The association between lower Hounsfield units on computed tomography and cage subsidence after lateral lumbar interbody fusion

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OBJECTIVE One vexing problem after lateral lumbar interbody fusion (LLIF) surgery is cage subsidence. Low bone mineral density (BMD) may contribute to subsidence, and BMD is correlated with Hounsfield units (HUs) on CT. The authors investigated if lower HU values correlated with subsidence after LLIF.

METHODS A retrospective study of patients undergoing single-level LLIF with pedicle screw fixation for degenerative conditions at the University of California, San Francisco, by 6 spine surgeons was performed. Data on demographics, cage parameters, preoperative HUs on CT, and postoperative subsidence were collected. Thirty-six-inch standing radiographs were used to measure segmental lordosis, disc space height, and subsidence; data were collected immediately postoperatively and at 1 year. Subsidence was graded using a published grade of disc height loss: grade 0, 0%–24%; grade I, 25%–49%; grade II, 50%–74%; and grade III, 75%–100%. HU values were measured on preoperative CT from L1 to L5, and each lumbar vertebral body HU was measured 4 separate times.

RESULTS After identifying 138 patients who underwent LLIF, 68 met the study inclusion criteria. All patients had single-level LLIF with pedicle screw fixation. The mean follow-up duration was 25.3 ± 10.4 months. There were 40 patients who had grade 0 subsidence, 15 grade I, 9 grade II, and 4 grade III. There were no significant differences in age, sex, BMI, or smoking. There were no significant differences in cage sizes, cage lordosis, and preoperative disc height. The mean segmental HU (the average HU value of the two vertebrae above and below the LLIF) was 169.5 ± 45 for grade 0, 130.3 ± 56.2 for grade I, 100.7 ± 30.2 for grade II, and 119.9 ± 52.9 for grade III ($p < 0.001$). After using a receiver operating characteristic curve to establish separation criteria between mild and severe subsidence, the most appropriate threshold of HU value was 135.02 between mild and severe subsidence (sensitivity 60%, specificity 92.3%). After univariate and multivariate analysis, preoperative segmental HU value was an independent risk factor for severe cage subsidence ($p = 0.017$, OR 15.694, 95% CI 1.621–151.961).

CONCLUSIONS Lower HU values on preoperative CT are associated with cage subsidence after LLIF. Measurement of preoperative HU values on CT may be useful when planning LLIF surgery.

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KEYWORDS LLIF; Hounsfield units; CT; cage subsidence; lateral lumbar interbody fusion; HU

CAGE subsidence is a well-known phenomenon that can occur after lateral lumbar interbody fusion (LLIF), and can result in loss of interbody distraction, loss of lordosis, and recurrent foraminal stenosis.¹ Previous studies have reported that older age, female sex, endplate violation, endplate abnormalities, cage size, and osteoporosis are associated with subsidence.^{1–3} Low bone

mineral density (BMD) secondary to osteoporosis has been shown to be one major factor in cage subsidence.⁴ Dual-energy x-ray absorptiometry (DXA) has long been considered the “gold standard” for measuring BMD, but many reports have shown that quantitative CT (qCT) may actually be more sensitive for assessing focal osteoporosis because it directly measures trabecular bone quality

ABBREVIATIONS AUC = area under the ROC curve; BMD = bone mineral density; BMP = bone morphogenetic protein; DXA = dual-energy x-ray absorptiometry; HU = Hounsfield unit; ICC = interclass correlation coefficient; LLIF = lateral lumbar interbody fusion; PACS = picture archiving and communication system; qCT = quantitative CT; ROC = receiver operating characteristic; ROI = region of interest; UCSF = University of California, San Francisco.

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without the superimposed cortical bone.⁵ However, DXA scans may not be routinely performed, and qCTs are rarer still.⁶ Multiple studies have shown that the Hounsfield units (HUs) measured on routine lumbar spine CT scans using the picture archiving and communication system (PACS) can estimate if osteoporosis is present.^{2,7,10,23,26} Because of correlation between HUs and BMD, we evaluated if preoperative HUs on CT are associated with cage subsidence after single-level LLIF for degenerative conditions of the spine.

