Research Square

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Clinical and Radiographic Outcomes of Two Composite Bone Grafts in Transcrestal Sinus Floor Elevation Using Osseodensification: A Randomized Controlled Trial

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Research Article

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Abstract

Objective

To compare the osteogenic efficacy and safety of allogeneic bone collagen combined with allogeneic bone graft versus collagen combined with xenogeneic bone graft in osseodensification-assisted transcrestal sinus floor elevation (TSFE), and to investigate the impact of sinus width (SW) and sinus angle (SA) on bone augmentation outcomes.

Materials and Methods

In this randomized controlled trial, 34 patients were randomly allocated to a test group (n = 17) and a control group (n = 17). All patients underwent TSFE assisted by osseodensification drills. Intraoperatively, allogeneic bone collagen (test group) and collagen (control group) were used as a basal layer to protect the sinus membrane. Six months postoperatively, implant stability was evaluated using resonance frequency analysis (RFA) from four directions. Cone-beam computed tomography (CBCT) data were acquired at baseline, immediately postoperatively, and at 6 months to comparatively analyze bone augmentation parameters.

Results

No sinus membrane perforations occurred during surgery in either group. At 6 months postoperatively, the implant stability quotient (ISQ) values measured from four directions were all above 80 in both groups, with no statistically significant differences between the groups ($P > 0.05$). Regarding bone augmentation, the test group demonstrated significantly superior vertical bone gain (VBG) (6.37 ± 1.11 mm) compared to the control group (5.13 ± 0.93 mm; $P = 0.001$). Although the graft resorption (GR) was slightly lower in the test group (1.51 ± 0.58 mm) compared to the control group (1.95 ± 1.03 mm), the difference was not statistically significant. Furthermore, statistical analysis confirmed no significant correlation between the 6-month bone augmentation outcomes and SW or SA.

Conclusions

Introduction

With the widespread adoption of minimally invasive concepts, transcrestal maxillary sinus floor elevation (TSFE) has been extensively applied for the rehabilitation of posterior maxillary sites with insufficient bone height, owing to its minimal trauma, mild postoperative reactions, and shorter surgical duration [1]. The clinical efficacy of this technique largely depends on the optimal selection of surgical instruments and the rational application of bone grafting materials.

The conventional osteotome technique relies on impact forces generated by malleting, which can cause patient discomfort and is associated with a relatively high risk of maxillary sinus membrane perforation [2]. To overcome these drawbacks, a series of modified transcrestal TSFE techniques and instruments have been developed [3]. Among these, Salah Huwais proposed a novel drill based on the concept of osseodensification, aiming to achieve safe sinus floor elevation via a transcrestal approach [4]. Featuring a unique geometric design, this drill utilizes a non-excavating compaction mechanism [5]. This mechanism not only densifies the surrounding bone during sinus floor elevation, thereby enhancing the primary stability of the implant [6], but also generates pressure waves through high-speed counterclockwise rotation combined with irrigation to uniformly elevate the maxillary sinus membrane [4]. This significantly reduces the risk of iatrogenic membrane perforation [7], providing a novel solution for minimally invasive implantology.

Despite advancements in surgical instruments optimizing the operative workflow, controversies regarding the choice of bone grafting materials persist. In TSFE, the primary functions of bone grafts are to maintain the elevated space, prevent elastic recoil, and guide new bone formation. Currently, xenografts, such as deproteinized bovine bone mineral (DBBM), are widely used as bone substitutes due to their excellent space-maintaining capacity [8, 9]. However, they lack osteoinductive properties and exhibit extremely slow degradation rates; long-term residual particles may impede the reconstruction of functional bone trabeculae [10, 11]. In contrast, allografts possess a natural three-dimensional structure similar to that of autogenous bone, and their degradation rate more closely mimics physiological bone remodeling in humans [12]. Under comparable conditions, allografts demonstrate superior new bone formation and tissue replacement rates compared to xenografts [13].

Notably, novel allogeneic bone collagen, a type of demineralized bone matrix (DBM), not only serves as a scaffold for cell migration but also preserves endogenous growth factors such as bone morphogenetic proteins (BMPs) [14]. Theoretically, this material, which combines osteoconductive scaffolding with osteoinductive activity, can more effectively promote the differentiation and proliferation of osteoblasts, thereby accelerating new bone maturation [15]. Furthermore, compared with particulate bone substitutes, decalcified allogeneic bone collagen exhibits superior flexibility and plasticity. It can be tailored and molded according to surgical requirements, making it highly suitable for basal lining and filling in sinus floor elevation procedures [16].

Nevertheless, there is currently a lack of high-quality comparative clinical data evaluating the efficacy of this material when combined with osseodensification drill technology in TSFE. Therefore, this prospective randomized controlled trial was designed to evaluate the clinical and radiographic outcomes of two composite bone grafting protocols (allogeneic bone collagen versus collagen as a basal lining, combined with allograft bone versus xenograft bone as filling materials) in TSFE assisted by osseodensification technology. We hypothesized that the group receiving allogeneic bone collagen would demonstrate superior VBG and ISQ compared to the collagen group. Furthermore, this study aims to analyze the correlation between maxillary sinus anatomy (width and angle) and the final bone

augmentation outcomes, thereby providing evidence-based support for clinical material selection and surgical planning.

