Journal of Clinical Neuroscience 21 (2014) 1632–1636

Contents lists available at ScienceDirect

Journal of Clinical Neuroscience

journal homepage: www.elsevier.com/locate/jocn

Laboratory studies

Corpectomy cage subsidence with rectangular *versus* round endcaps

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ARTICLE INFO

Article history:
Received 5 December 2013
Accepted 13 December 2013

Keywords:
Complication avoidance
Corpectomy
Expandable cage
Lateral approach
Minimally invasive
Rectangular endcap
Subsidence

ABSTRACT

Corpectomy cages with rectangular endcaps utilize the stronger peripheral part of the endplate, potentially decreasing subsidence risk. The authors evaluated cage subsidence during cyclic biomechanical testing, comparing rectangular *versus* round endcaps. Fourteen cadaveric spinal segments (T12–L2) were dissected and potted at T12 and L2, then assigned to a rectangular (n = 7) or round (n = 7) endcap group. An L1 corpectomy was performed and under uniform conditions a cage/plate construct was cyclically tested in a servo-hydraulic frame with increasing load magnitude. Testing was terminated if the test machine actuator displacement exceeded 6 mm, or the specimen completed cyclic loading at 2400 N. Number of cycles, compressive force and force-cycles product at test completion were all greater in the rectangular endcap group compared with the round endcap group (cycles: 3027 *versus* 2092 cycles; force: 1943 N *versus* 1533 N; force-cycles product: 6162 kN·cycles *versus* 3973 kN·cycles), however these differences were not statistically significant ($p \geqslant 0.076$). After normalizing for individual specimen bone mineral density, the same measures increased to a greater extent with the rectangular endcaps (cycles: 3014 *versus* 1855 cycles; force: 1944 N *versus* 1444 N; force-cycles product: 6040 kN·cycles *versus* 2980 kN·cycles), and all differences were significant ($p \leqslant 0.030$). The rectangular endcap expandable corpectomy cage displayed increased resistance to subsidence over the round endcap cage under cyclic loading as demonstrated by the larger number of cycles, maximum load and force-cycles product at test completion. This suggests rectangular endcaps will be less susceptible to subsidence than the round endcap design.

1. Introduction

Disorders of the thoracolumbar spine, such as infection, trauma and neoplasm often lead to instability and may be treated with posterior internal fixation and arthrodesis. However, vertebral body replacement (VBR) is often necessary to provide anterior column support and prevent implant failure [1–4]. In addition, essential goals of VBR are decompression of the spinal cord, removal of pathologic tissue, arthrodesis and maintenance of sagittal alignment [5]. Although effective, these techniques may be associated with high degrees of perioperative morbidity from wide exposure and significant blood loss, as well as postoperative complications such as cage subsidence and pseudarthrosis. This necessitates the successful creation of a biomechanically sound construct with the initial surgery [6–8]. Multiple approaches exist for corpectomy, ranging from minimally invasive retropleural approaches to lateral extracavitary transthoracic approaches [2,8,9]. The approach to the vertebral body determines the type of construct that can be built. This study will focus on the construct frequently built through the minimally invasive lateral retroperitoneal approach.

The number of graft options for VBR has increased over the years. A few of the more popular grafts include meshed titanium cages, as described by Lowery and Harms (DePuy AcroMed, Sulzbach, Germany) and the tricortical iliac crest bone graft [10–13]. Significant donor site morbidity and graft subsidence has led to further advances in VBR technology including expandable cages, and more recently, those with wide/rectangular endcaps [14–17]. Studies show the peripheral ring apophyseal bone to be the strongest part of the vertebral body endplate [18–21]. We hypothesize that a construct for VBR that takes advantage of the apophyseal ring bone will more likely succeed as a biomechanically sound construct on the first attempt. The purpose of this study is to prove that an expandable cage with a rectangular endcap resting on the apophyseal ring may decrease the rate of subsidence under cyclic axial loading when compared to an expandable cage with a round endcap. This hypothesis was tested through *in vitro* biomechanical testing.