Methods

Patient Population

A retrospective study of patients undergoing LLIF (either oblique lumbar interbody fusion or transposas LLIF) at the University of California, San Francisco (UCSF), from 2013 to 2018 by 6 spine surgeons was performed. The study was approved by the IRB of UCSF. Inclusion criteria were: age ≥ 18 years; single-level LLIF; bilateral pedicle screw fixation at the LLIF level; preoperative lumbar CT available to measure HUs; degenerative conditions of the lumbar spine, including scoliosis, spondylolisthesis, and degenerative disc disease; and at least 1 year of postoperative follow-up with radiographs and records. Patients were excluded if they had previous lumbar fusion, clearly identified endplate violation during surgery, endplate abnormalities such as Schmorl's nodes, tumor, infection, or trauma. Patients who had been taking osteoporosis medication such as bisphosphonates or parathyroid hormone analogs and patients with a history of chronic glucocorticosteroids were excluded. Data collected were demographics, cage parameters, preoperative HU measurements, and radiographic parameters. Operative times were calculated as skin-to-skin surgical times during the LLIF, not including induction, positioning, or posterior surgery. All enrolled patients used static polyetheretherketone cages and pedicle screw fusion, without the use of standalone integrated screw and cage devices, anterior plating systems, or any expandable cages. Data were collected and analyzed by an attending spinal neurosurgeon.

HU Measurements

HUs were measured based on the methods by Hendrickson et al. on preoperative CT (within 6 months before surgery) from L1 to L5, and each lumbar vertebral body was measured 4 separate times.⁸ The HU values were measured at the midsagittal plane, midbody axial plane, axial plane just below the superior endplate, and axial plane just above the inferior endplate.^{9,10} The HU values were measured by drawing a circular region of interest (ROI) using the radiology PACS. The ROI was expanded to as large a region as possible within the vertebral body, but it did not include any cortical bone, lateral walls, endplates, or osteophytes. After establishing a consistent and appropriate ROI, the mean HU values were calculated by the PACS. The final HU values were calculated as the mean of all 4 measurements in each vertebral body. The global HU values of the spine were defined as the average HU from L1 to L5. The segmental HU value was defined as the average of the HU values of the two vertebrae above and below the

FIG. 1. Measurements of HU values taken on the preoperative CT scan at the midsagittal plane (A), axial plane just below the superior endplate (B), axial plane at the midbody (C), and axial plane just above the inferior endplate (D).

LLIF. For example, the segmental HUs of an L3–4 LLIF was the average of the L3 and L4 vertebral bodies (Fig. 1).

Radiographic Assessment

Lumbar lordosis and segmental lordosis were measured from the superior endplate of L1 and the inferior endplate of L5. Traditional measurements of lumbar lordosis to S1 were not undertaken because the LLIFs were all performed from L1 to L5, and no surgery took place at L5–S1. Segmental lordosis was measured from the superior endplate of the vertebrae above the cage and the inferior endplate of the vertebrae below the cage. Disc height was measured as the average of the anterior and posterior disc space heights (Fig. 2A). The vertebral body segmental height was measured as the average of the anterior, middle, and posterior superior and inferior vertebral bodies spanning the fusion (Fig. 2B). Cage position was defined as anterior-, middle-, and posterior-third based on the cage's radiopaque markers' position relative to the lower vertebra on immediate postoperative lateral radiographs.