Materials and methods

Ethical considerations

This randomized controlled trial was conducted in accordance with the principles of the Declaration of Helsinki and the Consolidated Standards of Reporting Trials (CONSORT) guidelines. The study protocol was approved by the Medical Ethics Committee of West China Hospital of Stomatology, Sichuan University (Approval No.: WCHSIRB-D-2022-396) and registered at the Chinese Clinical Trial Registry (ChiCTR2200063382). Written informed consent was obtained from all participants prior to enrollment.

Eligibility criteria

Patients were recruited from the Department of Oral Implantology, West China Hospital of Stomatology, Sichuan University, between September 2022 and September 2023. The inclusion criteria were as follows: Age between 18 and 65 years; missing or extracted maxillary posterior teeth for at least 3 months; residual bone height (RBH) ranging from 3 to 7 mm; no systemic contraindications for implant surgery; and provision of written informed consent after understanding the potential benefits and risks. The exclusion criteria included: Pathological conditions in the ipsilateral maxillary sinus or a history of maxillary sinus surgery; RBH < 3 mm; uncontrolled systemic diseases; autoimmune disorders; long-term use of medications affecting bone metabolism; ongoing radiotherapy or chemotherapy; heavy smoking; psychiatric disorders, drug abuse, or alcoholism; and pregnancy or lactation.

Study design and sample size

This study was designed as a randomized, parallel-group, controlled clinical trial. Participants were allocated in a 1:1 ratio using block randomization (block size = 4). The randomization sequence was generated by an independent researcher not involved in patient enrollment or surgery. Allocation concealment was achieved using sequentially numbered, opaque, sealed envelopes, which were opened only after patient enrollment to determine the assigned bone graft material. All surgical procedures were identical between groups, differing solely in the graft material used. The surgeons were not blinded to the allocation; however, outcome assessors and statisticians were blinded to the group assignments.

Sample size estimation was performed using G*Power 3.1. Based on the primary outcome (maxillary sinus elevation height at 6 months postoperatively) from previous studies [17], we assumed an expected difference in bone gain of 1.6 mm with a standard deviation (SD) of 1.3 mm, For a two-sided independent-samples t-test with a significance level (α) of 0.05 and a statistical power (1-β) of 90%, the required sample size was calculated to be 17 participants per group. Accounting for a potential 15%

dropout rate, the final target sample size was set at 34. Ultimately, all enrolled participants completed the follow-up without loss to follow-up.

Surgical procedure

Prior to surgery, patients rinsed with a diluted povidone-iodine solution for 3 minutes. The surgical site and facial skin were disinfected, and sterile draping was performed. Local infiltration anesthesia (Articaine hydrochloride with epinephrine, 1.7 mL) was administered. A full-thickness mucoperiosteal flap was elevated to fully expose the buccal and palatal boundaries of the alveolar ridge. Figure. 1 illustrates the specific surgical steps of the TSFE procedure. An initial osteotomy was performed using a round bur, followed by a pilot drill (800–1000 rpm, forward rotation) to a depth 1 mm short of the sinus floor. Subsequently, osseodensification drill (Smart Drills; Beijing Segma Healthcare Co.,Ltd., Beijing, China) were used in reverse rotation (400–800 rpm) to gradually expand the osteotomy to the predetermined diameter. In the control group, a collagen sponge (Kejibang, Wuxi BIOT Biology Technology Co.,Ltd., Wuxi, China) was placed into the osteotomy. In the test group, allogeneic bone collagen (Osteolink; Hubei Osteolink Biomaterials Co., Ltd., Wuhan, China) was used. The sinus floor was then fractured using a reverse-rotating drill until a "drop-in" sensation was confirmed. The integrity of the Schneiderian membrane was verified via the Valsalva maneuver. A cushioning layer was placed at the sinus floor, followed by the advancement of the bone substitute material using a bone condenser in reverse rotation (25–50 rpm). The test group received allogeneic bone (Osteolink; Hubei Osteolink Biomaterials Co., Ltd., Wuhan, China), while the control group received xenogeneic bone (Geistlich Bio-Oss; Geistlich Pharma AG, Wolhusen, Switzerland). Dental implants were then placed using a submerged healing protocol, and cover screws were tightened. Soft tissue flaps were closed with 4 – 0 nylon sutures (Prolene; Ethicon, Inc., Somerville, NJ, USA). Postoperative management included oral amoxicillin and ornidazole for 7 days, 0.12% chlorhexidine mouthwash for 14 days, and analgesics as needed. Sutures were removed 14 days postoperatively.

Implant stability quotient (ISQ) measurement

Implant stability was evaluated non-invasively at the second-stage surgery, 6 months after maxillary sinus elevation, using the Osstell device (Osstell; Osstell AB, Gothenburg, Sweden). ISQ values were measured from four directions (mesial, distal, buccal, and palatal). Three readings were taken at each site, and the mean value was recorded for statistical analysis.

Radiographic evaluation

To assess the bone augmentation outcome, cone-beam computed tomography (CBCT) DICOM data were acquired preoperatively, immediately postoperatively, and at 6 months postoperatively. Images were imported into SIMPLANT 17.0 software for measurements. Anatomical parameters included: sinus width (SW), defined as bucco-palatal width at 10 mm above alveolar crest [18]; sinus angle (SA), defined

as the angle formed by the buccal and palatal sinus walls at 10 mm above the sinus floor [19]. And RBH, defined as the distance from the alveolar crest to the sinus floor at the implant site. The primary radiographic outcomes were: vertical bone gain (VBG), measured as the vertical distance from the original maxillary sinus floor to the apical border of the bone augmentation. And graft bone resorption (GR), calculated as the difference in vertical bone gain between the immediate postoperative scan and the 6-month follow-up scan.

