64–422)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>312 (162–891)</td>
</tr>
<tr>
<td>Cephalad/Caudad</td>
<td>7</td>
<td>50% of vertebral body vs. to cortex</td>
<td>134 (35–422)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>709 (252–1395)</td>
</tr>
<tr>
<td>Cephalad/Caudad</td>
<td>6</td>
<td>to cortex vs. through anterior cortex</td>
<td>434 (217–621)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1308 (576–2659)</td>
</tr>
</tbody>
</table>

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**FIG. 3.** Pull-out values for screws inserted into the sacrum. Forty-five degree lateral data represent combined values for screws aimed lateral from the level of the first sacral facet and from between the first and second dorsal sacral foramen.
Cyclic Loading

<table>
<thead>
<tr>
<th>SE Mean Number Cycles</th>
<th>Average % Difference</th>
<th>SE Mean % Difference</th>
<th>P Value 0.05 or Less</th>
</tr>
</thead>
<tbody>
<tr>
<td>53.3</td>
<td>91 (2-153)</td>
<td>21</td>
<td>*</td>
</tr>
<tr>
<td>116.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>52.4</td>
<td>1044 (111-3886)</td>
<td>516</td>
<td>*</td>
</tr>
<tr>
<td>152.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>57.8</td>
<td>194 (49-328)</td>
<td>43</td>
<td>*</td>
</tr>
<tr>
<td>314.6</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Variation of bone quality, comparisons were performed within opposite pedicles of the same vertebra. This large variation is evident by comparing different tests incorporating the same screw inserted in a similar manner. Testing was performed as specimens became available and often similar tests were performed upon vertebra from the same spine specimen. Large interspecimen variation can be attributed in part to the large difference encountered in bone quality among different specimens. Intraspecimen comparisons demonstrated that there were no overall average significant difference between pull-out forces of similar screws inserted in a similar manner in either the right or the left pedicles of the same vertebra.

Though very difficult to quantitate, the factor that appeared to play the largest role in determining the ability of a screw inserted into the pedicle to resist loosening was the bone quality of the specimen tested. Early in the experiment attempts were made to quantitate the bone density and correlate it to pull-out testing by using data obtained from computerized tomographically-scanned specimens. Standardization was difficult and no consistent trend could be found. A computed tomographic (CT) phantom was not available during this time. With the further refinement of

**TABLE 7. Transverse Pedicle Isthmus Width**

<table>
<thead>
<tr>
<th>Level</th>
<th>Number of Pedicles</th>
<th>Mean Width (mm)</th>
<th>Range (mm)</th>
<th>Standard Deviation</th>
<th>SE</th>
<th>% Less Than 6.5 mm</th>
<th>% Less Than 4.5 mm</th>
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<tr>
<td>L-5</td>
<td>56</td>
<td>18.0</td>
<td>9.1-29.0</td>
<td>4.1</td>
<td>0.5</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>L-4</td>
<td>36</td>
<td>12.9</td>
<td>9.1-17.0</td>
<td>2.1</td>
<td>0.4</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>L-3</td>
<td>49</td>
<td>10.3</td>
<td>5.3-16.0</td>
<td>2.6</td>
<td>0.4</td>
<td>12.2</td>
<td>6.6</td>
</tr>
<tr>
<td>L-2</td>
<td>30</td>
<td>8.9</td>
<td>4.0-13.0</td>
<td>2.2</td>
<td>0.4</td>
<td>16.5</td>
<td>6.6</td>
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(CT) scanning techniques, such as the use of the Genant Phantom and other noninvasive bone density measuring techniques, this correlation may become possible in the future. If bone density could be correlated to pull-out force values, an idea of the quality of pedicle screw fixation to be expected could be obtained preoperatively.

Partially-threaded screw designs obtained better vertebral purchase if the larger-threaded segment of the screw was in the pedicle. The vertebral pedicle offers much more solid bony material for thread purchase than does the cancellous center of an osteoporotic vertebral body. In each comparison of the partial threaded screw designs the screws inserted with the larger threads in the pedicle were significantly more resistant to pull-out failure than their more deeply inserted counterparts. When partial- and full-threaded screws were compared, the full-threaded screws purchasing the bone within the pedicle had significantly larger pull-out values.

