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Original Article

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Disuse Bone Loss in Fusion Constructs After Multilevel Lumbar Fusion: A Computed Tomography Hounsfield Unit Analysis

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Objective: To evaluate long-term bone quality changes within the fusion construct (FC) after 2- to 3-level lumbar fusion using computed tomography (CT)-derived Hounsfield units (HUs).
Methods: Among 520 screened patients, 222 who underwent 2- to 3-level posterior lumbar interbody fusion met the inclusion criteria. HU values were measured on CT scans preoperatively, at 1-year postoperative, and at final follow-up. The percentage change in HU (HU [final–pre]%) was calculated for each vertebral level.
Results: At the final follow-up, the FC demonstrated a significant decline in HU compared to preoperative values (median [10th–90th percentile], 132.0 [86.5–220.4]; 95% confidence interval [CI], 116.0–142.5 vs. 124.5 [71.0– 210.0]; 109.8–135.1; HU (final–pre)%: -11.0 [-62.0 to 48.5]; -19.9 to -6.1; $p < 0.001$). In contrast, HU increased significantly at the uppermost instrumented vertebra (HU (final–pre)%: median [10th–90th percentile], 28.3 [-19.9 to 102.9]; 95% CI, 21.1–36.4; $p < 0.001$), likely reflecting increased mechanical demands. Subgroup analysis revealed a more pronounced decline in HU in patients with longer follow-up durations, particularly in the FC group ($p = 0.003$).
Conclusion: CT-derived HU revealed progressive trabecular bone loss within FC over time after lumbar fusion. In patients with longer postoperative intervals, clinicians should remain aware of the potential weakening of the FC, which has important implications when considering implant removal or planning revision surgery.

Keywords: Lumbar fusion surgery, Hounsfield unit, Bone mineral density, Stress shielding, Fusion construct, Computed tomography

INTRODUCTION

Bone remodeling, which is essential for maintaining bone quality, requires mechanical stress.[1] Particularly in multilevel fusion surgeries, the segments between the uppermost and lowermost instrumented vertebrae (UIV and LIV, respectively) become immobilized, reducing mechanical stress and potentially degrading bone quality postsurgery.[2,3]

Bone quality is conventionally measured using dual-energy x-ray absorptiometry (DEXA), the prevailing method in current practice.[4] However, in spines with degeneration, scoliosis, or osteophytes, bone mineral density (BMD) and T scores measured using DEXA can be inaccurately high, making it difficult to assess bone quality accurately.[5,6] Because these inaccuracies limit the reliability of DEXA in postoperative and degenerative spines, a more robust imaging-based method is required.

Computed tomography (CT) measurements of BMD within specified regions of interest (ROIs) using Hounsfield units (HUs) were developed as an alternative capable of overcoming metal artifacts and providing more direct assessment of trabecular bone density.[7] CT measurements of HU in the spinal ROI correlate with BMD measurements obtained via DEXA. Other studies have demonstrated the interobserver, intraobserver, and interexamination reliabilities of these HU measurements.[7,8] Wanderman et al.[9] introduced a method for measuring instrumented segments using HU on CT, thereby facilitating accurate assessments. Several studies have reported that HU in the spine can be used as a predictor of pathologic and osteoporotic fractures. Zhang et al.[10-12] indicated that HU has a higher predictive efficacy for frailty fractures than vertebral bone quality measured by DEXA or magnetic resonance imaging. Although the bone quality of adjacent segments increases, changes in bone quality within the fused segment are not well understood.[13]

This study investigated the decline in bone quality within immobilized fusion segments over time, a crucial consideration for surgeons performing complex surgeries. Therefore, this research aims to explore trends in bone quality over time in each segment following fusion surgery during long-term follow-up, with a level-specific analysis that considered potential confounding factors, contributing significantly to the field.

MATERIALS AND METHODS

1. Study Population

This single-center retrospective study was approved by the Institutional Review Board of Gangnam Severance Hospital (3-2024-0192), which waived the requirement for informed consent. Conducted by 3 surgeons at a single institution between January 2012 and January 2022, this study included patients who underwent posterior lumbar interbody fusion using PEEK (polyetheretherketone) cages and pedicle screw fixation for degenerative lumbosacral diseases between L2 and S1.

The inclusion criteria were patients aged 20 years or older who underwent fusion surgery involving 2–3 segments and had preoperative CT scans as well as follow-up CT scans at least 2 years postsurgery. Exclusion criteria were patients with tumors, congenital disorders, deformities, or infections; those who had undergone revision surgery; patients who developed vertebral fractures during the follow-up period; and those diagnosed with osteoporosis (DEXA Tscore at the femoral neck $\leq$ -2.5).[14] Patients who used medications affecting bone formation, such as bisphosphonates, denosumab, romosozumab, or teriparatide, before surgery and during the follow-up period were excluded.

2. HU Assessment of the Instrumented and Adjacent Spine

HU assessment was performed using the technique described by Schreiber et al.[7] for noninstrumented vertebrae, where an ROI was drawn on axial cuts at the midpedicle, encapsulating the maximum cancellous bone volume while avoiding the cortical bone. All patients underwent DEXA and CT scans within 2 months prior to surgery. For instrumented vertebrae, the method described by Wanderman et al.[9] was used to measure the ROI in the first axial cut caudal to the instrumentation-induced halo, ensuring that measurements were taken at the same location on preoperative imaging. All measurements were calculated as the average HU values using a picture archiving and communication system (Centricity PACS, version 3.0, GE Healthcare, Chicago, IL, USA). The widest possible elliptical region was drawn while excluding the cortical margin in axial cuts.