Subsidence Grading

As shown in Fig. 3, the subsidence grading was performed using a published method by Marchi et al.¹¹ Using this method, subsidence was measured and classified based on the amount of cage subsidence into the vertebral endplates (as viewed on plain lateral radiographs) with the following grades: grade 0, 0%–24%; grade I, 25%–49%; grade II, 50%–74%; and grade III, 75%–100%.¹³ In our

FIG. 2. Disc heights were measured as illustrated in panel A, and segmental heights were measured as shown in panel B.

study, 36-inch standing lateral radiographs at immediate and 1-year postoperative follow-up were used to measure cage subsidence. For the subsidence risk analysis, patients were divided into two groups defined by previously published studies as mild subsidence (grades 0–I) and severe subsidence (grades II–III).^{1,11}

Statistical Analysis

Categorical variables were presented as number counts, and continuous variables were presented as means with standard deviations. One-way ANOVAs, independent-samples t-tests, and chi-square tests were used to evaluate differences. The interclass correlation coefficient (ICC) test was performed to determine reliability. A receiver operating characteristic (ROC) curve was used to establish separation criteria between mild subsidence (grades 0–I) and severe subsidence (grades II–III). The area under the ROC curve (AUC) was calculated for segmental HU values and subsidence. The most appropriate threshold (cutoff value) of HUs with a higher sensitivity and specificity was also established using the ROC curve. In addition, univariate analyses of possible risk factors were performed using a Cox proportional hazards regression model. The variables that achieved a significance level of $p < 0.2$ were entered into multivariate analyses for screening as independent risk factors via the Cox model. A p value < 0.05 was considered statistically significant, and

statistical analyses were performed using SPSS software (version 23.0, IBM Corp.).

Results

After identifying 138 patients who underwent single-level LLIF, 68 met inclusion criteria (Fig. 4). There were 27 males and 41 females (Table 1). After reliability analysis (Cronbach's $\alpha = 0.962$), the number of patients in each grade was: 40 grade 0, 15 grade I, 9 grade II, and 4 grade III. The mean patient age was 61.1 ± 13.3 years. There were 10 smokers and 25 patients with BMI ≥ 30 kg/m². The mean hospital stay was 4.4 days, and the mean surgical duration was 130.3 minutes. The primary diagnoses were degenerative disc disease, foraminal stenosis, scoliosis, spondylolisthesis, and adjacent-segment degeneration (Supplemental Table). There were no significant differences in age ($p = 0.190$), sex ($p = 0.584$), BMI ($p = 0.243$), smoking ($p = 0.820$), follow-up time ($p = 0.392$), hospital stay ($p = 0.528$), or operative times ($p = 0.516$) among the four grades. There were no significant differences in cage sizes ($p = 0.810$ for length, $p = 0.917$ for width, $p = 0.508$ for height), cage lordosis ($p = 0.230$), or preoperative disc height ($p = 0.544$). All patients received morcellized allograft or bone morphogenetic protein (BMP). The number of patients who had BMP was 5 for grade 0, 1 each for grades I and II, and 0 for grade III ($p = 0.797$). There was 1 patient in grade 0 and 2 patients in grade II who underwent revision surgery at the LLIF level ($p = 0.046$, Table 1).

HU Values and Subsidence Results

With regard to level of LLIF and subsidence, grade 0 and grade III had the highest proportions at the L4–5 level (grade 0: 23/40, 57.5%; grade III: 2/4, 50%), whereas grade I (8/15, 53.3%) and grade II (5/9, 55.6%) had the highest proportion at the L3–4 level ($p = 0.048$). The mean global HU values of the lumbar spine (L1–5) were 166.1 ± 43.2 for grade 0, 131.6 ± 55.7 for grade I, 102.0 ± 26.7 for grade II, and 108.3 ± 56.1 for grade III ($p < 0.01$). The mean segmental HU values (level of the LLIF) were 169.5 ± 45 for grade 0, 130.3 ± 56.2 for grade I, 100.7 ± 30.2 for grade II, and 119.9 ± 52.9 for grade III ($p < 0.01$, Table 1).

FIG. 3. Illustration of cage subsidence grades according to percentages of disc height loss: grade 0, 0%–24% (A); grade I, 25%–49% (B); grade II, 50%–74% (C); and grade III, 75%–100% (D).

FIG. 4. Flowchart demonstrating patient selection methods.