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http://dx.doi.org/10.1016/j.jocn.2013.12.028
0967-5868/

2. Materials and methods

Fourteen intact fresh-frozen cadaveric human spines were used. Anterior-posterior (A-P) and lateral radiographs confirmed specimens were free of gross deformity or degeneration. The spines were dissected into T12–L2 sections and cleaned of muscle and adipose tissue, while taking care to preserve ligamentous structures. Vertebral body bone mineral density (BMD) was assessed for each specimen by lateral plane dual-energy x-ray absorptiometry (DEXA) scans (Discovery C, Hologic, Bedford, MA, USA). Specimens were divided into two groups with similar average T12–L2 lateral BMD. Group 1 included seven specimens, with mean BMD = 0.41 (standard deviation 0.07) g/cm^2, and Group 2 also included seven specimens, with mean BMD = 0.41 (standard deviation 0.06) g/cm^2. Group 1 was assigned round endcaps, while Group 2 received rectangular endcaps. The cranial (T12) and caudal (L2) ends of each specimen were potted in polyurethane resin (Smooth Cast 300, Smooth-On, Easton, PA, USA) using custom potting frames with the L1 endplates horizontal. Construction screws were used to secure the segment ends to the potting material. After potting, specimens were sealed and frozen at −20 °C.

In preparation for testing, the specimens were thawed at room temperature before receiving an L1 corpectomy; removing the T12–L1 and L1–L2 intervertebral discs and the L1 vertebral body, while retaining the posterior elements. Specimens were then instrumented with an expandable corpectomy cage consisting of an expandable core with modular round or rectangular endcaps (X-CORE, NuVasive, San Diego, CA, USA) and stabilized with a four-screw lateral plate (Traverse, NuVasive). Corpectomy cages were sized to span the L1 corpectomy space and the appropriate endcaps for the respective test group were attached to the expandable core. Round endcaps were 26 mm diameter, and rectangular endcaps were 18 mm (A-P width) × 50 mm (lateral length). Lateral plates were sized to fit each spine over the expandable cage, and were either 40 or 45 mm in length, with 45 or 50 mm length posterior screws and 30 or 35 mm length anterior screws. All screws were 5.5 mm diameter. To ensure uniform cage expansion between specimens, the implants were distracted until a force of 100 N was created, with the top and bottom surfaces of the potting material staying parallel. The lateral plate was subsequently applied under a constant 200 N axial preload (Fig. 1).

Fig. 1. Test construct showing T12–L2 spinal segments, L1 corpectomy, expandable cage with rectangular endcaps, and four-screw lateral plate.

For testing, specimens were placed in a custom spine testing apparatus mounted on an MTS 858 Mini Bionix servo-hydraulic test frame (MTS Systems, Eden Prairie, MN, USA). Care was taken to keep the specimens moist with saline during testing. Each specimen was subjected to intervals of cyclic sinusoidal axial compression loading at a frequency of 2 Hz with increasing load magnitude. The loading profile began with 1000 cycles between 400 and 800 N of compression, after which time the maximum compressive load was increased to 1200 N for a further 1000 cycles. Additional 1000 cycle loading intervals were performed at 1600 N, 2000 N, and 2400 N. The minimum compressive load was maintained at 400 N during all cycles (Fig. 2). Initial load cycle parameters (400 to 800 N) were based on values measured in telemeterized VBR devices implanted in human subjects [22]. Testing was terminated if the test machine actuator displacement exceeded 6 mm, or the specimen completed cyclic loading at 2400 N. A-P and lateral fluoroscopy images were digitally recorded before and after testing.

