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Fusion cage with ipsilateral-impaction bone grafting in treating lumbar spinal stenosis combined with segmental instability

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Abstract

Background: This study investigates the feasibility and effectiveness of a fusion cage with ipsilateral-impaction bone grafting (IIBG) for treating lumbar spinal stenosis (LSS) combined with segmental instability.

Methods: From January 2018 to December 2021, 282 LSS patients undergoing minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF) at Union Hospital were enrolled (164 IIBG vs. 118 controls). The cohort comprised 97 males and 185 females (mean age 62.75 ± 6.88 years; body mass index [BMI] 24.02 ± 2.58 kg/m^2). Surgical levels included 218 single-level (L3–L4: 5, L4–L5: 113, L5–S1: 100), 42 double-level (L3–L5), and 22 multi-level (L3–S1) fusions. Visual analogue scale (VAS) and Oswestry disability index (ODI) were used to assess the severity of pain and spinal nerve function before surgery, as well as at one month, six months, and 12 months after surgery. Besides, the MacNab criteria were used to evaluate clinical efficacy at the last follow-up. Imaging indicators refer to the preoperative and postoperative ratio of intervertebral height and bone grafting area to vertebral body area. Fusion status was evaluated via the Bridwell Grade on 1-year computed tomography (CT).

Results: The mean operative time was 94.11 ± 38.11 min (range 68–238 min), with an intraoperative blood loss of 90.82 ± 40.35 mL (range 20–150 mL). Follow-up visits were conducted among all 282 patients, with an average follow-up time of 22.44 ± 6.84 months (range 12–34 months). Preoperative VAS of lower back pain and lower limb pain was 6.99 ± 1.42 points and 7.80 ± 1.33 points, respectively, which showed statistical differences ($F = 2{,}290.00$, $p < 0.001$; $F = 3{,}307.17$, $p < 0.001$) compared with postoperative results. The scores decreased to 2.20 ± 0.85 and 2.03 ± 0.84 at one month after surgery, 1.56 ± 0.60 and 1.51 ± 0.50 at six months after surgery, 0.89 ± 0.69 and 0.89 ± 0.69 at one year after surgery, and 0.85 ± 0.70 and 0.87 ± 0.69 at the last follow-up. ODI was 54.47 ± 2.89% (range 50%–59%) before surgery, 25.50 ± 2.88% (range 21%–30%) at one month after surgery, 15.02 ± 3.14% (range 10%–20%) at six months after surgery, 12.50 ± 1.71% (range 10%–15%) at one year after surgery, and 12.51 ± 1.71% (range 50%–59%) at the last follow-up; the difference was significant ($F = 734.432$, $p < 0.001$). MacNab criteria indicated excellent outcomes in 209 cases, good outcomes in 58 cases, and fair outcomes in 15 cases, with excellent and good results of 92.74% among all 282 patients. Mean intervertebral height was 5.72 ± 1.39 mm (range 3.14–8.34 mm) before surgery, 13.21 ± 0.43 mm (range 12.46–13.98 mm) after surgery, and 11.62 ± 0.22 mm (range 11.10–11.99 mm) at the last follow-up; the difference was significant ($F = 6{,}082.37$, $p < 0.001$). Postoperative CT revealed that the bone grafting area (including cage) at the ipsilateral level accounted for 33.63 ± 3.42% (range 32.56%–39.02%) of the vertebral endplate area in the IIBG group, which was significantly different ($T = 31.35$, $p < 0.001$) from the control group (22.83 ± 1.79%, range 18.57%–26.30%). CT at one year after surgery pointed out that significantly more patients in the IIBG group (91.5%, range 87.3%–95.7%) achieved successful fusion (Grade I or II in Bridwell) than the control group (76.53%, range 69.1%–83.9%), with a K value of 12.50 and a p value less than 0.001. Furthermore, a 3-year postoperative CT follow-up in a subset of patients consistently demonstrated more robust and extensive bridging bone formation across the entire disc space in the IIBG group, in contrast to the control group, where bridging bone was primarily confined within the cage windows. Besides, eight cases (4.8%) and 11 cases (9.3%) in the two groups appeared to have cage subsidence, but the difference was insignificant ($K = 2.03$, $p = 0.154$). Three patients (1.0%) developed bone graft particles breaking through the anterior longitudinal ligament, but this did not cause vascular injury. Complications included CSF leakage (0.7%), pedicle screw misplacement (0.7%), and screw revision (0.3%).

Conclusions: A fusion cage with ipsilateral impaction bone grafting ensures not only a large bone graft area outside the cage but also a shorter bone bridging distance between endplates and denser impaction of bone graft particles. Thus, this technique appears to be a safer impaction bone grafting method that provides a better environment for intervertebral fusion.

Abbreviations: BMD = bone mineral density, BMI = body mass index, IIBG = ipsilateral impaction bone grafting, LSS = lumbar spinal stenosis, MIS-TLIF = minimally invasive transforaminal lumbar interbody fusion, ODI = oswestry disability index, VAS = visual analogue scale.

Keywords: computed tomography, fusion cages, interbody fusion, ipsilateral-impaction bone grafting, minimally invasive, treatment outcome

1. Introduction

Lumbar interbody fusion (LIF) is an effective method for treating lumbar spinal stenosis (LSS) complicated by lumbar segmental instability, achieving clinical efficacy through decompression with fusion stabilization. Current surgical approaches include anterior, lateral, and posterior methods. The posterior approach is the most commonly used surgical approach in clinical applications. Minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF) is a modified TLIF technique that preserves paraspinal musculature through tubular retractors or self-retaining systems.[1] Relative to open TLIF, MIS-TLIF reduces hospitalization duration and facilitates accelerated recovery.[2,3] However, owing to limited visualization during disc space preparation, MIS-TLIF has limitations in disc space release, disc removal, endplate treatment, fusion cage placement, and bone grafting. The failure of fusion and stabilization in the late stage will lead to an increased incidence of complications such as pseudarthrosis, loosening and fracture of spinal implants, and subsidence of fusion cages, resulting in unfavorable clinical outcomes.[4,5]

Compared with the anterior and lateral approaches, the posterior approach is limited by the width of the fusion cage because it should pass through the spinal canal area. Thus, TLIF pseudarthrosis still exists, with an incidence rate of 7% to 20%.[6] A larger fusion cage and more bone grafts can increase the intervertebral fusion rate.[7] However, anatomical constraints limit cage dimensions, and a fusion cage that is too large will increase the risk of nerve root injury. Overall, MIS-TLIF causes higher incidences of fusion cage subsidence and pseudarthrosis than anterior/lateral fusion surgery.[6]

Therefore, intervertebral disc space treatment, endplate treatment, placement of fusion cages, and sufficient bone grafting are the critical determinants of surgical success.[8] Intracage bridging bone (Incbb) and extracage bridging bone (Excbb) are two key interbody fusion bone grafting points. It has been reported that the quality of bone grafts from fusion cages plays a key role in intervertebral fusion.[9] The location of the bone graft fusion cages can be categorized into anterior, lateral (ipsilateral and contralateral), and posterior.[10] Although anterior-impacted bone grafts benefit the anterior lordotic reconstruction of the intervertebral disc space, excessive anterior-impacted bone grafts are not conducive to the implantation depth of fusion cages. If overpacked, it may cause the breakthrough of the bone graft into the anterior longitudinal ligament, entering the abdominal cavity. Posterior bone grafting can carry potential graft migration into the spinal canal and cause neurological symptoms due to its inability to stabilize at the grafting site after surgery. Lateral bone grafting comprises ipsilateral and contralateral bone grafting. Excessive contralateral bone grafting can affect the placement of fusion cages. If the fusion cages that allow decompression are placed too high, they may provoke contralateral symptoms. Therefore, we introduced the IIBG technique with fusion cages in this study.

Our study evaluated the clinical efficacy and imaging results by introducing the key technical points of ipsilateral impaction bone grafting with fusion cages.