Statistical analysis

Categorical variables were described as absolute frequencies and percentages, and intergroup differences were analyzed using the Chi-square test or Fisher's exact test. Continuous variables were expressed as mean ± SD. Normality was assessed using the Shapiro-Wilk test, and homogeneity of variance was evaluated using the F-test. For normally distributed data, independent-samples t-tests were used for between-group comparisons; otherwise, the Mann-Whitney U test was applied. Multivariable linear regression was performed to evaluate between-group differences at 6 months, adjusting for baseline and immediate postoperative values. For correlation analyses of continuous variables, Pearson's correlation coefficient was calculated for normally distributed data, whereas Spearman's rank correlation coefficient was used for non-normally distributed data. All statistical analyses were performed using R software (version 4.6.1; R Foundation for Statistical Computing, Vienna, Austria). A two-sided P-value < 0.05 was considered statistically significant.

Results

A total of 34 patients were enrolled (17 per group), with comparable baseline characteristics between the two groups. No statistically significant differences were observed in sex ($P = 0.730$), age ($P = 0.812$), or implant site (70.59% first molars in both groups). The distribution of implant systems was also well-balanced between the groups ($P = 0.486$). Detailed information is presented in Table 1.

Table 1
Baseline characteristics of the enrolled patients (n, %, mean ± SD)

Variables	Control Group(n = 17)	Test Group (n = 17)	*P* value
Gender			0.730[a]
Male	10(58.82%)	9(52.94%)	
Female	7(41.18%)	8(47.06%)	
Age (years)	50.88 ± 9.49	49.47 ± 11.39	0.812[b]
Implant site			> 0.999 [a]
First molar	12(70.59%)	12(70.59%)	
Second molar	5(29.41%)	5(29.41%)	
Implant system			0.486 [a]
Straumann BLT	6(35.29%)	8(47.06%)	
Nobel PMC	11(64.71%)	9(52.94%)	
Notes: [a] χ^2 test was performed. [b] Mann-Whitney U test was performed.			

Implant stability analysis

All enrolled patients completed the restorative phase, achieving a 100% implant success rate. At 6 months postoperatively, the mean ISQ values in the control group were 96 ± 2.38 (mesial), 96 ± 2.88 (buccal), 95 ± 4.13 (distal), and 95 ± 4.10 (palatal). In the test group, the corresponding values were 97 ± 0.94 (mesial), 96 ± 1.78 (buccal), 96 ± 1.11 (distal), and 96 ± 2.15 (palatal). As illustrated in Figure. 2, the Mann-Whitney U test revealed no statistically significant differences in ISQ values across all four directions between the two groups. Furthermore, all ISQ values exceeded 80, indicating that the implants had achieved sufficient stability for functional loading.

Note

All *P* values were calculated using the Mann-Whitney *U* test.

Radiographic Measurement Results

Table 2 presents the baseline anatomical parameters of the maxillary sinus for both groups. The RBH was 5.41 ± 1.50 mm in the control group and 5.40 ± 0.91 mm in the experimental group. The SW was 14.69 ± 2.17 mm and 14.44 ± 2.50 mm, while the SA was 65.02° ± 18.13° and 59.37° ± 21.49°, respectively. Independent sample *t*-tests confirmed that the baseline anatomical profiles were well-

balanced and comparable between the two groups (all $P > 0.05$). Furthermore, after categorizing the SW and SA based on previous literature [18, 20] (e.g., width: <12 mm, 12–15 mm, > 15 mm; angle: <30°, 30°–60°, > 60°), no statistically significant differences were observed between the two groups.

Table 2
Baseline anatomical parameters of the maxillary sinus (n, %, mean ± SD)

Variables	**Control Group (N = 17)**	**Test Group (N = 17)**	***P* value**
RBH(mm)	5.41 ± 1.50	5.40 ± 0.91	0.973[a]
SW(mm)	14.69 ± 2.17	14.44 ± 2.50	0.759 [a]
<12	3(17.6%)	2(11.8%)	0.131[b]
12–15	5(29.4%)	11(64.7%)	
>15	9(52.9%)	4(23.5%)	
SA(°)	65.02 ± 18.13	59.37 ± 21.49	0.413[a]
30–60	7(41.2%)	10(58.8%)	0.493[c]
>60	10(58.8%)	7(41.2%)	
Notes:. [a] t-test was performed. [b] Fisher exact test was performed. [c] χ^2 test was performed.			

At 6 months postoperatively, the mean VBG in the experimental group was 6.37 ± 1.11 mm, which was significantly greater than that in the control group (5.13 ± 0.93 mm, $P = 0.001$) (Figure. 3a). Regarding GR(Figure. 3b), the control group exhibited a mean value of 1.95 ± 1.03 mm, while the experimental group showed a slightly lower value of 1.51 ± 0.58 mm; however, this difference was not statistically significant ($P = 0.144$). Additionally, the peri-implant apical bone height (ABH) at 6 months was comparable between the groups, measuring 0.90 ± 0.61 mm in the control group and 1.04 ± 0.71 mm in the experimental group, with no significant difference observed ($P = 0.326$).

