

Particulate versus collagen-stabilized deproteinized bovine bone mineral for labial bone preservation in modified periodontally accelerated osteogenic orthodontics: a retrospective CBCT study

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Abstract

Objectives

To compare particulate deproteinized bovine bone mineral (DBBM) with collagen-stabilized DBBM (DBBM-C) for preserving augmented labial bone dimension during orthodontic movement after modified periodontally accelerated osteogenic orthodontics (PAOO).

Materials and Methods

Retrospective cohort: 50 patients (233 mandibular anterior teeth with thin or deficient labial bone) undergoing modified PAOO before proclination received DBBM (21 patients, 98 teeth) or DBBM-C (29 patients, 135 teeth). Cone-beam computed tomography at baseline, immediately postoperatively and 6 months postoperatively was superimposed to measure labial vertical bone level, horizontal bone thickness, root length and proclination change. Mixed-effects models adjusted for the earlier time point compared groups; retention was modeled multivariably.

Results

Immediate augmentation was comparable. At 6 months both groups maintained a significant net gain at the middle and apical levels, and DBBM showed greater preservation of the augmented dimension at the labial middle level than DBBM-C (1.10 vs 0.70 mm; $P < 0.001$), with less postoperative loss at the cervical and middle levels (both $P < 0.01$). In multivariable analysis, DBBM was independently associated with higher retention at the labial vertical, cervical and middle levels (all $P < 0.05$). Root shortening was minimal and similar.

Conclusions

Both substitutes maintained significant labial augmentation at 6 months, but under orthodontic loading DBBM preserved the augmented dimension better, most clearly at the labial middle level.

Clinical Relevance:

Both materials restored the thin plate to at least 1 mm median labial thickness at the middle and apical levels; DBBM may be preferred when durable space maintenance is prioritized.

1 Introduction

Labial tooth movement can precipitate dehiscence, fenestration, gingival recession and root resorption [1, 2]. The risk concentrates in the mandibular anterior region of patients with sagittal skeletal discrepancy [3], where decompensation of Class III and camouflage of Class II both procline the lower incisors over a frequently thin labial plate that proclination thins further, even in thick phenotypes [4–7]. Where labial bone is deficient at the outset, the bony envelope constrains how far a tooth can safely be moved [8], so augmentation is needed before proclination.

Periodontally accelerated osteogenic orthodontics (PAOO) pairs selective corticotomy with simultaneous grafting [9]. Through the regional acceleratory phenomenon the corticotomy transiently increases cortical remodeling and porosity [10], lowering bone density and facilitating movement [11, 12], while grafting in the same window adds bone volume and permits greater proclination [13, 14]. Conventionally the particulate graft is prone to displacement, leakage and compression by soft-tissue tension, leaving cervical and vertical augmentation suboptimal [13]. The modified technique used here reduces displacement and preserves the augmentation by pouch-suturing a resorbable collagen membrane to the periosteum, with periosteal release for tension-free closure [2, 15].

Which substitute is grafted is a key determinant of the augmentation outcome, yet the two formulations in common use have never been compared directly under orthodontic loading. Deproteinized bovine bone mineral (DBBM; Bio-Oss, Geistlich Pharma AG, Wolhusen, Switzerland) is the most widely adopted xenograft in PAOO: porous, slowly resorbing and long-retained, but difficult to shape. Collagen-stabilized DBBM (DBBM-C; Bio-Oss Collagen, Geistlich Pharma AG, Wolhusen, Switzerland) binds 90% DBBM granules with 10% porcine type I collagen into a moldable block, which handles more easily and holds its form [16] but loses the collagen within weeks. Outcomes have been broadly comparable in periodontal intrabony defects [17] and sinus floor augmentation [18], although both are relatively static settings. In PAOO, DBBM predominates and DBBM-C has been examined in only a few observational and case reports [19, 20]. The labial mandibular anterior site differs in having only one or two bony walls and in bearing continuous soft-tissue pressure and orthodontic force, which places unusual demands on the space-maintaining capacity of the graft.

We therefore compared DBBM and DBBM-C in modified PAOO performed before planned labial proclination of the mandibular anterior teeth. Using cone-beam computed tomography (CBCT) at three timepoints, we asked which substitute better maintains the augmented labial dimension over 6 months of orthodontic loading and, secondarily, whether proclination is associated with the dimensional change and which patient- and tooth-level factors predict retention.

2 Materials and methods

2.1 Study design and participants

This retrospective cohort study followed the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) recommendations (checklist provided as Online Resource 1). It was approved

by the institutional ethics committee (approval no. 2022-03-432), which waived the requirement for additional informed consent for this retrospective secondary analysis of existing clinical and imaging data; all patients had provided written informed consent for treatment. Because the study was retrospective, bone-substitute allocation was non-randomized and based on patient choice.

The study was conducted at a single university-affiliated stomatology hospital in China, screening consecutive patients treated between 1 January 2020 and 31 July 2025. Eligible patients had deficient labial alveolar bone volume in the mandibular anterior region and underwent modified PAOO before planned decompensatory or compensatory labial movement, as part of combined orthodontic–orthognathic or orthodontic-only treatment; those receiving combined treatment did not undergo orthognathic surgery within the 6-month observation window.

Inclusion criteria

age ≥ 18 and ≤ 35 years; no previous orthodontic treatment; planned labial movement of the mandibular anterior teeth; preoperative CBCT showing thin labial bone (labial thickness < 0.5 mm) [21] or bony defect (dehiscence or fenestration); complete, clear CBCT at all three timepoints; good general health; good oral hygiene without untreated pulpal, periapical, or periodontal disease at the surgical or adjacent sites.

Exclusion criteria

long-term corticosteroids, bisphosphonates or non-steroidal anti-inflammatory drugs that may affect bone remodeling; uncontrolled diabetes or other severe systemic disease precluding surgery; pregnancy or lactation; smoking; active periodontitis; occlusal trauma; bruxism; cleft lip/palate or maxillofacial anomaly; missing teeth; moderate-or-greater tooth rotation ($> 10^\circ$); abnormal tooth morphology; anterior restorations; or preoperative mobility of anterior teeth.

Patients were grouped by the substitute used intraoperatively (DBBM or DBBM-C). Because eligibility required complete CBCT data at all three timepoints, patients with incomplete follow-up imaging were excluded during screening; no post-inclusion loss to follow-up occurred in the analytic cohort. Study size was determined by all consecutive eligible records in the prespecified study period; no a priori sample-size calculation was performed. Age, sex, tooth type, treatment information and graft material were extracted from the clinical and operative records.