When the question of optimal depth of screw insertion was addressed in both the 6.5-mm full-threaded cancellous and the 4.5-mm cortical screws, no difference was seen in pull-out force between similar size screws inserted to a 50% depth versus to anterior cortex. This was attributed to the fact that this specimen group was of advanced age and most demonstrated extreme degrees of osteoporosis. Deeper insertion into markedly poor-quality vertebral body bone did not appear to contribute to screw-holding ability unless the anterior vertebral cortex was penetrated. This deeper insertion into the vertebral body would be expected to contribute more in younger individuals. As expected, this observation was seen in the few younger specimens encountered. Purchase of the anterior vertebral cortex had a significant advantage in all group comparisons regardless of screw used. This finding was in contrast to that of Lavaste who found no significant difference in pull-out force by engaging the anterior vertebral cortex.15 This
difference could in part be attributed to a difference in specimen age and screw designs tested.

The difference between 4.5-mm cortical and 6.5-mm full-threaded cancellous screws varied according to the depth to which the screws were inserted. If the screws were inserted "to cortex," the larger, 6.5-mm screw obtained significantly better purchase in the cancellous bone of the vertebral body. If both screws were placed "through anterior cortex," the larger screw required an average of 32% more force to cause failure. This difference was not of statistical significance.

The 4.5-mm Louis pedicle screw was found to be only insignificantly stronger than the 4.5-mm cortical screw. The 6.5-mm full-threaded cancellous screw was significantly superior to the smaller Louis screw in pull-out testing. In this study the larger diameter 6.5-mm full-threaded cancellous screw was superior to both smaller 4.5-mm diameter screws tested. This observation was consistent with that of other studies testing pull-out in cortical bone. Comparisons of different thread designs between the 4.5-mm cortical and 4.5-mm Louis screws failed to demonstrate a significant difference in pull-out strength. This observation was similar to that of Lavaste and Krag. Methyl methacrylate has long been used to reinforce screw fixation in poor-quality bone either because of tumor or osteoporosis. Two cubic centimeters of methyl methacrylate was found to restore the pull-out force to very close to that of the original test. If cement was inserted under pressure, pull-out force was almost doubled. With pressurization the cement was noted to mushroom underneath the pedicle. The resultant configuration was not unlike that of a toggle bolt inserted into dry wall. Screws could be removed by unscrewing them from the methacrylate. Removal of the methacrylate required extensive destruction of either the vertebral body if removed anteriorly or the pedicle if removed posteriorly.

Obtaining consistent fusion to the sacrum has long been a problem. The reported high incidence of pseudoarthrosis and poor purchase of the sacrum have stimulated the development of newer instrumentation devices and surgical techniques. To identify satisfactory location for screw fixation of the sacrum, multiple pull-out tests were performed. Due to lack of complete sacral segments in specimens obtained for the study, left and right comparisons could not be performed.

Screws inserted into the second sacral pedicle engaging the anterior cortex had the lowest average pull-out force of all other locations tested in the sacrum. Screws aimed laterally into the ala at an angle of 45° demonstrated the highest average pullout. The 45° alar group required significantly more force to cause failure than did screws inserted directly anterior with no angulation into the sacral ala engaging the anterior cortex. By aiming screws laterally, problems of screw penetration and injury to neural, vascular, and visceral structures are avoided, as the screw does not exit bone. Consistently good purchase was noted even in laterally-aimed screws inserted in a more caudal location at the level of the second sacral pedicle. The possibility of and the resultant effect of crossing the sacroiliac joint may be of some concern, but was not addressed in this study.

The loads imparted to intrapeduncular screws are certainly not all along the longitudinal axis of the screw. Screws inserted into the pedicles at the end of a fusion will be subjected to rotational and bending moments. To determine the effect of depth of penetration upon forces exerted on screws in directions other than axial pullout, screws were cycled in a medial-lateral and cephalad-caudad direction. The testing end-point was chosen to be a 50% decrease in the force required to rock the screw through a constant arc, from the force encountered in the first cycle. These criteria were chosen because the testing equipment was only capable of operating in "displacement-defined mode and cycles greater than those required to reach the 50% point often caused loosening of the specimen-methacrylate embedding (despite multiple attempted variations in imbedding techniques).

The more deeply-inserted screws required more cycles to loosen in every specimen tested.
regardless of the direction of load. In tests where screws penetrated into the anterior cortex, the number of cycles needed to reach the testing end point were the greatest. This technique did not lend itself to testing screws inserted to the anterior cortex cycled in the medial-lateral direction. In this configuration the fixation was so strong that the 6-mm displacement resulted in pedicle fracture, screw bending, and/or specimen loosening in the embedding methacrylate within the first few cycles.

