Clinical Implant Dentistry and Related Research

WILEY

ORIGINAL ARTICLE OPEN ACCESS

Moldable and Particulate Bone Material in Alveolar Ridge Preservation: A Multicenter Randomized Controlled Trial

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Received: 17 October 2024 | **Revised:** 26 January 2025 | **Accepted:** 27 January 2025

Funding: This work was supported by the MedPark.

Keywords: alveolar ridge preservation | moldable bone | particulate bone

ABSTRACT

Introduction: This study aimed to determine possible histological and radiological differences in alveolar ridge preservation (ARP), using moldable bone versus particulate bone.

Methods: After tooth extraction, 39 patients (40 teeth) were randomized (1:1) to receive ARP using moldable bone materials (SBX group) or particulate bone materials (PBX group). An absorbable collagen membrane was placed over the graft material and the surgical site was sutured. Cone-beam computed tomography was taken immediately and 5 months after ARP. Bone core samples from the implantation site were obtained for histomorphometric analysis 5 months after ARP.

Results: Forty-six patients were screened and 39 of them completed the study. However, one patient who received split-mouth treatment was excluded, resulting in data from 38 patients being analyzed. In radiological evaluation, the changes in midbuccal alveolar bone height at 5 months were -0.753 ± 0.112 and -1.018 ± 0.111 mm in the SBX group and PBX groups, respectively ($F = 2.895$; $p = 0.098$; mean difference [MD] 0.265; 95% confidence interval [CI] = -0.051 to 0.582). Changes in the horizontal ridge width were measured at three levels (−1, −3, and −5 mm) below the most coronal aspect of the crest and showed a decrease in both groups, with no significant differences between the groups. The percent new bone area of the SBX group (39.156 ± 2.505) was significantly different from that of the PBX group (22.749 ± 2.476) ($F = 22.171$; $p < 0.001$; 95% MD 16.407; CI = 9.333 to 23.481). The percent residual material area was significantly lower in the SBX group (8.973 ± 2.211) compared to the PBX group (15.633 ± 2.186), with an F-statistic of 4.687 and p-value = 0.037 (MD −6.660; 95% CI = −12.904 to −0.415). The percent connective tissue area was 49.743 ± 4.199 and 56.657 ± 4.151 for the groups ($F = 1.401$; $p = 0.245$; MD −6.914; 95% CI = −18.773 to 4.944), respectively.

Conclusion: Radiological and histological results showed that use of moldable bone can achieve similar ARP parameters as those achieved by particulate bone.

Trial Registration: Clinical Research Information Service No. KCT0009560. This randomized clinical trial was not registered before participant recruitment and randomization. (Date of registration: 21/06/2024. https://cris.nih.go.kr/cris/search/detailSearch.do?seq=27272&searchpage=L)

The first two authors contributed equally to this article.

1 | Introduction

Tooth extraction triggers irreversible anatomical changes to the alveolar bone, including horizontal and vertical absorption [1–3]. The alveolar bone holds the teeth in place; removing a tooth leads to bone atrophy [4–6]. Resorbed alveolar bone prevents the placement of the implant in the optimal position when implantation is delayed for more than 2 months after tooth extraction. Such cases often require additional bone grafting in areas where the implant surface is exposed due to bone resorption. However, implantations that require bone grafting are complex and involve the risk of implant placement in the suboptimal position and that of damage to the surrounding soft tissue, which may lead to esthetic defects and infection at the graft site [7, 8].

To prevent alveolar bone resorption after tooth extraction and improve bone mass for future implantations, various methods of alveolar ridge preservation (ARP) have been proposed [9]. Many previous studies have found less bone resorption in the ARP site after tooth extraction compared to natural healing site without bone graft [10–12]. After tooth extraction, buccal bone undergoes more bone absorption than lingual bone in the extraction socket, ARP can prevent buccal bone absorption and both vertical and horizontal bone absorption [12, 13]. After the effectiveness of ARP became known, ARP experiments were conducted to prevent bone absorption in the extraction socket using various materials such as synthetic bone, xenograft, allograft, and platelet-rich fibrin (PRF), and so forth [13–19]. Although there were differences in preventing bone resorption depending on the material, many studies obtained results that prevented bone resorption compared to extraction sockets that did not ARP.

The deproteinized bovine bone mineral (DBBM) has been widely used as a xenograft, showing efficacy in preserving the alveolar bone after tooth extraction. DBBM is available in various forms, including in the particulate bone form, which is commonly used; however, particulate bone products that are not aggregated must be transplanted by the operator that gradually divides them with a device. Blood or water may flow out of the implantation site and the graft can be scattered or inhaled by suction. Immediately after a tooth extraction, the socket is an open wound that lacks soft tissue for primary closure. Consequently, performing ARP immediately after tooth extraction comes with a challenge whereby the particulate bone-type material cannot be fixed within the socket and may fall out.