2.2 Surgical procedure

All patients underwent the same modified PAOO procedure, performed at a single center by a single experienced surgeon to minimize inter-operator variation [2, 15]. Under local infiltration anesthesia, a papilla-sparing horizontal incision was made from canine to canine with bilateral vertical releasing incisions and a full-thickness flap was elevated to expose the labial plate to the apical region.

Piezoelectric vertical corticotomies were cut in the interradicular cortex from 3 mm below the alveolar crest to the apical level, to the depth of the marrow space, with additional decortication perforations. A 25 × 25 mm resorbable collagen membrane (Bio-Gide; Geistlich Pharma AG, Wolhusen, Switzerland) was

halved and the halves sutured together; after 3–4 mm of periosteal release to reduce flap tension, it was secured by pouch suturing to the periosteum. The substitute (particulate DBBM, 0.25–1 mm particle size, Bio-Oss; or DBBM-C, Bio-Oss Collagen) was placed to cover the labial surface evenly from canine to canine and from the cemento-enamel junction (CEJ) to the apical level. The membrane was laid over the graft and the flap repositioned and sutured tension-free. Postoperatively, patients took antibiotics for 3–5 days and rinsed with cetylpyridinium chloride for one week; sutures were removed at 2 weeks, when orthodontic loading commenced.

2.3 Imaging and measurements

CBCT was acquired at T0 (preoperative), T1 (immediately postoperative) and T2 (6 months postoperative) on a single unit (NewTom VGi evo; Cefla s.c., Imola, Italy; 110 kV, 17 × 19 cm field of view, 3.5–4.8 s exposure, 0.3 mm isotropic voxel size). DICOM data were reconstructed in Dolphin Imaging (v11.9, Chatsworth, CA, USA). Sagittal skeletal relationships were assessed on a lateral cephalometric image synthesized from the T0 volume by ray-sum projection, on which the sella–nasion–A point (SNA), sella–nasion–B point (SNB) and A point–nasion–B point (ANB) angles were measured. Each T1 scan was oriented and superimposed onto the T0 and T2 scans using stable mandibular landmarks (point B, pogonion, menton, mental foramen, genial tubercle, gonion), so that all three timepoints shared identical measurement planes. For each mandibular incisor and canine, the maximum labiolingual section was obtained following a standardized plane-orientation protocol [22], and the following linear parameters were measured (Fig. 1a):

- Labial vertical bone level (LaVBL) – the labial CEJ-to-crest distance; a larger value indicates more crestal bone loss.
- Labial horizontal bone thickness (LaCHBT, LaMHBT, LaAHBT) – bone thickness at the cervical, middle, and apical thirds of the root, recorded on the labial sides.
- Total horizontal bone thickness (CHBT, MHBT, AHBT) – the sum of labial and lingual horizontal thickness at each level, used to offset the effect of labial tooth displacement on single-side measurements.
- Root length (RL) – the distance from the midpoint of the line connecting the labial and lingual CEJs to the root apex on the maximum labiolingual section, recorded as a safety measure for orthodontically induced root resorption.

All thickness and level values represent the radiographically mineralized contour, which in grafted sites may comprise both new bone and residual substitute and cannot be resolved into the two on CBCT. Change in proclination ($\Delta\alpha$) was computed as the difference between the long-axis-to-mandibular-plane angle at T2 and T1, derived from incisal-edge and apex coordinates on the superimposed maximum labiolingual sections (Fig. 1b). Retention at each labial site was defined as net augmentation at 6 months as a percentage of immediate augmentation, $(T2 - T0)/(T1 - T0) \times 100\%$. All measurements were performed by a single calibrated operator blinded to group allocation and repeated after a 2-week interval, demonstrating excellent intra-rater reliability (intraclass correlation coefficients 0.92–0.98).

2.4 Statistical analysis

Analyses used SPSS Statistics v23.0 (IBM Corp., Armonk, NY, USA). The net change in labial middle level (LaMHBT, T2 vs T0) was the key outcome; this post hoc selection is addressed in the Limitations. After Shapiro–Wilk test, continuous variables are reported as mean $\pm$ SD or median (Q1, Q3) and categorical variables as frequency (percentage). Patient-level baseline variables were compared with the independent-samples t or Mann–Whitney U test and categorical variables with the χ^2 or Fisher exact test. Because teeth were clustered within patients, baseline tooth-level measurements at T0 were compared using linear mixed-effects models with a patient random intercept. Within-group change was assessed with the Wilcoxon signed-rank test.

Change scores were signed so that a positive value denotes bone gain for T0 $\rightarrow$ T1 and T0 $\rightarrow$ T2 and bone loss for T1 $\rightarrow$ T2. Because a larger LaVBL denotes greater vertical bone loss, LaVBL change scores were computed as T0 – T1, T0 – T2 and T2 – T1, and all horizontal bone-thickness scores as T1 – T0, T2 – T0 and T1 – T2. In the T1 $\rightarrow$ T2 comparison a smaller score therefore indicates better maintenance. Between-group differences in each change score were tested with linear mixed-effects models (patient random intercept), adjusted for the corresponding earlier time-point value. Where LaCHBT change scores showed a high proportion of zero values, a generalized estimating equation (GEE; binomial, logit link, exchangeable correlation) modeled the probability of a cervical increase (> 0 vs ≤ 0), with the baseline-adjusted model as primary and the unadjusted as a consistency check. The bone change– $\Delta\alpha$ association was assessed by Spearman correlation and mixed models with a material interaction term. Retention was modeled by mixed-effects regression on material, proclination change, sex, age and tooth type (specified a priori; patient random intercept), with tooth-type effects tested by Wald χ^2 and Bonferroni-adjusted pairwise comparisons. Retention was undefined when immediate augmentation was zero (those teeth excluded), reducing the analyzable sample to 176 teeth at the vertical and cervical sites (LaVBL, LaCHBT), 233 at the middle (LaMHBT) and 210 at the apical (LaAHBT). No multiple-testing correction was applied, so secondary findings are hypothesis-generating. No data were missing for the primary analyses and no imputation was performed. All tests were two-sided ($\alpha = 0.05$).