The maximum compressive force and cycle count was recorded at test completion (failure or completion of test). The average compressive forces, cycle counts, and average force-cycles products (compressive forces multiplied by the cycle counts) for each group (round and rectangular endcaps) were compared using a one-tailed *t*-test, with significance set at $p < 0.05$. These parameters were also compared after normalization by individual specimen BMD. To normalize the results, individual specimen BMD was first divided by the average BMD for all specimens. The compressive forces and cycle counts at test completion for each specimen were then divided by the BMD ratio for that specimen. These measures were then averaged, including the normalized force-cycle product, and compared between groups using a one-tailed *t*-test.

3. Results

One sample in the round endcap group failed within the first 1000 cycle interval; all others completed at least the first interval of testing. The average number of cycles at test completion for the round endcap group was 2092 cycles compared with the rectangular endcap group that failed at 3027 cycles (Fig. 3A). Despite the 45% increase in cycles, this did not reach statistical significance ($p = 0.104$). After normalizing for individual specimen BMD, there was a 62% statistically significant ($p = 0.030$) difference between the number of cycles for the round endcap (1855 cycles) and the rectangular endcap group (3014 cycles).

The average force at test completion was 1533 N for the round endcap group, compared with 1943 N for the rectangular endcap group (Fig. 3B), which was a 27% increase, however significance was again not reached ($p = 0.076$). Normalizing for specimen

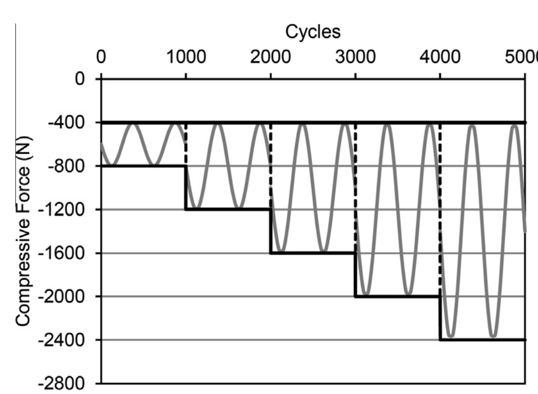

Fig. 2. Representation of interval cyclic loading profile starting with 1000 cycles between 400 and 800 N, with the maximum compressive load increasing by 400 N after each 1000 cycle interval.