Notes: T0, preoperative; T2, 6 months after surgery. Intergroup comparisons were performed using the independent-samples t test for RBH, VBG, GR and the Mann-Whitney U test for peri-implant ABH.

Correlation and Multiple Linear Regression Analyses

Correlation analysis in Fig. 4 indicated that maxillary sinus anatomical factors were generally not significantly correlated with the bone formation indicators at 6 months postoperatively. Only in the subgroup analysis of the experimental group did the SA show a significant correlation with the amount of GR; the other anatomical variables exhibited no statistically significant associations with bone formation outcomes. Overall, the immediate postoperative maxillary sinus elevation height was strongly correlated with several indicators at 6 months, although subgroup analyses revealed some variations.

Notes: T1, immediately after surgery; T2, 6 months after surgery. r = Pearson correlation coefficient; rs = Spearman correlation coefficient. Red highlighting denotes statistically significant correlation coefficients following corresponding statistical tests.

To control for potential confounding effects arising from baseline correlations and inter-group differences, this study further employed multiple linear regression analysis to accurately evaluate the independent effects of immediate postoperative indicators, maxillary sinus anatomical factors (RBH, SW, and SA), and group allocation on the VBG (Figure. 5a) and GR (Figure. 5b) at 6 months postoperatively.

The regression analysis revealed that the immediate postoperative VBG was the strongest predictor of the final VBG at 6 months (β = 0.61, $P < 0.001$), indicating that a greater initial bone gain during surgery was associated with more favorable bone gain at 6 months. Regarding inter-group differences, the experimental group demonstrated significantly superior elevation outcomes compared to the control group (β = 0.82, $P = 0.006$).

In terms of GR, the immediate postoperative VBG was positively correlated with subsequent GR (β = 0.39, $P < 0.001$), suggesting that a greater elevation magnitude was accompanied by a correspondingly higher amount of resorption. However, the experimental group exhibited significantly less GR at 6 months postoperatively (β = -0.82, $P = 0.006$), indicating superior bone stability in this group. Consistently, the maxillary sinus anatomical factors showed no significant predictive effects on the VBG, or GR at 6 months postoperatively ($P > 0.05$), confirming that they are not independent factors influencing long-term bone formation outcomes.

Notes: T0, preoperative; T1, immediately after surgery.

Discussion

This prospective randomized controlled trial systematically evaluated the clinical efficacy of two combined composite bone graft materials used in conjunction with bone densification techniques for TSFE.

Primary implant stability is a critical determinant of implant restoration success and serves as a direct indicator for evaluating the biomechanical properties of bone graft materials. In this study, resonance frequency analysis was employed to measure the ISQ at 6 months postoperatively. The results demonstrated no statistically significant differences in ISQ values across four directions between the experimental and control groups, with both groups achieving exceptionally high values (95–97). This finding holds significant clinical implications. Dhore et al. previously reported that bone densification techniques yield higher stability coefficients at both the initial implant placement and the final restoration stages compared to the traditional osteotome technique [6]. The remarkably high ISQ values observed in our study reflect excellent osseointegration quality. This outcome is likely the synergistic result of the Smart drill bone densification technique and the biological properties of the graft materials. On one hand, the Smart drill compresses and densifies the trabecular bone surrounding the implant site, thereby

increasing local bone density and bone-to-implant contact area. On the other hand, the composite graft materials demonstrated excellent osteogenic potential. Although the lower-strength basal lining material might superficially appear to compromise the mechanical strength at the base of the implant site, it did not impair osseointegration; rather, the newly formed bone exhibited a high degree of mineralization and mechanical strength.

Imaging and multivariate regression analyses jointly indicated that the experimental group achieved a significantly greater mean VBG compared to the control group. Furthermore, although the difference in GR between the groups did not reach statistical significance, the experimental group showed a favorable trend toward less bone loss. Previous studies have noted that DBBM is characterized by a slow resorption rate and excellent space-maintaining properties [21]. It can achieve predictable bone augmentation height in maxillary sinus elevation procedures [22, 23], and compared to allografts with faster resorption rates, xenografts should theoretically exhibit less volumetric change [24]. This seemingly contradictory result is reconciled by the fact that, to protect the sinus membrane, our study utilized a highly flexible material as a basal lining for bone augmentation. In the xenograft group, collagen was used, which degrades rapidly. This rapid absorption led to a lack of sufficient mechanical support at the apical portion of the implant, prematurely exposing the underlying xenograft to inflammatory challenges or mechanical instability, thereby resulting in greater observed bone resorption. In contrast, the allogeneic bone collagen used in the experimental group combines the mechanical advantages of collagen with a slower, more controllable degradation profile. Its degradation rate is highly congruent with the pace of physiological bone remodeling in the human body. This synchronicity ensures that the space-maintaining scaffold remains intact until sufficient new bone formation occurs. During the bone healing phase, the dual capabilities of osteoconduction and osteoinduction provided by the allogeneic bone collagen also promote the formation of functional trabecular bone. Consequently, the experimental group benefited from a more stable graft environment, leading to superior maintenance of vertical height and a trend toward reduced apical resorption.