3 Results

3.1 Baseline characteristics

Of 81 patients screened, 31 were excluded (22 incomplete imaging, 7 periodontitis, 2 outside the age criterion), leaving 50 patients and 233 of 300 possible mandibular anterior teeth (77.7%) for analysis, with similar tooth-level exclusion rates in both groups (22.2% vs 22.4%; Fig. 2). Twenty-one patients (98 teeth) received DBBM and 29 (135 teeth) DBBM-C. All 50 completed the fixed 6-month assessment, none was lost to follow-up, and no data were missing for the primary analyses.

The two groups were comparable in sex, age, cephalometric values, proclination change ($\Delta\alpha$ $9.92 \pm 7.44^\circ$ vs $9.29 \pm 6.01^\circ$), tooth-type distribution and all baseline labial bone dimensions (all $P > 0.05$; Table 1). The

only significant baseline difference was a smaller total (labial plus lingual) cervical thickness in the DBBM group (CHBT 0.40 vs 0.60 mm; $P = 0.014$). All between-group models were adjusted for the corresponding earlier time-point value.

Table 1
Characteristics of the study groups and CBCT measurements at T0.

Variable	DBBM (21 patients; 98 teeth)	DBBM-C (29 patients; 135 teeth)	<i>P</i>
Patient characteristics			
Female sex, <i>n</i> (%)	13 (61.9%)	17 (58.6%)	0.815
Age, years	24.05 ± 4.35	22.66 ± 3.91	0.260
Cephalometric angles, °			
SNA	82.40 ± 3.55	80.91 ± 3.77	0.165
SNB	84.24 ± 5.32	84.52 ± 4.62	0.844
ANB	-1.84 ± 3.94	-3.60 ± 3.18	0.086
Tooth characteristics			
Tooth type, <i>n</i> (%)			
Central incisor	36 (36.7%)	49 (36.3%)	0.996
Lateral incisor	32 (32.7%)	44 (32.6%)	
Canine	30 (30.6%)	42 (31.1%)	
Proclination change			
Δα, °	9.92 ± 7.44	9.29 ± 6.01	0.947
CBCT measurements at T0, mm			
LaVBL	2.00 (1.50, 3.12)	1.50 (1.10, 2.25)	0.095
LaCHBT	0.25 (0.00, 0.40)	0.30 (0.00, 0.60)	0.057
LaMHBT	0.30 (0.20, 0.40)	0.30 (0.20, 0.40)	0.968
LaAHBT	0.60 (0.40, 1.10)	0.80 (0.60, 1.10)	0.638

Data are presented as mean ± SD, median (Q1, Q3), or *n* (%), as appropriate. Percentages are based on patients for patient-level variables and teeth for tooth-level variables. P values were obtained using the independent-samples t test or Mann–Whitney U test for continuous variables, Pearson's χ^2 test or Fisher's exact test for categorical variables, and linear mixed-effects models with patient as a random intercept for T0 CBCT measurements. Higher LaVBL values indicate greater labial crestal bone loss. *DBBM* deproteinized bovine bone mineral, *DBBM-C* collagen-stabilized deproteinized bovine bone mineral, *CBCT* cone-beam computed tomography, *T0* preoperative assessment, $\Delta\alpha$ change in proclination angle, *SNA* sella–nasion–A point angle, *SNB* sella–nasion–B point angle, *ANB* A point–nasion–B point angle, *LaVBL* labial vertical bone level, *LaCHBT* labial cervical horizontal bone thickness, *LaMHBT* labial middle horizontal bone thickness, *LaAHBT* labial apical horizontal bone thickness, *CHBT* cervical horizontal bone thickness, *MHBT* middle horizontal bone thickness, *AHBT* apical horizontal bone thickness

Variable	DBBM (21 patients; 98 teeth)	DBBM-C (29 patients; 135 teeth)	P
CHBT	0.40 (0.00, 0.80)	0.60 (0.30, 1.05)	0.014*
MHBT	0.95 (0.60, 1.58)	1.30 (0.65, 1.70)	0.547
AHBT	2.35 (1.70, 3.90)	2.70 (1.90, 3.75)	0.747

Data are presented as mean $\pm$ SD, median (Q1, Q3), or n (%), as appropriate. Percentages are based on patients for patient-level variables and teeth for tooth-level variables. P values were obtained using the independent-samples t test or Mann–Whitney U test for continuous variables, Pearson's χ^2 test or Fisher's exact test for categorical variables, and linear mixed-effects models with patient as a random intercept for T0 CBCT measurements. Higher LaVBL values indicate greater labial crestal bone loss. *DBBM* deproteinized bovine bone mineral, *DBBM-C* collagen-stabilized deproteinized bovine bone mineral, *CBCT* cone-beam computed tomography, *T0* preoperative assessment, $\Delta\alpha$ change in proclination angle, *SNA* sella–nasion–A point angle, *SNB* sella–nasion–B point angle, *ANB* A point–nasion–B point angle, *LaVBL* labial vertical bone level, *LaCHBT* labial cervical horizontal bone thickness, *LaMHBT* labial middle horizontal bone thickness, *LaAHBT* labial apical horizontal bone thickness, *CHBT* cervical horizontal bone thickness, *MHBT* middle horizontal bone thickness, *AHBT* apical horizontal bone thickness

3.2 Immediate augmentation (T1 vs T0)

Both groups achieved significant labial augmentation immediately after surgery at every level (all within-group $P < 0.001$), with LaMHBT gains of 1.70 mm (DBBM) and 1.80 mm (DBBM-C). No between-group difference reached significance at any level (all $P > 0.25$; Table 2), establishing a comparable starting point for the 6-month comparison.

3.3 Net dimensional change at 6 months

Change from baseline (T2 vs T0). Both groups maintained a significant net increase in labial bone dimension at the middle and apical levels (all $P < 0.001$; Table 2). DBBM showed a greater net gain than DBBM-C at LaMHBT (1.10 vs 0.70 mm; adjusted between-group difference 0.38 mm favoring DBBM, 95% CI 0.16 to 0.60, $P < 0.001$; Cohen's d 0.65 by tooth, 0.95 by patient) and at the corresponding total thickness MHBT (0.27 mm favoring DBBM, $P = 0.039$). At LaCHBT the mixed model was not significant ($P = 0.097$), but the binary GEE showed that teeth in the DBBM group were more likely to gain cervical bone dimension than those in the DBBM-C group (49.0% vs 22.2%). After adjustment for baseline LaCHBT, DBBM-C had lower odds of cervical gain (odds ratio 0.35, 95% CI 0.15 to 0.80, $P = 0.013$), with a similar unadjusted result. LaAHBT change did not differ between groups ($P = 0.229$).