Several approaches for maintaining graft material stability within the socket during ARP have been proposed, including methods using a free gingival graft, palatal rotation flap, releasing incision, and using a collagen membrane. Among them, using a collagen membrane helps prevent the graft material implanted in the extraction socket from slipping out and supports secondary healing [20, 21]. It has been suggested that the use of membranes may help maintain ridge contour rather than affecting the amount of bone resorption in ARP [22]. Nonabsorbable membranes have been used for guided bone regeneration (GBR) for a long time and are particularly advantageous in maintaining bone graft material vertically [23]. Therefore, nonabsorbable membranes have been used to retain bone graft material for ARP as well as GBR. However, it has the disadvantage of having to be removed through a second surgery and being vulnerable to bacterial infection when exposed in the oral cavity [23]. Absorbable membranes have the advantage of convenient maneuverability for application, prevent epithelial cell invasion and do not need to be removed, making them more convenient for ARP where vertical volume maintenance of the bone graft is not required. Additionally, absorbable membranes do not show a significant difference in the effectiveness of ARP compared to nonabsorbable membranes [15, 24].

While some studies have focused on developing methods that prevent leakage of graft material, others have aimed to develop alternative graft materials. The use of absorbable and nonabsorbable membranes can help retain bone graft material, but can be costly for the patient and time consuming for the dentist due to the use of additional materials. Therefore, there have been attempts to develop bone graft material in a form that is more convenient to handle. Concentrated growth factors (CGFs) or PRF have been blended with bone graft materials to make them more maneuverable and still function as bone grafts [25]. It is not just a bone graft material, but also has the advantage of retaining its shape and is less likely to dislodge from the graft site due to its sticky character. However, their clinical benefits, including effects on the alveolar bone preservation, remain unclear. These materials should be evaluated in comparative studies against traditional materials. This study aimed to evaluate the histological and radiological effects of the particulate bone and moldable bone grafts on the alveolar bone preservation.

2 | Materials and Methods

2.1 | Study Design

This study was performed according to the STROBE guidelines [26]. This parallel-group, randomized, controlled, single-blind clinical trial was conducted at two university dental hospitals in Korea between October 2021 and September 2023. This study was approved by the Institutional Review Board (IRB) of Yonsei University Dental Hospital and Dankook University Dental Hospital prior to the trial commencement in accordance with the ethical standards of the Declaration of Helsinki (IRB numbers: 2-2021-0037, 2021-7-006). This study was registered with the Clinical Research Information Service (CRIS No. KCT0009560). All patients were informed of the study purpose and provided written informed consent prior to being enrolled. All data were anonymized to ensure the participants' confidentiality.

2.2 | Participants

This study recruited 39 patients and performed a total of 40 cases (20 per group). Based on the results of the study by Fischeder et al., the sample size was calculated using G-Power 3.1.9.7, with an effect size of 1.2, significance level of 0.05, and statistical power of 95%, considering a dropout rate of 20% [27]. The participants were sequentially enrolled in the study and were randomly divided into two groups (SBX and PBX) before the start of the study, using block randomization (block size: 4) in computer software (Excel, Microsoft, Redmond, Washington). Group allocation was blinded to participants, and surgeons were informed of group allocation after tooth extraction by an independent administrator.

During ARP, the SBX group used sticky bovine bone mineral (S1, MedPark, Busan, Korea), and the PBX group used particulate bovine bone mineral (Bio-Oss, Geistlich Pharma AG, Wolhusen, Switzerland). The participant flowchart is shown in Figure 1.

The following inclusion criteria were applied: aged ≥18 and ≤65 years; one tooth requiring extraction, prospectively scheduled for implant placement 4–6 months after the extraction; all extraction sites had adjacent teeth; presence of four-wall or three-wall sockets of teeth recommended for extraction due to endodontic failure, caries, or root fracture, which required ridge preservation following tooth extraction; no possibility of plans to become pregnant.

Exclusion criteria were as follows: Maxillary and mandibular second or third molars; smoking > 10 cigarettes per day; uncontrolled diabetes or hypertension; soft tissue transplant surgery at the tooth extraction site undergone within the previous 6 months; long-term steroid or nonsteroidal anti-inflammatory drug therapy; history of intravenous or oral rheumatism medication; history of intravenous or oral bisphosphonate treatment for more than 3 months; presence or history of osteonecrosis of the jaws or bone diseases such as cysts and tumors; radiation or chemotherapy treatment completed within the previous 5 years; known allergy to any material or medication used in the study; poor oral hygiene; an acute infection (abscess) or presence of pus in or close to the site intended for extraction; mental or psychiatric disorder; pregnancy or lactation.

2.3 | Biomaterials

In this study, xenogeneic bone substitutes were used to fill sockets after tooth extraction and soft tissue substitutes were used to