Beyond bone substitute materials, the bone augmentation outcomes following TSFE are influenced by multiple factors, among which anatomical factors are considered paramount. Numerous studies have observed that SW affects both the quality and quantity of final bone formation. In wider maxillary sinuses, new bone formation may require a longer duration; the ratio of sinus width to new bone formation is negatively correlated [18, 25], while it is positively correlated with GR [26, 27]. Specifically, a greater bucco-palatal distance of the maxillary sinus and a larger SA are associated with increased resorption of bone graft materials [19]. Contrary to these findings, our study did not observe any significant impact of these anatomical factors on the increase in VBG or GR. The Smart drill used in the surgery operates on the principle of bone densification, compressing a substantial amount of autogenous bone chips and graft materials laterally and apically. This creates a high-density integration around the implant, providing exceptional primary stability. Local bone densification provides adequate mechanical support and space maintenance, while the osseodensification drill uniformly elevates the sinus membrane, effectively minimizing the mechanical instability caused by a wide sinus cavity.

Consequently, volumetric changes in the grafted region are primarily dictated by the properties of the bone grafting materials.

Maxillary sinus membrane perforation is the most common and challenging complication in TSFE procedures. The SA can affect the ease of membrane detachment and elevation; steep sinus angles typically increase the risk of membrane perforation due to shear forces [25, 28]. Compared to the traditional osteotome technique, bone densification technology, through specialized drill design and a minimally invasive approach, can reduce the perforation rate to 7.31% [7]. In our study, through defensive optimization of the surgical strategy, we reduced the perforation rate to 0%. First, we excluded high-risk cases with residual alveolar ridge height of less than 3 mm. Second, we employed a defensive basal lining technique: prior to the drill penetrating the sinus floor and the insertion of particulate bone substitutes, we pre-placed allogeneic bone collagen (experimental group) or collagen (control group), both possessing excellent flexibility and elasticity. This formed a buffering barrier in front of the maxillary sinus membrane. This buffering effect allowed the material to conform to the varying angles of the sinus floor, effectively dispersing localized stress and preventing stress concentration points. Consequently, even in anatomically challenging cases, the Schneiderian membrane was protected, further reducing the incidence of membrane perforation.

Despite the positive outcomes of this study, several limitations warrant acknowledgment and future improvement. First, this single-center study had a relatively small sample size (n = 34), which may affect the statistical power of the results. Second, due to the nature of the TSFE procedure, we were unable to obtain bone core biopsies via secondary surgery to histologically analyze differences in new bone formation morphology between the two groups. Third, the relatively short follow-up period (limited to 6 months postoperatively) restricts a comprehensive evaluation of long-term implant stability and the sustainability of bone augmentation. Therefore, future studies should consider expanding the sample size and extending the follow-up duration to provide more robust data support.

Conclusion

In conclusion, this randomized controlled trial confirms that transcrestal sinus floor elevation assisted by osseodensification is a safe and predictable protocol, ensuring high primary implant stability and effectively minimizing the risk of membrane perforation regardless of the grafting material used. Regarding the grafting material, the use of allogeneic bone collagen as a basal lining proved superior to the xenograft-collagen composite, yielding significantly greater VBG at 6 months postoperatively. Furthermore, the analysis indicates that the final augmentation outcome is independent of the maxillary sinus width and angle. These findings suggest that allogeneic bone collagen is a highly effective grafting material for TSFE, capable of optimizing VBG in the posterior maxilla.

Declarations

Ethics Approval and Trial Registration

This clinical trial was approved by the Medical Ethics Committee of West China Hospital of Stomatology, Sichuan University (Approval No. WCHSIRB-D-2022-396) and prospectively registered in the Chinese Clinical Trial Registry (ChiCTR) (Registration No. ChiCTR2200063382).

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Author contributions Zhang XQ and Feng YZ contributed equally to this work and share first authorship. Zhang XQ: Conceptualization, methodology, formal analysis, investigation, data curation, writing—original draft preparation. Feng YZ: Conceptualization, methodology, validation, investigation, resources, writing—review and editing, visualization. Mo A: Conceptualization, validation, resources, writing—review and editing, supervision, project administration, funding acquisition. All authors read and approved the final manuscript.

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Consent for publication Not applicable.

Competing interests The authors declare that they have no conflict of interest.

