Biomechanical evaluation of the ventral and lateral surface shear strain distributions in central compared with dorsolateral placement of cages for lumbar interbody fusion

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Object. The purpose of this study was to measure and compare the ventral and lateral surface strain distributions and stiffness for two types of interbody cage placement: 1) central placement for anterior lumbar interbody fusion (ALIF); and 2) dorsolateral placement for extraforaminal lumbar interbody fusion (ELIF).

Methods. Two functional spine units were obtained for testing in each of 13 cadaveric spines, yielding 26 segments (three of which were not used because of bone abnormalities). Bilateral strain gauges were mounted adjacent to the endplate on the lateral and ventral walls of each vertebral body in the 23 motion segments. Each segment was cyclically tested in compression, flexion, and extension in the following conditions: while intact, postdiscectomy, and instrumented with interbody fusion cages placed using both insertion techniques.

No significant differences were observed between ALIF and ELIF in compressive stiffness, bending stiffness in flexion and extension (p ≥ 0.1), ventral and lateral strain distribution during the intact tests (p ≥ 0.24), and during the flexion tests after fusion (p ≥ 0.22). In compression, higher ventral and lower lateral strain was observed in the ALIF than in the ELIF group (ventral, p = 0.05; lateral, p = 0.04), and in extension, higher ventral (p = 0.01) and higher lateral strain (p = 0.002) was observed in the ELIF than in the ALIF group.

Conclusions. Preservation of the ventral anulus and dorsolateral placement of the interbody cages during ELIF allow alternate load transfer pathways through the dorsolateral vertebral wall and ventral anulus that are not observed following ALIF. These may be associated with a lower incidence of subsidence and a higher rate of fusion due to a more concentrated application of bone healing–enhancing compression forces during the fusion and healing process.

Key Words • biomechanical testing • strain gauge • stiffness • lumbar interbody fusion • interbody implant positioning

Lumbar interbody fusion is used to provide support for the ventral spinal column. Providing this support with an interbody implant increases the chance of bone fusion. Even though many interbody devices have been developed to achieve successful fusion, each design leads to different load transfer patterns. Subsidence, one of the major complications associated with lumbar interbody fusion, occurs when stresses at the bone–implant interface exceed the strength of the bone because of a modulus mismatch between the fusion device and the vertebrae, irregular endplate geometry, poor endplate preparation techniques, and low BMD.

Autologous bone grafts may fail when their strength is reduced following graft resorption. Even though interbody fusion devices may provide superior mechanical stability compared with stand-alone autologous iliac bone, subsidence into the adjacent VB remains a very important factor that is associated with failure. The modulus of elasticity of the implant and the surface area of contact are two of the most important contributing factors. Stiff implants with a higher modulus than bone tend to subside more, whereas less stiff implants, such as carbon fiber–reinforced cages and femoral ring allografts, are associated with less subsidence.

Regional geometry and endplate preparation techniques have been shown to affect subsidence. Hollowell and colleagues described a minimal mechanical advantage in preserving the vertebral endplate in ventral column reconstructions, whereas Lim and associates emphasized the importance of preserving vertebral bone endplate for the prevention of subsidence. The portion of the endplate ad-

Abbreviations used in this paper: ALIF = anterior lumbar interbody fusion; ALL = anterior longitudinal ligament; BMD = bone mineral density; ELIF = extraforaminal lumbar interbody fusion; SEM = standard error of the mean; VB = vertebral body.
jacent to the vertebral shell has been shown to be stronger, with a higher modulus of elasticity. This may mean that the peripheral portion of the endplate is stiffer than the central one.\textsuperscript{1,5,10,23}

Interbody fusion devices provide mechanical stability and a means of load transfer. Bone geometry and surgical technique can alter transfer of the axial load from the periphery to the center of the vertebral endplate. With central placement of an interbody device, the greatest stress is transferred through the center of the ventral body, and with eccentric placement of the device, the stress is transferred through the periphery of the endplate. Such factors may significantly affect outcome.