Although there were no significant differences in disc height loss ($p = 0.540$) and segmental height loss ($p = 0.167$) among the different groups (Table 1), when divided into mild subsidence (grades 0–I) and severe subsidence (grades II–III), the severe subsidence group showed more disc height loss (2.9 ± 1.2 vs 1.3 ± 1.9 mm, $p = 0.046$) and segmental height loss (8.1 ± 8.7 vs 4.1 ± 5.0 mm, $p = 0.029$; Table 2). The revision rate of the mild subsidence group was 1.8% (1/55) compared with 15.4% (2/13) for the severe subsidence group ($p = 0.032$, Table 2). The mean vertebral HU values from L1 to L5 were 146.1 ± 50.0 , 141.4 ± 55.4 , 145.4 ± 53.1 , 152.5 ± 51.7 , and 155.2 ± 56.0 , respectively.

After using an ROC curve to establish separation criteria between mild (grades 0–I) and severe subsidence (grades II–III), the AUC was 0.81 (95% CI 0.684–0.936), and the most appropriate threshold was 135.02 HUs (sensitivity 60%, specificity 92.3%; Fig. 5).

Univariate Analysis

In the univariate analysis, risk factors for cage subsidence were analyzed. The variables that achieved a significance level of $p < 0.2$ were identified: sex ($p = 0.183$, OR 2.581, 95% CI 0.639–10.422), cage height ($p = 0.160$, OR 1.578, 95% CI 0.835–2.979), cage lordosis ($p = 0.116$, OR 1.102, 95% CI 0.976–1.243), level of LLIF ($p = 0.096$, OR 0.540, 95% CI 0.261–1.116), and mean segmental HU ($p = 0.007$, OR 18.000, 95% CI 2.182–148.486; Table 3).

Multivariate Analysis

After multivariate analysis of risk factors for cage sub-

sidence, the results showed sex ($p = 0.090$, OR 5.317, 95% CI 0.772–36.629), cage height ($p = 0.103$, OR 1.930, 95% CI 0.875–4.261), cage lordosis ($p = 0.108$, OR 1.143, 95% CI 0.971–1.346), and level of LLIF ($p = 0.419$, OR 0.654, 95% CI 0.234–1.832) were not significant. The preoperative mean HU value was determined to be the only independent risk factor for severe cage subsidence ($p = 0.017$, OR 15.694, 95% CI 1.621–151.961; Table 3).

Discussion

The LLIF has unique advantages of a minimally invasive approach, acceptable lordosis induction, foraminal stenosis alleviation, and enhancement of arthrodesis.^{12–14} However, a critical feature that gives LLIF these advantages is the ability to maintain vertebral body separation, but these advantages can quickly disappear with subsidence.¹⁵ In a systematic review of LLIF, Macki et al. reported a 10.3% subsidence rate,¹⁶ and previous reports have shown subsidence rates ranging from 0% to 29.7%.^{11,17} However, there is controversy as to whether or not cage subsidence is even a complication, with the idea that this is an expected sequela of LLIF, and clinical and radiographic outcomes are not necessarily compromised by subsidence.^{3,11,13} On the other hand, some reports state that subsidence is a significant issue that often necessitates revision surgery because of symptomatic manifestations.^{11,18,19}

Although many reports have published subsidence rates, there is no single, established method to measure subsidence, with many papers using different methods