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Figures

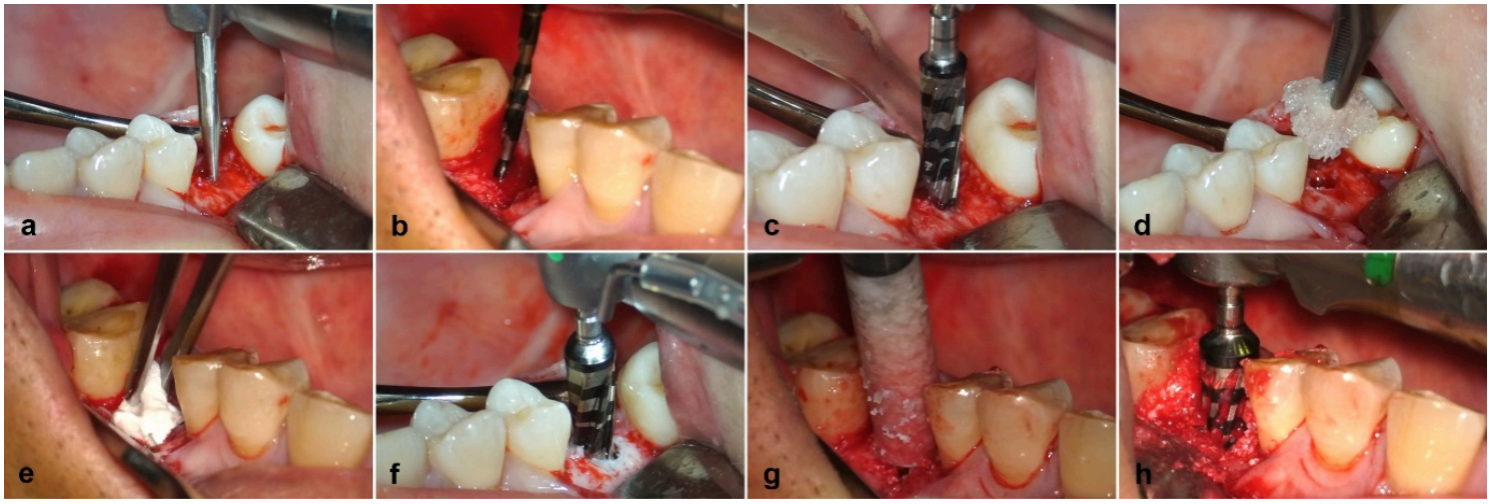


Figure 1

Surgical steps of TFSE using osseodensification technique. (a) round bur marking;(b) initial pilot drilling; (c) Sequential osseodensification (reverse rotation); (d) test group: allogeneic bone collagen buffer layer; (e) control group:collagen buffer layer; (f) reverse osseodensification for sinus membrane elevation; (g) bone substitute placement; (h) bone substitute delivery (slow reverse rotation)

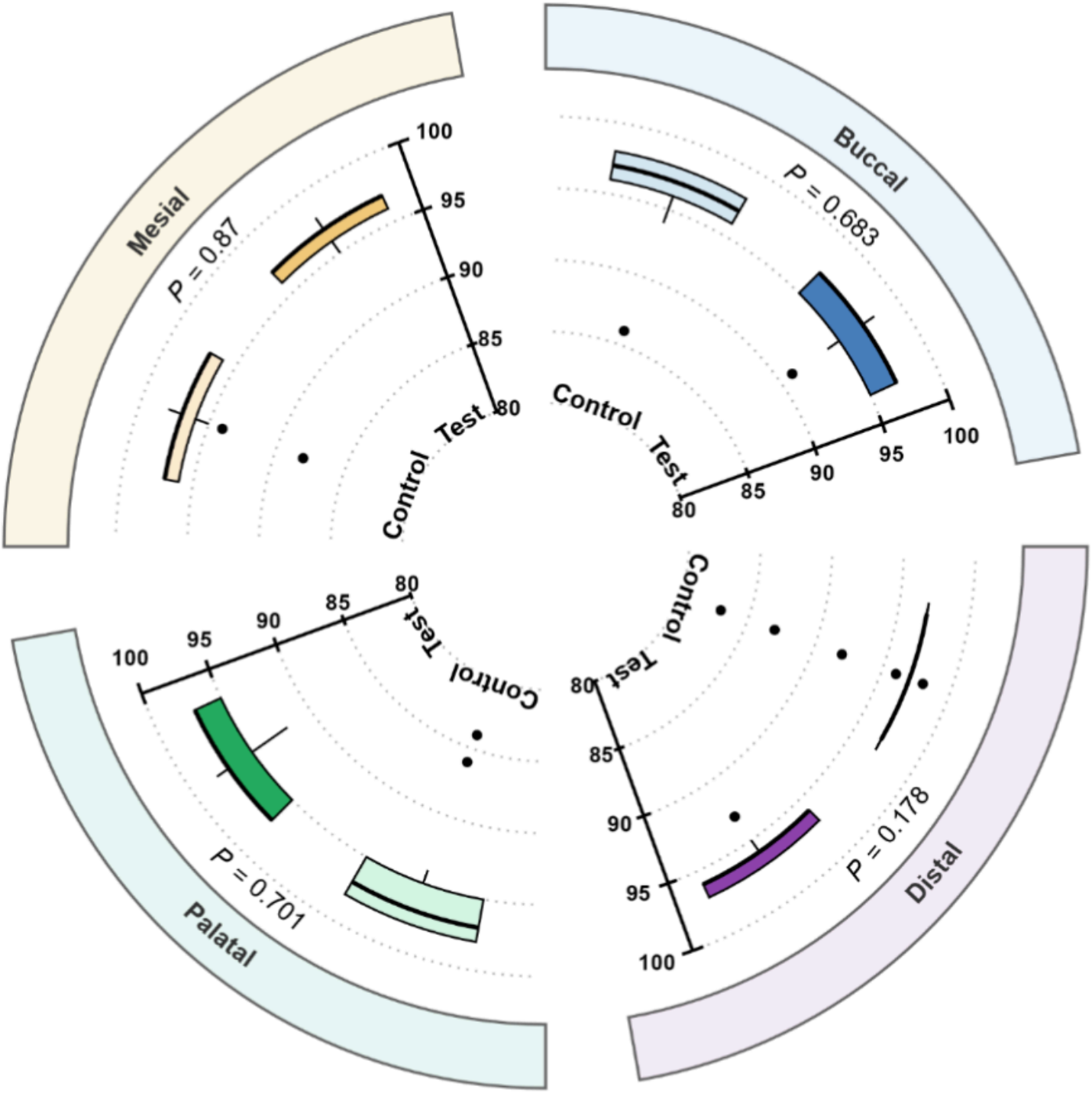


Figure 2

ISQ values of implants in different orientations at 6 months postoperatively

Note: All *P* values were calculated using the Mann-Whitney *U*test.