Change from immediate postoperative (T2 vs T1). Between the immediate and 6-month scans median dimensions decreased at all labial levels (Table 2; Fig. 3a-d). DBBM lost less than DBBM-C at LaCHBT (0.40 vs 0.70 mm; adjusted between-group difference 0.14 mm favoring DBBM, 95% CI 0.03 to 0.24, $P = 0.009$) and LaMHBT (0.70 vs 1.10 mm; 0.38 mm favoring DBBM, 95% CI 0.16 to 0.59, $P < 0.001$) levels; differences at other levels were not significant. This greater interval loss accounts for the smaller 6-month net gain in DBBM-C.

Table 2
Changes in alveolar bone dimensions and root length across study timepoints

Measure	Group	Earlier value, mm	Later value, mm	Within- group <i>P</i>	Change score, mm ^a	Between- group <i>P</i>
Immediate postoperative augmentation (T0 → T1)						
LaVBL	DBBM	2.00 (1.50, 3.12)	1.10 (0.62, 1.70)	< 0.001	0.95 (0.20, 1.80)	0.396
	DBBM-C	1.50 (1.10, 2.25)	0.90 (0.50, 1.40)	< 0.001	0.50 (0.00, 1.35)	
LaCHBT	DBBM	0.25 (0.00, 0.40)	0.80 (0.40, 1.08)	< 0.001	0.40 (0.03, 0.80)	0.253
	DBBM-C	0.30 (0.00, 0.60)	0.90 (0.50, 1.30)	< 0.001	0.50 (0.10, 0.90)	
LaMHBT	DBBM	0.30 (0.20, 0.40)	2.00 (1.60, 2.50)	< 0.001	1.70 (1.20, 2.10)	0.930
	DBBM-C	0.30 (0.20, 0.40)	2.10 (1.50, 2.60)	< 0.001	1.80 (1.10, 2.35)	
LaAHBT	DBBM	0.60 (0.40, 1.10)	2.90 (2.10, 3.50)	< 0.001	2.10 (1.07, 2.80)	0.552
	DBBM-C	0.80 (0.60, 1.10)	2.60 (1.80, 3.60)	< 0.001	1.80 (0.80, 2.75)	
Net dimensional change at 6 months (T0 → T2)						
LaVBL	DBBM	2.00 (1.50, 3.12)	1.60 (1.20, 2.80)	0.038	0.45 (-0.78, 1.40)	0.560
	DBBM-C	1.50 (1.10, 2.25)	1.80 (1.20, 3.05)	0.042	-0.20 (-1.10, 0.50)	
LaCHBT	DBBM	0.25 (0.00, 0.40)	0.30 (0.00, 0.50)	0.094	0.00 (0.00, 0.40)	0.097
	DBBM-C	0.30 (0.00, 0.60)	0.30 (0.00, 0.40)	< 0.001	-0.10 (-0.30, 0.00)	
LaMHBT	DBBM	0.30 (0.20, 0.40)	1.40 (0.90, 1.80)	< 0.001	1.10 (0.53, 1.50)	< 0.001
	DBBM-C	0.30 (0.20, 0.40)	1.00 (0.60, 1.30)	< 0.001	0.70 (0.30, 0.90)	
LaAHBT	DBBM	0.60 (0.40, 1.10)	2.40 (1.80, 3.48)	< 0.001	1.75 (0.83, 2.58)	0.229

Measure	Group	Earlier value, mm	Later value, mm	Within- group <i>P</i>	Change score, mm ^a	Between- group <i>P</i>
	DBBM-C	0.80 (0.60, 1.10)	2.30 (1.80, 2.85)	< 0.001	1.40 (0.90, 2.05)	
CHBT	DBBM	0.40 (0.00, 0.80)	0.40 (0.00, 0.70)	0.832	0.00 (-0.30, 0.38)	0.999
	DBBM-C	0.60 (0.30, 1.05)	0.40 (0.20, 0.70)	< 0.001	-0.20 (-0.60, 0.05)	
MHBT	DBBM	0.95 (0.60, 1.58)	1.95 (1.30, 2.60)	< 0.001	0.90 (0.23, 1.30)	0.039
	DBBM-C	1.30 (0.65, 1.70)	1.80 (1.30, 2.30)	< 0.001	0.50 (0.10, 0.90)	
AHBT	DBBM	2.35 (1.70, 3.90)	3.80 (2.73, 4.40)	< 0.001	0.90 (0.10, 1.77)	0.597
	DBBM-C	2.70 (1.90, 3.75)	3.60 (3.00, 4.50)	< 0.001	0.80 (0.20, 1.45)	
RL	DBBM	12.35 (11.20, 13.88)	12.05 (10.80, 13.30)	< 0.001	0.00 (0.00, 0.60)	0.977
	DBBM-C	12.10 (10.95, 13.20)	11.70 (10.70, 12.80)	< 0.001	0.00 (0.00, 0.60)	
Postoperative dimensional loss (T1 → T2)						
LaVBL	DBBM	1.10 (0.62, 1.70)	1.60 (1.20, 2.80)	< 0.001	0.70 (0.10, 1.48)	0.366
	DBBM-C	0.90 (0.50, 1.40)	1.80 (1.20, 3.05)	< 0.001	0.90 (0.45, 1.60)	
LaCHBT	DBBM	0.80 (0.40, 1.08)	0.30 (0.00, 0.50)	< 0.001	0.40 (0.10, 0.70)	0.009
	DBBM-C	0.90 (0.50, 1.30)	0.30 (0.00, 0.40)	< 0.001	0.70 (0.30, 1.00)	
LaMHBT	DBBM	2.00 (1.60, 2.50)	1.40 (0.90, 1.80)	< 0.001	0.70 (0.10, 1.20)	< 0.001
	DBBM-C	2.10 (1.50, 2.60)	1.00 (0.60, 1.30)	< 0.001	1.10 (0.60, 1.60)	
LaAHBT	DBBM	2.90 (2.10, 3.50)	2.40 (1.80, 3.48)	0.072	0.10 (-0.67, 1.07)	0.378
	DBBM-C	2.60 (1.80, 3.60)	2.30 (1.80, 2.85)	< 0.001	0.40 (-0.45, 1.20)	

