Transforaminal lumbar interbody fusion (TLIF) was first described as an alternative to posterior interbody fusion in 1982 by Harms and Rolinger, utilizing a titanium mesh cage packed with bone graft material placed into the disc space via a transforaminal route, providing anterior column support and theoretically increasing the fusion surface area.

The increased popularity of the TLIF procedure has led to numerous studies examining short- and long-term clinical and radiographic results, which have generally been reported as excellent. However, postoperative subsidence of the interbody device can result in loss of lordosis and foraminal height, and a theoretical risk of recurrence of nerve root impingement and radicular symptoms. Various clinical and biomechanical studies have evaluated the effects of different cage materials, sizes/shapes, bone mineral density (BMD), and cage position on the occurrence of subsidence.

Additionally, the increasing prevalence of osteoporosis...
sis and low BMD within the patient population presents unique clinical challenges for treating spine surgeons, and vertebral body Hounsfield units (HUs) have been proposed as an opportunistic surrogate for traditional BMD measurement techniques.\(^{11-13}\) However, to our knowledge, no studies have evaluated the relationship between preoperative disc heights of the affected and suprajacent levels, HU measurements of a single standardized lumbar vertebral body, and postoperative cage subsidence rates. We hypothesized that a relationship exists between preoperative disc height, first lumbar vertebral body (L1) HU measurements, and cage subsidence. We attempted to determine if preoperative disc heights can be utilized to create a template for the size of implanted TLIF cages to minimize subsidence rates, and if standardized measurements of lumbar vertebral HUs correlate with increased subsidence rates.

**Methods**

**Study Population and Criteria**

After IRB approval, we retrospectively reviewed all patients aged 50 years or older who underwent instrumented TLIF from two military institutions (Walter Reed National Military Medical Center and Fort Belvoir Community Hospital) between July 2004 and June 2014. Only patients with the following imaging were included in the study: preoperative MRI within 6 months of surgery, immediate postoperative radiographs, and minimum 12-month follow-up radiographs. Additionally, patients with routine postoperative CT scans within 6 months of surgery were also identified within the TLIF cohort. Patients undergoing multilevel TLIF or revision surgery were included in the study. We recorded demographic information and bone morphogenetic protein (BMP) use. Final fusion status was evaluated on final 12-month radiographs and recorded for each patient. Lastly, a chart review was performed to determine recurrence or persistence of symptoms.

**Data Collection**

We measured the central disc height at both the operative and suprajacent level on preoperative MRI (Fig. 1). In the case of multilevel surgery, the cephalad-most level was used as the operative level measurement. Disc height was measured on the T1-weighted midsagittal image at the midway point of the vertebral bodies. We then obtained all cage heights and types from operative reports. Finally, we identified cages that subsided using postoperative CT scans (Fig. 2). Subsidence was defined as greater than 2 mm of cage protrusion through the cephalad or caudal (or both) vertebral endplates. We then calculated the difference in cage height and the preoperative disc heights at both the operative and suprajacent levels in each patient.

CT HU measurements of L1 were recorded in all patients with routinely obtained CT scans within 6 months of surgery, utilizing a previously described technique.\(^{14,15}\) The first lumbar segment was chosen as an opportunistic BMD measurement level due to its nonroutine use in instrumented TLIF procedures, lack of suspected degenerative changes, and the prevalence of level inclusion in chest, abdominal, lumbar, and pelvic CT scans. HU values were calculated on postoperative CT scans by using axial, sagittal, and coronal circles of best fit of L1.
Results
We identified 89 patients with complete imaging and follow-up information. The cohort was 59.6% male and the average age was 59.9 years. Forty-five patients (50.6%) had evidence of interbody cage subsidence on follow-up CT scans. Patients had an average clinical follow-up of 27 months. No significant differences in preoperative demographic were noted (Table 1). BMP use was reported in 30 patients, and there was no increased rate of subsidence between groups based on BMP use (50% vs 50.8%, p > 0.05). The vast majority of interspace implants (97%) were polyetheretherketone (PEEK) bullet-shaped cages. The average cage subsidence was 5.5 mm (range 2.2–10.8 mm).