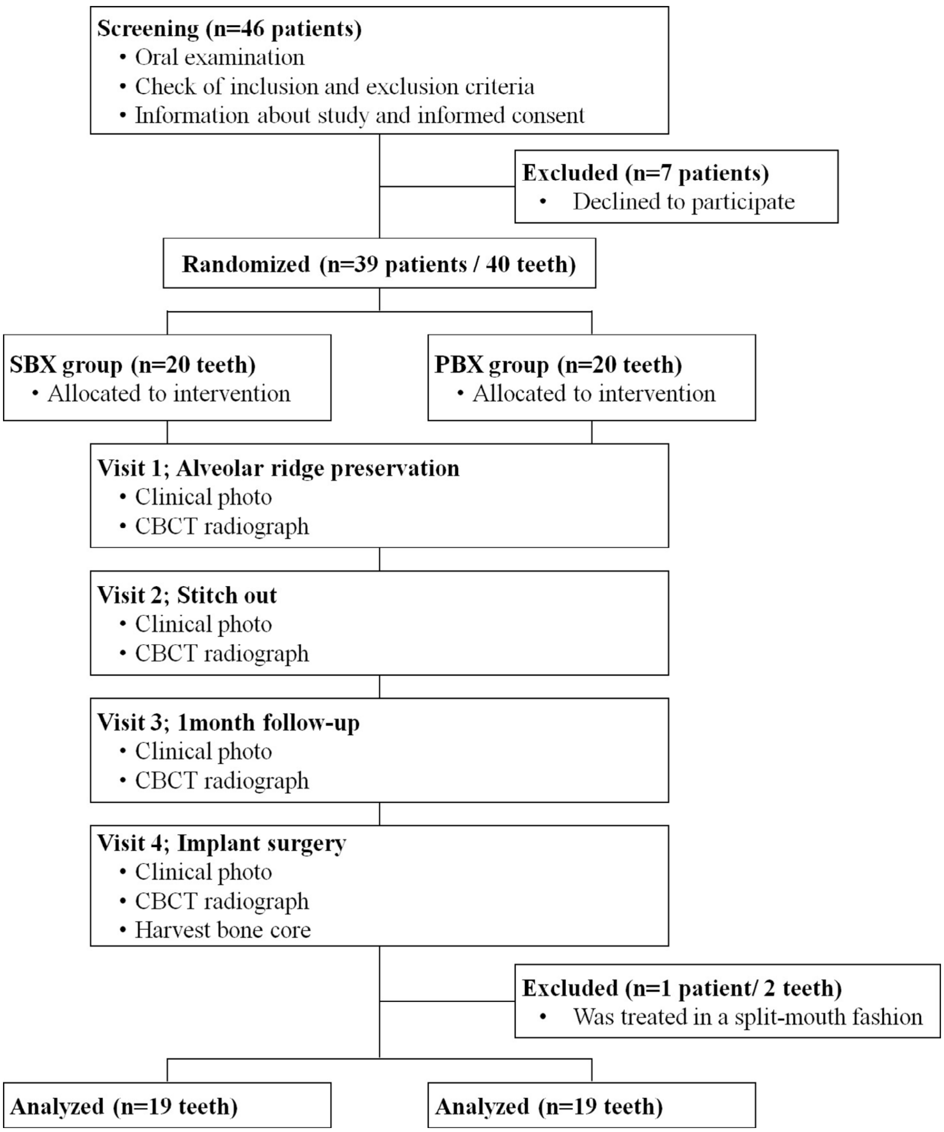


FIGURE 1 | Study flow chart. A total of 46 patients were screened, with seven declining to participate. The remaining 39 patients (40 teeth) were randomized into the SBX group (20 teeth) and the PBX group (20 teeth). The SBX group used moldable bovine bone mineral (S1, MedPark, Busan, Korea), and the PBX group used particulate bovine bone mineral (Bio-Oss, Geistlich Pharma AG, Wolhusen, Switzerland). Four visits were conducted. One patient (two teeth) was excluded due to split-mouth treatment, leaving 19 teeth analyzed in each group. ARP, alveolar ridge preservation; CBCT, cone-beam computed tomography.

cover the defect area. The xenogeneic bone substitutes included moldable and customizable bovine bone mineral (S1, MedPark, Busan, Korea), primarily composed of hydroxyapatite (HA) derived from bovine cancellous bone, with a particle size ranging from 0.20 to 1 mm. This material is mixed with saline to achieve a sticky and moldable consistency, facilitating its adaptation to the socket shape. Deproteinized collagen-coated bovine bone mineral (Bio-Oss, Geistlich Pharma, Wolhusen, Switzerland) in the form of granules with a diameter ranging from 0.25 to 1 mm. Xenogeneic bone samples were used separately according to the group assignment. According to the manufacturer's instructions, sticky bone samples were mixed with the recommended amount of saline and molded into a socket shape. An absorbable collagen membrane (Bio-Gide, Geistlich Pharma), measuring 13 × 25 mm, was used to cover the grafted area.

2.4 | Surgical Protocol

All participants were instructed to take 625 mg amoxicillin/potassium clavulanate, 400 mg dexibuprofen, and 150 mg rebamipide 1 h before the surgery [28, 29]. Surgical procedures were performed under local anesthesia after the administration of 2% lidocaine with 1:100 000 epinephrine (Huons, Gyeongki, Korea). The extraction was performed with minimal surgical trauma to the tissue surrounding the teeth. After tooth extraction, granulation tissue and residual periodontal ligament fibers were curetted and removed. ARP was performed using the bone graft material assigned to each group. An absorbable collagen membrane was placed on top and closed using 4-0 vicryl sutures.

We prescribed 625 mg amoxicillin/potassium clavulanate, 400 mg dexibuprofen, and 150 mg rebamipide twice daily for 3 days after surgery. Following the surgery, the participants were instructed not to brush the surgical area for 10 days, and the sutures were removed around 10 days after surgery. The participants were instructed to use a very soft toothbrush in the surgical area until 1-month follow-up after surgery.

Five months after tooth extraction, radiological and clinical measurements were repeated, and implant placement surgery was performed. One hour before the surgery, 625 mg amoxicillin/potassium clavulanate was administered as a prophylactic antibiotic. Surgery was performed under local anesthesia after the administration of 2% lidocaine with 1:100 000 epinephrine. After opening the surgical site flap, bone biopsy of the grafted site was performed using a 2.5-mm internal diameter trephine bur (Dentium, Gyeongki, Korea). Subsequently, implant osteotomy was completed using a surgical handpiece, and the implant was inserted.