2. Materials and methods

2.1. Study participants

We retrospectively reviewed the clinical efficacy of MIS-TLIF (with or without ipsilateral impaction bone grafting [IIBG]) for patients with persistent lower back pain, leg pain, or neurological symptoms secondary to lumbar instability who failed 3-month conservative treatment. All patients were consecutively enrolled based on surgical date (January 2018–December 2021), and the grouping of the IIBG group versus the control group was based on the surgeon's technique preference (some surgeons preferred the IIBG technique). The consolidated standards of reporting trials (CONSORT) flowchart details the patient screening, exclusion, grouping, follow-up, and analysis procedures.

Inclusion and exclusion criteria: Patients were included if they had received surgical intervention and had documented preoperative and postoperative visual analogue scale (VAS) and Oswestry disability index (ODI) scores, along with relevant imaging follow-up ≥ 12 months. Patients with a history of lumbar surgery; Individuals with comorbidities (mental illness or Alzheimer dementia) unable to complete outcome measures and subsequent follow-up; A fatal error is found in the patient's scale, or data are considered not available by two specialists.

This retrospective study was approved by the Ethics Committee of Union Hospital, Tongji Medical College, Huazhong University of Science and Technology, China(approval No. 2021-059, March 1, 2024). The requirement for written informed consent was waived by the committee due to the retrospective nature of the study. Patient data were anonymized before analysis, and all procedures were performed in accordance with the

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Declaration of Helsinki. This study constitutes level IV evidence (retrospective cohort study) and adheres to the Oxford Centre for Evidence-Based Medicine guidelines (OCEBM Level IV).

2.2. Baseline characteristics

Preoperatively, patients underwent routine lumbar spine X-rays (anteroposterior and lateral views and flexion-extension views), lumbar spine computed tomography (CT) scans, three-dimensional (3D) reconstructions, and magnetic resonance imaging (MRI) examinations. The treatment outcomes were evaluated before surgery, one month, six months, and one year after surgery, including VAS scores for back pain and leg pain, ODI scores, and MacNab satisfaction. All patients underwent anteroposterior, lateral, and dynamic radiographs before surgery, one month, six months, and one year after surgery. The fusion level was assessed by sagittal and coronal CT reconstruction imaging one year after surgery.[11] Fusion levels I-IV are based on the Bridwell fusion rating.[12] Levels 1 and 2 were suggestive of successful fusion. The last comprehensive follow-up was performed in May 2024. According to the sagittal and coronal CT images, the subsidence degree of the fusion cage was classified into no subsidence, subsidence < 2 mm, and subsidence more than 2 mm. Subsidence of more than 2 mm was considered clinically significant. Continuous variables were compared using independent *t* tests. Categorical variables were analyzed with chi-square tests. A P value of < 0.05 was deemed statistically significant.

3. Key points of surgical techniques

3.1. Anesthesia and patient positioning

After general anesthesia, the patient was positioned prone on a radiolucent table with chest and iliac supports to allow abdominal decompression. The table height and patient position were adjusted to facilitate C-arm fluoroscopy and provide an ergonomic surgical window perpendicular to the floor.

3.2. Positioning, line scratching, disinfection, and draping

Anatomical landmarks were marked on the skin under fluoroscopic guidance. For a single-level procedure, a single spinal needle was used to project the disc space; for multilevel procedures, pedicle projections were marked. Bilateral paramedian skin incisions (approximately 3 cm from the midline) were then drawn. Routine disinfection and draping followed.

3.3. Incision and exposure

Bilateral small incisions were made: one incision was used for intermuscular space decompression and fusion cage insertion, and the other incision was used for intermuscular space screw placement. The skin, superficial, and deep fascia were opened successively according to the predrawn line position. A pencil-tip dissection technique was utilized to cut open the intermuscular space, seek the position of the superior and inferior facet joints, and push away the soft tissue around the two articular processes.

A self-retaining retractor was positioned to displace paraspinal musculature, and the residual tissues under the automatic hook were removed to expose the bone surface. After finding the pars interarticularis on the outer side of the facet joints (on the cephalad side) at seven o'clock, an incision was made on the outer side of the pars interarticularis, a channel was created, and a marker was placed. The correct segment was confirmed by fluoroscopy again.

3.4. Bone removal and spinal canal decompression

The soft tissues surrounding the bone surface were removed to identify anatomical structures. At first, the inferior articular process was resected, followed by osteotomy on the superior articular process parallel to the caudal articular process of caudal facet joints, with the inner boundary to be the root of the spinous process and the vertebral plate transition area, caudal boundary slightly higher than the cephalad side, corresponding to the contralateral vertebral plate. Since the disc spaces at the L4/L5 and L5/S1 levels were tilted, the bone removal on the cephalad side can be slightly enlarged to avoid affecting the placement angle of the cage. Second, the apex of the superior articular process was excised. The superior articular process consisted primarily of the apex, the lower mastoid process, and the medial aspect. TLIF mainly excises the apex to expose the intervertebral disc space, with the boundary parallel to the superior pedicle cortex. The apical cortex of the superior articular process at the base extends to the cortical bone of the pedicle's superior fence (Fig. 1A). A nerve hook was used to probe the hinge area, and a burr was used to create a groove at the base to prevent splitting into the pedicle's superior wall.

At this stage, the ligamentum flavum was exposed. However, for severe spinal canal stenosis or large disc protrusions, over-the-top decompression should be performed before spinal canal decompression. Over-the-top decompression requires adequate bone removal. The superior boundary was the cranial ligamentum flavum insertion, and the medial boundary was the midline of the ligamentum flavum. Residual bone at the spinous process root was maximally removed.

The superficial layer of the ligamentum flavum was excised, leaving the deep layer intact. The deep ligamentum flavum has two breakthrough sites to expose the dural sac: one is at the junction between the superior vertebral plate and the spinous process, and the other is at the intersection between the superior articular process in the lower vertebral body and the inferior outer side of the lower vertebral plate. Hofmann ligament exists around the dura mater, including the space between the nerve sleeve and the ligamentum flavum, as well as the space between the dura mater and the ligamentum flavum. If