The level between the UIV and LIV was referred to as the fusion construct (FC) in this study. In cases of 3- to 4-level surgeries, 2 to 3 vertebrae were considered the FC; therefore, the average HU values of these FCs were used to represent the HU of the FC. For example, in an L3-4-5-S1 fusion surgery, L4 and L5 were considered FCs, and their HU values were averaged (Fig. 1).

The time interval between the date of surgery and the last CT scan was calculated. HU values were measured preoperatively, 1-year postoperative, and at the final follow-up. The percentage change in HU (HU [final–pre]%) was calculated as ([final follow-up HU–preoperative HU]/preoperative HU) $\times$ 100. Additionally, patients were divided into subgroups based on the follow-up period to analyze changes in bone quality over longer follow-up durations. In addition, the reason for postoperative CT imaging was classified into 3 categories based on clinical context: (1) check-up, performed in patients without specific symptoms; (2) pain, obtained in cases with persistent low back or leg pain despite no abnormal findings on radiographs; and (3) adjacent segment disease (ASD), performed to evaluate adjacent segment degeneration and determine the need for revision surgery. HU measurements were independently performed by 2 board-certified spine neurosurgeons, each with more than 5 years of clinical experience, who were blinded to patient clinical information. Each observer repeated the measurements twice at a 1-month interval, and the average of the 4 measurements was used for analysis. The intra- and interobserver reliability was excellent across all levels, with intraclass correlation coefficients ranging from 0.823 to 0.973 (Supplementary Table 1).

3. Statistical Analysis

All statistical analyses were performed using IBM SPSS Sta-

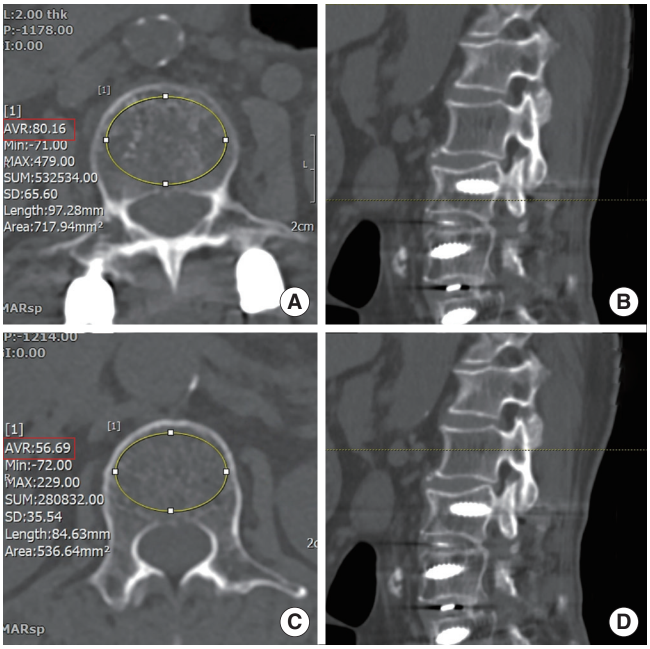

Fig. 1. Example of Hounsfield unit (HU) assessment at instrumented and noninstrumented levels. This patient underwent L3–S1 fusion surgery. (A) Example of HU measurement at an instrumented vertebra. The region of interest (ROI) was drawn to encapsulate the maximum cancellous bone volume while avoiding cortical bone. The average HU measured was 80.16. (B) Sagittal computed tomography (CT) image corresponding to the axial slice shown in panel A. HU measurements at instrumented levels were obtained on the first axial cut caudal to the instrumentation-induced halo. (C) Example of HU measurement at a noninstrumented vertebra, using the same ROI method as in panel A. The average HU measured was 56.69. (D) Sagittal CT image corresponding to the axial slice shown in panel C. HU was measured on axial cuts taken at the midpedicle level for noninstrumented vertebrae.

tistics ver. 27.0 (IBM Co., USA). The normality of data distribution was assessed using the Shapiro-Wilk test. Normally distributed values were expressed as mean ± standard deviation, and comparisons were made using the t-test or 1-way analysis of variance, as appropriate. Nonnormally distributed values were expressed as the median [10th percentile–90th percentile], and group comparisons were performed using nonparametric tests: the Mann-Whitney U-test for 2-group comparisons, the Kruskal-Wallis test for multiple-group comparisons, and the Wilcoxon rank-sum test (paired) with Bonferroni correction for *post hoc* analysis. To identify independent factors affecting HU (final–pre)%, we performed multivariable linear regression analyses using robust (HC3) standard errors. The dependent variable was HU (final–pre)% for each vertebral level (UIV+2, UIV+1, UIV, FC, and LIV), and the following covariates were included: age, sex, baseline BMD, BMI, smoking, steroid use, number of fusion levels, mean cage height, presence of nonunion, and follow-up period. Statistical significance was defined as $p < 0.05$.