2.5 | Radiological Analysis

The analysis of the cone-beam computed tomography (CBCT) was performed by one researcher blinded to the data, as described by Jung et al. [3]. To perform radiographic measurements, CBCT images taken immediately after socket preservation (T1) and after 5 months of healing (T2) were superimposed using the original Digital Imaging and Communications in Medicine data. Measurements were performed at T1 and T2 using the same reference points and lines. To set a reference, the most apical point of the extraction socket was defined in the baseline image, and two reference lines were drawn. A vertical reference line was drawn at the center of the extraction socket, crossing the apical reference point. A horizontal reference line was drawn perpendicular to the vertical line, crossing the apical reference point. The height of the alveoli at the midbuccal, midlingual, and horizontal ridge widths were measured at three levels (−1, −3, and −5 mm) below the most coronal aspect of the crest and were evaluated for dimensional changes over time (Figure 2).

2.6 | Histologic and Histomorphometric Analysis

After fixation in 10% neutral-buffered formalin, the specimens were embedded in paraffin and decalcified using EDTA disodium salt. Paraffin blocks were serially sectioned at 5-μm thickness. Representative slides were stained with hematoxylin–eosin and Masson-Goldner trichrome.

Tissue specimens were processed at ×100 magnification and digitized, and the total augmented area (TAA; mm^2), new bone area (NBA; mm^2), residual material area (RMA; mm^2), and connective tissue area (CTA; mm^2) were measured using Adobe

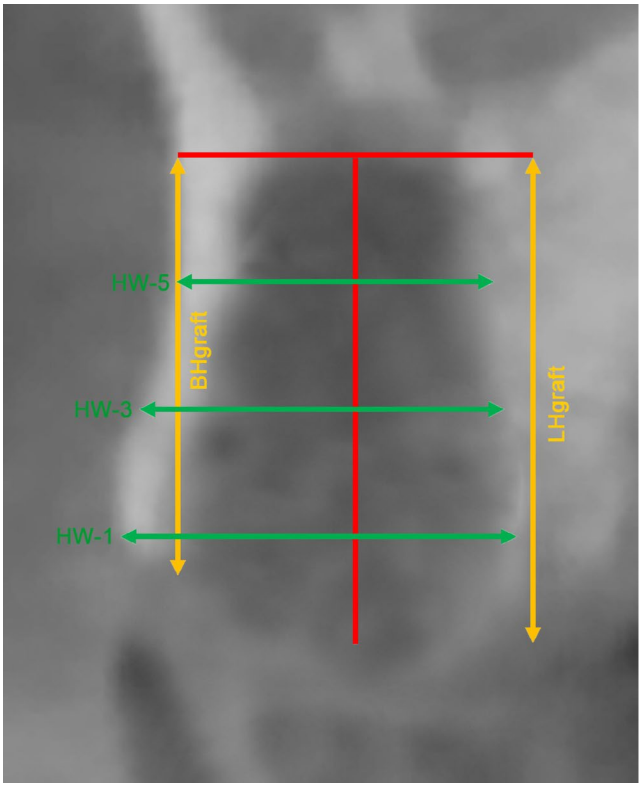


FIGURE 2 | Analysis of cone-beam computed tomography. Measurements were made at baseline (after ARP) and at 5 months using the same reference points and lines. To set a reference, the most apical point of the extraction socket was defined in the baseline image and two reference lines were subsequently drawn. BH graft, height of alveolar at the midbuccal; HW-1, horizontal ridge width measured at −1 mm below the most coronal aspect of the crest; HW-3, horizontal ridge width measured at −3 mm below the most coronal aspect of the crest; HW-5, horizontal ridge width measured at −5 mm below the most coronal aspect of the crest; LH graft, height of alveolar at the midlingual.

Photoshop (Adobe Photoshop, CA, USA). The stained slides were randomly assigned to and analyzed by two researchers who were blinded to other data. Each parameter was expressed as a percentage of RMA (%RMA; RMA/TAA100), percentage of NBA (%NBA; NBA/TAA100), and percentage of CTA (%CTA; CTA/TAA100).

2.7 | Statistical Analysis

Data were statistically analyzed using IBM SPSS (version 25.0; IBM Corporation, NY, USA). Categorical variables are presented as frequencies (%). To account for the multicenter design of the study, a linear mixed model was used to compare the changes in ridge height and width between groups at the 5-month follow-up. In this analysis, both biomaterials and center were treated as fixed effects. Histological analysis results were compared with the same test. Statistical significance was set at p-values of < 0.05.

3 | Results

3.1 | Study Participants

Patient recruitment began in October 2021, with the final participant recruited in March 2023. All follow-up visits were completed in September 2023, corresponding to the last visit of the final recruited participant. Forty-six participants were screened and 39 of them were enrolled and none dropped-out. No postoperative complications were observed at any of the included sites. Ultimately, 21 women and 18 men participated in the study, with an average age of 52.47 ± 11.19 years (range 27–65 years). During the analysis, one participant who received split-mouth treatment involving two teeth was excluded to ensure consistency in the data set. As a result, the final analysis included data from 38 participants. Table 1 shows the general characteristics of the participant's case in both groups.

TABLE 1 | General characteristics of the participant's case.