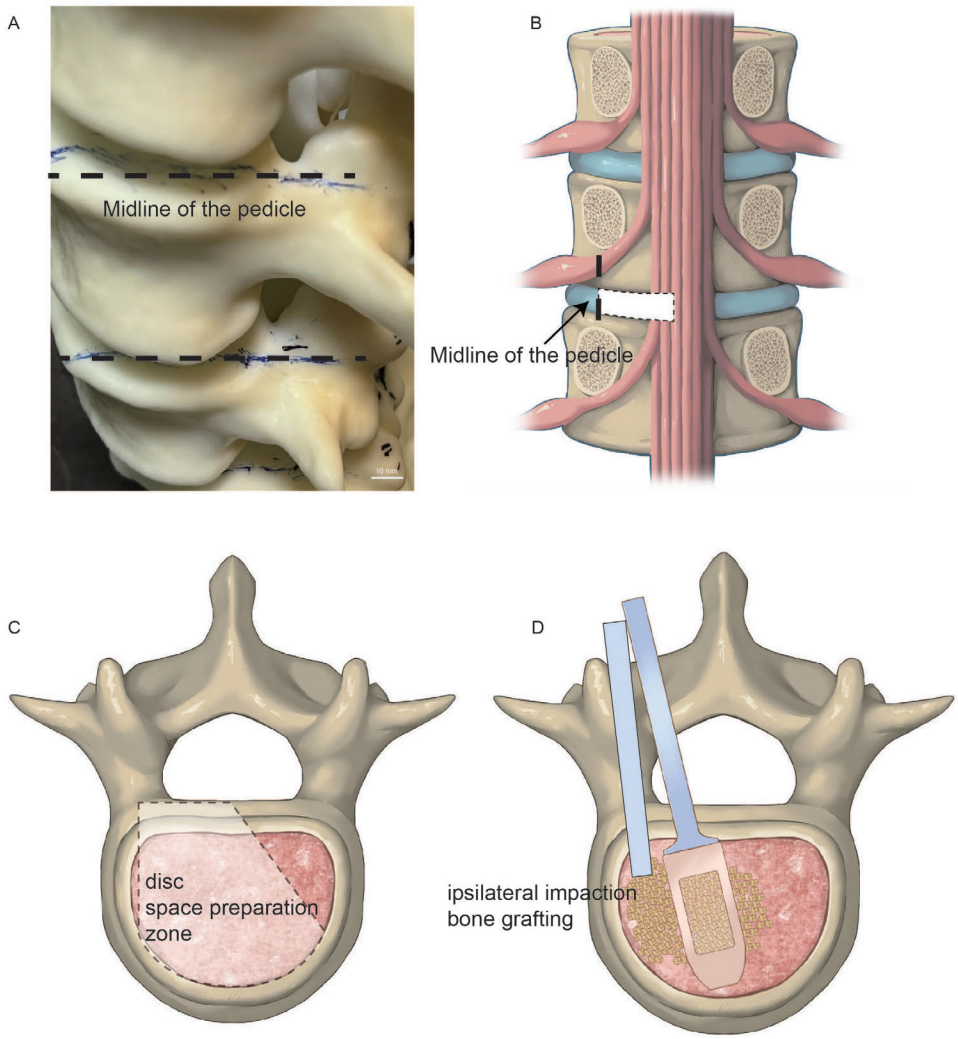


Figure 1. Schematic diagram of the IIBG procedure. (A) The lateral boundary of the IIBG zone is defined by the midline of the pedicle. The superior articular process has been resected to expose the disc space. (B) The annulotomy window is created with its medial border at the spinal canal midline and its lateral border at the mid-pedicular line (dashed line). (C) The shaded area indicates the extent of complete disc space preparation, including nucleus pulposus removal and cartilaginous endplate curettage. (D) Following cage placement in a slightly contralateral position, the remaining ipsilateral space is filled with impacted autograft. IIBG = ipsilateral impaction bone grafting.

forcibly torn, the broken Hofmann ligament may cause cerebrospinal fluid leakage due to dural disruption. It is recommended that the deep ligamentum flavum be carefully separated and cut with a bipolar or sharp knife and then removed during the process of dural sac exposure.

3.5. Intervertebral disc space treatment

Following complete annular fenestration, the disc space was decompressed through nucleus pulposus evacuation under direct visualization. Cartilaginous endplates were carefully denuded using curettage, with sequential irrigation confirming complete removal of residual tissue.

The epidural space was accessed using a nerve hook, and bipolar cautery was applied for preliminary hemostasis to maintain clear vision. The intervertebral disc space was incised with a sharp knife to ensure the inner and outer boundaries were in place: the inner side should be close to the midline of the vertebral body, and the outer side should be at the midline of the lower vertebral body pedicle. The nucleus pulposus forceps were adopted to remove the incised annulus fibrosus, and pituitary rongeurs were then systematically applied to eliminate the residual annulus fibrosus edges and corners, exposing the intervertebral disc space treatment window (the outer side close to the midline of the inferior pedicle) (Fig. 1B). This way, the intervertebral disc space treatment was more thorough and safe.

After partial removal of the nucleus pulposus with pituitary rongeurs, a cylindrical trial was used to sequentially dilate and mobilize the disc space. Residual disc fragments were then removed. The intervertebral disc space with bones of good quality was further sequentially dilated using graded rasps in succession; nucleus pulposus forceps were again adopted to clean the residual nucleus pulposus and scrape off the cartilage endplates of the upper and lower endplates (preserving endplate integrity to prevent hemorrhagic complications). For those with

bones of good quality, a reverse curette was applied to treat the upper and lower cartilage endplates again, and angled nucleotomy instruments were utilized to remove the residual nucleus pulposus and cartilage endplates in the intervertebral disc space. After thoroughly treating the intervertebral disc space, it was rinsed with normal saline (Fig. 1C).

After a few contralateral and anterior bone grafts, the fusion cage is then placed, followed by ipsilateral impaction bone grafting (Fig. 1D).

3.6. Bone grafting, fusion cage insertion, and impaction bone grafting from the side of the fusion cage

Autogenous bone grafts were delivered via a specialized bone graft funnel (Fig. 2A, B), and the morselized bone fragments were moved to the opposite side of the intervertebral disc space. Then, we impacted the autografts forward at L5/S1, and the cage was angled at 45° during insertion. The cage was placed in the middle, slightly contralateral to the vertebra, preserving space for ipsilateral graft impaction bone grafting. After cage insertion, the lateral window required a width of 0.8 to 1.0 cm. An 8 mm reamer was used to decorticate the adjacent space next to the cage and eliminate the residual soft tissue again. Bone grafting devices were employed to load all the remaining autografts into the side of the fusion cage, and the impactor of the bone grafting devices was used to tamp the column beside the fusion cage (Fig. 2C).

3.7. Screw insertion, rod bending, and rod mounting

The screw placement required meticulous attention to the protection of the articular process and capsule of the adjacent segment on the cephalad side, as well as screw head-induced irritation, to prevent accelerating the degeneration of the adjacent segment. The cephalad screws should not be placed exceeding superior articular margins. Optimal positioning required an inferior and lateral placement, slightly inferior and laterally positioned. Additionally, the screws should not be inserted too deeply to reduce the irritation and pressure from the screw tail on the facet joints.

Caudal screws should not be positioned too inferiorly or even block the pedicle's superior wall, as too deep insertion of inferior pedicle screws may cause damage to the cortical bone. Otherwise, patients with elevated pelvic incidence (PI) and sacral slope (SS), osteoporosis, or high body weight will have a risk of distal segment spondylolysis or even spondylolisthesis. These screws should be inserted slightly superiorly, laterally, and not too deeply to reduce tail-caused pressure and damage to the cortical bone. Before insertion of contralateral caudal screws, routine decompression of the facet joints is recommended.

For lumbar spondylolisthesis, we first used a reduction device to reposition the displaced vertebra. Afterward, a prebent short rod (contoured to appropriate length) was inserted into the screw tail. The tail cap was tightened at the cephalad end to provide suspension for reduction. For patients without spondylolisthesis, the cephalad tail cap was pulled first, followed by posterior compression to enhance lordosis (this compression better aligns with

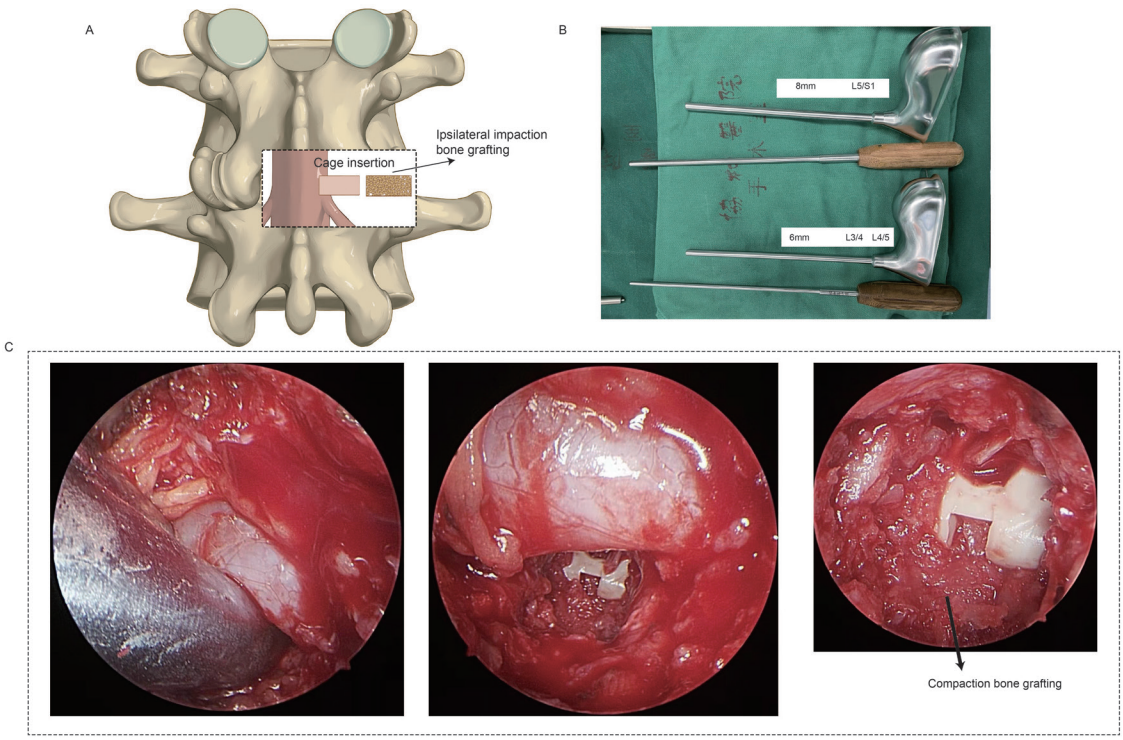


Figure 2. Intraoperative procedures of ipsilateral impaction bone grafting. (A) Cage insertion and position of ipsilateral impaction bone grafting. (B) Bone grafting devices of two different sizes. (C) Intraoperative images of ipsilateral impaction bone grafts.

the curvature of the rod), and then the caudal screw tail cap was tightened.