Measure	Group	Earlier value, mm	Later value, mm	Within- group <i>P</i>	Change score, mm ^a	Between- group <i>P</i>
CHBT	DBBM	0.90 (0.50, 1.38)	0.40 (0.00, 0.70)	< 0.001	0.45 (0.20, 0.80)	0.649
	DBBM-C	1.20 (0.80, 1.60)	0.40 (0.20, 0.70)	< 0.001	0.80 (0.30, 1.20)	
MHBT	DBBM	2.85 (2.10, 3.70)	1.95 (1.30, 2.60)	< 0.001	0.90 (0.42, 1.50)	0.050
	DBBM-C	3.20 (2.30, 3.70)	1.80 (1.30, 2.30)	< 0.001	1.30 (0.70, 1.80)	
AHBT	DBBM	4.65 (3.80, 5.90)	3.80 (2.73, 4.40)	< 0.001	1.00 (0.13, 1.77)	0.938
	DBBM-C	4.90 (3.55, 6.00)	3.60 (3.00, 4.50)	< 0.001	1.00 (0.20, 1.90)	

^a Change scores are oriented so that positive values denote bone gain in the T0 → T1 and T0 → T2 sections and bone loss in the T1 → T2 section. A larger LaVBL value indicates a more apically positioned labial alveolar crest and therefore greater labial vertical bone loss. Accordingly, LaVBL change scores were calculated as T0 – T1, T0 – T2 and T2 – T1, and change scores for all horizontal bone-thickness measures as T1 – T0, T2 – T0 and T1 – T2.

Data are presented as median (Q1, Q3). T0 denotes the preoperative assessment, T1 the immediate postoperative assessment and T2 the 6-month postoperative assessment; earlier and later values correspond to the timepoints indicated in each section heading. Within-group *P* values were obtained using the Wilcoxon signed-rank test. Between-group *P* values were obtained using linear mixed-effects models with patient as a random intercept, adjusted for T0 in the T0 → T1 and T0 → T2 comparisons and for T1 in the T1 → T2 comparison. RL was assessed only for T0 → T2; RL change was calculated as T0 – T2, with positive values indicating root shortening. *DBBM* deproteinized bovine bone mineral, *DBBM-C* collagen-stabilized deproteinized bovine bone mineral, *LaVBL* labial vertical bone level, *LaCHBT* labial cervical horizontal bone thickness, *LaMHBT* labial middle horizontal bone thickness, *LaAHBT* labial apical horizontal bone thickness, *CHBT* cervical horizontal bone thickness, *MHBT* middle horizontal bone thickness, *AHBT* apical horizontal bone thickness, *RL* root length

3.4 Association between bone change and proclination change

Change in proclination ($\Delta\alpha$) was positively associated with net LaAHBT gain ($\beta = 0.057$ mm per degree, $P < 0.001$) and negatively with LaVBL improvement ($\beta = -0.073$ mm per degree, $P = 0.034$); greater proclination therefore tended to accompany greater labial vertical bone loss and greater labial apical

thickening (Online Resource 2). Significant $\Delta\alpha \times$ graft-material interactions were observed for LaMHBT ($\beta = 0.028$, $P = 0.029$), LaAHBT ($\beta = -0.040$, $P = 0.037$) and MHBT ($\beta = 0.038$, $P = 0.012$), indicating that these associations differed between DBBM and DBBM-C (Online Resource 2). No other main effect or interaction was significant for net dimensional change, and neither $\Delta\alpha$ nor its interaction with graft material was associated with any postoperative dimensional-loss parameter from T1 to T2 (all $P > 0.05$).

3.5 Root length

Root length decreased slightly but significantly from T0 to T2 in both groups (both $P < 0.001$; Table 2), with no between-group difference ($P = 0.977$).

3.6 Predictors of graft retention

In the multivariable mixed-effects model of labial retention (material, proclination change, sex, age and tooth type; patient random effect), material was independently associated with retention after adjustment for the other variables: DBBM showed significantly higher retention than DBBM-C at the LaVBL ($\beta = +107.27$ percentage points, $P = 0.010$), LaCHBT ($\beta = +59.93$, $P = 0.028$) and LaMHBT ($\beta = +30.07$, $P < 0.001$) levels, whereas LaAHBT retention did not differ between groups (Online Resource 3).

Sex and age were independent determinants only at LaCHBT, where male sex ($\beta = -63.60$, $P = 0.030$; female as reference) and older age ($\beta = -13.59$, $P < 0.001$) were each associated with lower retention (Online Resource 3). Proclination change was not associated with retention at any labial level (all $P > 0.05$). Tooth type showed a significant overall effect at LaMHBT ($P = 0.004$) and LaAHBT ($P = 0.048$); on Bonferroni-adjusted pairwise testing, canines retained significantly more than central incisors at LaMHBT ($P = 0.001$), with no other pairwise difference surviving correction. Because sex and age were balanced between groups at baseline (Table 1), these associations reflect within-cohort patient factors rather than a group imbalance.

4 Discussion

4.1 Principal findings

In modified PAOO before labial proclination of thin-plate mandibular anterior teeth, the two substitutes produced comparable immediate augmentation, yet over 6 months of orthodontic loading DBBM held that augmentation better. The advantage was clearest at the labial middle level, where DBBM showed greater net gain, less postoperative loss and higher retention; at the cervical level the continuous comparison fell short of significance while the categorical and retention analyses both favored DBBM. What distinguished the materials was thus space maintenance under load, not initial grafting capacity. CBCT resolves the mineralized contour rather than histological bone, and a grafted contour holds both new bone and residual substitute; these differences therefore describe maintenance of the augmented dimension, not new bone formation.

That a difference emerged at all probably reflects the loading environment. In periodontal intrabony defects and sinus floor augmentation, where the two materials perform comparably [17, 18], the graft sits within several bony walls that shield it from force. The PAOO labial site offers one or two walls and bears continuous orthodontic force and soft-tissue pressure; there a graft is judged more by its capacity to hold space than by its osteoconductive potential. Because the pouch-design suture and tension-free closure were standardized, both grafts had the same early containment [23, 24], which narrows procedural variability without removing individual differences in bone metabolism and local vascularity.