The average preoperative disc height for the operative levels and the immediately suprajacent levels was 7.1 mm and 9.3 mm for all patients, which was statistically significantly different (p < 0.0001). This finding remained true within both the subsidence and nonsubsidence groups (nonsubsidence group: 7.1 vs 9.9 mm, p < 0.0001; subsidence group: 7.1 vs 8.8 mm, p = 0.001). The average suprajacent disc height was significantly larger in the nonsubsidence group (9.9 vs 8.8 mm, p = 0.02). The preoperative disc height at the surgical levels was not significantly different between the subsidence and nonsubsidence groups (7.1 vs 7.1 mm, p > 0.05).

The average cage height in the subsidence group was significantly larger than in the nonsubsidence group (12.6 vs 11.2 mm, p < 0.0005). Additionally, the percentage of patients with an implant height greater than the median (12 mm) was significantly higher in the subsidence group (42.2% vs 20.5%, p = 0.03). The height difference between cage and operative level disc was significantly larger in the subsidence group compared to the nonsubsidence group (5.5 vs 3.9 mm, p = 0.01). Similarly, the subsidence group had a significantly larger height difference between cage and suprajacent level disc in comparison to the nonsubsidence group (3.8 vs 1.2 mm, p < 0.0001; Table 2). A representative example of initial disc height, immediately postoperative and at final follow-up, that demonstrates the discordance between initial disc height, cage height, and subsidence is shown in Fig. 3.

We performed ROC curves to compare the difference between cage height and disc height at the surgical and suprajacent levels (Figs. 4 and 5). The ROC curve for operative disc height differential followed a relatively linear pattern, while the curve for suprajacent level height differential followed a more predictable ROC curve pattern. A height difference at the suprajacent level of 1.3 mm yielded 93.3% sensitivity for developing subsidence, with a false-positive rate of 53%. For the operative level, a height difference of 2.1 mm also yielded a sensitivity of 93.3% for subsidence (false-positive rate 77.0%). Utilizing height differential cutoffs of 3.6 mm and 5.5 mm for the suprajacent and operative levels, respectively, would yield sensitivities of 57% and 51.1% for subsidence, but with much lower false-positive rates (18.8% and 27%, respectively). Similarly, we found that a greater than 3.0-mm cage to suprajacent level differential threshold yielded a significant odds ratio of 3.9 (95% CI 1.61–9.37) for subsidence. We failed to identify a difference in the rates of fusion between the subsidence and nonsubsidence groups (82% vs 93%, p = 0.08). We did not find any statistically significant differences in the percentage of patients reporting persistence or recurrence of radiculopathy between the groups at final follow-up (47% [subsidence] vs 38% [nonsubsidence], p = 0.383).

We compared subsidence and nonsubsidence HU measurements. First lumbar vertebral body (L1) HU measurements were significantly higher in the nonsubsidence versus subsidence group in all measured planes: coronal (170.69 ± 15.61 vs 138.64 ± 14.21 HUs, p = 0.003), sagittal (175.14 ± 17.26 vs 140.16 ± 13.71 HUs, p = 0.002), axial HUs (157.57 ± 12.26 vs 134.35 ± 12.30 HUs, p = 0.009), and composite HUs (167.8 ± 14.04 vs 137.71 ± 12.83 HUs, p = 0.002). A total of 17 patients had average L1 HU values < 110, which is a previously defined cutoff value for osteoporosis;12 70.6% of patients in that group showed evidence of subsidence, while only 45.8% of patients with average HUs > 110 showed subsidence (p = 0.06).