3.8. Suture and postoperative management

A closed suction drain was placed, and the wound was closed in layers. The fascial layer was approximated using 1–0 sutures, followed by subcutaneous and subcuticular closure. Through the drainage volume observation, the drainage tube with a low drainage volume was maintained for 24 h or until the drainage volume was less than 50 mL for 24 h before removal. On the second day after surgery, the patients were instructed to wear waist protectors for out-of-bed activities. Generally, the patients are discharged four to five days after surgery.

4. Assessment criteria

Outpatient follow-up was conducted at one, six, and 12 months after surgery, and the final intensive follow-up was conducted in May 2024. Lumbar X-ray and CT examinations were carried out one year after surgery. The intraoperative blood loss and postoperative blood drainage were calculated. Clinical efficacy measures included VAS score for low back pain and lower limb pain, and ODI score for lumbar function. The overall efficacy was evaluated using the modified MacNab criteria: excellent, complete disappearance of symptoms and restoration to normal life; good, mild symptoms and limited mobility but no impact on daily life and work; fair, still obvious symptoms and restricted mobility, which affect normal life and work; poor, no relief of symptoms and no improvement and even worsening of limited mobility.

Imaging assessment parameters are intervertebral disc space height of the surgical segments before and after surgery; bone graft area (including the fusion cage) at the ipsilateral level after surgery; Bridwell fusion criteria: grade I—complete fusion with trabecular bridging, with bone remodeling and trabecular bone; grade II—intact graft, not entirely shaped or integrated, and no lucency; grade III—intact graft, with possible lucency at the top and bottom of the graft; level IV—no fusion, with bone graft resorption and collapse. These measurements were taken from CT scans before and after surgery, with the axial plane at the mid-disc level and the sagittal and coronal positions at the broadest part of the vertebral body. Measurements for large implant areas were taken using the picture archiving and communication system in the imaging department of Wuhan Union Hospital. All radiographic parameters were measured by an experienced spine surgeon, and the mean of three repeated measurements was reported.

5. Statistical processing

The necessary sample size was determined to be at least 120 cases per group, based on the variance in fusion rates documented in prior literature (anticipated effect size $\Delta = 15\%$), $\alpha = 0.05$, and test power = 80%. This study's IIBG group (148 cases) and the control group (134 cases) satisfied this criterion. Statistical analysis was conducted using the software SPSS 27.0 (SPSS Corporation). The measurement data (VAS for lower back pain, VAS for lower limb pain, ODI, intervertebral disc space height of the surgical segments, and proportion of bone graft) following a normal distribution were expressed in the form of mean ± standard deviation. The comparison at different time points before and after surgery was conducted using repeated measures analysis of variance and Tukey's multiple comparison test. Enumeration data (excellent and reasonable rate according to MacNab criteria, fusion rate) were described as frequency (n, %) and compared using the chi-square test. Statistical significance was defined as $P < 0.05$ (two-tailed).

6. Results

6.1. Baseline characteristics

The CONSORT flowchart shows that of the 282 patients finally included in the analysis, 148 were in the IIBG group and 134 were in the control group (Fig. 3). This study enrolled 97 male and 185 female patients with a mean age of 62.75 (45–78). In total, the study involved 368 segments, including 218 cases of single-level TLIF (45 cases for L3; 113 cases for L4L5; 100 cases for L5S1), 42 cases of double-level TLIF (L3–L5), and 22 cases of multi-level TLIF (L3–S1). The follow-up period for 282 patients was (22.44 ± 6.84) months (ranging from 12 to 34 months). The baseline characteristics of the patients are presented in Table 1. Table 2 indicates that the baseline characteristics of the two groups were adequately matched, encompassing sex, age, height, weight, body mass index (BMI), and bone mineral density (BMD).

6.2. Clinical efficacy

None of the patients received blood transfusions. The mean duration of operation was 94.11 ± 38.11 min (ranging from 68 to 238 min), intraoperative blood loss was 131.37 ± 47.52 mL (ranging from 50 to 200 mL), and postoperative blood drainage was 90.82 ± 40.35 mL (ranging from 20 to 150 mL). Preoperative VAS scores for lower back pain and lower limb pain were 6.99 ± 1.42 and 7.80 ± 1.33 points, respectively, and 1-month postsurgery scores were reduced to 2.20 ± 0.85 and 2.03 ± 0.84 points. The VAS scores were 1.56 ± 0.60 and 1.51 ± 0.50 points 6-month postsurgery, 0.89 ± 0.69 and 0.89 ± 0.69 points 1-year postsurgery, and 0.85 ± 0.70 and 0.87 ± 0.69 points at the final follow-up (Fig. 4A). The differences were statistically significant ($F = 2{,}290.00$, $p < 0.001$; $F = 3{,}307.17$, $p < 0.001$). The ODI values before surgery (Fig. 4B), one, six, and 12 months after surgery, and at the final follow-up were 54.47 ± 2.89% (a range of 50%–59%), 25.50 ± 2.88% (a range of 21%–30%), 15.02 ± 3.14% (a range of 10%–20%), 12.50 ± 1.71% (a range of 10%–15%), and 12.51 ± 1.71% (a range of 50%–59%), respectively, showing statistically significant differences ($F = 734.432$, $p < 0.001$). According to the