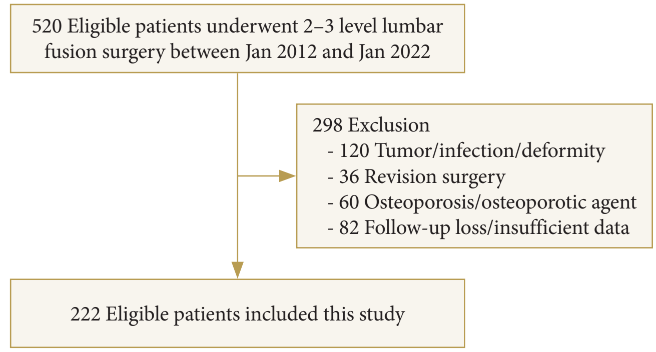

Fig. 2. Flowchart of the patient enrollment process.

RESULTS

We initially screened 520 patients who underwent 2- to 3-level lumbar fusion surgery. After applying the inclusion and exclusion criteria, our final study cohort consisted of 222 individuals (Fig. 2), of whom 64.4% were female (n = 143). The median age at the time of surgery was 65 (61.0–70.0) years. The fusion surgery levels included 2 segments in 85 patients (38.3%) and 3 segments in 137 patients (61.7%), with a median follow-up period of 45 (range, 24-177) months. Preoperative femoral neck BMD was 0.7 (0.6–0.9) g/cm^2, and the T score was -0.8 ± 1.1, while the preoperative total spine BMD was 1.0 (0.9–1.1) g/cm^2 with a T score of -0.2 (-1.1 to 1.0). The median HU values from L2 to S1 were 124.0, 113.8, 116.0, 132.0, and 154.5, respectively, with S1 being the highest. The correlation coefficient (r) between femoral neck BMD T score and HU at each level ranged from 0.42 to 0.53 ($p < 0.05$), while for total spine BMD, it ranged from 0.52 to 0.59 ($p < 0.05$). This indicates that comparing preoperative HU values with those obtained after instrumentation is reasonable (Supplement Table 2).

Fifty patients in the cohort had immediate postoperative CT scans (within 1 week postoperatively). We compared the preoperative and immediate postoperative HU from L1 to S1 to evaluate the validity of HU measurements obtained from postoperative CTs without instrumentation. Preoperative median HU values for L1–S1 were 131.0, 126.0, 122.5, 129.0, 153.0, and 179.5, respectively. Immediate postoperative values were 135.5, 113.5, 122.5, 128.5, 151.0, and 175.5. Wilcoxon signed-rank test p-values for preoperative versus immediate postoperative HUs were

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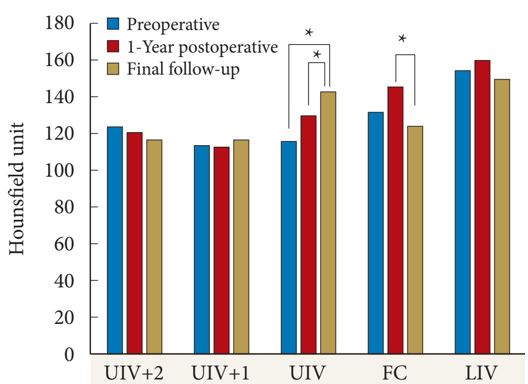
Table 1. Comparison of preoperative and immediate postoperative Hounsfield unit (HU) values at each level (n = 50)

Level	Preoperative	Immediate postoperative	p-value
L1	131.0 (97.0–165.2)	135.5 (100.2–163.5)	0.348
L2	126.0 (92.5–158.8)	113.5 (95.8–160.8)	0.105
L3	122.5 (90.5–162.8)	122.5 (92.8–166.0)	0.185
L4	129.0 (102.8–175.5)	128.5 (103.0–172.8)	0.214
L5	153.0 (108.2–217.5)	151.0 (111.0–218.0)	0.260
S1	179.5 (149.8–249.8)	175.5 (144.8–228.0)	0.348

Values are presented as median (10th percentile–90th percentile).
p-values were calculated using the Wilcoxon signed-rank test for paired samples.
The p-values indicate that there is no significant statistical difference in HU values before and after surgery at any vertebral level, as determined by the paired t-test (all p-values > 0.05).
Data was obtained from a subset of 50 patients (out of 222 total) who underwent both preoperative and immediate postoperative computed tomography scans.



	UIV+2	UIV+1	UIV	FC	LIV
Preoperative	124.0	113.8	116.0	132.0	154.5
1-Year postoperative	121.0	113.0	130.0	145.5	160.0
Final follow-up	117.0	117.0	143.0	124.5	150.0

Level

Fig. 3. Changes in Hounsfield unit (HU) over time at different vertebral levels. This graph illustrates changes in HU values at different vertebral levels (UIV+2, UIV+1, UIV, FC, and LIV) at 3 time points: preoperatively, 1 year postoperatively, and at the final follow-up. Significant differences in HU (final–pre)% were observed at UIV, and FC. In the *post hoc* analysis, HU at the UIV was significantly higher at the final follow-up compared with both the preoperative and 1-year postoperative measurements, while HU at the FC was significantly lower at the final follow-up compared with the 1-year postoperative value (*p < 0.05). These values correspond to the median HU at each time point, as presented in Table 3. UIV, uppermost instrumented vertebra; FC, fusion construct; LIV, lowermost instrumented vertebra.