Multivariate logistic regression identified cage to su-
prajacent disc height difference and average L1 vertebral body HUs to be independent, significant predictors of cage subsidence (p = 0.01 and 0.008, respectively). All other variables, including the number of levels treated, cage height, patient BMI, BMP use, age, and sex, were not shown to be independently significant.

Discussion

TLIF, when utilized in a short-segment construct, is typically indicated for instability and radiculopathy. In addition to the anterior column support and large surface area for 360° fusion, the indirect decompression afforded by the increase in foraminal height is also effective in the treatment of radiculopathy. If the interbody device subsides, foraminal height is lost, potentially leading to a recurrence or persistence of symptoms. We found an overall subsidence rate of 44%, consistent with other published data; Lee et al. found a subsidence rate of 38% in a series of 21 patients with 2-year follow-up.16 Increased implant height was found to be a risk factor for subsidence in our series, with a significant difference between the subsidence and nonsubsidence groups of 1.4 mm (12.6 vs 11.2 mm, p < 0.001), which is in contradistinction to several prior studies showing this factor to have no impact on subsidence.7,16,17

In our study, multivariate logistic regression identified the height difference between the suprajacent disc height and interbody cage (measured on non-weightbearing MRI18), as well as average L1 vertebral body HUs, to be independent significant predictors of interbody cage subsidence after TLIF (p = 0.01 and 0.008, respectively). As our results suggest, an interbody cage that is larger than the suprajacent (nonsurgical) disc space may be prone to subsidence. The subsidence group had a significantly larger discrepancy between the suprajacent level disc height and implanted cage height, as compared to the nonsubsidence group (3.8 vs 1.2 mm, p < 0.0001). An ROC curve calculated for the suprajacent level height difference yielded a threshold of 1.3 mm for 93.3% sensitivity for subsidence, or 3.6 mm for an 18.9% false-positive rate. Our results also demonstrate that suprajacent level disc height may be a reliable adjunct for templating cages, as the level being treated is often collapsed or asymmetrical, making height estimation and comparisons more difficult. In the subsidence group, the measured height discrepancy between operative level disc height and implanted cage was significantly larger (5.5 vs 3.9 mm, p = 0.01). The ROC curve for the operative level height yielded 93.3% sensitivity for subsidence with a height differential threshold of 2.1 mm, or 5.5 mm with a low false-positive rate (27.0%), but this association followed a more linear ROC pattern. On multivariate analysis, the operative level disc height was not found to be independently associated with cage subsidence.

FIG. 3. Preoperative sagittal MR image (A), 6-month postoperative sagittal CT scan (B), and 6-month postoperative lateral plain radiograph (C) obtained in a patient with multilevel evidence of subsidence.

FIG. 4. ROC curve of operative disc height and cage height difference.

FIG. 5. ROC curve of suprajacent disc height and cage height difference.
Ultimately, our results suggest that placing a larger interbody device into a smaller disc space may predispose toward subsidence, and we hypothesize that utilization of the preoperative suprajacent disc height as a sizing template may more appropriately reflect the ideal cage size, and potentially minimize the incidence of subsidence. We theorize that increased differential between cage and disc height may ultimately lead to violation of the endplate over time, due to increased contact pressure and poor force distribution. It is important to note, however, that the vast majority of the interbody cages used in this study were PEKK bullet cages, which have a large endplate contact surface area within the central portion of the disc space, rather than anterior/edge-loading crescent cages, and so our findings are specific to this type of TLIF interbody cage with regard to subsidence risk.