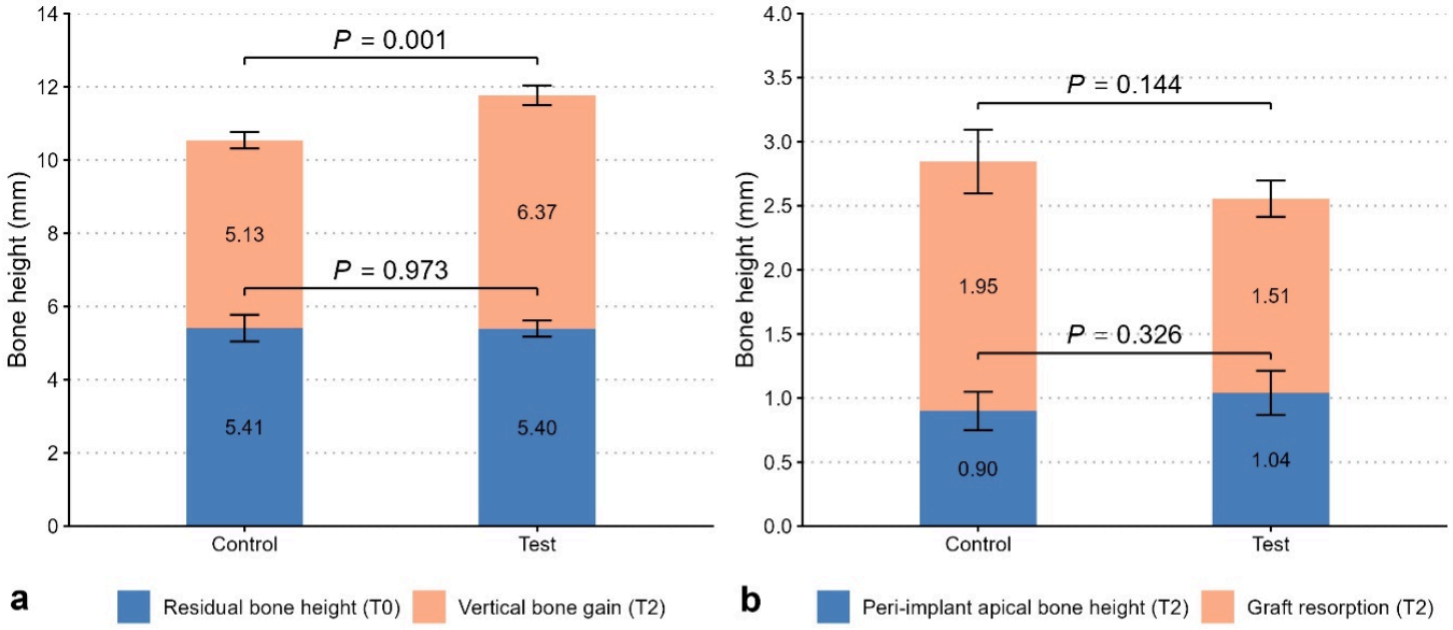


Figure 3

Radiographic outcomes between the control and test groups at 6 months. (a) comparison of RBH and VBG; (b) Comparison of peri-implant ABH and GR

Notes: T0, preoperative; T2, 6 months after surgery. Intergroup comparisons were performed using the independent-samples t test for RBH, VBG, GR and the Mann-Whitney U test for peri-implant ABH.