Table 2. Comparison of Hounsfield unit (HU) values and percentage change in HU (HU [final–pre]%) across vertebral levels

Variable	Preoperative (HU)	1-Year postop (HU)	Final follow-up (HU)	ΔHU (final–1-year postop)	HU (final–pre)%	p-value	*Post hoc* comparison
UIV+2	124.0 (78.2–191.9)	121.0 (80.2–199.9)	117.0 (75.0–193.9)	-0.5 (-35.9 to 31.6)	-1.2 (-38.0 to 31.9)	0.723	NS
UIV+1	113.8 (70.1–190.7)	113.0 (71.3–193.9)	117.0 (78.9–206.8)	5.0 (-29.9 to 58.6)	7.1 (-34.0 to 61.9)	0.075	NS
UIV	116.0 (71.1–196.0)	130.0 (76.0–216.9)	143.0 (91.0–262.0)	15.0 (-37.8 to 85.0)	28.3 (-19.9 to 102.9)	< 0.001	Final – preop, p < 0.001 Final – (1-year postop), p = 0.006
FC	132.0 (86.5–220.4)	145.5 (90.1–235.4)	124.5 (71.0–210.0)	-15.5 (-71.0 to 22.5)	-11.0 (-62.0 to 48.5)	< 0.001	Final – (1-year postop), p = 0.001
LIV	154.5 (90.2–267.0)	160.0 (98.0–269.9)	150.0 (91.0–278.4)	-6.0 (-62.0 to 61.0)	-1.7 (-64.9 to 67.9)	0.549	NS

Values are presented as median (10th percentile–90th percentile).
HU (final–pre)% represents the percentage change in HU from the preoperative to the final follow-up, calculated as ([final follow-up HU–preoperative HU]/preoperative HU) × 100.
p-values were obtained using the Kruskal-Wallis test with Bonferroni-corrected *post hoc* pairwise comparisons (Wilcoxon rank-sum test [paired]).
UIV, upper instrumented vertebra; FC, fusion construct; LIV, lower instrumented vertebra; postop, postoperative; preop, preoperative; NS, not statistically significant.

0.348, 0.105, 0.185, 0.214, 0.260, and 0.348, respectively, indicating no statistically significant differences in HU values before and immediately after surgery at any vertebral level (Table 1).

At final follow-up (124.5 [71.0–210.0]), FC showed a significant decrease in HU compared with the preoperative value (132.0 [86.5–220.4]; HU (final–pre)% = -11.0 [-62.0 to 48.5]; 95% confidence interval (CI), -19.9 to -6.1; $p < 0.001$). *Post hoc* analysis revealed a significant decrease between 1-year postoperative and final follow-up ($p = 0.001$). In contrast, the UIV level demonstrated a significant HU increase at final follow-up (143.0 [91.0–262.0]) compared with the preoperative value (116.0 [71.1–196.0]; HU (final–pre)% = 28.3 [-19.9 to 102.9]; 95% CI, 21.1–36.4; $p < 0.001$). *Post hoc* comparisons showed a significant increase between 1-year postoperative and final follow-up ($p = 0.006$) and between preoperative and final follow-up ($p < 0.001$). No significant HU changes were observed at the UIV+1, UIV+2, or LIV levels ($p = 0.075$, $p = 0.723$, and $p = 0.549$, respectively) (Table 2, Fig. 3).

To assess differences in HU values at each level according to follow-up duration, we stratified patients into subgroups based on follow-up periods (2, 3, 4, 5, 6, 7, and ≥ 8 years). The 3-year follow-up group comprised the largest number of patients (n = 51), whereas the 7-year follow-up group included the fewest (n = 17). Significant differences in demographic characteristics were observed across these subgroups. Patients with longer follow-up durations were younger ($p = 0.005$), with differences observed in fusion surgery levels ($p = 0.045$) and baseline femoral neck BMD ($p = 0.008$). The indication for CT acquisition also varied significantly ($p < 0.001$), shifting from routine check-ups in early follow-up to ASD evaluation in later years (Table 3). Regarding HU (final–pre)%, only FC demonstrated a significant difference across follow-up durations (2 years: -3% [-13% to 22%] vs. ≥ 8 years: -19% [-38% to -2%]; 95% CI for between-group difference, -22.5 to -7.3; $p = 0.003$). No significant changes were observed at the UIV+2, UIV+1, UIV, or LIV levels (Table 4, Fig. 4).

To account for potential confounding variables, multivariate linear regression analyses were conducted including age, BMD, body mass index, reason for CT acquisition, smoking, steroid use, fusion levels, average cage height, and nonunion. Results indicated that a longer follow-up period was significantly associated with HU reduction, especially at the FC ($\beta = -0.12$, p =

