

Development of a Rat Caudal Interbody Fusion Model: A Pilot Feasibility Study

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Abstract

Rat caudal vertebrae are widely used in bone regeneration and spinal fusion research as convenient sites for testing bone graft materials and implants. Prior rat tail fusion models have achieved intervertebral fusion through disc removal and bone grafting, or with external fixation devices. Nonetheless, no such small-animal model has been developed that uses an interbody fusion cage analogous to that used clinically. It was hypothesized that an evaluable bone fusion environment could be established without neurological complications by performing a posterior cage insertion mimicking clinical procedures, supplemented with plate fixation, in the rat caudal vertebrae. This preliminary pilot study (n = 1) was designed to evaluate technical feasibility. A surgical approach was developed in which a miniaturized titanium cage was precisely inserted into the resected disc space between the adjacent caudal vertebrae, closely mirroring the human surgical procedure. Titanium was selected for the cage owing to its widespread clinical use and biocompatibility. The initial results demonstrated the technical feasibility of this approach. The implanted cage maintained disc height and spinal alignment. Progressive bone ingrowth through the cage was observed, culminating in confirmed continuous bone bridging across the intervertebral space by 12 weeks postoperatively. The presence of continuous trabecular structure and the absence of intervening fibrous tissue were confirmed radiologically and histologically. Overall, this cage-based rat tail fusion model provides a promising platform for evaluating novel biomaterials and investigating mechanisms of intervertebral bone fusion. However, the lack of a control group and statistical analysis, due to the single-subject design, limits the generalizability of these findings and necessitates further validation.

Introduction

Interbody fusion is an established surgical treatment for various spinal disorders, including instability, spondylolisthesis, and degenerative diseases; notably, it has evolved over approximately 70 years as a standard procedure^{1,2}. The procedure involves removing the intervertebral disc and inserting a cage or bone graft to promote solid fusion between adjacent vertebrae^{3,4}. Moreover, adding posterior instrumentation with cages reduces pseudarthrosis rates and expands its clinical indications⁵. Nevertheless, complications such as pseudarthrosis and cage

subsidence remain significant clinical challenges, warranting reliable preclinical model development to evaluate new materials and fusion-promoting factors^{6,7}.

Rats have been widely used in spinal fusion research owing to their economic feasibility, rapid reproduction, rapid healing, and handling ease^{8,9}. Nonetheless, the existing rat interbody fusion models exhibit significant limitations. Specifically, the anterior lumbar interbody fusion (ALIF) approach in rats requires major abdominal vessel and organ manipulation, resulting in high surgical invasiveness and substantial complication risks^{10,11}. The

posterior lumbar interbody fusion (PLIF) approach involves an unavoidable risk of neurological injury due to the extremely small spinal canals and neural elements, making neural retraction nearly impossible¹². Consequently, most rat studies have been limited to posterolateral fusion (PLF), which structurally fails to investigate the mechanisms of bone fusion within the cage, a critical aspect in clinical settings¹³. Furthermore, while caudal models exist, they lack an evaluation system that integrates a clinical-like interbody cage with posterior plate fixation.

The caudal spine of rats offers unique interbody fusion research advantages. Caudal discs demonstrate strong geometric, compositional, and mechanical similarities to the human lumbar discs, making them increasingly popular in disc research^{14,15}. Additionally, caudal spine surgery provides easy surgical access, cost-effectiveness, and rapid postoperative recovery compared with lumbar approaches¹⁶. However, to date, no studies have reported successful posterior cage insertion in the rat caudal spine with a detailed histological evaluation of bone formation within and around the cage.

Histological assessment, particularly of undecalcified bone histomorphometry, remains the gold standard for evaluating osseointegration and bony fusion^{17,18}. Specifically, it enables quantitative analysis of critical bone formation parameters, including bone volume/tissue volume (BV/TV), trabecular number, and trabecular thickness, while allowing bone maturity qualitative assessment by distinguishing woven from lamellar bone^{19,20}. Such a detailed histomorphometric evaluation can reveal the spatial and temporal osteoconduction patterns within the cage and at the cage-vertebra interfaces^{21,22}. Nonetheless, a comprehensive histomorphometric evaluation of cage osteoconduction in rat models is lacking.

This study aimed to develop a pilot rat caudal interbody fusion model using posterior cage insertion and supplemental plate fixation to demonstrate its technical feasibility. This study presents a detailed surgical technique and a comprehensive histological evaluation of bone formation within the cage and at the vertebral endplate interfaces. It was hypothesized that an evaluable bone fusion environment could be established without neurological complications by performing a posterior cage insertion mimicking clinical procedures, supplemented with plate fixation, in the rat caudal vertebrae. This model provides an efficient platform for evaluating interbody fusion materials and, in the existing literature, represents an initial technical exploration of successful posterior cage placement using histomorphometric osteoconduction assessment in a rat model.