	SBX (n = 19)	PBX (n = 19)
Age (years; mean ± SD)	52.76 ± 11.41	52.47 ± 11.63
Sex		
Male	9 (47.37)	9 (47.37)
Female	10 (52.63)	10 (52.63)
Cause of extraction		
Endodontic failure	1 (5.26)	1 (5.26)
Caries	3 (15.79)	1 (5.26)
Periodontitis	10 (52.63)	13 (68.42)
Fracture	5 (26.32)	4 (21.06)
Location		
Maxillary	9 (47.37)	8 (42.11)
Mandibular	10 (52.63)	11 (57.89)
Teeth		
Incisor	1 (5.26)	1 (5.26)
Premolar	7 (36.85)	6 (31.58)
Molar	11 (57.89)	12 (63.16)

Note: Values are n (%) as indicated.
Abbreviation: SD, standard deviation.

3.2 | Radiological Analysis

Changes in ridge height and width 5 months and immediately after ARP were compared with the corresponding baseline values obtained on the CBCT scans. The midbuccal alveolar height change was −0.753 ± 0.112 mm and −1.018 ± 0.111 mm in the SBX and PBX groups, respectively; the between-group difference was nonsignificant (F = 2.895; p = 0.098; MD 0.265; 95% CI = −0.051 to 0.582). Similarly, the midlingual alveolar height change was nonsignificant, with the observed values of −0.417 ± 0.154 and −0.583 ± 0.153, respectively (F = 0.597; p = 0.445; MD 0.166; 95% CI = −0.270 to 0.602). Changes in the horizontal ridge width were measured at three levels (–1, –3, and –5 mm) below the most coronal aspect of the crest and showed a decrease in both groups, with no significant differences between the groups (Figure 3).

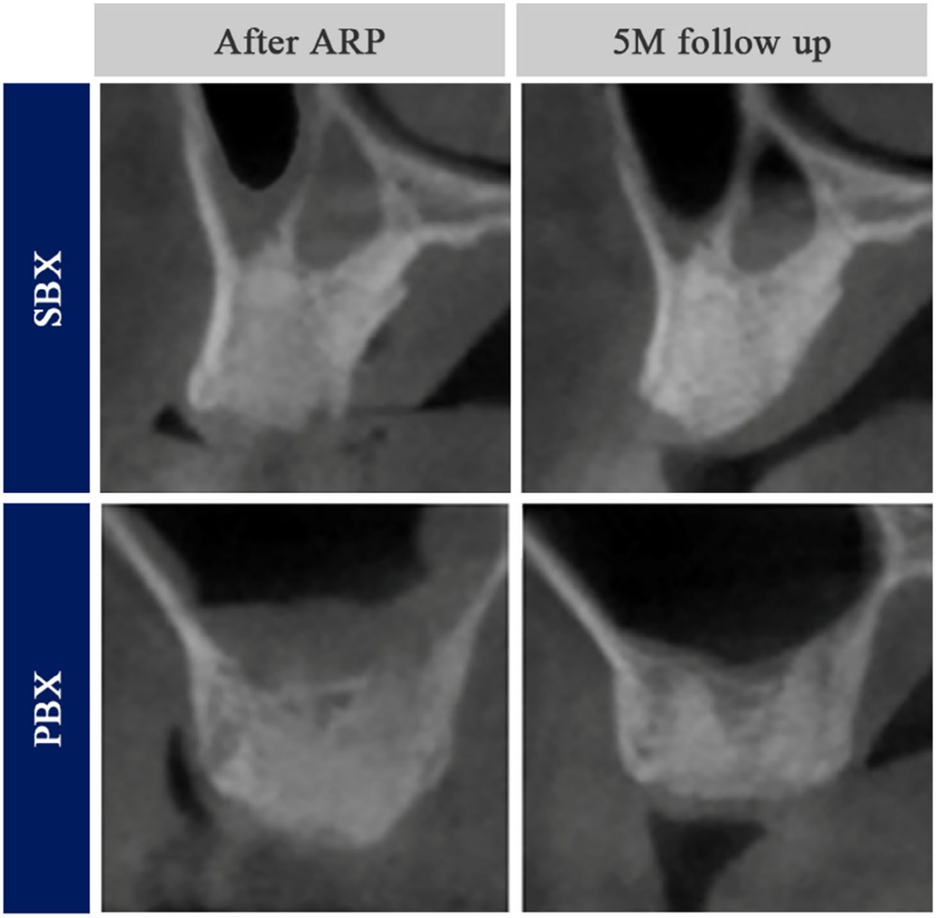
3.3 | Histologic and Histomorphometric Analysis

New bone formation was observed in both groups. In the SBX group, the formation of new bone was well distributed, and the absorption of the remaining graft material was more active. In the PBX group, new bone was observed around most of the remaining graft material, veins were observed in between, and new bone in the form of large islands was observed in areas distant from the autologous bone. Active resorption was only observed in the remaining graft material in the central region (Figure 4).

Histomorphometric analysis results obtained from the grafted sites of all specimens indicated that the %NBA of the SBX group was 39.156 ± 2.505, which was significantly different from the %NBA of PBX group of 22.749 ± 2.476 (F = 22.171; p < 0.001; MD 16.407; 95% CI = 9.333–23.481). The %RMA was 8.973 ± 2.211 for the SBX group and 15.633 ± 2.186 for the PBX group, showing a significant difference (F = 4.687; p = 0.037; MD −6.660; 95% CI = −12.904 to −0.415). In contrast, the %CTA was 49.743 ± 4.199 for the SBX group and 56.657 ± 4.151 for the PBX group, with no significant difference (F = 1.401; p = 0.245; MD −6.914; 95% CI = −18.773 to 4.944) (Figure 5).