Table 3. Subgroup analysis comparing demographics by follow-up duration

Variable	Follow-up year							p-value
	2 (N = 32)	3 (N = 51)	4 (N = 39)	5 (N = 31)	6 (N = 22)	7 (N = 17)	Over 8 (N = 30)	
Sex, male:female	9:23 (28.1)	17:34 (33.3)	13:26 (33.3)	13:18 (41.9)	8:14 (36.4)	9:8 (52.9)	10:20 (33.3)	0.700
Age (yr)	64.4 ± 7.0	67.5 ± 7.8	66.7 ± 6.0	64.5 ± 7.6	63.9 ± 10.0	62.2 ± 12.5	60.3 ± 8.1	0.005*
UIV, L2:L3:L4	6:24:2	12:39:0	10:27:2	7:24:0	8:14:0	1:16:0	4:25:1	0.311
LIV, L5:S1	18:14	29:22	20:19	17:14	11:11	9:8	21:9	0.789
Fusion level, 2:3 segments	15:17 (53.1)	18:33 (64.7)	12:27 (69.2)	10:21 (67.7)	4:18 (81.8)	8:9 (52.9)	18:12 (40.0)	0.045*
Reason for follow-up CT								< 0.001*
For check-up	22 (68.8)	10 (19.6)	11 (28.2)	5 (16.1)	7 (31.8)	6 (35.3)	6 (20.0)	
Pain	4 (12.5)	29 (56.9)	20 (51.3)	13 (41.9)	2 (9.1)	3 (17.6)	4 (13.3)	
Adjacent segment disease	6 (18.8)	12 (23.5)	8 (20.5)	13 (41.9)	13 (59.1)	8 (47.1)	20 (66.7)	
Baseline BMD								
Femur neck (g/cm²)	0.8 ± 0.2	0.7 ± 0.2	0.7 ± 0.1	0.7 ± 0.1	0.8 ± 0.2	0.7 ± 0.1	0.8 ± 0.2	0.008*
Femur neck T score	-0.5 ± 1.2	-1.0 ± 0.9	-1.0 ± 1.0	-0.9 ± 1.1	-0.4 ± 1.2	-0.9 ± 1.1	-0.3 ± 1.2	0.072
Total spine (g/cm²)	1.0 ± 0.2	1.0 ± 0.2	1.0 ± 0.2	1.0 ± 0.2	1.0 ± 0.3	1.1 ± 0.3	1.0 ± 0.1	0.327
Total spine T score	-0.2 ± 1.1	-0.0 ± 1.5	0.2 ± 1.7	0.2 ± 1.5	0.3 ± 2.1	0.5 ± 2.3	-0.5 ± 1.1	0.486

Values are presented as number (%), mean ± standard deviation, or median (10th percentile–90th percentile).
HU (final–pre)% represents the percentage change in HU from preoperative to final follow-up. Depending on the distributional characteristics of each variable, group comparisons were performed using analysis of variance or the Kruskal-Wallis test for continuous variables, and Fisher exact test for categorical variables.
UIV, upper instrumented vertebra; LIV, lower instrumented vertebra; CT, computed tomography; BMD, bone mineral density; HU, Hounsfield unit.
*$p < 0.05$, statistically significant differences.

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Table 4. Subgroup analysis comparing Hounsfield unit (HU) by follow-up duration

Variable	Follow-up year							p-value
	2 (N = 32)	3 (N = 51)	4 (N = 39)	5 (N = 31)	6 (N = 22)	7 (N = 17)	Over 8 (N = 30)	
Baseline HU								
UIV+2	116.4 (89.0–148.5)	101.0 (89.0–128.9)	124.0 (98.5–141.5)	135.0 (105.0–164.0)	129.5 (116.0–165.0)	144.0 (94.0–181.6)	136.0 (116.0–170.0)	0.014*
UIV+1	106.5 (87.5–132.6)	99.0 (77.0–132.5)	112.0 (87.5–137.0)	125.0 (96.0–160.5)	119.5 (107.0–163.0)	130.0 (92.0–152.0)	131.1 (101.0–169.0)	0.045*
UIV	115.8 (90.8–129.0)	101.0 (76.0–134.0)	113.0 (94.2–144.5)	124.0 (89.7–156.5)	118.5 (102.0–143.0)	133.0 (93.0–156.0)	130.3 (92.0–160.7)	0.195
FC	131.0 (103.5–189.5)	116.0 (95.0–146.0)	129.5 (101.0–155.0)	132.0 (111.0–179.0)	146.2 (118.0–201.0)	132.0 (98.0–173.0)	148.5 (114.5–167.0)	0.168
LIV	137.9 (116.5–210.8)	134.0 (105.5–191.0)	158.0 (112.0–201.0)	169.0 (140.5–195.0)	173.0 (140.0–243.0)	159.4 (132.0–180.0)	152.0 (116.0–211.0)	0.353
Final follow-up								
UIV+2	108.3 (90.5–128.5)	110.0 (89.5–139.0)	111.0 (93.5–146.5)	131.0 (98.0–181.0)	127.0 (110.0–139.0)	135.0 (101.0–176.0)	125.8 (97.0–158.0)	0.217
UIV+1	111.0 (92.5–130.3)	111.0 (90.5–147.0)	117.0 (101.0–147.5)	140.0 (102.0–181.5)	131.5 (109.0–179.0)	115.0 (92.0–197.0)	118.0 (103.0–155.0)	0.216
UIV	135.5 (118.5–181.5)	131.0 (101.0–187.0)	151.0 (127.5–182.5)	152.0 (119.0–236.0)	145.5 (105.0–223.0)	132.0 (97.0–210.0)	153.0 (123.0–184.9)	0.728
FC	139.1 (110.0–164.0)	127.0 (91.5–171.5)	129.0 (98.0–157.7)	119.5 (94.2–203.0)	118.2 (103.1–133.9)	105.5 (88.0–163.0)	114.2 (84.0–155.0)	0.399
LIV	151.5 (115.5–213.5)	151.0 (116.5–205.0)	152.0 (108.5–211.5)	159.0 (117.5–246.5)	189.0 (146.0–238.0)	137.0 (106.0–220.0)	120.5 (104.0–190.4)	0.305
HU (final–pre)%								
UIV+2	-2 (-15 to 7)	4 (-14 to 17)	1 (-9 to 18)	4 (-13 to 18)	-10 (-15 to 6)	-17 (-21 to 3)	-6 (-27 to 17)	0.229
UIV+1	5 (-10 to 28)	12 (-11 to 30)	15 (1–29)	-1 (-10 to 54)	2 (-10 to 44)	9 (-16 to 29)	0 (-18 to 15)	0.304
UIV	43 (1–71)	20 (5–72)	42 (7–85)	27 (14–60)	25 (-8 to 44)	6 (-12 to 19)	14 (-2 to 41)	0.164
FC	-3 (-13 to 22)	4 (-15 to 27)	-1 (-24 to 21)	-7 (-29 to 14)	-18 (-28 to -3)	-22 (-39 to -6)	-19 (-38 to -2)	0.003*
LIV	-2 (-12 to 19)	2 (-12 to 29)	3 (-13 to 19)	-1 (-21 to 22)	0 (-9 to 14)	-14 (-22 to 4)	-11 (-32 to 3)	0.120