Protocol

All animal experiments were conducted in accordance with the protocols approved by the Jikei University Animal Care and

Use Committee (approval number 2023–034C1). This study was designed as a pilot feasibility study. To assess the technical viability of this highly delicate and novel posterior cage insertion in the rat caudal spine prior to large-scale validation, a single animal ($n = 1$) was used, per ethical guidelines, to minimize animal use during the initial technical evaluation. Male Sprague-Dawley (SD) rats were selected as the standard strain for spinal fusion research. The inclusion criteria were healthy males aged 8–10 weeks, weighing between 200–250 g, to ensure that the intervertebral disc height (1.8–2.2 mm) is compatible with the 2 mm cage. Animals exhibiting > 10% weight loss during the acclimatization period, decreased activity, or visible tail deformities were excluded. For this study, a male Sprague-Dawley rat (8 weeks old, weighing 221.8 g; Japan SLC, Shizuoka, Japan) was utilized. The animal was housed in a controlled environment at 25°C and a relative humidity of 50% (allowable range 30–70%) with a 12 h light/dark cycle and was provided *ad libitum* access to water and a standard rodent diet. Rats were housed in solid-bottom cages provided with nesting materials and chew sticks for environmental enrichment. A 3-day acclimatization period was implemented prior to the surgical procedure. To prevent cage mates from gnawing on the tail implants, the rat was maintained under single-housing conditions throughout the study, which was a critical factor in this experimental design.

Preparation of screws and plates

Internal fixation materials were prepared prior to the surgical procedure. Commercially available stainless-steel screws (original diameter: 1.2 mm, length: 14 mm) were cut to a precise length of 6 mm using a wire cutter (**Figure 1A**). These screws were sterilized via standard steam autoclaving at 121 °C for 20 min. In a polyoxymethylene (POM) internal fixation plate (18 mm length, 3 mm width, 1 mm thickness), screw holes with a diameter of 1.2 mm were drilled at 12 mm intervals using a manual drill (**Figure 1B–D**). Subsequently, the corners of the POM plates were rounded using a wire cutter to minimize irritation to the surrounding soft tissue (**Figure 1E**). The plates were sterilized using ethylene oxide (EtO) gas or hydrogen peroxide gas plasma, given the polymer's thermal sensitivity. **The titanium cage features an interconnected lattice structure with longitudinal channels measuring 300–500 μ m in diameter. Its surface was prepared using Lamellar 3D Titanium Technology to achieve a micro-surface roughness of 3–5 μ m, which facilitates direct bony ongrowth.**

Anesthesia and surgical procedure

No preoperative fasting was performed to avoid unnecessary metabolic stress. Anesthesia was induced via a triple anesthetic mixture consisting of medetomidine (0.15 mg/kg), midazolam (2 mg/kg), and butorphanol (2.5 mg/kg), which was administered via subcutaneous injection into the dorsum using a 25-gauge needle²³. Adequate surgical plane of anesthesia was assessed every 15 min by confirming the loss of the pedal withdrawal

reflex (toe pinch), maintaining pink mucous membranes, and monitoring the respiratory rate (70–110 breaths/min). The surgical procedure for interbody fusion of the caudal vertebrae was subsequently performed. The animal was placed in the prone position (Figure 2A), and the entire tail was disinfected following a three-round alternating scrub protocol (70% ethanol, povidone-iodine scrub, and 70% ethanol) to ensure a sterile field. To identify the target vertebrae, manual palpation was performed starting from the sacrum distally. The first mobile joint was identified as the sacrum-Co1 junction, and the segment immediately proximal was designated as Co2, defining the Co2–Co3 target segment. A longitudinal incision of approximately 2 cm was made on the dorsal aspect, spanning from the second to the third caudal vertebrae (Co2–Co3) (Figure 2B), to expose the posterior surface of each vertebra. During the exposure, care was taken to identify and avoid damage to the dorsal caudal vein; blunt dissection and bipolar electrocautery were used to manage minor bleeders. To prepare the fusion site, the annulus fibrosus between the Co2 and Co3 vertebrae was incised using a scalpel (Figure 2C). The annulus fibrosus and nucleus pulposus were then meticulously removed via curettage using a curette and small forceps (Figure 2D). This step was performed under high-power surgical magnification ($\geq 3.5\times$). Completeness of removal was objectively defined by the visual confirmation of punctate bleeding (the "bloody endplate" sign) and the total absence of residual soft tissue. Unacceptable endplate damage was defined as deep erosions involving $> 25\%$ of the total area or penetration into the cancellous bone > 0.5 mm. A titanium cage (2×2 mm cross-section, 2 mm height) (Figure 2E) was subsequently inserted deep into the intervertebral space until a physical stop was reached and full-surface contact with both endplates was visually confirmed, creating a firm interference fit (Figure 2F, 2G).