4 | Discussion

ARP performed after tooth extraction might minimize overall changes in residual ridge height and width9. Several studies have shown that bone grafting in ARP has prognostic implications, which are determined by the condition of the extraction socket and bone grafting material used, as well as the technique involved and amount of force applied [30, 31]. The operability and stability of any bone graft material are important parameters for dentist performing ARP; thus, the present study aimed to compare them between the two materials of interest.



	SBX	PBX	DF	F-Statistic	*p*-value	MD [95% CI]
Vertical changes (mm)						
BH graft	-0.753 ± 0.112	-1.018 ± 0.111	35	2.895	0.098	0.265 [-0.051 to 0.582]
LH graft	-0.417 ± 0.154	-0.583 ± 0.153	35	0.597	0.445	0.166 [-0.270 to 0.602]
Horizontal changes (mm)						
HW-1	-0.270 ± 0.062	-0.251 ± 0.061	35	0.048	0.827	-0.019 [-0.193 to 0.155]
HW-3	-0.428 ± 0.057	-0.567 ± 0.056	35	3.075	0.088	0.139 [-0.022 to 0.300]
HW-5	-0.147 ± 0.029	-0.128 ± 0.029	35	0.229	0.636	-0.019 [-0.101 to 0.062]

Data are mean ± standard error; DF, degrees of freedom; MD, mean difference; CI, confidence interval.

FIGURE 3 | Changes in ridge height and width over 5 months. The figure shows vertical and horizontal ridge changes immediately after ARP and at the 5-month follow-up. Bone height (BH graft) and lingual height (LH graft) reduction was greater in the PBX group compared to the SBX group, but the difference was not statistically significant. Measurements at 1 mm (HW-1), 3 mm (HW-3), and 5 mm (HW-5) from the crest showed no significant differences between groups. Data are mean ± standard error. BH graft, height of alveolar at the midbuccal; CI, confidence interval; DF, degrees of freedom; HW-1, horizontal ridge width measured at −1 mm below the most coronal aspect of the crest; HW-3, horizontal ridge width measured at −3 mm below the most coronal aspect of the crest; HW-5, horizontal ridge width measured at −5 mm below the most coronal aspect of the crest; LH graft, height of alveolar at the midlingual; MD, mean difference.

Radiographic and histological analysis results showed similar rates of ARP between the moldable and particulate bone. In addition, moldable bone showed a slightly higher rate of new bone synthesis. Overall, this evidence suggests that this material may be suitable for clinical use.

CBCT scanning was performed immediately after ARP and immediately before implant placement (5 months after ARP), and the values measured in the cross-sectional view were compared [3]. The results revealed that both groups showed vertical bone resorption before implant placement compared to baseline. This finding suggests that vertical bone loss may not be preventable, independent of the graft material used. This finding is consistent with those of some previous studies. In addition, the PBX group showed more bone loss on both the buccal and lingual sides compared to the SBX group. However, differences on the buccal or lingual sides were nonsignificant. In terms of horizontal bone resorption (horizontal change), in absolute terms, the SBX group showed less bone loss in the HW-3, but more bone loss in the crestal side (HW-1) and apex side (HW-5); however, none of these differences were significant. Overall, this radiographic evidence suggests comparable rates of bone resorption in both groups with the moldable bone offering ARP effects equivalent to those of the particulate bone.