TABLE 1. Demographic variables and radiographic parameters of cage subsidence

Variable	Both Cohorts	Subsidence Grade				p Value
		0	I	II	III	
No. of patients	68	40 (58.9%)	15 (22.1%)	9 (13.2%)	4 (5.9%)	
Age (yrs)	61.1 ± 13.3	58.3 ± 13.9	65.6 ± 11.2	66.1 ± 10.1	60.8 ± 17.1	0.190
Sex						0.584
Male	27	17	7	2	1	
Female	41	23	8	7	3	
Smoker						0.820
No	58	35	12	8	3	
Yes	10	5	3	1	1	
BMI (kg/m ²)						0.243
≥30	25	16	4	2	3	
<30	43	24	11	7	1	
Follow-up length (mos)	25.3 ± 10.4	22.1 ± 9.4	28.9 ± 10.6	27.3 ± 11.3	27 ± 9.8	0.392
Hospital stay (days)	4.4 ± 2.1	4.6 ± 2.2	4.2 ± 1.7	3.6 ± 2.2	4.0 ± 1.2	0.528
Surgical duration (mins)	130.3 ± 70.9	139.5 ± 79.4	113.4 ± 50.3	111.2 ± 55.2	143.8 ± 78.9	0.516
Cage length (mm)	52.0 ± 4.2	51.9 ± 4.2	51.5 ± 3.2	52.5 ± 3.8	53.8 ± 7.5	0.810
Cage width (mm)	51.9 ± 4.2	19.6 ± 2.0	19.6 ± 2.0	20 ± 2.1	20 ± 2.3	0.917
Cage height (mm)	9.7 ± 2.1	9.7 ± 2.1	10.2 ± 1.7	10.8 ± 3.4	11 ± 2.0	0.508
Cage lordosis (°)	10.2 ± 5.0	9.8 ± 4.5	9.5 ± 4.2	13.6 ± 7.6	9.8 ± 4.5	0.230
Lumbar lordosis (°)	30.2 ± 12.0	28.2 ± 10.8	33.4 ± 9.2	28.8 ± 16.5	21.8 ± 16.9	0.116
Segmental lordosis (°)	14.0 ± 8.1	13.5 ± 8.3	15.1 ± 6.6	15.7 ± 8.9	12 ± 10.6	0.801
Preop disc height (mm)	7.0 ± 2.0	6.9 ± 2.0	7.0 ± 1.8	7.0 ± 1.9	8.4 ± 1.9	0.544
No. used BMP-2	7	5	1	1	0	0.797
Level of LLIF						0.048
L1–2	2	0	1 (6.7%)	0	1 (25%)	
L2–3	9	4 (10%)	2 (13.3%)	2 (22.2%)	1 (25%)	
L3–4	26	13 (32.5%)	8 (53.3%)	5 (55.6%)	0	
L4–5	31	23 (57.5%)	4 (26.7%)	2 (22.2%)	2 (50%)	
Mean global HU value	146.6 ± 50.9	166.1 ± 43.2	131.6 ± 55.7	102.0 ± 26.7	108.3 ± 56.1	<0.001
Mean segmental HU value	166.1 ± 43.2	169.5 ± 45.0	130.3 ± 56.2	100.7 ± 30.2	119.9 ± 52.9	<0.001
Cage position						0.762
Anterior	15	10	2	2	1	
Middle	50	27	13	7	3	
Posterior	3	3	0	0	0	
Mean disc height loss (mm)	2.3 ± 1.6	1.2 ± 1.9	2.2 ± 1.1	2.8 ± 1.3	3.3 ± 1.3	0.540
Mean segmental height loss (mm)	5.0 ± 6.3	3.9 ± 5.3	5.3 ± 3.9	7.5 ± 1.7	8.3 ± 9.7	0.167
Fusion	55	31	14	6	4	0.270
Revision	3	1	0	2	0	0.046

Values are presented as the number of patients (%) or mean ± SD, unless indicated otherwise.

such as CT and radiography.^{19–21} Rentenberger et al.¹ had used a grading scale defined by Marchi et al.¹¹ to report subsidence. The scale proposed by Marchi et al. (which is the one used in our study) uses a continuous quantitative variable (percentage of subsidence) and is reported in an ordinal fashion (4-point severity scale); furthermore, they defined grades 0 and I as mild subsidence and grades II and III as severe subsidence.¹³ One reason that we used the grading scale published by Marchi et al. is that the scale uses plain radiographs to assess subsidence. In our practice, plain radiographs are obtained preoperatively,

TABLE 2. Revision surgery rate, disc height, and segmental height loss in mild and severe subsidence groups