Fixation and wound closure

To facilitate plate fixation, the bone surface around the designated hole sites in the Co2 and Co3 vertebrae was flattened using an electric handheld router operating at 7,800 RPM equipped with a 2.0 mm spherical file-type burr (Figure 2H). Bone holes were individually drilled at intervals corresponding to the screw holes of the plastic internal fixation plate using a hand drill equipped with a 1.2 mm diameter drill bit (Figure 2I). Two 6 mm stainless steel screws were then pre-loaded into the holes of the plastic plate (Figure 2J). Screws were inserted at a 90° angle to a standardized depth of 5 mm with a 12 mm center-to-center spacing (Figure 2K). Finally, the skin incision was closed with 4-0 nylon sutures, and the tail was disinfected once again with 70% ethanol to complete the procedure.

Postoperative management and euthanasia

During the immediate recovery phase (Day 0), the animal was monitored every 15 min, and rectal temperature was supported until it achieved full sternal recumbency and purposeful

ambulation. For long-term assessment (Weeks 1–12), a daily scoring system based on Body Condition Score (BCS), grooming status, and general activity was implemented, alongside daily surgical site monitoring for infection or dehiscence. Moist chow was provided on the cage floor during the first 48 h. Body weight was measured weekly. Humane endpoints for early euthanasia were strictly defined as: weight loss $\geq 20\%$, BCS ≤ 2.0 , persistent inability to reach food/water > 12 h, signs of severe pain/dyspnea, or severe surgical site complications (e.g., necrosis). Animals meeting these criteria were humanely euthanized within 24 h. Postoperative care included the administration of cefalexin (15 mg/kg) intramuscularly immediately after surgery and at 24 h postoperatively to prevent infection, and for analgesia, carprofen (2 mg/kg) was administered subcutaneously immediately after surgery and at 12, 24, and 48 h postoperatively, for a total of four doses. At 12 weeks post-implantation, the rat was euthanized via an isoflurane overdose. The segment from the second to the third caudal vertebra was then harvested *en bloc* and fixed in 70% ethanol.

Training recommendations, troubleshooting, and sample size. To facilitate the successful adoption of this demanding protocol, new operators must perform 3–5 practice procedures on rat cadavers, achieving proficiency when three consecutive placements show no radiographic malpositioning. Common troubleshooting includes pre-measuring disc height via X-ray to optimize cage size selection and re-verifying dorsal bone flatness to prevent cage migration. If the screw purchase is insufficient, utilizing lower drill speeds is recommended. For future validation studies, a minimum sample size of $n = 6$ to 10 per group is recommended (with an additional 10–20% for attrition) to achieve sufficient statistical power. Furthermore, future studies must incorporate control groups (e.g., empty cage or autograft) to validate the biomaterial's performance.

Radiographic and histological analysis

Micro-computed tomography (CT) scanning and digital radiography were performed using a micro-CT scanning system with a tube voltage of 80 kV and a current of 0.1 mA. A 1.0 mm-thick aluminum filter was utilized during acquisition to minimize beam-hardening artifacts caused by the titanium implant. For longitudinal assessment, *in vivo* imaging was conducted at 1 and 4 weeks postoperatively with a 120 μm voxel size. *Ex vivo* imaging was conducted at 12 weeks postoperatively using a 24 mm specimen holder with a 24 μm voxel size. CT data and radiographic images were reconstructed using a standard filtered back-projection algorithm and analyzed using a DICOM viewer. Quantitative criteria were defined to assess bone union. Radiologically, successful fusion was confirmed when a continuous trabecular structure bridging the cranial and caudal vertebral endplates was observed across at least three consecutive slices on micro-CT. A global threshold of 700