Furthermore, we found that lower average composite HU measurements of L1 were independently associated with an increased risk of cage subsidence. The patients without evidence of cage subsidence had significantly higher HUs compared to patients with subsidence (167.8 ± 14.04 HUs vs 137.71 ± 12.83 HUs, respectively; p = 0.002). These findings suggest that a relationship exists between lower HUs and the likelihood of cage subsidence after TLIF, despite these measurements being performed on a level not included in the surgical construct. Multiple studies have validated the correlation between HUs as measured on CT and BMD on dual-energy x-ray absorptiometry to determine bone quality and fracture risk, as well as the utility of HU measurement as an opportunistic surrogate for quantitative BMD assessment. Hendrickson et al. reported excellent reproducibility and accuracy in identifying osteoporosis of the spine using CT attenuation measures such as HUs. Our study demonstrated a significant trend of lower lumbar vertebral body HUs in the subsidence group, and corroborates the work of several studies demonstrating low BMD to be a risk factor for subsidence. Pickhardt et al. demonstrated L1 thresholds of 135 HUs for balanced sensitivity and specificity, and a threshold of 110 HUs for 90% specificity for osteoporosis, which are similar numbers to those reported by Wagner et al. Our series confirms several prior studies that failed to show any statistically significant correlation with subsidence and recurrence of preoperative symptoms. In reviewing 139 operative segments, Oh et al. found that subsidence did not correlate with worse clinical outcomes. The rate of fusion in this study is similar to the rate in the published literature. Additionally, we identified a trend toward a decreased fusion rate in the group with subsidence, although this finding was not statistically significant (82% vs 93%, p = 0.08). A correlation between subsidence and pseudarthrosis has not been previously reported in the literature.

Our study was subject to several limitations. First, as with any retrospective cohort analysis, clinical data are limited by the accuracy of documentation. Furthermore, despite a minimum age of 50 years for inclusion in this study, our patients were still relatively young with an average age of 58.9 years, and future studies may consider evaluating older patients with greater BMD loss. Preoperative MRI was used to measured disc height, which may not be as accurate as CT; however, few patients in this cohort had preoperative CT scans for evaluation, while MRI was ubiquitous. We did not include patient-reported outcome measures in this study, and our primary clinical outcome was merely defined as persistence or recurrence of symptoms. Lastly, we did not establish the final location of the cage on the endplates, and cages placed more anteriorly or along the apophyseal ring are theoretically supported on denser bone. Future studies utilizing HUs to map the density of the lumbar vertebral bodies are ongoing. Interestingly, we were unable to show any association between BMP use and subsidence, which contradicts published literature on the topic. This finding highlights a limitation of our study, i.e., it is not clear from the operative reports whether BMP was placed within the disc space or in the posterolateral gutter. Because this study incorporates multiple surgeons at more than one institution, there was no rigorously standardized surgical technique, and our results must be interpreted within that context. Finally, many patients with degenerative lumbar conditions develop endplate sclerosis that, despite an actual diagnosis of central osteopenia or osteoporosis, may paradoxically be protected from subsidence; this statement is only a hypothesis, however, and has not been studied. Despite these limitations, we were able to demonstrate a positive correlation between lower vertebral HUs and the risk for subsidence, as well as validate the use of preoperative disc height on MRI for creating a cage template and planning the size of the implant.

Conclusions

We found a significant association between larger interbody devices and postoperative cage subsidence after TLIF. In addition, we found that the suprajacent level disc height may be used to accurately create a template the size of the planned interbody cage. Targeting an implant size similar to the preoperative template size may reduce the rate of postoperative cage subsidence after TLIF. Finally, our findings suggest that lower lumbar vertebral body HU measurements may be a risk factor for interbody cage subsidence.

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Conception and design: Fredericks, Pisano, Steelman, Riccio, Wagner. Acquisition of data: Fredericks, Pisano, Steelman, Wagner. Analysis and interpretation of data: Pisano, Riccio, Wagner. Drafting the article: Fredericks, Pisano, Steelman, Riccio. Critically revising the article: Fredericks, Steelman, Riccio, Helgeson, Wagner. Reviewed submitted version of manuscript: Helgeson. Statistical analysis: Wagner. Administrative/technical/material support: Pisano, Helgeson, Wagner. Study supervision: Pisano, Helgeson, Wagner.

Supplemental Information
Previous Presentations
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