4.2 Material properties and the middle-level difference

The two materials share an identical mineral phase but differ in persistence: the 10% porcine collagen in DBBM-C resorbs within weeks, whereas DBBM particulate lasts years. Because the inorganic phase is identical, both grafts act mainly by osteoconduction, and the collagen itself has limited osteoinductive potential in this context. While present, the collagen provides a provisional matrix that aids early cell infiltration and osteoblastic differentiation [25, 26] and improves handling and hemostasis [27]. Once it resorbs, the two grafts are compositionally similar, so any durable difference should lie in space maintenance rather than osteogenic capacity. The porous DBBM architecture supports vascular ingrowth, matrix deposition and osteogenic gene expression [28–30], and its granules stay in bone contact for years [31]. Because bioresorption and space maintenance are inversely related [32], the faster-resorbing collagen phase plausibly weakens early space maintenance, consistent with animal data showing greater shrinkage of collagen-stabilized grafts [33] and poorer maintenance of non-crosslinked collagen [34].

During tipping, periodontal-ligament stress is highest cervically and apically and passes through a near-zero transition zone at mid-root [35], where the center of resistance and rotation also lie [36–38]. Least exposed to orthodontic force, the middle level should therefore reflect intrinsic graft stability most directly, which is where a material difference is easiest to detect.

At the cervical and vertical levels the mixed models were mostly non-significant even though within-group and categorical analyses still favored DBBM (49.0% vs 22.2% of teeth gaining cervical bone). Part of this is statistical: cervical change scores contained many zero values, which limited the continuous model and prompted the categorical GEE that did detect a difference. Part of it is a floor effect, since the DBBM group began with numerically greater vertical loss (LaVBL 2.00 vs 1.50 mm, $P = 0.095$; Table 1), leaving more scope for within-group gain, whereas a between-group difference requires a larger effect. Adjustment for the earlier measurement addresses the between-group comparison but not this asymmetry within groups, so these results warrant confirmation in a larger, better-balanced sample.

DBBM nonetheless maintained the vertical level, cervical thickness and apical augmentation at 6 months, matching earlier particulate-DBBM PAOO series [14, 39–43], whereas direct DBBM-C comparators are still lacking. In a canine peri-implant model, a collagen-stabilized graft showed weaker late bone formation while particulate DBBM remained stable [44]. Being peri-implant rather than PAOO,

that evidence is supportive rather than direct, but it points the same way. Comparisons of collagenated substitutes likewise attribute their advantage mainly to handling [27].

4.3 Orthodontic movement and bone change

Greater proclination was associated with more labial vertical bone loss and more labial apical thickening. The pattern fits labial tipping, in which compressive stress concentrates at the cervical crest while tensile stress is distributed apically [45, 46], and cervical loss was more pronounced where the labial plate was already deficient [47]. Both directions have precedent: proclination increases apical thickness during decompensation [7, 48], and it lowers the labial crest [48, 49], with crestal loss accelerating beyond a proclination threshold [6]. Proclined incisors carry a lower crest even without treatment [50]. $\Delta\alpha$ also interacted with graft material at LaMHBT, LaAHBT and MHBT, suggesting that the two substitutes respond differently under load.

Most other parameters, and every postoperative change parameter, showed no association with $\Delta\alpha$, matching studies in which thickness changes without a linear dose relationship [51, 52]. Once placed, the graft appears to hold the radiographic contour as an osteoconductive scaffold, so measured thickness no longer tracks tooth displacement closely.

4.4 Retention determinants and clinical implications

The retention models corroborate the middle-level finding. Material was independently associated with 6-month retention at the labial vertical, cervical and middle levels, favoring DBBM, whereas sex and age were determinants only at the cervical level. Proclination change was not associated with retention at any level, although it did track the direction of the underlying dimensional changes. Across the range of proclination studied, retention therefore appears to be governed more by the graft material and the local site environment than by how far the tooth moved; this does not exclude an effect of proclination beyond the range examined here.

Female sex was associated with greater labial cervical retention, consistent with the protective action of estrogen on bone remodeling [53], although women may also be more susceptible to orthodontic bone loss [54]. This interpretation is tentative: hormonal status was not measured, and in this young-adult cohort sex may be a proxy for unmeasured anatomical or behavioral factors. Retention also declined with age, which may reflect age-related differences in bone remodeling capacity [55, 56], though the restricted age range and absence of bone-turnover markers limit mechanistic inference. Tooth type carried a significant overall effect at the labial middle level, where canines retained more than central incisors ($P = 0.001$); this may reflect a percentage-scaling artifact of the smaller graft volume placed at the arch corner, where surgical access is limited, as much as a true biological effect, although the canine's offset from the principal loading direction may also contribute [7].

Clinically, by 6 months both materials had restored the thin baseline plate to a median labial thickness of at least 1 mm at the middle and apical levels, a dimension associated with greater periodontal stability [57]. The DBBM advantage was concentrated at the labial middle level and amounted to roughly 0.4 mm,

but its long-term periodontal benefit remains uncertain. At a one- or two-wall site under continuous loading, the slowly resorbing particulate may be preferred when durable space maintenance is the priority, whereas DBBM-C remains reasonable when handling is the priority, accepting somewhat greater early loss. Because intraoperative handling data were not recorded, this handling–maintenance trade-off could not be quantified here. Root shortening was minor in both groups (median ≈ 0) and did not differ by material, so neither substitute appeared to aggravate root resorption, although root length warrants monitoring over the full treatment course.

4.5 Limitations

First, the study was retrospective and single-center, with non-random, patient-chosen allocation; although the groups were comparable at baseline and the models were adjusted, residual confounding cannot be excluded. Second, the sample was one of convenience, and the labial middle level was chosen as the key outcome post hoc rather than pre-specified, which should temper interpretation. The between-group effect at that site was large and the study was adequately powered to detect it; the smaller effects at other sites were underpowered and are inconclusive rather than equivalent. Third, CBCT limits interpretation to contour maintenance. Partial-volume effects at the 0.30-mm voxel can underestimate thin plates [58], new bone cannot be distinguished from residual substitute, and the thin preoperative cortex precludes reliable density or volumetric quantification [59]. These findings are most relevant to young adults with deficient mandibular anterior labial bone treated using this modified PAOO protocol. Generalizability to older patients, other centers, different patient populations or surgical protocols remains uncertain.

5 Conclusions

At 6 months after modified PAOO, both DBBM and DBBM-C maintained significant net labial augmentation at the middle and apical levels of thin-plate mandibular anterior teeth, restoring a median labial thickness of at least 1 mm there. Under orthodontic loading DBBM preserved the augmented dimension better, most clearly at the labial middle level, where it retained about 0.4 mm more. DBBM may therefore be preferred when durable space maintenance is the clinical priority.