Hounsfield Units (HU) was applied during image segmentation. Histomorphometrically, a BV/TV ratio of 70% or greater within the cage was considered the threshold for physical spatial fulfillment and fusion. Histologically, bone union was defined by complete osseous bridging from the cranial to caudal sides without the interposition of fibrous tissue. For histological analysis, sequential fluorochrome labeling was performed by subcutaneous injection of calcein (8 mg/kg) 2 days before euthanasia to identify the spatial distribution of active mineralization at the terminal 12-week time point. The excised caudal vertebrae were fixed in 70% ethanol for 7 days and stained *en bloc* with Villanueva bone stain. Specimens were dehydrated through ascending grades of ethanol, embedded in methyl methacrylate resin, and mid-sagittally sectioned at the precise geometric center of the cage, as determined by pre-sectioning Micro-CT guidance, using a diamond saw microtome. Undecalcified ground specimens (5 µm thickness) were prepared at the Ito Bone Histomorphometry Institute (Niigata, Japan). Images were acquired using a bright-field microscope and a confocal laser-scanning microscope for fluorescence merging. Further examination was performed under a polarized light microscope, and histomorphometric analysis was conducted using a computerized image analyzer. The Region of Interest (ROI) was defined as the total internal volume of the cage, excluding the metal struts, and was subdivided into Cranial and Caudal Intracage ROIs. Bone tissue was identified by its purple/magenta color under Villanueva staining. Lamellar bone (Lm.V) was defined by its highly organized, parallel-lamellar structure under polarized light, whereas woven bone (Wo.V) displayed disorganized fiber patterns.

Results

Body weight (Table 1)

Body weight was measured up to 12 weeks postoperatively, demonstrating a steady increase (from 221.8 g to 346.8 g), indicating physiological homeostasis and indirectly supporting the absence of severe chronic distress. This was corroborated by daily multimodal assessments confirming normal activity and uncomplicated wound healing.

Wound (Figure 3)

Wound healing was achieved 4 weeks postoperatively; **spontaneous suture extrusion occurred**, and the postoperative course was uneventful, with no signs of infection observed for 12 weeks.

Micro-CT and digital radiography

Sequential radiological assessment using micro-CT confirmed no cage loosening or migration between 1 and 12 weeks postoperatively (**Figure 4A–4F**). Likewise, digital radiography at 12 weeks demonstrated no evidence of screw loosening or migration (**Figure 4G, 4H**), supporting the technical feasibility of the interbody fusion model. At 4 weeks, new bone formation extended from the extra-cage vertebral endplates into the intervertebral space (**Figure 4D**, arrow). By 12 weeks, the cranial and caudal vertebral bodies were completely bridged by new bone, both inside and outside the cage (**Figure 4E, 4F**, arrows).

Histological and histomorphometric assessment at 12 weeks

In the Villanueva bone-stained sections obtained at 12 weeks postoperatively, bright-field microscopy demonstrated complete bony bridging connecting the cranial and caudal sides of the cage (**Figure 5A**). Fluorescence microscopy revealed a clear regional difference in calcein labeling (**Figure 5B**). Extensive fluorescence labeling, indicating active mineralization, was observed in the caudal region, whereas minimal labeling was observed in the cranial region. Consistent with these findings, histomorphometric analysis (**Table 2**) showed that the Bone Volume fraction (BV/TV) within the cage reached 73.9% in the cranial region and 70.5% in the caudal region, indicating extensive osseous filling. Additionally, polarized light microscopy-based bone quality evaluation confirmed these trends (**Figure 5C–E**): the Lamellar Bone Volume (Lm.V) constituted 32.5% of the bone volume in the cranial region, whereas it accounted for only 12.3% in the caudal region, which remained predominantly occupied by woven bone. The experimental timeline is shown in **Figure 6**.

DATA AVAILABILITY:

The raw data supporting the findings of this study have been deposited in the Zenodo repository and are publicly available at the following DOI: 10.5281/zenodo.19627405.