Values are presented as median (10th percentile–90th percentile).
HU (final–pre) represents the percentage change in HU from preoperative to final follow-up. Depending on the distributional characteristics of each variable, group comparisons were performed using analysis of variance or the Kruskal-Wallis test for continuous variables, and Fisher exact test for categorical variables.
UIV, upper instrumented vertebra; LIV, lower instrumented vertebra; FC, fusion construct.
*$p < 0.05$, statistically significant differences.

0.004) and UIV ($\beta = -0.08$, $p = 0.017$). At the FC level, nonunion was associated with less HU decline ($\beta = 0.09$, $p = 0.031$), while at the LIV, a greater number of fused levels showed a significant association with HU reduction ($\beta = -0.11$, $p = 0.022$). No significant predictors were identified at the UIV+1 or UIV+2 levels. (Table 5).

DISCUSSION

This study primarily examined long-term changes in bone quality within the FC following multilevel lumbar fusion surgery.

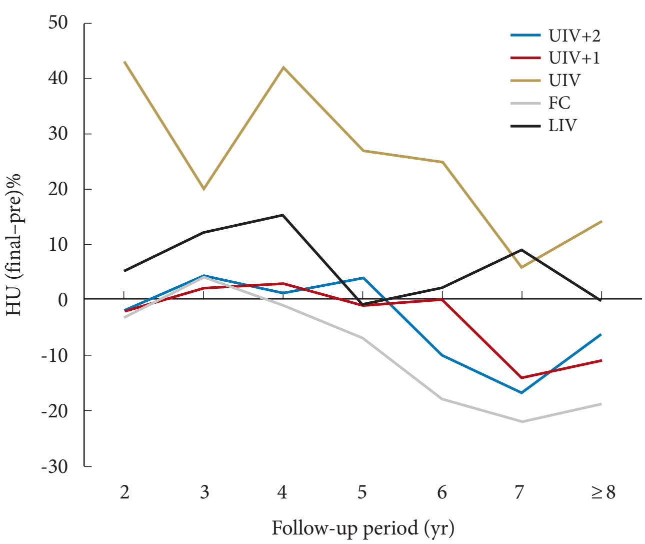

Fig. 4. HU (final–pre)% across vertebral levels by follow-up duration. This figure illustrates the percentage change in Hounsfield unit (HU [final–pre]%) across different vertebral levels, categorized by follow-up duration (2, 3, 4, 5, 6, 7, and 8 years). The data represent the median HU (final–pre)% values for each level, demonstrating how bone quality changes between the preoperative and final follow-up periods. UIV, uppermost instrumented vertebra; FC, fusion construct; LIV, lowermost instrumented vertebra.

Our results indicated that at the final follow-up, the FC demonstrated significant bone loss compared with preoperative measurements (HU [final–pre]%: -11.0 [-62.0 to 48.5], $p < 0.001$). Notably, while HU values at UIV increased—possibly reflecting increased mechanical loading and localized bone sclerosis due to adjacent segment degeneration—the FC exhibited a distinct decline.[15,16] In multivariable analyses including follow-up duration and other covariates, longer follow-up periods were independently associated with a greater HU reduction at the FC and UIV, but not at the LIV, UIV+1, and UIV+2. These results suggest that time-dependent remodeling and mechanical unloading within the fusion segment contribute to progressive bone density loss, particularly at the central and upper portions of the construct.

Although HU values at the UIV consistently increased compared with preoperative measurements, the magnitude of this increase diminished over time.[17] Prior studies have reported that lower HU at the UIV may predispose patients to adjacent-level fractures; however, individuals who developed such fractures during follow-up were excluded from our cohort, which may partly explain the relatively elevated HU observed at the UIV.[18] In contrast, the FC showed a true decline in HU relative to baseline, suggesting a more clinically meaningful deterioration in bone quality over time. Interestingly, the presence of nonunion at the FC was associated with less HU decline ($\beta = 0.09$, $p = 0.031$). This may reflect localized sclerosis induced by micromotion or reduced stress-shielding effects in segments that had not fully fused.[19] At the LIV, a greater number of fused levels was significantly related to HU reduction, suggesting that longer constructs may impose greater mechanical unloading on distal vertebrae, although supporting biomechanical data remain limited.