Declarations

Competing interests

The authors declare that they have no competing interests.

Ethics approval

This retrospective study was approved by the Ethics Committee of the Affiliated Stomatology Hospital, Zhejiang University School of Medicine on 28 January 2022 (approval no. 2022-03-432) and was

conducted in accordance with the Declaration of Helsinki.

Consent to participate

The requirement for informed consent to participate in this retrospective secondary analysis of existing clinical and imaging data was waived by the Ethics Committee. All patients had provided written informed consent for their clinical treatment.

Consent to publish

Not applicable. No identifiable individual participant data are presented in this article.

Use of generative AI in the writing process

During the preparation of this manuscript the authors used Claude (Anthropic) to improve the language and readability of the text. After using this tool the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Author Contribution

M.C., S.M., J.S. and Z.X. conceived the study, and S.M. and J.S. designed the methodology. M.C., W.X., L.H., H.P., Y.S. and J.S. performed the investigation, and M.C., S.M., W.X., L.H., H.P. and Y.S. curated the clinical and imaging data. M.C. carried out the formal analysis, prepared the figures and wrote the first draft of the manuscript. S.M., W.X., L.H., H.P., Y.S., J.S. and Z.X. reviewed and edited the manuscript. J.S. and Z.X. supervised the study, Z.X. provided resources and administered the project, and S.M., J.S. and Z.X. acquired funding. M.C. and S.M. contributed equally to this work. All authors read and approved the final manuscript.

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Data Availability

The de-identified data supporting the findings of this study are available from the corresponding authors upon reasonable request, subject to institutional and ethical requirements.

Code availability

Not applicable.

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Figures

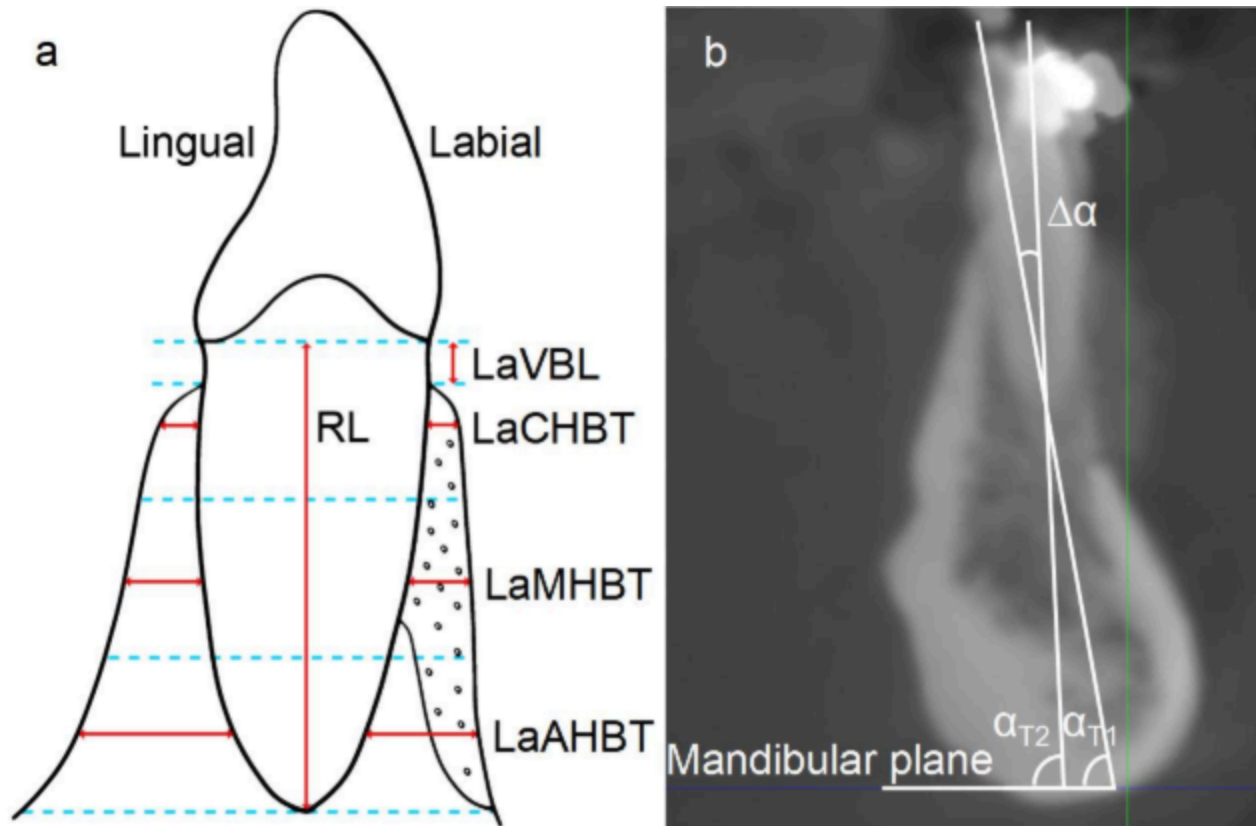


Figure 1

Radiographic measurements and calculation of proclination change. **a** Measurements obtained on the maximum labiolingual section of each mandibular anterior tooth. LaVBL is the vertical distance from the cementoenamel junction to the labial alveolar crest; LaCHBT, LaMHBT and LaAHBT are the labial horizontal bone thicknesses at the cervical, middle and apical thirds of the root; RL is the distance from the midpoint of the line connecting the labial and lingual cementoenamel junctions to the root apex. **b** Proclination change ($\Delta\alpha$) was calculated as the difference between the long-axis-to-mandibular-plane angle at 6 months (α_{T2}) and immediately postoperatively (α_{T1}): $\Delta\alpha = \alpha_{T2} - \alpha_{T1}$. LaVBL labial vertical bone level, LaCHBT labial cervical horizontal bone thickness, LaMHBT labial middle horizontal bone thickness, LaAHBT labial apical horizontal bone thickness, RL root length, T1 immediately postoperative, T2 6 months postoperative