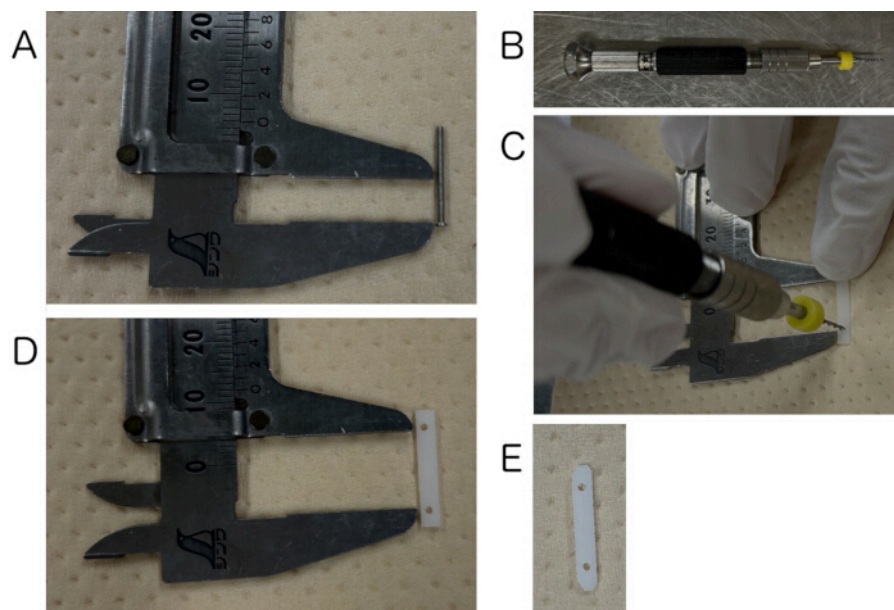


Figure 1: Preparation of screws and the internal fixation plate. (A) A commercially available stainless steel screw (diameter: 1.2 mm, length: 14 mm) was cut to 6 mm. (B) The manual drill used to create screw holes. (C) A commercially available plastic plate before processing. (D) Creation of two screw holes (diameter: 1.2 mm) at a 12 mm interval using a manual drill. (E) The final processed plate with rounded corners, adapted for the fixation of the caudal vertebrae. [Please click here to view a larger version of this figure.](#)

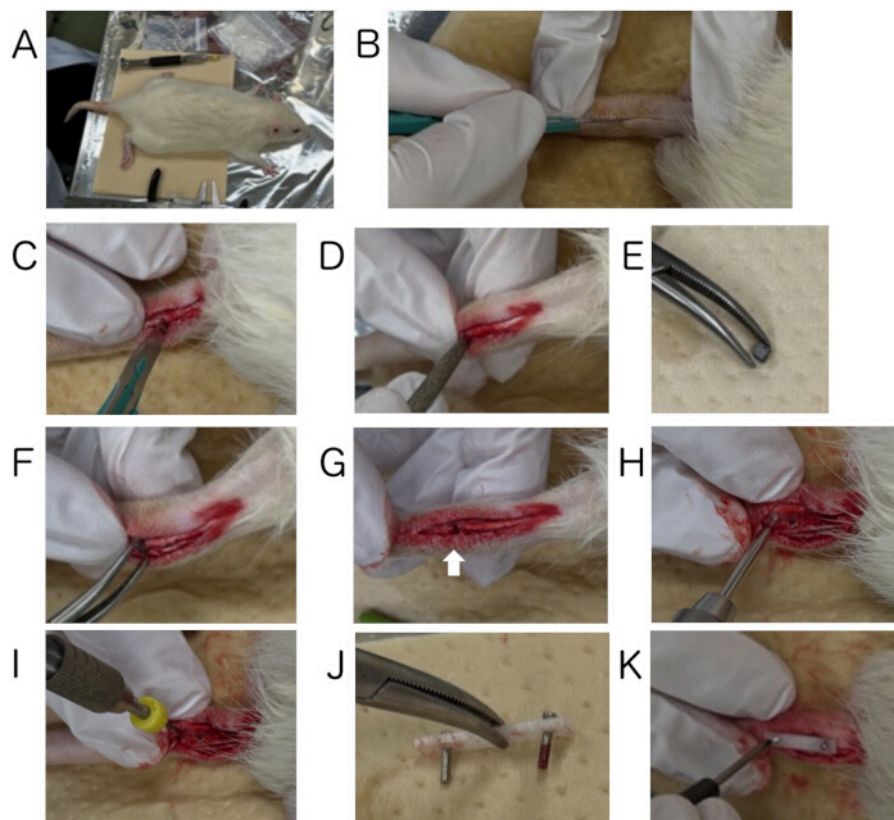


Figure 2: Surgical procedure for interbody fusion of the caudal vertebrae. (A) The rat was placed in the prone position. (B) A midline dorsal incision was made to expose the target vertebrae. (C, D) The annulus fibrosus was incised, and the nucleus pulposus was removed to prepare the intervertebral space. (E) The titanium cage is used for interbody fusion. (F) Insertion of the cage into the disc space. (G, H) The bone surface was flattened using an electric burr to prepare for plate fixation. (I) Bone holes were drilled corresponding to the plate holes. (J) The plastic plate is pre-loaded with stainless steel screws. (K) Final fixation of the plate and screws bridging the caudal vertebrae. [Please click here to view a larger version of this figure.](#)