Ventralateral vertebral surface strain distribution and segment stiffness depend on the configuration and geometry of devices used during interbody fusion. The goal of this study was to compare ventral and lateral strain distribution and segment stiffness with two different methods of cage insertion: ALIF with centrally placed cages and ELIF with peripherally placed cages.

Materials and Methods

This study was conducted in accordance with the Cleveland Clinic Foundation policy of research ethics and did not involve animals or live humans.

Specimen Preparation

Twenty-three motion segments removed from 13 human cadaveric spines were used for biomechanical testing (three motion segments were eliminated from the study because of bone abnormalities). The BMD was measured using a dual-energy x-ray absorptiometry scanner (model QDR 4500A; Hologic, Waltham, MA). Each lumbar spine was divided into two functional units (L2–3 and L4–5), which were disarticulated from the rest of the lumbar spine, leaving the intervertebral discs and the ligaments intact. Each functional spine unit was wrapped in saline-soaked gauze and then stored at $-20^\circ$C in a plastic bag.

Strain Gauge Preparation

On the day before biomechanical testing, each specimen was thawed. The ventralateral vertebral walls were prepared for strain gauge placement by using a procedure developed from previously described methods.\textsuperscript{2,3,6,16,25} The surface preparation of the ventral and lateral cortices of the vertebral bodies involved sanding with 220-grit sandpaper, surface cleaning with swabs soaked in ethyl ether (Fisher Scientific, Pittsburgh, PA) followed by ethanol (LabChem, Inc., Pittsburgh, PA), and final treatment with a neutralizer (M-Prep Neutralizer 5A; Micro-Measurements Group, Inc., Raleigh, NC). These four steps in succession were repeated three times. After air-drying the surfaces, the rectangular gauges (FAER-6B-35-S6EL; BLH Electronics, Inc., Canton, MA) were applied bilaterally on the lateral walls, and T-rosette gauges (FAET-12B-35-S6EL; BLH Electronics, Inc.) were applied on the ventral walls in each specimen (L2–3 and L4–5) by using cyanoacrylate (Krazy Glue; Elmer’s Products, Inc., Columbus, OH).

Lead wires were attached to the gauges by using three lead wire methods to reduce measurement errors. Wax insulation was applied to the solder joint connections between the strain gauge wires to avoid short circuits. The main lead wires were then connected to the signal conditioning equipment and were embedded into the polyester resin for strain relief. The lead wires from the strain gauges were connected to strain gauge cards (model 5110; Micro-Measurements Group, Inc.) in a scanner (model 5100 A; Micro-Measurements Group, Inc.). The strain gauge cards were connected by a peripheral connect interface card to a personal computer (PC-Dell Dimension 4300 PIV; Dell, Round Rock, TX).

Fixtures and Materials Testing Machine

The gripping aluminum fixtures had rotating potentiometers for angular measurements. Linear compression was measured by the displacement transducers in the materials testing machine. The potentiometers were connected through lead wires to high-level input transducer cards (model 5130 A; Micro-Measurements Group, Inc.) that were located in the scanner. The transducer cards used the same connection through the peripheral connect interface card to the personal computer. The computer was used to collect data with Strain-Smart software (Version 2.23; Micro-Measurements Group, Inc.). The data were exported into Microsoft Excel (Microsoft Office 2000; Microsoft Corp., Redmond, WA), and after processing they were then exported into the SPSS system for Windows (Version 12.0; SPSS, Inc., Chicago, IL). The materials testing machine (Alliance RT 10, S/N M2280/102099; MTS Systems Corp., Eden Prairie, MN) was used to collect data with the TestWorks software (Version 4.07; MTS Systems Corp.), and the data were exported into Microsoft Excel. After processing, the data were then exported into the SPSS system for Windows (Version 12.0; SPSS, Inc.).