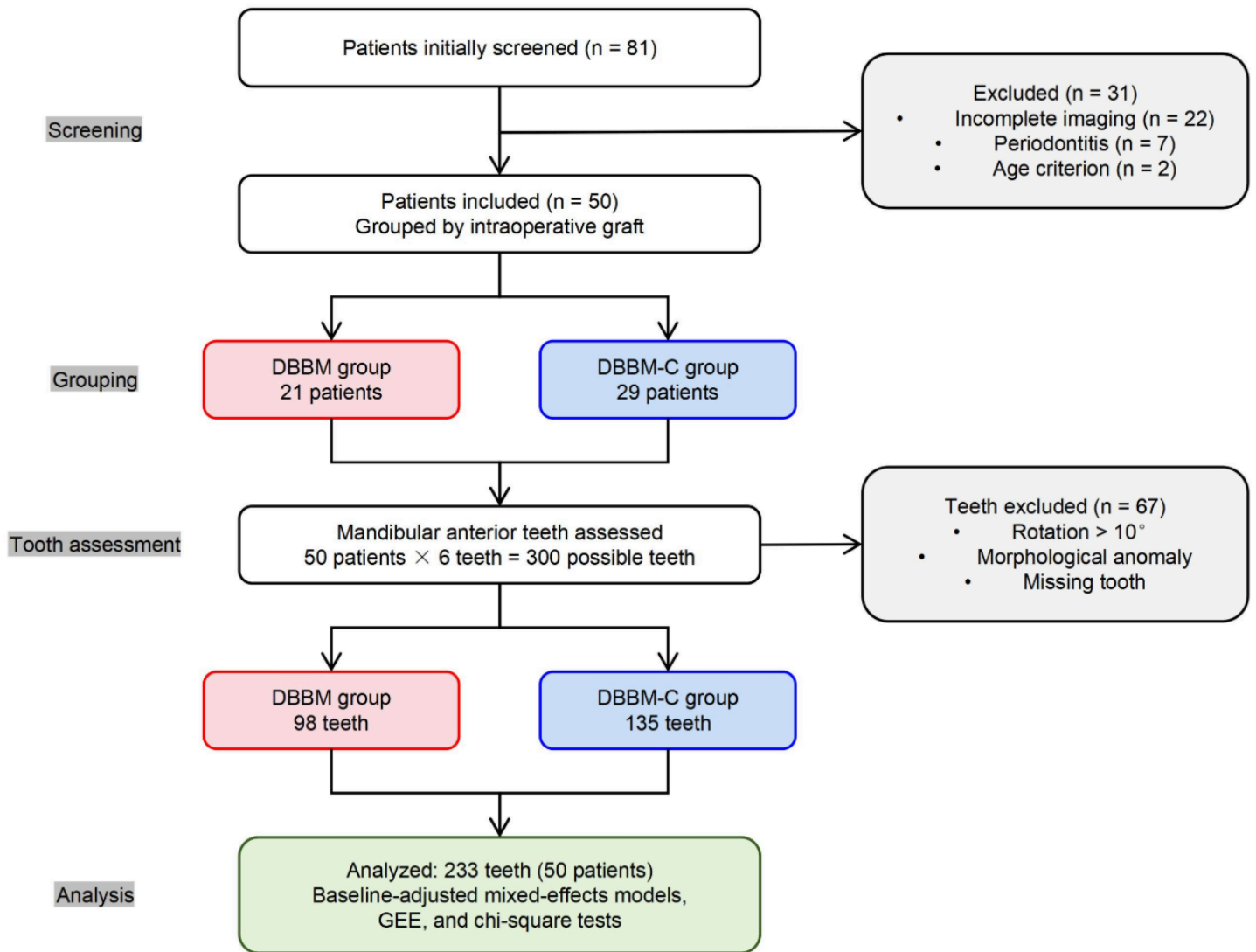


Figure 2

Flow diagram of patient and tooth selection. Patient-level screening was followed by tooth-level eligibility assessment; the final analysis included 50 patients and 233 mandibular anterior teeth. *DBBM* deproteinized bovine bone mineral, *DBBM-C* collagen-stabilized deproteinized bovine bone mineral, *GEE* generalized estimating equation

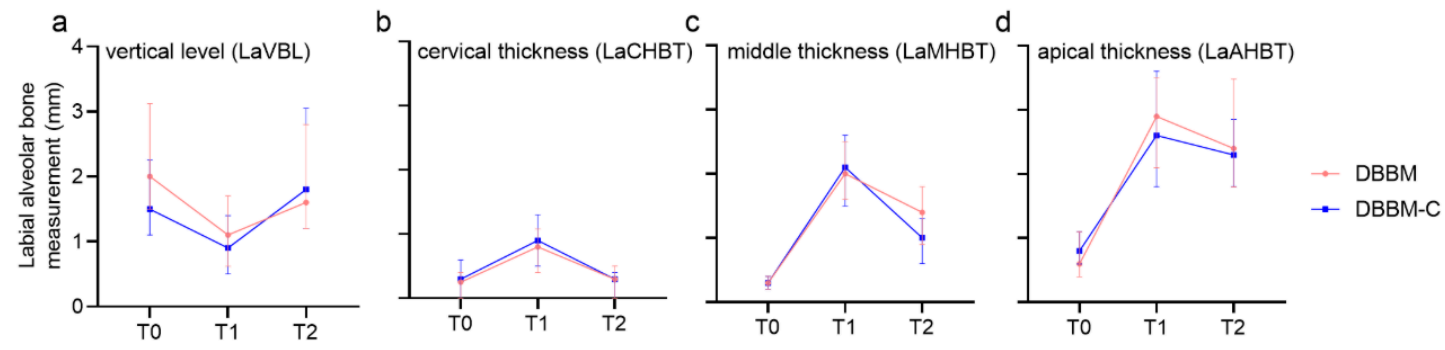


Figure 3

Labial alveolar bone dimensions across the three timepoints after modified PAOO. **a–d** Median values and interquartile ranges (Q1, Q3) of LaVBL, LaCHBT, LaMHBT and LaAHBT at baseline (T0), immediately postoperatively (T1) and 6 months postoperatively (T2) in the DBBM and DBBM-C groups. A lower LaVBL value indicates a more favorable labial vertical bone level, whereas higher LaCHBT, LaMHBT and LaAHBT values indicate greater labial bone thickness. *PAOO* periodontally accelerated osteogenic orthodontics, *DBBM* deproteinized bovine bone mineral, *DBBM-C* collagen-stabilized deproteinized bovine bone mineral, *LaVBL* labial vertical bone level, *LaCHBT* labial cervical horizontal bone thickness, *LaMHBT* labial middle horizontal bone thickness, *LaAHBT* labial apical horizontal bone thickness

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