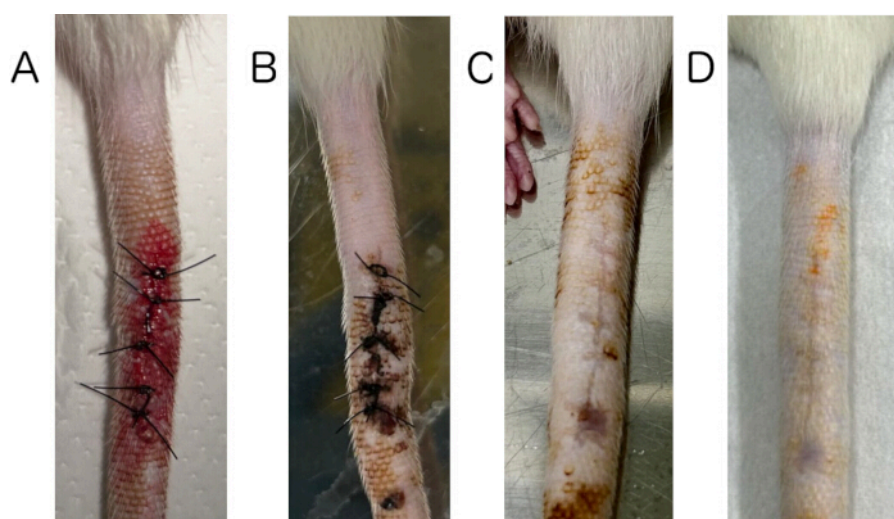


Figure 3: Postoperative wound healing. Sequential macroscopic images of the surgical site are shown. (A) Immediate postoperative view displaying the sutured wound. (B) Postoperative week 1. (C) Postoperative week 4. (D) Postoperative week 12. [Please click here to view a larger version of this figure.](#)

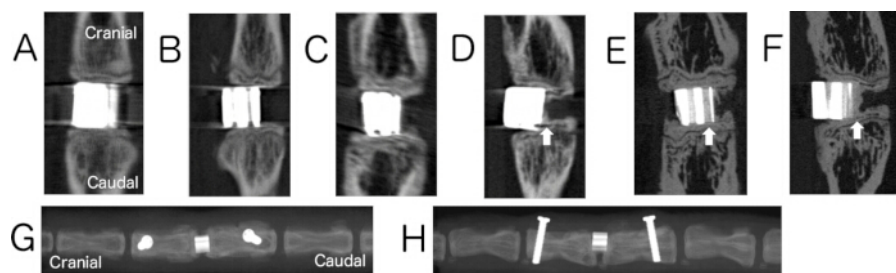


Figure 4: Sequential radiological assessment. (A–F) Micro-CT images confirmed no cage loosening or migration from 1 to 12 weeks postoperatively. (G, H) Digital radiography at 12 weeks similarly demonstrated no screw loosening or migration, validating the interbody fusion model's success. (D) At 4 weeks, new bone formation was observed extending from the vertebral endplates into the disc space outside the cage (arrow). (E, F) At 12 weeks, the cranial and caudal vertebrae were completely bridged by new bone both inside and outside the cage (arrows). This continuous bony bridge, observed across at least 3 consecutive slices and accompanied by an intra-cage BV/TV of $\geq 70\%$, met the predefined quantitative threshold for successful fusion. [Please click here to view a larger version of this figure.](#)