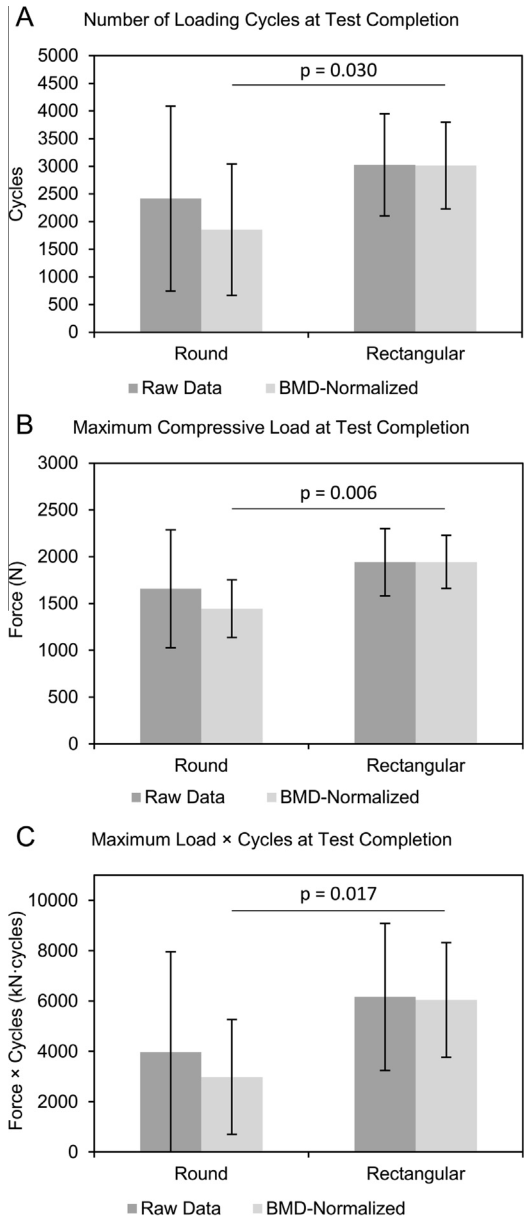

Fig. 3. Mean result values at test completion for corpectomy cages with round or rectangular endcaps; error bars represent ±1 standard deviation. Results are also shown after normalization by bone mineral density. (A) Number of loading cycles at test completion, (B) maximum compressive force at test completion, and (C) maximum compressive force at test completion multiplied by number of loading cycles at test completion.

BMD revealed a significant 35% increase in the force for the rectangular endcap group (rectangular: 1944 N, round: 1444 N; $p = 0.006$).

The force-cycles product at test completion was 3973 kN·cycles in the round endcap group and 6162 kN·cycles in the rectangular endcap group (Fig. 3C). This represented a 55% increase for the rectangular endcaps, although this difference was not statistically significant ($p = 0.139$). After normalizing by BMD, the force-cycles product was 103% greater in the rectangular group, which was a statistically significant difference (rectangular: 6040 kN·cycles, round: 2980 kN·cycles; $p = 0.017$).

Specimens failed by subsidence of the corpectomy cage endcaps into one of the adjacent vertebral endplates leading to height loss of the T12–L2 construct (Fig. 4). Round endcap devices created a circular indentation in the endplate, while the rectangular endplates created an impression that spanned the width of the endplate.

4. Discussion

Historical limitations and failures propel technological advancement. The introduction of titanium cages for use in the thoracolumbar spine after a corpectomy allows for increased mechanical support, potentially decreased rate of pseudarthrosis, and supports radiation therapy after tumor resection, which was difficult with autologous bone grafts [10,11,23]. Although still utilized, expandable titanium cages have largely replaced mesh cages for a number of reasons: ease of insertion, expansion to the desired length to optimize sagittal correction, and insertion at a smaller volume making them more feasible for minimally invasive surgery [1,12,13,24–26]. In addition, expandable cages no longer need a vertebral distraction device or compressive instrumentation configurations, removing an additional opportunity to damage the adjacent vertebral endplate, and reducing the risk of subsidence.

In this same manner, the rectangular endcap has been suggested as an improvement on the existing expandable cage. Taking into account physical relationships between stress, force and surface area, the following equation may be explained intuitively and is the basis for the improved design on expandable cages:

$$\text{Stress} = \text{Force}/\text{Surface area}$$

Reinhold et al. [26] evaluated this relationship and determined that a larger endcap may reduce subsidence. Given an equal force, a larger stress will be exerted with a smaller surface area than with a larger surface area. In other words, a small circular endcap will exert a higher stress on the adjacent vertebral body endplate than will a wide rectangular endcap, given that the force remains equal for both. We hypothesize that the increased stress will manifest as cage subsidence. In addition to the increased stress, another factor that may limit subsidence with a rectangular endcap is the location of contact between the cage and bone. Various studies have demonstrated that the ring apophysis is the strongest region of the vertebral endplate [18,20,26,27]. Taking this into consideration, subsidence should be reduced in the case of a rectangular endcap that contacts the periphery rather than the center of the endplate. This is especially the case if the cage endcap spans the entire width of the vertebral body endplate.

The purpose of our study was to evaluate these claims biomechanically by comparing (1) the number of cycles to failure, and (2) failure load between two groups of corpectomy constructs similar in all regards except cage endcap shape. Although unable to be tested in an *in vitro* setting, another theoretical benefit from increased stability/less micromotion with a rectangular endcap is decreased pseudarthrosis. This however, will be better suited for a future clinical series.