Variable	Subsidence Grade		p Value
	Mild (0–I)	Severe (II–III)	
Mean disc height loss (mm)	1.3 ± 1.9	2.9 ± 1.2	0.046
Mean segmental height loss (mm)	4.1 ± 5.0	8.1 ± 8.7	0.029
Revision surgery rate	1/55 (1.8%)	2/13 (15.4%)	0.032

FIG. 5. An ROC curve evaluating segmental HU values and cage subsidence.

within 1 month postoperatively, and 6 weeks, 3 months, 6 months, 1 year, and 2 years postoperatively. CT images are not routinely obtained postoperatively, and thus, using a grading scale based on plain radiographs would allow our study to be most consistent with previously published methods.^{13,19} In our study, when assessing the disc height loss and segmental height loss, there were no significant differences among the 4 grades, but when assessing by mild (grades 0 and I) and severe subsidence (grades II and III), the severe subsidence group had more loss of disc height and segmental height loss. Marchi et al. also defined severe subsidence as segmental height loss greater than 6 mm, which is consistent with our results of an average of

more than 8 mm of segmental height loss in the severe subsidence cohort.¹¹

Previous reports have shown that older age, female sex, endplate injury, endplate cystic lesion (Schmorl's nodes), cage size, unilateral pedicle screw fixation, and osteoporosis may be risk factors for cage subsidence.^{1-4,22} Because osteoporosis reflects low BMD, it is important to consider BMD prior to LLIF.²³⁻²⁵ As a general rule, bone density is measured by DXA, but not all patients obtain a preoperative DXA scan. It is also very important to ensure that the DXA value be measured at the hip because the spine (which should be measured at L1-4) may have degenerative changes or deformity that make the spine DXA inaccurate. In addition, the International Society for Clinical Densitometry has official statement positions regarding DXA and measurement of bone density as reference.^{26,27} However, many authors have advocated that CT HU values can serve as a potential proxy to DXA given the moderate correlation between HU values and osteoporosis.^{5,7,9,10,28} Another reason that HUs on preoperative CT are valuable as opposed to DXA is that it can be readily measured on the PACS, a system that nearly all modern medical centers use. For instance, in our study, 93 of 138 patients who underwent single-level LLIF had preoperative CT scans, but only 12 of 138 patients had a DXA scan before surgery. Zaidi et al. have shown correlation between HU values and success of lumbar fusions.²⁸ Mi et al. showed that in patients undergoing transforaminal lumbar interbody fusion with unilateral pedicle screw fixation, lower HU values were significantly associated with subsidence (113.4 vs 127.9 HUs, $p < 0.05$).⁴ To our knowledge, there is very limited literature published about HUs and subsidence in LLIF. Because Mi et al. showed significant subsidence with unilateral pedicle screw fixation, we only included patients with single-level LLIF and bilateral pedicle screw fixation. Patients with standalone cages, anterior plate or screw fixation, unilateral pedicle screws, expandable cages, or integrated screw-cage constructs were all excluded. In our study, both preoperative global HU values and segmental HU values had significant differences among the four subsidence groups ($p < 0.001$), with lower HU values having greater subsidence. We also found that

TABLE 3. Univariate and multivariate analysis of risk factors for cage subsidence

Variable	Univariate Analysis		Multivariate Analysis	
	OR (95% CI)	p Value	OR (95% CI)	p Value
Age	1.067 (0.308–3.689)	0.919		
Sex	2.581 (0.639–10.422)	0.183	5.317 (0.772–36.629)	0.090
Smoking status	1.068 (0.199–5.748)	0.939		
BMI	1.094 (0.315–3.799)	0.888		
Cage length	1.069 (0.911–1.255)	0.411		
Cage width	1.600 (0.453–5.652)	0.465		
Cage height	1.578 (0.835–2.979)	0.160	1.930 (0.875–4.261)	0.103
Cage lordosis	1.102 (0.976–1.243)	0.116	1.143 (0.971–1.346)	0.108
Level of LLIF	0.540 (0.261–1.116)	0.096	0.654 (0.234–1.832)	0.419
Segmental HU	18.000 (2.182–148.486)	0.007	15.694 (1.621–151.961)	0.017