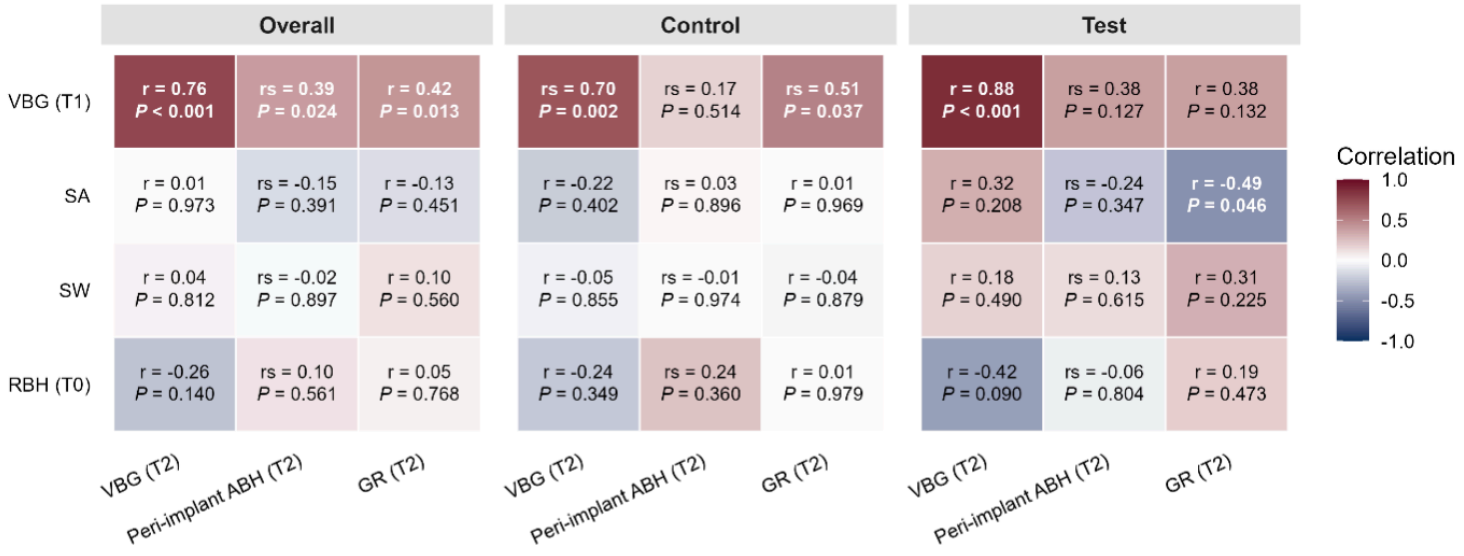


Figure 4

Correlation analysis between six-month postoperative measurements and baseline parameters

Notes: T1, immediately after surgery; T2, 6 months after surgery. r = Pearson correlation coefficient; rs = Spearman correlation coefficient. Red highlighting denotes statistically significant correlation coefficients following corresponding statistical tests.

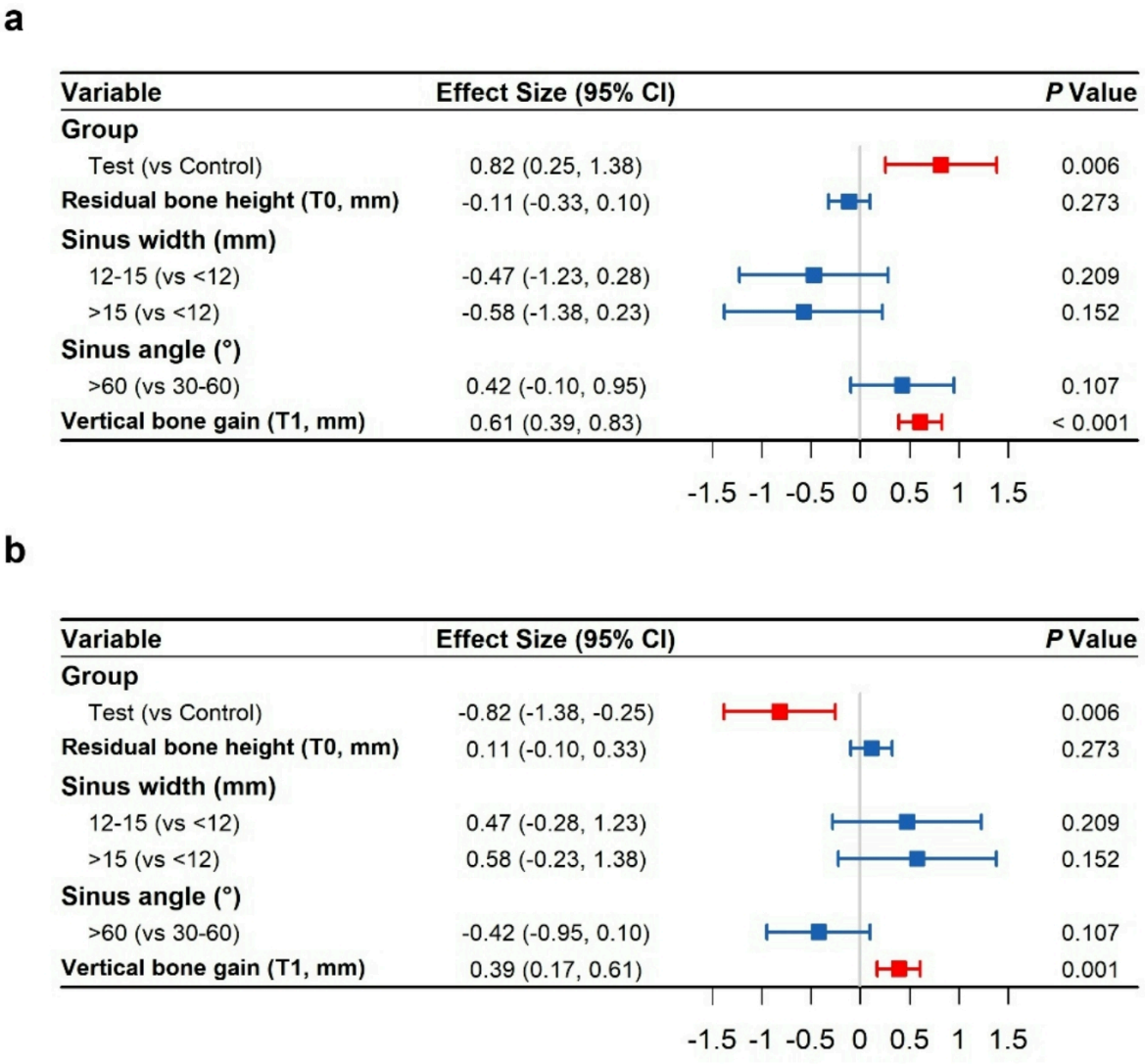


Figure 5

Multivariable regression forest plot for VBG and GR at 6 months postoperatively. (a) VBG; (b) GR;

Notes: T0, preoperative; T1, immediately after surgery.