In a recent study by Pekmezci et al. [17], an *ex vivo* biomechanical comparison of rectangular *versus* round endcaps revealed a load to failure of 2481 N and 1310 N ($p = 0.003$), respectively, and construct stiffness of 1054 N/mm and 473 N/mm ($p < 0.0001$), respectively. In addition to testing endcaps in contact with intact endplates, the authors should be commended on also including biomechanical data on segments with a rectangular endcap spanning an endplate with a central defect. Even with a prior central defect from a round endcap tested to failure (10 mm subsidence), the rectangular endcap had higher load to failure (1636 N *versus* 1310 N) and greater stiffness (754 N/mm *versus* 473 N/mm) compared with the round endcap [17].

Though similar, our study differs in a few respects. We used a multi-level T12–L2 human cadaveric spine with a single level (L1) corpectomy model, rather than various thoracolumbar

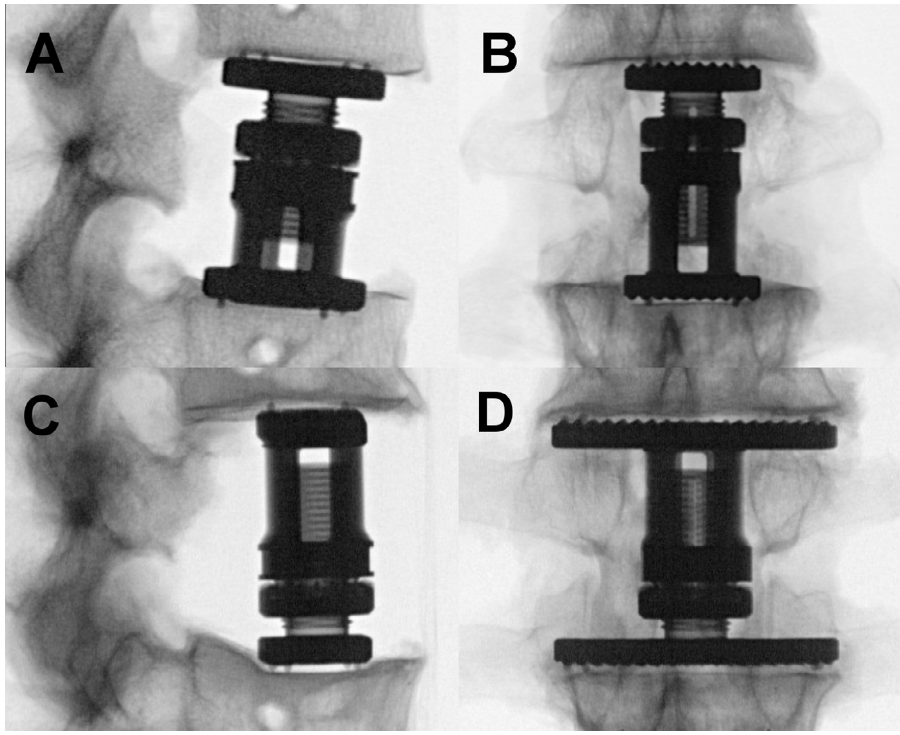

Fig. 4. Lateral (A, C) and anterior-posterior (B, D) fluoroscopy images of specimens after testing. Round (A, B) and rectangular (C, D) endcaps were noted to subside into the superior endplate of the inferior vertebral bodies in both these instances. Note: lateral plates were removed after testing and prior to fluoroscopy.

individual vertebrae, and evaluated subsidence under cyclic as opposed to static loading, which we feel is more clinically relevant to longer term stability. Each sample was used only once in our model and tested to failure, rather than re-using samples with an existing central defect. In the current study, all specimens were instrumented with a rigid four-screw plate on the lateral aspect of the vertebral bodies. In addition to resembling the true surgical scenario of a thoracolumbar corpectomy, the lateral plate also provides a stabilizing element for the construct [28]. Although testing without the lateral plate may produce more substantial differences between the endcap designs, the cage/plate construct used in this study may be more clinically useful. Pedicle screw fixation, which may or may not be used in an *in vivo* model, was not utilized in order to keep our model as simple and reproducible as possible.