lower segmental HU values were independent risk factors for severe cage subsidence ($p = 0.017$, OR 15.694, 95% CI 1.621–151.961). We found that patients with HU values of less than 135.02 were 15.694 times more likely to develop severe cage subsidence compared to those with HU values of more than 135.02. An HU value of 110 has previously been reported as a cutoff for osteoporosis.^{29,30} Because of this, we divided the patients into groups above and below the 110 HU threshold and calculated the percentages of subsidence and nonsubsidence. Of the patients with HU values lower than 110, 80% (12/15) had cage subsidence, and in patients with HU values higher than 110, 35.8% (19/53) had cage subsidence ($p = 0.002$).

To keep the number of confounding variables as low as possible, we excluded patients with factors that could have affected cage settling, i.e., endplate violations during surgery, steroid use, or teriparatide use. We also excluded patients who had factors that could have affected the HU measurements such as patients with prior fusion, endplate anomalies, or Schmorl's nodes. Although very few patients in this study had preoperative DXA, we evaluated the data to see if there was any correlation. There were 10 patients who had preoperative DXA, 7 cases in the mild subsidence group and 3 cases in the severe subsidence group, and the mean T-score was -1.34 ± 0.9 versus -2.33 ± 0.9 ($p = 0.196$). Thus, the numbers were small, the p value was not significant, and the cohorts were underpowered to make any meaningful statement.

There are limitations to this study. First, this is a retrospective, single-center study. A multicenter study with a larger sample size would have been more representative. Second, the study size is relatively small. Although there was a total of 68 patients analyzed, when subgrouping them into 4 grades, the statistical power is decreased, and the study may have been underpowered to accurately assess each of the 4 grades. Thus, the power was increased when grouping the patients into 2 groups (mild and severe subsidence). Larger studies with more patients regarding this topic will be very useful. Another limitation is that because there were so few patients with DXA scans (only 10), correlation of HU, DXA, and subsidence could not be performed. However, many other studies have already evaluated HU and DXA results, and they have shown good correlation between the two. Moreover, our study focused specifically on HUs and subsidence after LLIF, and not necessarily on DXA findings. Ideally, having more patients with DXA would also be useful. Nonetheless, our findings do corroborate the findings of other authors that HUs are associated with poor bone density, and because of low BMD, there is an increased association with subsidence. With regard to clinical management, if patients are found to have low HU values by CT, they are sent for a formal DXA evaluation. If the DXA shows osteoporosis, the surgery is postponed, and the patient is placed on a parathyroid hormone analog. The medication is administered for a minimum of 3 months, but ideally 6–12 months. However, some patients who are in severe, disabling pain may undergo surgery at 3 months. In cases of osteopenia, the magnitude of surgery and surgical goals are considered before surgery. For instance, if the patient simply needs an LLIF in a fairly mobile segment for spondylolisthesis, then

surgery is reasonable to proceed. However, if the patient has severe scoliosis requiring resection of osteophytes in the anterior spine, or significant correction, they may be placed on medication prior to proceeding with surgery.

Conclusions

Lower HU values on preoperative CT correlate with severity of cage subsidence after LLIF, with patients having HU values less than 135.02 being 15.694 times more likely to develop severe cage subsidence. Preoperative CT measurement of HUs may be a useful tool to assess bone quality prior to LLIF surgery.

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Author Contributions

Conception and design: Chou. Acquisition of data: Xi, Wang. Analysis and interpretation of data: Xi. Drafting the article: Xi, Chou. Critically revising the article: Mummaneni, Burch, Berven, Chou. Reviewed submitted version of manuscript: Mummaneni, Berven, Chou. Statistical analysis: Xi, Wang, Chou. Administrative/technical/material support: Mummaneni, Ruan, Burch, Deviren, Clark, Berven. Study supervision: Mummaneni, Chou.

Supplemental Information

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