If the screw was inserted only to a depth of 50% of the vertebral body diameter or up to but not engaging the anterior cortex, cyclic toggling in either direction caused a "teeter-totter" motion with the fulcrum or axis of rotation located in the pedicle. The distal tip of the more deeply-inserted screws in the vertebral body had a larger arc of motion than did the shallower-inserted screws, and required more bony material to be displaced as the screw was cycled. If anterior vertebral body cortex purchase was obtained with the distal tip of the screw, the axis of rotation was noted to shift more distally to the tip of the screw and a "windshield-wiper-like" motion was seen. There was no loss of anterior cortical screw purchase noted in the six specimens tested in this manner. The pedicle is oval shaped in cross section and is large enough to accommodate this "windshield-wiper" motion in the cephalad-caudal direction, but not in the medial-lateral direction where the pedicle is much narrower. Attempts at cyclic loading of screws inserted through the anterior cortex in the medial-lateral direction resulted in pedicle fracture, screw bending, and/or specimen loosening from embedding media in the testing frame within the first few cycles. In all of the cyclic tests represented in Table 4, no pedicle fracturing or thread erosion through the pedicle was observed.

The data presented in this experiment demonstrate that placement of the screw through anterior cortex results in the strongest screw purchase in either axial pull-out or cyclic loading. However, a large amount of clinical data suggest that this may not be necessary on a routine basis and that the added risk to anterior vital structures is not warranted.5,11,18,19,22,23,29,32,36,39

Using roentgenograms of individual vertebra, the outer pedicle cortex could be easily identified and measurements could be accurately obtained directly from the film. The soft tissue was not a factor interfering with measurements as it was noted to be in performing direct specimen measurements. Measurements obtained directly through the scanner software eliminated any error encountered by measuring reduced images from roentgenographic film and calculating magnification. The narrowest dimension of the pedicle in the thoracolumbar spine limiting the diameter of screws inserted is in the medial-lateral direction. This width is largest in the lumbar spine at L5 and progressively narrows in more cephalad levels. In the midthoracic spine the width then begins to progressively increase again to the first thoracic vertebra. (Fig. 4 and Table 7). The authors' data agree well with that of Saillant, who reported only average values.33 Included in the authors' data, which will be presented in more detail elsewhere,45 are ranges of pedicle sizes encountered. Similar values and ranges were observed by Krag et al.13,14 Multiple pedicles were found during the course of this study that had smaller outer cortical diameters than either the 6.5-mm or 4.5-mm screws (Table 7). Consideration must be given to pedicle dimension prior to attempting screw insertion. The pedicles are seen to slant laterally approximately 30° in the fifth lumbar vertebra and gradually return to a neutral inclination in the upper lumbar and lower thoracic levels.14,32,42 More cephalad, their angulation is essentially neutral with a slight medial inclination. In the laboratory the authors found that oversized screws expanded the pedicle by fracturing the bone of the lateral wall of the pedicle more frequently than the medial wall. If the screw was angled too far medial during insertion the threads were seen to fracture or cut through the medial wall of the pedicle at a point just posterior to where it joins the vertebral body.
In summary, in this laboratory experiment screws of various design were inserted into vertebral specimens through the pedicle. Biomechanical testing was then performed using pull-out and cyclic load testing. The degree of osteoporosis, though very difficult to quantify, was the factor that appeared to have the greatest effect upon screw fixation. Testing of partial-threaded screw designs demonstrated that the strongest fixation was obtained if threads purchased within the pedicle or if screws were threaded throughout their full length. Screws inserted through the anterior cortex were stronger than were screws inserted to 50% of the vertebral body or to the anterior cortex. The larger-diameter screw was stronger than either small-diameter screw designs tested. Methyl methacrylate restored pull-out strength in screws previously pulled to failure and pressurization doubled the original pull-out value. The S2 pedicle demonstrated the worst pull-out strengths in the sacrum, and screws angled 45° laterally into the sacral ala, and medially into the first pedicle, were stronger than screws directed straight anteriorly into the ala. Deeper-inserted screws withstood the greatest number of cycles before screw loosening occurred.

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REFERENCES