Specimen Embedding

The vertebrae at the ends of the segments (L-2 and L-4 [rostral], L-3 and L-5 [caudal]) were partially embedded in polyester resin (Bondo Mar-Hyde Corp., Atlanta, GA). These polyester resin blocks were then gripped with the custom-made gripping aluminum fixtures in the materials testing machine. The functional spine units were randomly assigned to either an ALIF or ELIF procedure. The specimens were tested in three different stages: intact, after discectomy, and after insertion of the different cage configurations (either ALIF [central, 11 specimens] or ELIF [peripheral, 12 specimens]).

Biomechanical Testing

The specimens were centered by applying a 100-N load and by displacing the specimen in the sagittal plane until the least deflection was measured by the angular potentiometers. For future reference, two points were made with an indelible marker, one on the fixture and the other on the specimen, to allow the specimen to be accurately aligned when it was again placed in the fixtures.

Mechanical testing was performed using a standard loading protocol. The segments were cyclically tested for six cycles in each of the following modes in both the intact and fused states: compression (0–500 N), flexion, and extension (0–5 Nm for these two modes). We sampled strain excursion (maximum – minimum) and stiffness from the sixth cycle. Flexion was created by shifting the load application point 2 cm ventral to the center of rotation, whereas extension was created by shifting the load application point 2 cm dorsal to the center of rotation. The results from the first series of tests were designated intact measurements. After discectomy and endplate preparation, either ALIF (central cage insertion) or ELIF (dorsolateral/peripheral cage insertion) was performed, followed by the standard loading protocol measurements, yielding ALIF and ELIF values. Data for all the tests were sampled at 50 Hz.

Surgical Preparation and Methods of Cage Insertion

Jaguar lumbar interbody fusion carbon fiber–reinforced cages (DePuy Spine, Inc., Raynham, MA) were used in both ALIF and ELIF procedures.

The ALIF Procedure for Central Placement of Cages

The ventral aspect of the anulus fibrosus of the disc was removed sufficiently to insert carbon fiber–reinforced cages after discectomy on the potted specimens. The cartilaginous endplate was completely removed, manual distraction was applied to the polyester resin blocks to open the interbody space, and two cages were placed appropriately in the central portion of interbody space (Fig. 1 left) through the anterior anular window. Care was taken to avoid injuring the osseous endplate during the surgical procedure.

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Comparison of central and dorsolateral lumbar cage placements

The ELIF Procedure for Dorsolateral, Eccentric Cage Placement

An intertransverse, extraforaminal discectomy was performed bilaterally, without violation of the facet joints on the potted specimens. The dorsolateral aspect of the anulus fibrosus was excised to facilitate placement of each cage into the disc space on each side (Fig. 1 center) through the space in the axilla of the laterally retracted nerve root (Fig. 1 right). The cartilaginous endplate was completely excised, taking care not to disrupt the osseous endplate, and manual distraction of the interbody space was performed by repositioning the polyester resin blocks, allowing each cage to be placed appropriately in the lateral portion of interbody space through the extraforaminal windows.

Data Management

Stiffness was defined as the steepest slope of the load compared with the displacement curve generated for all the testing cycles in compression. The bending stiffness was defined as the steepest slope of the moment compared with the angular displacement curve for testing in flexion and extension. Shear strain data were collected using StrainSmart software (Version 2.23; Micro-Measurements Group, Inc.). The excursion in strain was sampled from the sixth cycle of the cyclic tests and from the only cycle of the failure tests. Similarly, stiffness was sampled from the sixth cycle of the cyclic tests (see Biomechanical Testing for standard loading protocol).

Statistical Analysis

Using multivariate analysis, stiffness and strain were compared in the ALIF and ELIF groups of specimens. The significance level was set at 0.05; with least significant difference post hoc tests.

Results

The demographic features of the specimens tested are shown in Table 1. Of the 13 spines tested in each group, seven were from male and six from female cadavers. The mean age of the donors was 67.9 ± 14.6 years (T-score 0.22). Figure 1 shows the differences in strain distribution postfusion. A higher ventral strain was observed in the ALIF than in the ELIF group in compression (ventral, p = 0.05; lateral, p = 0.04). In extension there was higher ventral (p = 0.01) and higher lateral strain (p = 0.002) in the ELIF than in the ALIF group.