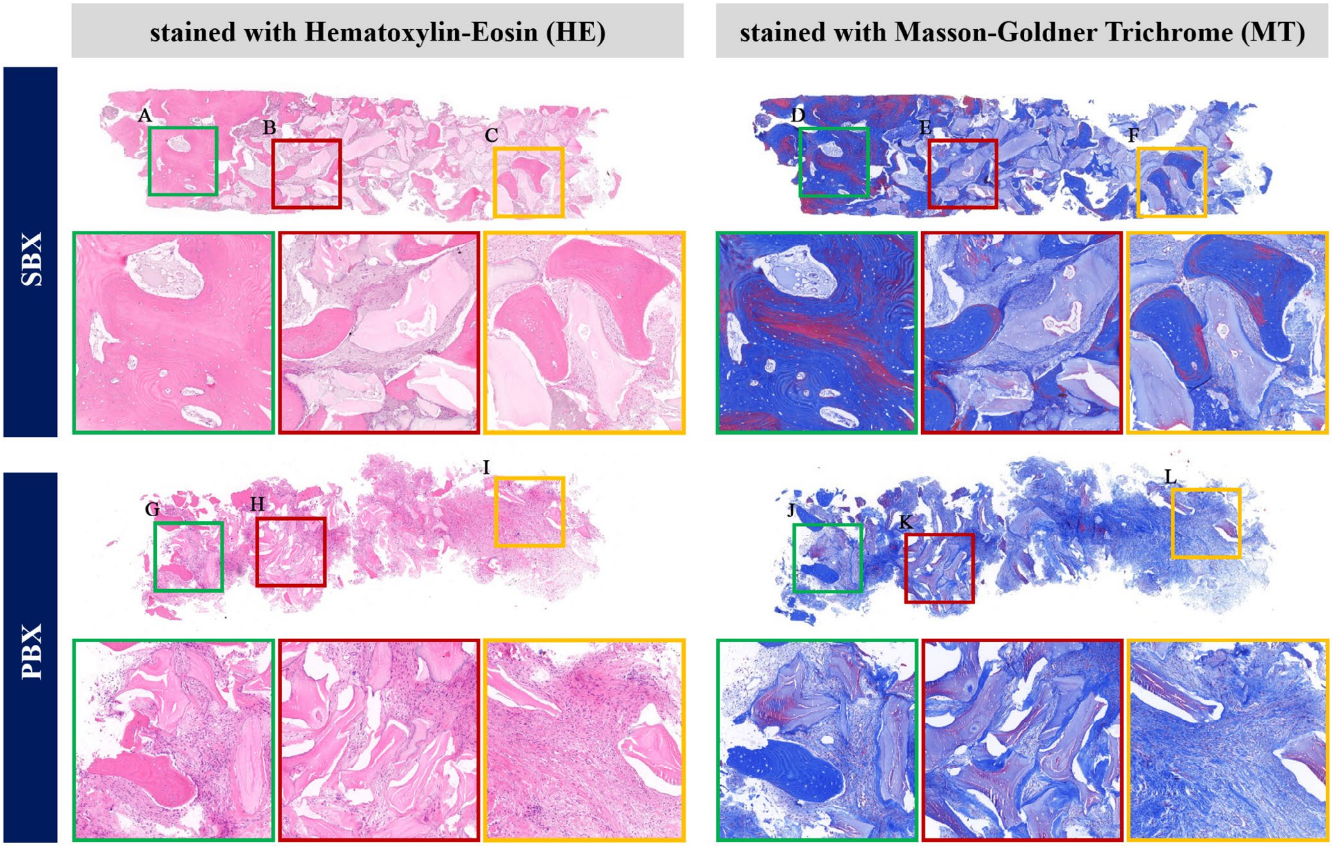
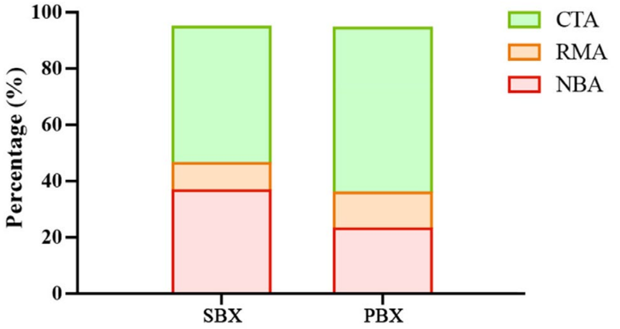


FIGURE 4 | Representative histological images illustrating regenerated bone in each group. The figure presents histological sections of the SBX and PBX groups stained with Hematoxylin–Eosin (HE) and Masson–Goldner Trichrome (MT) for qualitative assessment of new bone formation, residual material, and connective tissue. In the SBX group, HE staining demonstrates evenly distributed new bone formation (A), with residual material well integrated with the newly formed bone (B). The interaction between new bone and connective tissue is also evident (C). In the PBX group, HE staining shows localized new bone formation with clear separation from the original bone (G), residual material surrounded by new bone (H), and connective tissue integrated with limited new bone formation (I). MT staining in the SBX group highlights well-distributed mineralized new bone and residual material in (D), along with active resorption of residual material in (E) and extensive new bone formation in (F). In contrast, the PBX group shows localized new bone formation with residual material in (J), connective tissue filling spaces between graft material and newly formed bone in (K), and minimal mineralized new bone formation in peripheral regions in (L).

In histological analysis, the SBX group showed similar patterns to the PBX group. In the bone specimen taken from the extraction site, it was observed that new bone formation was occurring around the grafted material evenly from crest to apex. The quantitative analysis showed that the %NBA was higher in the SBX group with a statistically significant difference. The histological observations and quantitative analysis suggest that this moldable bone used in this research does not differ from the widely used particulate bone as a bone graft material for ARP.

DBBM has been widely studied and used as a graft material, and has shown efficacy in GBR and in ARP [32]. Many studies have shown that performing ARP immediately after extraction using DBBM is effective. The disadvantage of DBBM bone graft is that because it is particulate, it is difficult to maintain the graft by suturing it immediately after extraction when primary closure is difficult [33, 34]. Therefore, many researchers have tried to prevent the bone graft from escaping through collagen membranes, collagen plugs, releasing incisions, FGGs, and so forth. Among them, the use of a membrane has been associated with reduced patient discomfort. As various types of bovine bone products are being released, comparative studies are required to ascertain which material type is most effective at preventing bone resorption and inducing new bone formation before clinical recommendations can be made. Previous studies have shown that ARP using a shielding membrane prevents dislodging of the bone graft material and obtains sufficient soft tissue volume [35, 36].