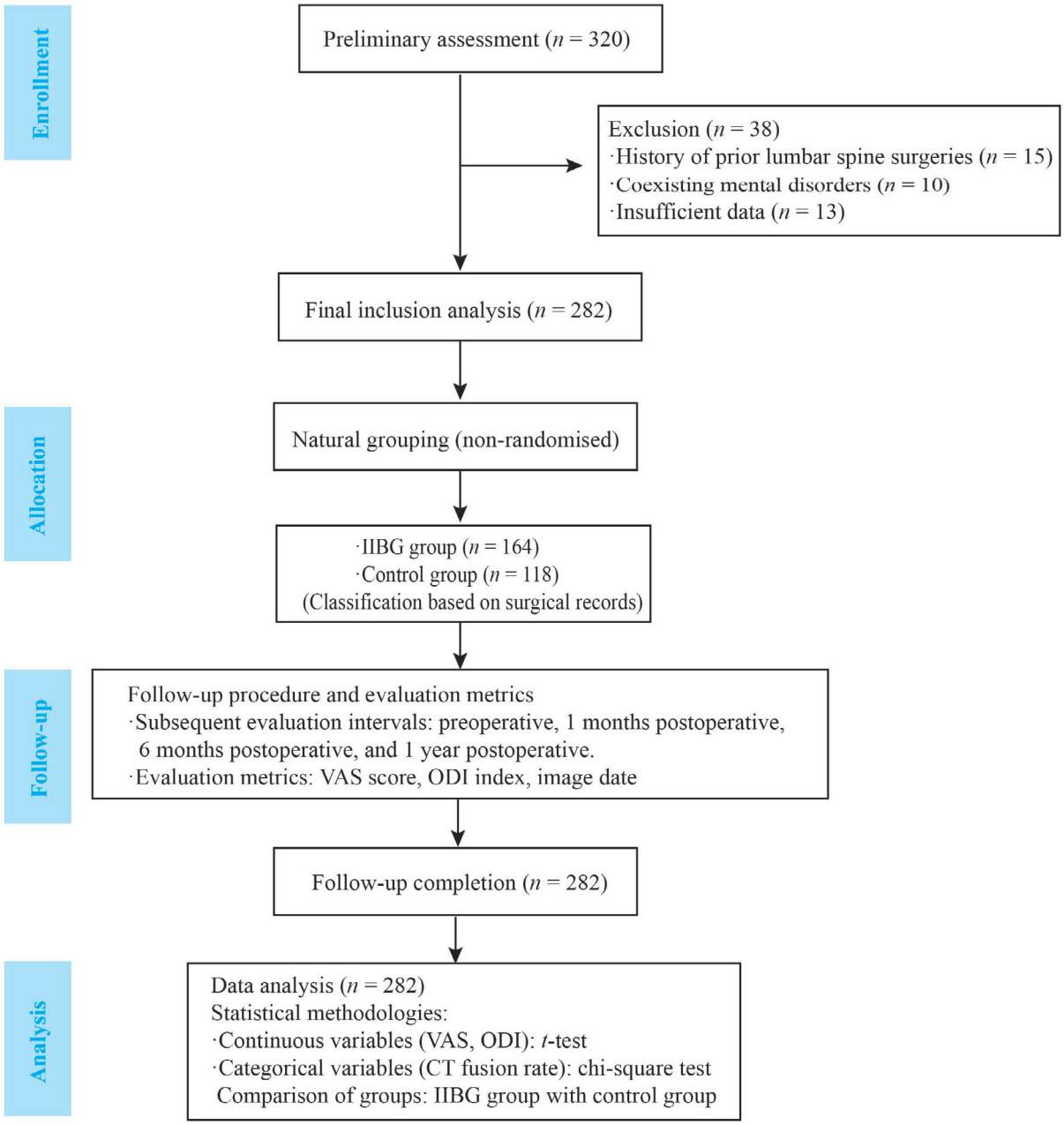


Figure 3. CONSORT flow chart for this retrospective cohort study. CT = computed tomography, IIBG = ipsilateral impaction bone grafting, ODI = Oswestry disability index, VAS = visual analogue scale.

MacNab criteria (Fig. 4C), among the 282 patients at the final follow-up, there were 209 cases of excellent fusion, 58 instances of good fusion, and 15 cases of fair fusion. One year after surgery, a CT scan showed that the IIBG group (91.5%, range 87.3%–95.7%) achieved successful fusion (Grade I or II in Bridwell) compared to the control group (76.53%, range 69.1%–83.9%). A significant difference was found regarding the successful fusion rate between the two groups ($\chi^2 = 12.50$, $p < 0.001$) (Fig. 4D).

6.3. Imaging results

Postoperative CT scan exhibited that the bone graft area (including the fusion cage) of patients in the IIBG group accounted for 33.63% ± 3.42% (32.56%–39.02%) of the bone endplate area, while that of patients in the no IIBG group accounted for 22.83% ± 1.79% (18.57%–26.30%) (Fig. 5A–D). The mean height of the intervertebral disc space was 5.72 ± 1.39 mm (3.14–8.34 mm), 13.21 ± 0.43 mm (12.46–113.98 mm), and 11.62 ± 0.22 mm (11.10–11.99 mm) before surgery, after surgery, and at the last follow-up, respectively, demonstrating a statistically significant difference ($F = 6,082.37$, $p < 0.001$) (Fig. 5E). A statistically significant difference was noted between the two groups ($T = 31.35$, $p < 0.001$) (Fig. 5F). At the 1-year follow-up, CT evaluation according to Bridwell criteria showed that the IIBG group achieved a significantly higher successful fusion rate

Table 1

Total subjects' baseline characteristics.

Characteristics	Total (n = 282)
Sex	
M: F	97:185
Age (year)	62.75 ± 6.88
Follow-up (month) (12–34)	22.44 ± 6.84
Fusion segment	
1	218
2	42
3	22
Segmental distribution	
L3/L4	69
L4/L5	177
L5/S1	164

Values are given as mean ± SD.
SD, standard deviation.

(grade I or II) of 91.5% compared with 76.53% in the control group (χ^2 = 12.50, p < 0.001). Although cage subsidence was observed in 8 cases (4.8%) in the IIBG group and 11 cases (9.3%) in the control group, this difference did not reach statistical significance (K = 2.03, p = 0.154).

Beyond the quantitative increase in graft volume, the structural advantages conferred by the IIBG technique were further elucidated on postoperative CT. In the IIBG group, the impacted bone particles formed a densely compacted lateral column adjacent to the cage. As shown in Figure 6A, this technique markedly shortened the inter-endplate bridging distance, while the crushed autografts were compressed into direct and extensive contact with the bony endplates (Fig. 6B). This optimized mechanical and biological microenvironment is considered a key factor in accelerating early bony union.

To assess the long-term stability of fusion, we obtained additional CT scans at the 3-year postoperative mark for 45 patients (25 from the IIBG group and 20 from the control group) who were randomly selected and agreed to participate in the extended follow-up. The imaging results revealed a striking difference in the pattern of bridging bone formation: in the control group, bridging bone was predominantly limited to the area within the cage's graft windows, with sparse or absent extracage bone formation (Fig. 7A–C). Conversely, in the IIBG group, continuous and mature bridging bone was observed spanning the entire intervertebral space, both inside and outside the cage (Fig. 7D–F). This qualitative evidence further substantiates the superior osteogenic environment and fusion potential afforded by the IIBG technique.

Meanwhile, there was no significant difference in VAS ratings (3.1 ± 1.2 vs. 2.8 ± 1.1, p = 0.23) and ODI (24.5% ± 6.8% vs. 22.1% ± 5.9%, p = 0.15) at the last check-up between patients who had subsidence (eight patients in the IIBG group and 11 patients in the control group) and those who did not have subsidence. No remarkable difference was detected based on the subsidence of the fusion cage (K = 2.03, p = 0.154).

Measurement methodology: the graft area (including the cage, red outline) and the vertebral endplate area (green outline) were traced on axial CT at the mid-disc level. The graft area ratio was calculated as graft area/endplate area × 100%.

6.4. Complications

Three cases showed bone graft granulates breaking through the anterior longitudinal ligament without vascular damage (Fig. 8). Surgical complications included two cases of cerebrospinal fluid leakage, two cases of misplacement of pedicle screws, and one case of revision of screws. During the follow-up, no screw loosening or cage retraction was found.

7. Discussion

7.1. Intervertebral disc space preparation and sufficient bone grafting

In this study, we introduced a new bone grafting method. MIS-TLIF effectively reduced patients' VAS scores and ODI values, and this technique has a low incidence of surgical complications. None of the patients received blood transfusions. Imaging data also showed a high fusion rate with few complications, such as fusion cage subsidence. The degree of intervertebral disc space treatment varies in different approaches.

Table 2

Subjects' baseline characteristics of both groups.

Characteristics	IIBG group	Control group	p value	Between-group difference
				(95% CI)
Sex				0.42
Male	80	50		
Female	88	64		
Age (year)	62.33 ± 7.18	63.17 ± 6.58	0.32	(–2.19 to 0.51)
Height (cm)	158.17 ± 10.90	160.86 ± 12.14	0.06	(–0.10 to 5.48)
Weight (kg)	64.54 ± 8.35	65.24 ± 4.16	0.93	(–1.61 to 1.47)
BMI (kg/m^2)	25.28 ± 6.98	25.21 ± 5.58	0.93	(–1.56 to 1.42)
BMD (g/cm^2)	1.10 ± 0.12	1.09 ± 0.14	0.83	(–0.07 to 0.09)

Values are given as mean ± SD.
BMI, body mass index; BMD, bone mineral density; SD, standard deviation.