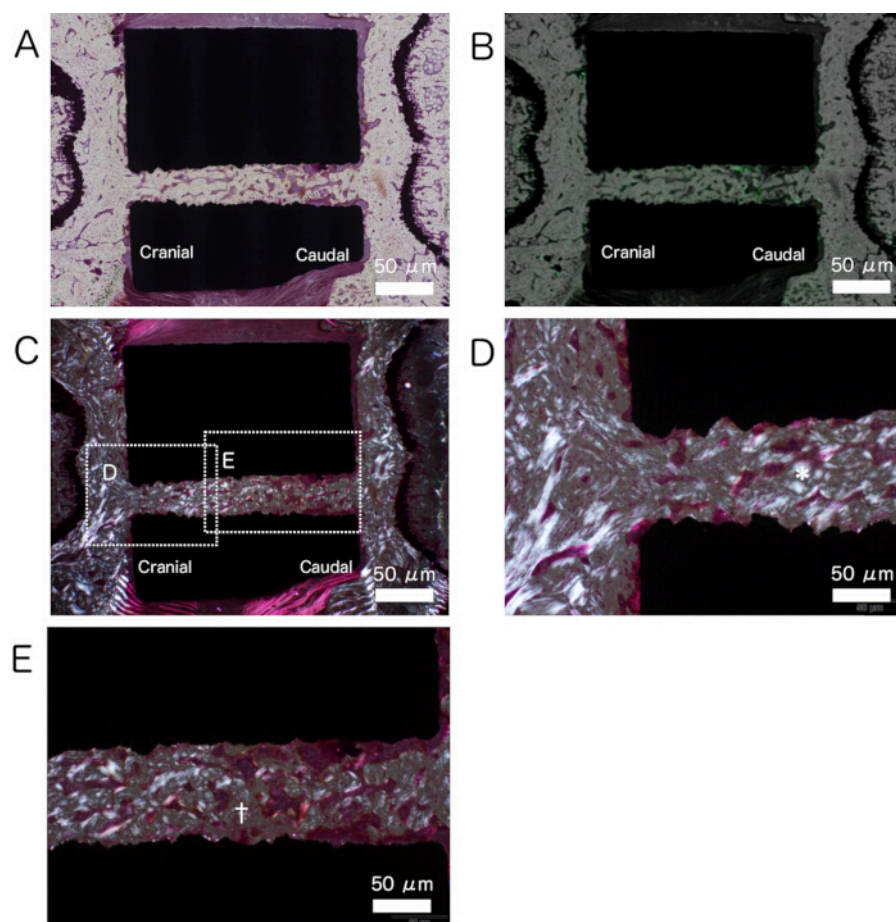
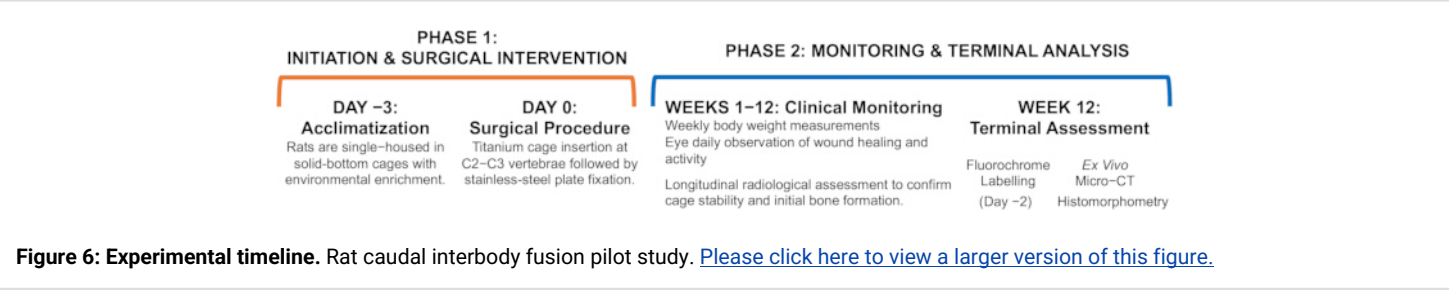


Figure 5: Histological assessment at 12 weeks postoperatively. (A–E) Undecalcified sections stained with Villanueva bone stain. Scale bars = 50 μm . (A) Bright-field microscopy image demonstrating complete bony bridging within the cage connecting the cranial and caudal vertebral endplates. Mineralized bone tissue is stained purple, while osteoid and fibrous tissues appear in shades of pink/red. (B) Fluorescence microscopy image displaying calcein labeling. Intense labeling is observed on the caudal side, indicating active mineralization, whereas the cranial side demonstrates minimal labeling, suggesting that bone formation is nearing completion. (C–E) Polarized light microscopy images. The cranial side is primarily composed of lamellar bone (mature) (Lm.V: 32.5%, BV/TV: 73.9%), while the caudal side is predominantly occupied by woven bone (immature), indicating delayed bone maturation in the caudal region (See Table 2 for the full histomorphometric dataset). The asterisk (*) in (D) indicates lamellar bone, and the dagger (†) in (E) indicates woven bone. [Please click here to view a larger version of this figure.](#)



	At surgery	1 w	4 w	8 w	12 w
Weight (g)	221.8	230.1	283.1	325.9	346.8

Table 1: Time course of body weight. The data represent values from a single rat used in this study. w, week.

Intracage	BV	BV/TV	OV/TV	Tb.Th	OS/BS	Wo.V	Lm.V	Wo.V/BV	Lm.V/BV
Unit	μm ²	%	%	μm	%	μm ²	μm ²	%	%
Cranial	182,533.07	73.8916	0.5276	67.7499	10.8905	117,448.15	56,607.55	67.4773	32.5227
Caudal	174,055.70	70.4598	2.9576	64.6076	39.8625	160,165.10	22,367.97	87.7458	12.2542

Table 2: Histomorphometric analysis of the cranial and caudal intracage regions. The data represent values from a single rat used in this study. BV, bone volume; BV/TV, bone volume/tissue volume (Bone Volume Fraction); OV/TV, osteoid volume/tissue volume; Tb.Th, trabecular thickness; OS/BS, osteoid surface/bone surface; Wo.V, woven bone volume; Lm.V, lamellar bone volume; Wo.V/BV, woven bone volume/bone volume; Lm. V/BV, lamellar bone volume/bone volume.