In addition to using membranes, there have been attempts to change the properties of the bone graft material. Graft materials have been developed with high viscosity to ensure that they remain stable in the grafted area without detachment and to maintain their shape during bone remodeling [25, 37, 38]. Materials such as CGF, platelet rich plasma, and autogenous fibrin glue have been introduced to increase viscosity. Therefore, there is a need for research on the effectiveness of clinical use of sticky or moldable materials. This study aimed to perform the ARP procedure using two different types of bovine bone-based bone grafting materials and a collagen membrane to compare bone grafting outcomes between the two materials. The sticky bone used in this study is a form of a binding particulate material obtained by mixing bovine bone powder with liquid fibrinogen, and was developed to enable better manipulation and molding



	SBX	PBX	DF	F-Statistic	p-value	MD [95% CI]
%NBA	39.156 ± 2.505	22.749 ± 2.476	35	22.171	**0.000***	16.407 [9.333 to 23.481]
%RMA	8.973 ± 2.211	15.633 ± 2.186	35	4.687	**0.037***	-6.660 [-12.904 to -0.415]
%CTA	49.743 ± 4.199	56.657 ± 4.151	35	1.401	0.245	-6.914 [-18.773 to 4.944]

Data are mean ± standard error.; DF, degrees of freedom; MD, mean difference; CI, confidence interval.

FIGURE 5 | Histomorphometric analysis. The bar plot shows the percentage composition of NBA, RMA, and CTA for the SBX and PBX groups. %NBA was significantly higher in the SBX group (39.156 ± 2.505) compared to the PBX group (22.749 ± 2.476), with an F-statistic of 22.171 and p-value < 0.001. %RMA was significantly lower in the SBX group (8.973 ± 2.211) compared to the PBX group (15.633 ± 2.186), with an F-statistic of 4.687 and p-value = 0.037. %CTA showed no significant difference between groups, with an F-statistic of 1.401 and p-value = 0.245. Data are presented as mean ± standard error. %CTA, percent connective tissue area; %NBA, percent new bone area; %RMA, percent residual materials area; CI, confidence interval; DF, degrees of freedom; MD, mean difference. *Statistically significant ($p < 0.05$).

compared to particulate bone materials. These graft materials are easy to handle and stabilize in the extraction socket, compared to the less stable physical characteristics of particulate bone graft materials [39].

The moldable bone used in this study is characterized by the fact that the provided bone graft material is not mixed with other materials, but is a cuboidal block that is already mixed with materials, and when mixed with saline as recommended by the manufacturer, it becomes viscous and turns into a manipulable form. Once it becomes viscous, it has the ability to maintain its shape as it is manipulated, which prevents it from slipping out of the tooth when ARP is performed, and it has the advantage of maintaining its shape even when there is a defect. Many studies have shown that moldable bone is effective as a bone graft material because of its ability to retain its shape in various types of defects [25]. No previous study has compared the outcomes associated with particulate and moldable DBBM; thus, this study aimed to perform these comparisons. In addition, radiographic and histological analyses were performed to examine bone resorption and synthesis outcomes in the extraction sockets filled using different types of bone graft materials. Several previous studies have compared implants using two-dimensional radiographs [2, 20, 38, 40–43]; however, no study has included radiological, histological, and three-dimensional CBCT scan results; this study is first to evaluate all these parameters.

This study has some limitations. First, there is no control group that did not receive ARP after tooth extraction. If we had compared the three groups, the group that did not ARP and the group that did ARP using different two materials, it would have been more helpful in proving the effectiveness of ARP and making comparisons between the two groups. However, many previous studies have already demonstrated the effectiveness of ARP, so this study focused on comparing two materials with different properties [44]. Second, the participating surgeons were dentists with over 10 years of experience, which allowed them to recognize the types of materials used and may have lowered the sensitivity of the technique. Finally, although this study did not account for the force used when packing the material inside the socket or for the use of saline during the procedure, the surgeons' palpation of the surrounding tissues during the procedure may have affected their approach. While these factors may affect outcomes in general, no complications were observed in this study after either ARP or implant surgery, and all patients received initial fixation of 25 N or more on the day of implant placement.

5 | Conclusion

In conclusion, the radiographic and histological results obtained in this study revealed that use of moldable bone can achieve similar ARP parameters as those achieved by particulate bone. Meanwhile, moldable bone can achieve greater new bone synthesis rate than particulate bone, suggesting that its use may be clinically recommended. This study had a short follow-up period, and further studies are required to evaluate long-term outcomes and the impact of patient bone quality at the time of surgery on subsequent bone dynamics.

Author Contributions

Yiseul Choi: concept/design, data analysis/interpretation, drafting article, critical revision of article, approval of article. **Jieun Cheong:** data analysis/interpretation, drafting article, critical revision of article, approval of article. **Yoolbin Song**, **Jaeyeon Kim**, **Dae-Young Kang**, and **Hyeon-Seong Ahn:** critical revision of article, data collection, approval of article. **Sanghoon Park** and **Marco Esposito:** critical revision of article, approval of article. **Hyun-Seung Shin** and **Wonse Park:** concept/design, data analysis/interpretation, critical revision of article, data collection, approval of article.

Acknowledgments

The authors would like to thank MedPark (Busan, Korea) for the support of this clinical trial.

Ethics Statement

This study was approved by the Institutional Review Board (IRB) of Yonsei University Dental Hospital and Dankook University Dental Hospital (IRB numbers: 2–2021-0037, 2021–7-006).

Consent

All patients were informed of the study purpose and provided written informed consent prior to being enrolled.

Conflicts of Interest

The authors declare a competing conflict of interest with being funded by MedPark (Busan, Korea). However, MedPark had no role in the collection, analysis, or interpretation of the trial data.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.