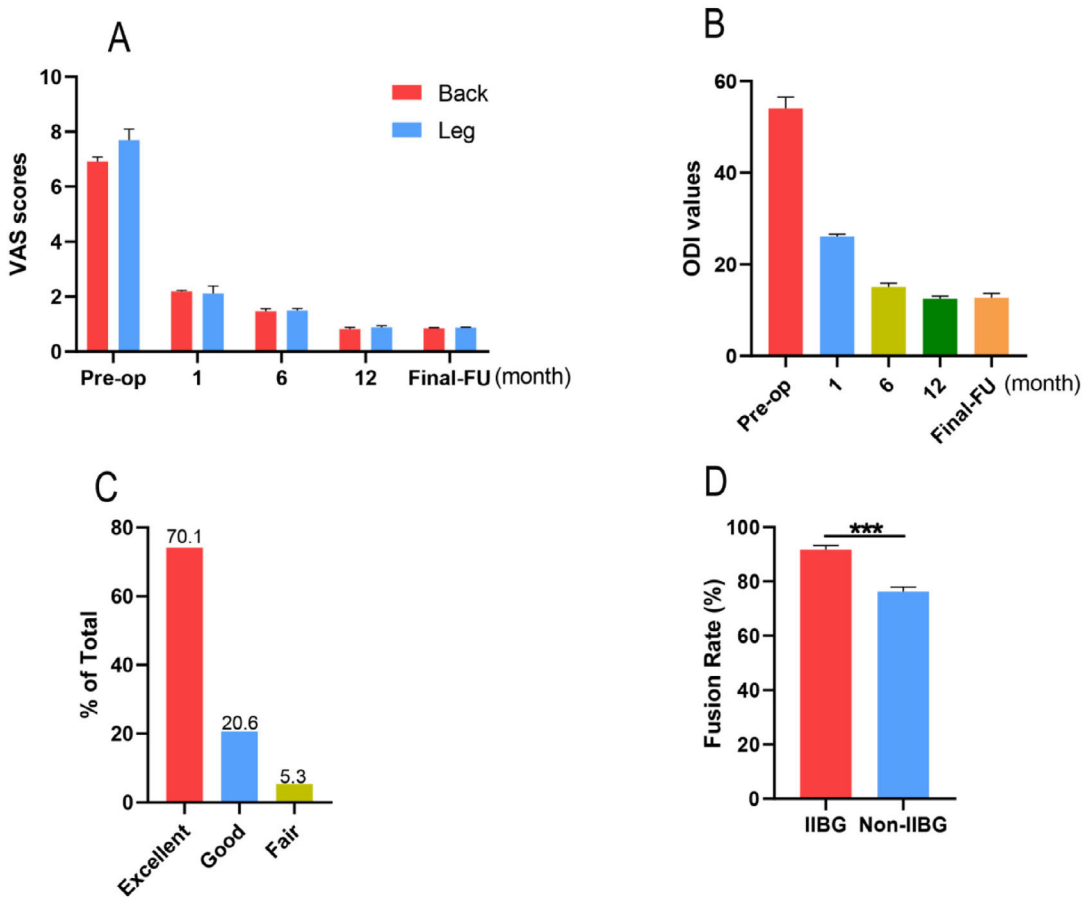


Figure 4. Clinical efficacy quantitative results chart. (A) Scores for back pain and lower limb pain. (B) ODI value results (before surgery, 1, 6, 12 months after surgery, and at the final follow-up). (C) MacNab criteria results at the final follow-up. (D) Fusion rate results at the final follow-up. ***$p < 0.001$. ODI = Oswestry disability index, VAS = visual analogue scale.

Intervertebral disc removal and endplate treatment are essential steps for intervertebral fusion.[13] Studies have illustrated the greatest extent of intervertebral disc space preparation in extreme lateral interbody fusion (90%), followed by minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF) (65%), posterior lumbar interbody fusion (43%), and anterior lumbar interbody fusion (40%). Good intervertebral disc space treatment is a prerequisite for suitable fusion cage implantation and adequate bone grafting.[14] A bone graft contact area exceeding 50% for joint fusion is more conducive to fusion, reducing the risk of pseudarthrosis.[15] The entire intervertebral disc space region can be divided into the annulus fibrosus and central nucleus pulposus regions. In consideration of safety, the annulus fibrosus region can be partially resected, except for the posterior and ipsilateral aspects, during MIS-TLIF.[16] Still, it is difficult to achieve a bone graft area of 50% or more due to the inability to remove contralateral and anterior annular fibers. Therefore, the amount of bone graft in the well-managed nucleus pulposus region is crucial. The rate of lumbar fusion surgery has increased in the past few decades, but postoperative complications such as nonunion or pseudarthrosis remain a significant challenge.[17]

7.2. Controversy over the fusion rate and fusion cage subsidence in MIS-TLIF

Fusion cage subsidence represents the major postoperative complication of LIF, with incidences of 15.9% to 70%, varying depending on the type of fusion cage, surgical technique, follow-up time, and imaging evaluation.[18,19] Since the application of tibial bone transplantation for spinal fusion was first described in 1911, a diversity of methods has been applied for spinal fusion assessment. Static X-rays are commonly used for clinical evaluation of fusion but often overestimate the fusion rate. Dynamic X-rays improve accuracy, but their reliability and consistency have been questioned, and the lack of activity in the fusion segments does not confirm fusion. CT is now widely accepted as the standard for spinal fusion assessment. Features such as thin-layer imaging, multiplane reconstruction, and reduced metal artifacts have strengthened the ability to evaluate spinal fusion on CT.[20] Yet,