As expected, our results echoed those of Pekmezci et al. [17] due to the rectangular endcaps resting on the stronger peripheral apophyseal ring of the endplate as opposed to the weaker central region. We were able to demonstrate that, keeping all other variables similar, a round endcap applied to a corpectomy cage will lead to subsidence in fewer cycles (2092 *versus* 3027, $p = 0.104$) and with a smaller load (1553 N *versus* 1943 N, $p = 0.076$) than a wide/rectangular endcap. There did appear to be a wider range, as demonstrated by the larger standard deviations, in the number of cycles, load, and force-cycles product at test completion for the round endcap group *versus* the rectangular endcap, which likely is a function of the variable strength of the underlying cancellous bone in the center and relatively constant cortical bone in the periphery [18]. Normalizing the results by specimen BMD increased the percentage differences between the groups and provided statistically significant differences ($p \leqslant 0.030$) for the three results. This indicates a relationship between BMD and subsidence test parameters. The standard deviation in the round endcap groups were proportionally decreased to a greater extent than in the rectangular groups after normalizing by BMD. For example, the standard deviation of the force to failure was 38% of the mean in the round endcap group and 19% in the rectangular. After normalizing by BMD, these percentages decreased by 17% and 4%, respectively. This suggests a stronger relationship between BMD and the test results with the round endcaps, implying that subsidence in the rectangular endcap group is less dependent on BMD than the round endcap group. With an aging population it is likely that the prevalence of osteopenia/osteoporosis will increase, necessitating improvements in our technology in fusing patients with low BMD.

The finding by Pekmezci et al. [24] that increased contact area is seen with expandable *versus* fixed cages leads to the assumption that expandable cages have a higher rate of fusion according to Wolff's law. Although our study did not compare contact area for rectangular *versus* round endcaps, it stands to reason that assuming proper insertion, a cage with a rectangular endcap will have greater surface area contact with the vertebral endplate, leading to increased rates of fusion and further stability. This hypothesis should be examined with further study.

The authors realize several limitations exist with this study. No matter how close to an actual clinical scenario, we understand that an *in vitro* examination does not obviate the need for a randomized controlled trial. The loads exerted onto the samples, though standardized between the groups, are not necessarily representative of an *in vivo* system. Axial compressive loads were applied, whereas in activities of daily living there are combinations of loads and motions in multiple planes. However, the test parameters provide a repeatable method to evaluate the cage endcaps. As with other cadaveric studies, variation in specimen anatomy and bone density increases variability within test results. Our sample sizes were limited to seven specimens per group. The cages were expanded to the height of the corpectomy defect and to the same force for each cage, thus attempting to reduce variability and standardize preload. However, because great care was taken to preserve the T12 and L2 endplates, and more importantly because cages were inserted attempting to maximize the surface contact area with the vertebral endplate, we believe that this closely resembles the true clinical VBR technique and may be considered a strength of our study.

5. Conclusions

In conclusion, the results of our study demonstrate that an expandable corpectomy cage with rectangular endcaps placed in the thoracolumbar spine better resists subsidence when compared with a cage with round endcaps, when tested with a cyclical load. The stronger apophyseal ring of the vertebral endplate supports the wide, rectangular endcap. In addition, the reduced contact pressure on the vertebral endplate due to the larger surface area likely increases resistance to subsidence. Bone quality seems to play an important role in subsidence with a round endcap, while the rectangular endcap appears to be less dependent on BMD.

Conflicts of Interest/Disclosures

NuVasive, (San Diego, CA, USA) provided research materials for this study. Dr. Uribe is a paid consultant and receives research grants from NuVasive. Alex Turner is employed by NuVasive.

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