Discussion

Our study did not demonstrate a difference in stiffness between the two groups of specimens. Instead, it showed differences in the regional distribution of ventral and lateral strain in compression and extension. The fact that stiffness was not altered, but that the strain distribution was, implies a theoretical physiological bone healing-enhancing effect associated with lateral and peripheral cage placement used in the ELIF technique. In contradistinction to the ELIF procedure, during ALIF, the ALL and ventral anulus are excised. With an intact ALL and ventral anulus, and a peripheral location of interbody cage placement, a greater distribution of ventral strain was observed in extension in the ELIF group. This is partly due to the transmission of the tensile load through the ALL and ventral anulus to the adjacent vertebrae. The tension band effect on the interbody implant placed dorsolaterally in the ELIF group also contributed to the wide and nonfocal lateral strain distribution. Finally, a central cage/fusion mass transmits the load centrally, thus increasing the pressure within the cancellous bone. This pressure change, in turn, distorts the VB wall, thus altering the VB’s strain response to loading.

The mapping of the structural properties of the lumbo-sacral endplate has demonstrated greater stiffness and strength in the dorsolateral than in the central regions of...
Cage placement in the dorsolateral regions, therefore, has the advantage of minimizing subsidence relative to that expected with central cage placement. Finite element analysis has shown that endplate stresses are dependent on the surface area of the implant–bone graft; the larger the surface area, the smaller the endplate stresses. Closkey and associates found that bone grafts covering more than 30% of the endplate area were able to carry significantly greater loads. In this study, the comparison between the two groups involved similar carbon fiber implants that effectively controlled for the effect of surface area.

Frei and coworkers demonstrated the importance of the disc nucleus in central load transfer. With nucleotomy, load transfer from endplate to endplate was reduced in compression, but peripheral transfer along the vertebral rims was not. The anulus was mainly responsible for transmitting shear forces to the adjacent vertebrae. In our study, higher ventral shear strains were transmitted through the ALL and ventral anulus in the ELIF group than in the ALIF group. This is due to the resection of the ALL and ventral anulus in the ALIF group and the peripheral location of the cages in the ELIF group. These results illustrate the differences between the two procedures with respect to load transfer. The additional locations of load transfer associated with the ELIF technique allow less stress to be placed on the implant–bone interface, with an associated diminished likelihood of subsidence. Palm, et al. using finite element analysis, studied the stress distribution on interbody implants and showed that long-term success of fusion was dependent on load transfer within the physiological limits of the implant–bone interface, an effect labeled “effective load transfer.” The fact that ELIF spares the ventral elements implies that the load transfer mechanism is more physiological in this procedure than that following ALIF. Hollowell and colleagues tested various implants against each other and found that there was no significant difference in stiffness and strength of the implant–bone interface. In the current study, in which one type of implant was used, the position of the device and tissue removal (anulectomy) determined the effectiveness of load transfer.

Various biomechanical studies of implants in the lumbar spine have consistently shown that the most arduous tests of the constructs are in torsion (axial rotation) and extension. In a biomechanical study of implants placed via a ventral approach, Nibu and associates demonstrated a significant reduction in stiffness, with the spine in extension, from the loss of the ventral anulus and ALL. Although there was no significant difference in stiffness between the two groups with the spine in extension, there were higher strain distributions ventrally (the effect of the ventral anulus and ALL) and laterally (stiffer dorsolateral region) in the ELIF group. The presence of alternative load distribution pathways results in placement of