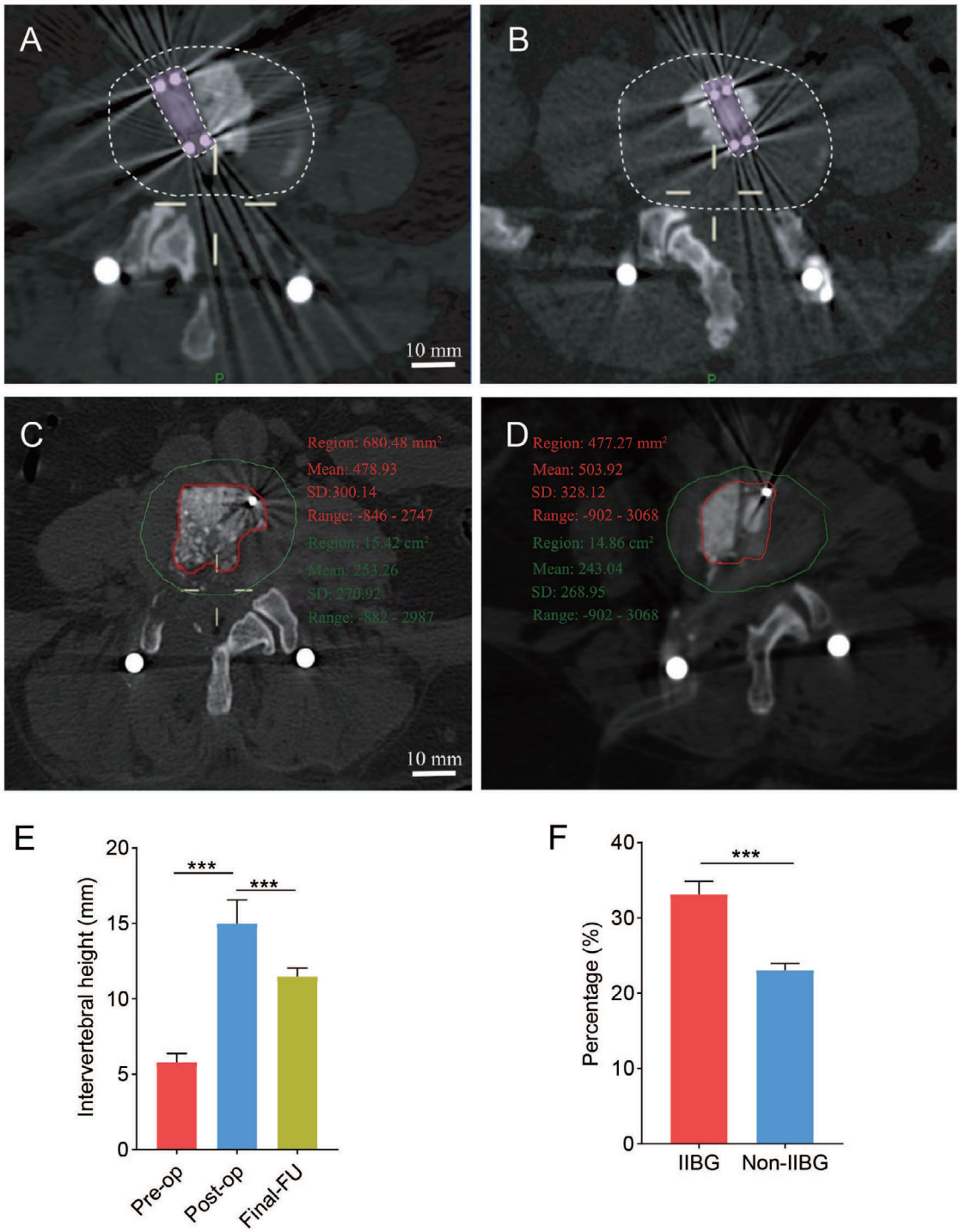


Figure 5. Postoperative CT reexamination. (A) Axial CT reexamination with ipsilateral impaction bone grafting. (B) Axial CT reexamination without ipsilateral impaction bone grafting. (C) Bone graft area measurement, Red outline indicates the bone graft area. (D) The proportion of bone graft area in the vertebral cross-section, Red outline indicates the bone graft area. (E–F) Quantitative map of disc height and bone graft area. ns$p > 0.05$, *$p < 0.05$, **$p < 0.01$, and ***$p < 0.001$. CT = computed tomography, IIBG = ipsilateral-impaction bone grafting.

its application is tempered by high radiation exposure. Although MRI does not emit radiation, its clinical utility for fusion assessment remains unproven.[21] Previously, it was believed that the fusion process was inevitably accompanied by fusion cage subsidence, a common occurrence during fusion. At present, fusion cage subsidence exceeding 2 mm is considered clinically significant, indicating that there is a loss of intervertebral height and loss of lumbar lordosis during postoperative follow-up, consequently leading to symptom recurrence and poor clinical outcomes.[22] While subsidence did not result in immediate clinical decline, further follow-up is necessary to assess its impact on lumbar anterior kyphosis and adjacent segment degeneration.

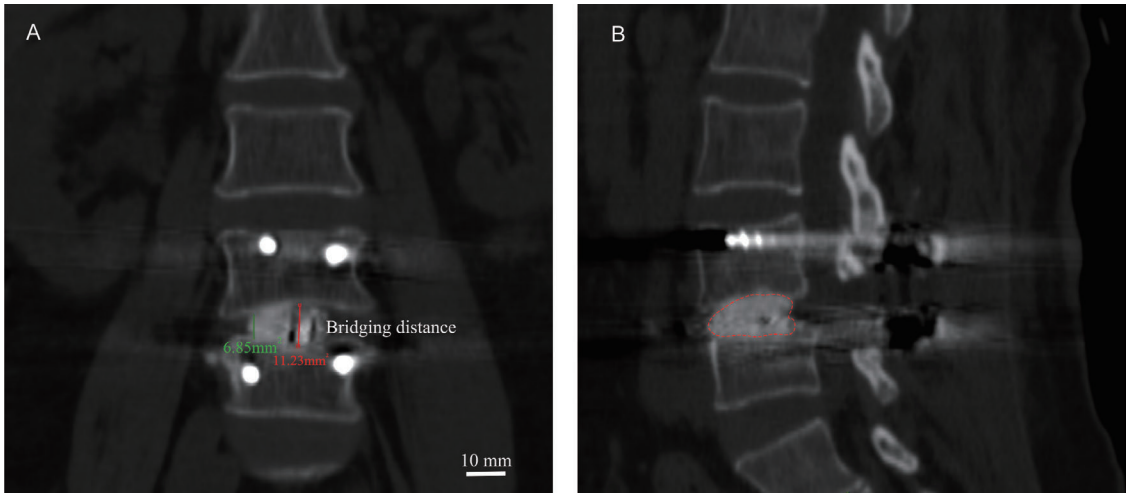


Figure 6. Postoperative CT imaging demonstrates the advantages of IIBG in optimizing the fusion environment. (A) The coronal CT image shows that the compressed lateral graft column shortens the interlaminar bridging distance (double-headed arrow). (B) The sagittal CT image shows that the crushed bone particles (dashed line), under compression, fully fill the space adjacent to the intervertebral fusion device and come into direct contact with the bony laminae on both sides. CT = computed tomography, IIBG = ipsilateral-impaction bone grafting.

7.3. Importance of adequate bone graft in intervertebral fusion

Bone endplate injury is considered a significant risk factor for fusion cage subsidence,[23] and the optimal utilization of harvested autografts is the key to successful fusion. Studies have shown that the autografts obtained from decompression are sufficient to complete the bone grafting at the intervertebral disc space.[24] Compared with loose bone grafting, impaction bone grafting shows faster fusion speed and higher fusion quality.[25,26] Meanwhile, impaction bone grafting may increase the volume of bone grafts. Studies have shown that loose bone grafting can implant 1.23cc bone, while impaction bone grafting can implant 6.42cc bone.[25] It has been reported that a higher fusion rate can be achieved with artificial bone mixtures with graft volumes of more than 12 mL.[27] For easier implantation of more autografts in the intervertebral disc space, many specially designed bone grafting devices have been developed.[28] We used bone grafting devices of two different diameters in this research. To optimize lateral

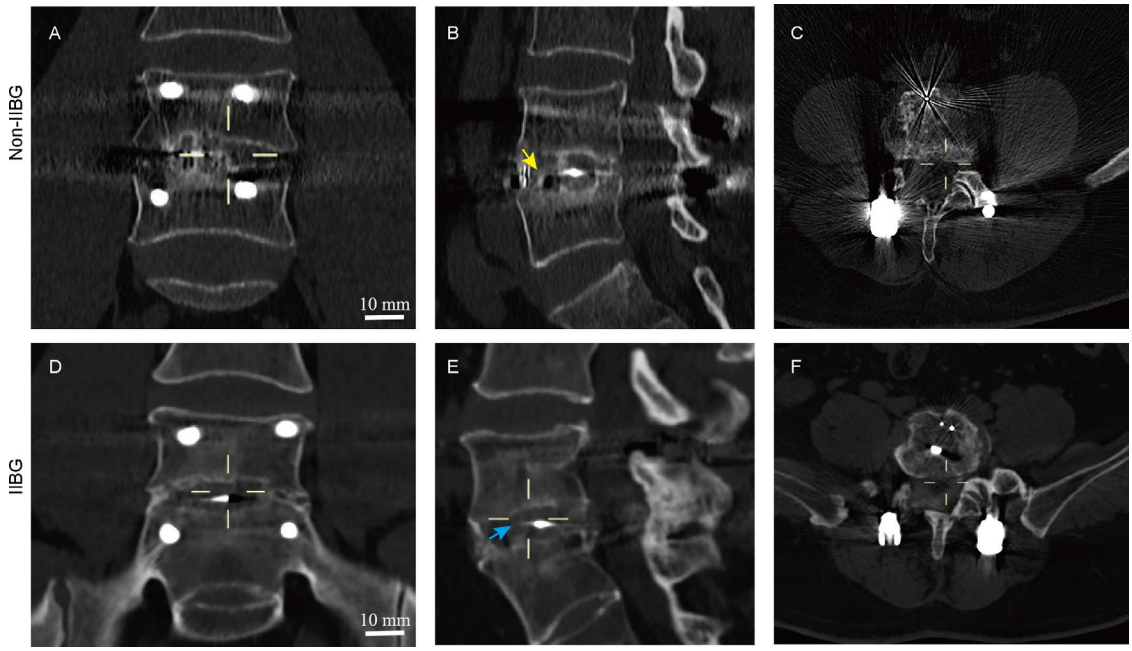


Figure 7. Representative 3-year postoperative CT images illustrating long-term fusion patterns. (A–C) Corresponding views of a patient from the control group. Yellow arrows indicate bridging bone primarily confined within the cage's graft windows, with sparse or absent extracage bone formation. (D–F) Coronal, sagittal, and axial CT views of a patient from the IIBG group. Blue arrows indicate continuous and mature bridging trabecular bone spanning the entire intervertebral space, both inside and outside the cage, with complete integration with the vertebral endplates. CT = computed tomography, IIBG = ipsilateral-impaction bone grafting.