The reduction of mechanical stress on bone leads to decreased osteoclast-mediated bone resorption and osteoblast-mediated

Table 5. Multivariable linear regression for factors associated with HU (final–pre)%

Level	Significant variables (β [95% CI])	p-value	R^2
UIV+2	-	-	0.07
UIV+1	-	-	0.08
UIV	Follow-up period (mo): -0.08 (-0.15 to -0.02)	0.017	0.18
FC	Follow-up period (mo): -0.12 (-0.20 to -0.04)/presence of nonunion: 0.09 (0.02–0.16)	0.004/0.031	0.21
LIV	No. of fusion levels: -0.11 (-0.19 to -0.03)	0.022	0.16

Values represent regression coefficients (β) and p-values derived from multivariable linear regression analyses adjusted for age, sex, baseline bone mineral density, body mass index, smoking, steroid use, number of fusion levels, cage height, presence of nonunion, and follow-up period (months).
HU, Hounsfield unit; UIV, uppermost instrumented vertebra; FC, fusion construct; LIV, lowermost instrumented vertebra.

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bone formation.[20,21] Several previous studies have highlighted the influence of mechanical unloading on bone remodeling, and spinal instrumentation is known to contribute to such stress redistribution.[22-24] Consequently, it has been suggested that after implant removal, the FC may be at risk for fractures and that during fusion extension procedures, bridging between the original and new implants may be necessary.[23] For example, Lipscomb et al.[25] reported that bone quality initially declined due to postoperative bracing but gradually increased by the first postoperative year. In another study by Swart et al.,[26] which analyzed HU values after an average of 35 years following Harrington rod placement, the mid-construct fused segment demonstrated the lowest HU compared to other spinal regions. However, studies directly measuring long-term BMD within the FC itself remain limited. Our findings expand on previous literature by providing level-specific, multivariable-adjusted analyses of HU changes over time, encompassing not only the FC but also the UIV, LIV, and adjacent levels (UIV+1 and UIV+2).

The subgroup analyses stratified by follow-up duration further highlighted the complexity of these changes. While caution is warranted due to demographic differences, such as variations in age, baseline BMD, and fusion surgery level, the data consistently show that patients with longer follow-up periods experience a more marked decline in FC HU.[13,25] In our study, based on median values, HU in the FC began to show negative changes compared to preoperative values starting from year 4; in UIV+1 and LIV, this decline began from year 5, and in UIV+2, from year 6. In the subgroup with the longest follow-up duration (≥8 years), the HU (final–pre)% at the FC had a median of -19%, indicating a substantially greater decline than in other segments (UIV+2, -6%; UIV+1, 0%; UIV, 14%; LIV, -11%). Over time, this resulted in a significant decline in bone quality, as reflected by our HU measurements. Conversely, increased mechanical demands at the UIV, may stimulate bone formation, resulting in transient increases in HU.

These findings have significant clinical implications. Traditional imaging modalities like DEXA often fail to capture localized changes in bone quality, particularly within the FC.[7,15] CT-derived HU, while not a replacement for DEXA, may serve as a valuable adjunct for evaluating bone quality at specific vertebral levels.[9] The similarity of HU measurements between preoperative and immediate postoperative CT scans suggests that postoperative CT-based HU assessment remains reliable even in the presence of instrumentation. Given the progressive bone loss observed within the FC, particularly in patients with extended follow-up durations, patients with long-standing FCs may benefit from closer surveillance and potentially earlier interventions to mitigate further bone loss.[27] Notably, from 4 years postoperatively onward, the decline in HU at the FC indicates that surgeons should exercise greater caution regarding bone quality when removing screws from the FC.

Our study has some limitations. The retrospective design and extended data acquisition period of 10 years introduced inherent biases, including potential variations in surgical techniques, patients activity level and instrumentation over time. In addition, our patient cohort was heterogeneous, with a wide age range and varying degrees of preoperative bone quality. The exclusion of patients with osteoporosis or those receiving bone-modifying agents, as well as the restriction of fusion levels to the lower lumbar segments, may further limit the generalizability of our findings. HU measurement provides a useful surrogate for bone quality, some variability is inevitable due to slice selection, region-of-interest placement, and metallic artifacts. Ideally, postoperative HU changes should be evaluated in noninstrumented (posterolateral fusion only) cases; however, such procedures are rarely performed in current clinical practice, making this approach impractical. In our study, the inter- and intraobserver reliability for HU measurement showed excellent agreement, consistent with previous reports, indicating minimal measurement bias.[9] Although the indications for CT acquisition differed among follow-up year subgroups, raising the possibility of selection bias, the multivariate linear regression analysis demonstrated that CT indication was not significantly associated with HU changes, suggesting that its effect on the main outcomes was minimal. While we focused on trabecular bone quality as assessed by HU measurements, cortical bone—which also plays a critical role in spinal stability—was not evaluated.[28-30] Longitudinal observation of HU changes within the same patient using multiple CT scans over time would be ideal. In clinical practice, however, follow-up periods are heterogeneous across patients, and it is possible that symptomatic individuals were more likely to undergo long-term follow-up. Nevertheless, due to the risks associated with radiation exposure from frequent CT scans, conducting such longitudinal observational studies is challenging.[31,32] Despite these limitations, a strength of our study is that it provides an indirect means of predicting changes in bone quality over time at different surgical sites, using HU on CT as a complementary assessment tool.