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Age (yrs)</th>
<th>Sex</th>
<th>Cause of Death</th>
<th>T-Score</th>
<th>BMD (g/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>52, F</td>
<td>CHF</td>
<td>congestive heart failure</td>
<td>−2.10</td>
<td>0.81</td>
</tr>
<tr>
<td>2</td>
<td>53, F</td>
<td>unknown</td>
<td></td>
<td>−2.40</td>
<td>0.83</td>
</tr>
<tr>
<td>3</td>
<td>70, F</td>
<td>renal failure</td>
<td></td>
<td>−1.85</td>
<td>0.94</td>
</tr>
<tr>
<td>4</td>
<td>83, F</td>
<td>hypertension, heart disease</td>
<td></td>
<td>−2.03</td>
<td>0.82</td>
</tr>
<tr>
<td>5</td>
<td>89, F</td>
<td>sepsis</td>
<td></td>
<td>−2.30</td>
<td>0.78</td>
</tr>
<tr>
<td>6</td>
<td>97, F</td>
<td>acute MI</td>
<td></td>
<td>−4.13</td>
<td>0.58</td>
</tr>
<tr>
<td>7</td>
<td>49, M</td>
<td>lung cancer</td>
<td></td>
<td>−3.35</td>
<td>0.74</td>
</tr>
<tr>
<td>8</td>
<td>55, M</td>
<td>cardiogenic shock</td>
<td></td>
<td>−1.55</td>
<td>0.95</td>
</tr>
<tr>
<td>9</td>
<td>65, M</td>
<td>acute MI</td>
<td></td>
<td>0.55</td>
<td>1.19</td>
</tr>
<tr>
<td>10</td>
<td>66, M</td>
<td>acute GI hemorrhage</td>
<td></td>
<td>0.25</td>
<td>1.13</td>
</tr>
<tr>
<td>11</td>
<td>67, M</td>
<td>Alzheimer dementia</td>
<td></td>
<td>−2.68</td>
<td>0.83</td>
</tr>
<tr>
<td>12</td>
<td>67, M</td>
<td>renal failure</td>
<td></td>
<td>−1.03</td>
<td>1.01</td>
</tr>
<tr>
<td>13</td>
<td>70, M</td>
<td>CHF</td>
<td></td>
<td>−1.50</td>
<td>0.96</td>
</tr>
</tbody>
</table>

* CHF = congestive heart failure; GI = gastrointestinal; MI = myocardial infarction.
diminished loads on the less stiff and weaker central regions of the endplate. This probably results in less subsidence, which is one of the major complications of ALIF.

Limitations of the Study

This study involved analysis of ventrolateral strains and did not consider dorsal strain. It is possible that the changes in dorsal strain make up for the observed differences in ventral and lateral strains. Although possible, this is unlikely; dorsal strain tends to be much less than ventral and lateral ones, because the anterior column bears greater loads. Strain gauge studies of the distribution of strain on thoracolumbar vertebrae have previously demonstrated this fact.13,22 The major disadvantage associated with measurement of dorsal strain is the associated partial or full resection of the dorsal elements that is required by strain gauge application. Thus, the native strain distribution would be artificially altered, and that is why dorsal strain was not assessed in this study.

In this study we did not use instrumentation to augment the simulated fusion. Instrumentation placed across the fusion shares the load and therefore alters the load distribution pattern through the interbody implant.

Knowledge of cage strain under the conditions of this study could further illuminate the issues involved. Applying strain gauges and calibrating them to known loads allows the cages to serve as miniature load cells. This, however, poses technical problems related to the difficulties associated with attaching strain gauges to carbon fiber–reinforced cages by using miniature solder connections. Such an analysis may be the topic of future studies.

This study involved the use of L2–3 and L4–5 motion segments. Using the ELIF technique approach at the L5–S1 interbody space is very difficult without resection of the sacral ala. In addition, damage to the exiting nerve root is likely to occur with this approach. For this reason, the study was limited to motion segments that are amenable to both ELIF and ALIF.

Conclusions

Preservation of the ventral anulus and a lateral placement of the cages produce higher ventral and lateral vertebral strains in extension. This more physiological redistribution of load transfer pathways through the dorsolateral vertebral wall and ventral anulus associated with ELIF are not observed with ALIF. This may result in a lower rate of subsidence and a more physiologically favorable load distribution.

Disclosure

The carbon fiber–reinforced cages were donated by DePuy Spine, Inc., Raynham, MA. No other financial support was received from this company.

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