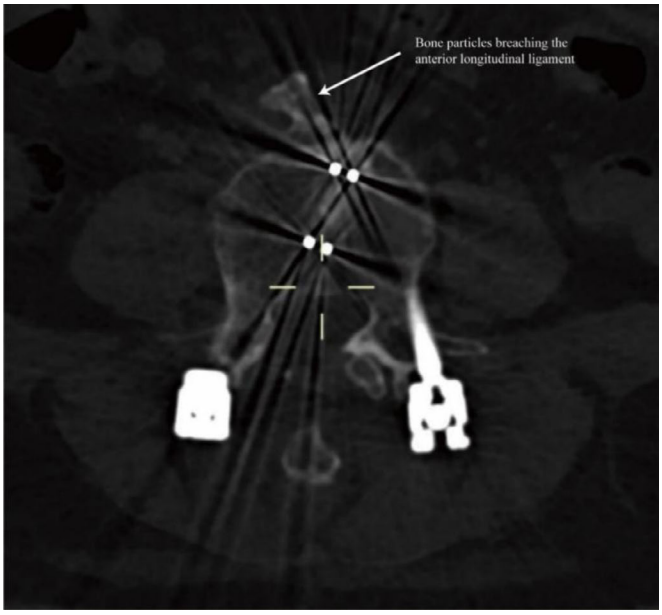


Figure 8. Bone graft granulates broke through the anterior longitudinal ligament but did not cause vascular damage.

space utilization, a thinner bone grafting device can be inserted into the side of the fusion cage. Good endplate preparation and sufficient extracage bone grafting are critical for intervertebral fusion.

7.4. Advantages of new bone grafting techniques

The amount of bone graft after complete intervertebral disc space treatment is key to successful fusion. The loading of bone grafts in the entire intervertebral disc space can be achieved via two approaches: inside and outside the fusion cage. The amount of autografts that can be loaded by the fusion cage is limited, and it often falls off during the implantation process, making the extracage bone graft volume critical. In the past, bone grafting was achieved through impaction anterior to the intervertebral disc space before fusion cage insertion. The amount of bone grafts using this method should not be too large; otherwise, it would affect the implantation position of the fusion cage. Even the insertion depth of the fusion cage may prove inadequate, potentially causing posterior migration in the late stage.[29,30] Forcible insertion of the fusion cage with excessive bone grafts often leads to rupture of the anterior longitudinal ligament, the entrance of bone graft granules into the abdominal cavity, and even accidental deep insertion of the fusion cage, which will cause damage to the anterior blood vessels.[31] Postoperative CT also showed many bone grafts; adequate impaction bone granulates, and a reduced inter-endplate bridging distance (Fig. 6A–B). Placing many autografts ensured contact between the bony endplate and the autografts. At the same time, because there is no obstruction from the autografts in the front, the fusion cage can reach the epiphyseal rings in the front, which ensures anterior support and is beneficial to the reconstruction of lordosis.[32] The long-term superiority of this technique is further corroborated by our 3-year CT follow-up data. The consistent observation of complete intervertebral bridging bone in the IIBG group, as opposed to the cage-centric fusion in the control group, underscores two critical advantages: first, the larger graft volume and denser impaction achieved by IIBG create a more conducive biological milieu for bone healing that extends beyond the cage's boundaries; second, the resulting fusion mass provides a broader and more biomechanically stable load-sharing structure, which may potentially reduce long-term risks of cage subsidence and adjacent segment degeneration (Fig. 7A–F). This sustained enhancement of fusion quality highlights the lasting clinical value of the IIBG procedure. The fusion rate of 91.5% achieved with the IIBG technique in this study compares favorably with previously reported rates of 76% to 85% for conventional MIS-TLIF using standard bone grafting methods and approaches the rates reported for anterior or lateral interbody fusion procedures.[33] This improvement in fusion rate, achieved without increasing complication rates, underscores the clinical value of maximizing both the volume and the mechanical quality of the autograft through impaction.

7.5. Regarding the potential for Iatrogenic nerve root traction injury

The IIBG technique requires a deliberate annulotomy and lateral-to-medial manipulation, which theoretically could increase the risk of nerve root retraction injury, particularly at the L3/L4 level where the nerve root is more constrained. Several aspects of our surgical protocol are designed to mitigate this risk. First, an extensive bony decompression, including resection of the apex of the superior articular process, is performed before disc space access, creating an ample working corridor that minimizes the need for forceful retraction. Second, the annulotomy is placed with strict adherence to anatomical landmarks, with its lateral boundary at the mid-pedicular line, ensuring a controlled exposure without risking injury to the exiting nerve root. Finally, care is taken to place the fusion cage at a greater angle to avoid nerve root traction during exposure. Clinically, our results showed no significant difference in postoperative leg pain VAS scores between the IIBG and control groups, and no cases of new-onset persistent radiculopathy were documented. Nevertheless, we acknowledge that in patients with a particularly narrow disc space at L3/L4, this technique is technically demanding and should be applied with caution, as noted in the Section 8.

8. Limitation

Several limitations still exist in this research. First, this was a retrospective study, and patient grouping was based on the operating surgeon's preferred technique. This introduces potential selection bias, which is an inherent limitation of the retrospective design. To mitigate this concern, we have demonstrated that the two groups were well-matched in baseline characteristics, including age, sex, BMI, and BMD

(Table 2). Furthermore, all consecutive patients meeting the inclusion criteria during the study period were enrolled, and the IIBG technique was the standard practice of the surgeons who adopted it, rather than being selectively applied to patients with more favorable anatomy. Nevertheless, future prospective randomized studies are warranted to eliminate this potential bias. Although the mean follow-up exceeded 22 months, standardized CT beyond 12 months was lacked for all patients. Although we presented compelling 3-year CT data for a subset of patients, this was not a systematic follow-up for the entire cohort, which may introduce selection bias. Future studies with a prospective design and standardized long-term imaging for all participants are warranted to confirm these findings. Longer-term follow-up with systematic imaging and functional assessments would provide stronger evidence regarding fusion stability and clinical sustainability. Second, all surgeries were conducted by a single surgeon from a single center, and the results may vary if performed by spinal surgeons from other hospitals. Third, this technique is not applicable for all intervertebral disc spaces, and this bone grafting technique is technically challenging in small-framed females at L3/L4 and L4/L5 levels due to insufficient width of the intervertebral disc space. Fourth, not all patients undergo CT scans during follow-up, so there may be result bias.

9. Conclusion

Owing to blind operation, the posterior approach still shows issues like incomplete intervertebral disc space treatment and insufficient bone grafting. The fusion rate and fusion cage subsidence after lumbar TLIF remain challenges. The ipsilateral impaction bone grafting technique we introduced here can improve the amount and quality of bone grafts. No statistically significant difference in subsidence incidence was seen between the two groups; however, the fusion rate was significantly greater in the IIBG group. In the future, additional investigations are warranted to improve fusion materials and designs, increase the number of bone grafts in fusion cages for higher fusion rates, and improve TLIF surgical techniques.

Acknowledgements

Not applicable.

Ethical statement

This study was approved by the Ethics Committee of Union Hospital, Tongji Medical College, Huazhong University of Science and Technology (approval No. 2021-059, March 1, 2024). The requirement for written informed consent was waived by the committee due to the retrospective nature of the study. Patient data were anonymized before analysis, and all procedures were performed in accordance with the Declaration of Helsinki. Patient data were anonymized to protect privacy, and all procedures were performed in compliance with relevant institutional and national regulations.

Conflicts of interest

Cao Yang serves as Associate Editor-in-Chief of this journal. He was not involved in the editorial review or decision-making process for this manuscript. All editorial decisions were made independently by other members of the Editorial Board who have no conflicts of interest.

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Data availability statement

The data that support this study are available from the corresponding author upon reasonable request.

Author contributions

WW, HF—conceptualization, Writing—original draft.
KW, XF—methodology.
XZ, CY—investigation.
LX—funding acquisition, project administration.
All authors—Writing—review & editing: all authors. All authors have read and approved the final manuscript and agree to be accountable for all aspects of the work.

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