Discussion

Here, a novel interbody fusion model of the rat caudal spine was established. This model involves inserting a titanium cage via a posterior approach augmented with plate-and-screw fixation. Subsequently, intracage bone formation was evaluated using detailed histomorphometric analysis. The distinct features of this model are threefold: 1) it closely mimics clinical posterior lumbar interbody fusion or transforaminal lumbar interbody fusion procedures by combining an interbody cage with posterior instrumentation; 2) it utilizes the caudal vertebrae, an anatomically accessible site, thereby ensuring surgical technique and animal welfare standardization; and most importantly, 3) it enables systematic histomorphometric analysis and polarized light microscopy of the entire region of interest, including the cage interior using undecalcified sections. Consequently, this model assesses "intracage bone volume" and "bone maturity," which have been challenging to measure in conventional rat models, thereby serving as a suitable platform for preclinical evaluation of interbody cage materials and bone substitutes. The combination

of higher bone volume, higher lamellar bone ratio, and lower fluorescence labeling in the cranial region indicated that bone formation was near completion and had entered the maturation phase, whereas the caudal region findings indicated ongoing active new bone formation.

Compared to rat lumbar models (such as the lateral XLIF-like approach), which more closely approximate clinical biomechanical environments (axial compression and shear) and surgical pathways, the present caudal model serves a different purpose. The caudal model provides simplified surgical access, higher throughput, lower costs, and a negligible risk of major neurological complications. It is uniquely suited for detailed histomorphometric analysis of entire regions using undecalcified sections. Therefore, its value lies in providing a stable preliminary *in vivo* screening platform rather than fully replacing load-bearing lumbar models.

Beyond serving as a technical demonstration, this caudal interbody fusion model has a broader scientific impact and can be utilized to answer fundamental research questions. Specifically, it provides an efficient *in vivo* screening platform for evaluating the osteoconductivity of novel implant surface

treatments and assessing the *in vivo* performance of next-generation biodegradable cages. Furthermore, by utilizing genetically modified or disease-induced rat models, this approach can be applied to investigate the impact of systemic metabolic diseases—such as osteoporosis or diabetes—on intracage bone maturation and the overall spinal fusion process.

Therefore, bone formation patterns and the rate of remodeling into lamellar bone observed in this model may not strictly correspond to the postoperative behavior of human lumbar interbody fusion. Second, this study was a pilot feasibility study describing the surgical protocol and histological methodology, and its evaluation was limited to a single animal ($n = 1$). Therefore, no statistical analysis was performed. The lack of statistical validation and the absence of an independent control group (e.g., sham surgery or autograft) are primary limitations; however, this $n = 1$ design was justified ethically to verify surgical safety before committing a larger cohort. Third, the histological evaluation was limited to a single time point. For future dynamic histomorphometry, a double-labeling protocol (e.g., with a 5–7 day interval) should be employed. Finally, achieving a perfect fit with a standardized 2 mm titanium cage can be challenging and causes beam-hardening artifacts. Suboptimal placement may lead to fibrous tissue interposition at the cage edges. Future studies should consider using radiolucent materials (e.g., PEEK) or 3D-printed customized cages tailored to individual pre-operative measurements to standardize placement and enhance evaluation. Due to the single-subject design, inter-operator variability and procedural repeatability have not been evaluated. This is a crucial limitation regarding methodological robustness. To overcome this limitation, future studies must include inter-rater reliability assessments among multiple operators. Furthermore, rigorous preoperative training is essential to reduce subjective biases during surgical execution and data interpretation.

Nevertheless, this model has some limitations. First, the biomechanical environment of the rat caudal spine significantly differs from that of the human lumbar spine. Caudal vertebrae are not structures that routinely bear direct body weight, and the axial compression, shear forces, and flexion-extension stress patterns are not identical to those of the human lumbar spine, as noted in existing caudal models^{14,15}. Additionally, rat vertebrae retain active growth plates throughout adulthood, which may influence healing patterns differently than in adult humans, and no graft material was used in this specific model, differing from typical clinical interbody fusion practices.

Disclosures

The authors declare that they received no salary, consultant fees, or other personal financial benefits from the company.

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