In summary, our study demonstrated that significant bone loss occurred in the FC at the final follow-up, with the degree of bone loss becoming more pronounced as the follow-up period increased. While changes at other vertebral levels provide addi-

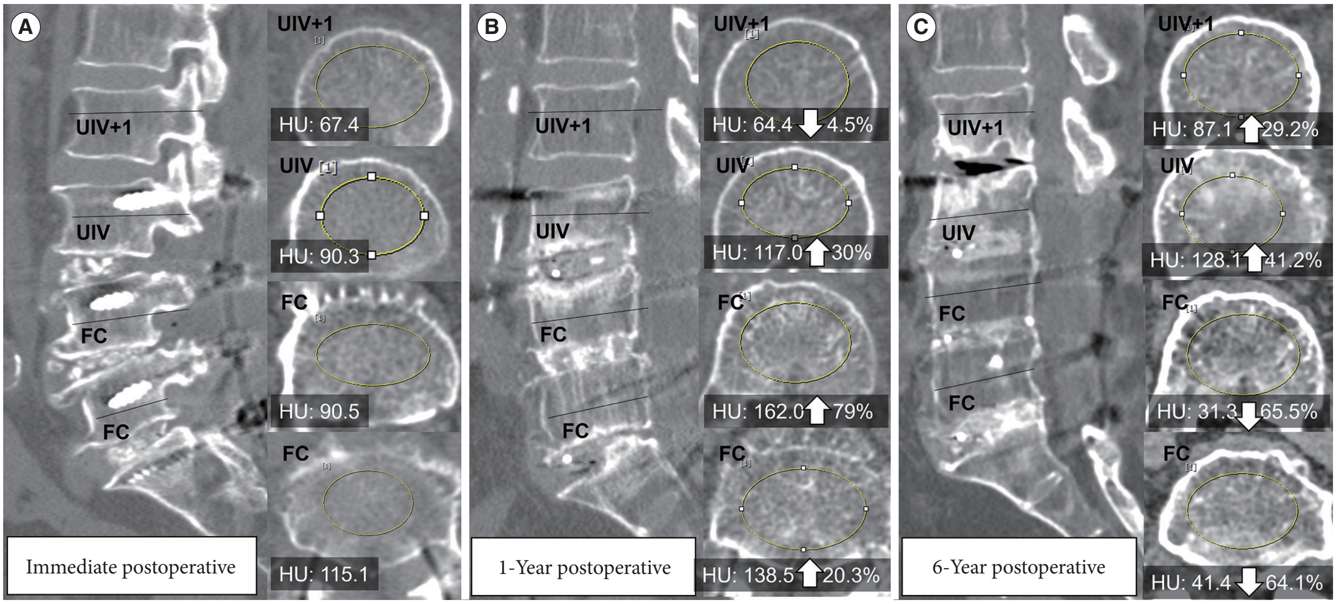

Fig. 5. Illustrative case of Hounsfield unit (HU) assessment over time in multilevel lumbar fusion surgery. (A) Immediate postoperative computed tomography (CT) scan showing HU measurements at different vertebral levels, including uppermost instrumented vertebra (UIV)+1, UIV, and the fusion construct (FC). (B) CT scan at the 1-year postoperative, demonstrating changes in HU values. (C) CT scan at the 6-year postoperative follow-up, showing further HU changes over a longer period. Each column displays axial cuts with HU measurements at various vertebral levels. Arrows indicate the percentage change in HU values compared to the immediate postoperative period. Upward arrows represent an increase in HU values, while downward arrows indicate a decrease. Notably, HU values increased at the 1-year follow-up but decreased significantly by the 6-year follow-up, particularly at the FC, suggesting bone quality degradation due to disuse osteoporosis.

tional context, the FC emerges as the primary site of concern. These findings not only reinforce the utility of CT-derived HU measurements in postoperative monitoring but also highlight the need for tailored long-term management strategies to preserve bone quality within the FC. When performing procedures such as screw removal or revision in patients with long-standing FCs, surgeons should be aware of the potential for substantial bone quality deterioration within the FC (Fig. 5). Preoperative efforts to evaluate and optimize bone quality may therefore be necessary to minimize intraoperative risks and improve surgical outcomes. Future prospective studies with more frequent imaging intervals and larger, homogeneous cohorts are necessary to further delineate these relationships and develop effective interventions to counteract stress shielding in patients with lumbar fusion.

CONCLUSION

Multilevel lumbar fusion is associated with progressive trabecular bone loss within the FC, as demonstrated by declining CT-derived HU values at long-term follow-up. This deterioration becomes more pronounced in patients with longer postoperative intervals, highlighting the need for careful assessment of fusion-site bone quality when considering implant removal or revision surgery.

NOTES

Supplementary Materials: Supplementary Tables 1-2 are available at https://doi.org/10.14245/ns.2551272.636.

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