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Long Term Comparison of Marginal Bone Loss Around Implants Placed in Ridge-preserved Versus Non-preserved Sites Following Tooth Extraction: A Retrospective Radiographic Study

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ABSTRACT

Aim and Hypothesis

This retrospective radiographic study aimed to compare the short and long-term MBL around implants placed in ridge-preserved (ARP) sites versus non-preserved sites following tooth extraction. The primary hypothesis was that implants placed in ARP sites would exhibit comparable MBL to those placed in non-ARP sites. A secondary aim was to identify subject-level and implant-level risk indicators associated with MBL at different time points.

Materials and Methods

The analysis included a total of 120 dental implants from 111 patients, 60 in the no ARP group and 60 in the ARP group. A calibrated examiner assessed marginal bone levels radiographically at implant placement (T1), abutment connection (T2), prosthesis insertion (T3), and at least five years after functional loading (T4). Linear measurements were made from the implant shoulder to the first bone-to-implant contact mesially and distally. Statistical analysis included descriptive tests, t-tests, and multivariable linear regression models to assess differences and predictors of MBL between the two groups.

Results

The mean follow-up time from T3 to T4 was 8.83 ± 2.67 years. At T1, the average MBL was significantly lower in the ARP group (-0.07 ± 0.64 mm) than in the no ARP group (0.25 ± 0.48 mm; $P=0.003$). By T2, the ARP group still had lower MBL values (0.50 ± 0.59 mm) than the no ARP group (0.81 ± 0.64 mm; $p > 0.05$). This trend continued at T3 (1.06 ± 0.74 mm vs. 1.31 ± 0.70 mm) and T4 (1.70 ± 0.98 mm vs. 1.92 ± 0.80 mm), with no significant differences

(*P*=0.173; Table 1; Figure 1). A total of 48 implants (40%) had ≥2 mm of MBL at T4, with a higher percentage in the no ARP group (45%, 27 implants vs 35%, 21 implants) (*P=0.190*; Figure 2). During the initial phase of healing (T1-T3), the ARP group had slightly higher bone loss (1.13±0.62 mm) than the no ARP group (1.06±0.60 mm; *P = 0.596*). After prosthesis insertion (T3-T4), bone loss continued at a decreased rate with comparable MBL, 0.63 ± 0.63 mm in the ARP group and 0.61 ± 0.52 mm in the no ARP group (*P = 0.842*; Table 2). The multivariable linear regression analysis indicated that between T1 and T3, arch location and prosthesis type were significant predictors of MBL. Maxillary implants and fixed bridges showed significantly higher MBL than mandibular implants and single crowns (0.281 mm, *p = 0.010*; 0.275 mm, *P = 0.014*, respectively). In the long-term (T3 to T4), patient age significantly correlated with increased MBL. As age increased, MBL decreased by 0.014 mm (*P = 0.004*). Other covariates were not statistically significant.

Conclusions

Despite distinct histological differences, implants placed in ridge-preserved sites demonstrated similar early and long-term MBL compared to those placed in non-preserved sites, suggesting ARP does not result in a different pattern of bone remodeling and long-term stability over time. While ARP may provide initial structural benefits, its long-term effects on MBL appear comparable to spontaneous healing. These findings support the clinical use of ARP to maintain ridge dimensions without increasing the risk of excessive MBL.

DEDICATION

To my husband, my love, and my hero, Mohammad.

To my parents, Mama and Baba, with all my love and gratitude.

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LIST OF ABBREVIATIONS

ARP – Alveolar Ridge Preservation

MBL – Marginal Bone Loss

FDBA – Freeze-Dried Bone Allograft

DFDBA – Demineralized Freeze-Dried Bone Allograft

ICC – Intraclass Correlation Coefficient

T1 – Implant insertion

T2- Abutment connection

T3- Prosthesis insertion

T4- ≥ 5 years post-loading

LIST OF SYMBOLS

Mm: millimeters

≤: less than or equal to

≥: greater than or equal to

<: less than

>: greater than

±: plus/minus

Long Term Comparison of Marginal Bone Loss Around Implants Placed in Ridge-preserved Versus Non-preserved Sites Following Tooth Extraction: A Retrospective Radiographic Study

Early marginal bone loss (MBL) is defined as "a non-infectious remodeling process that occurs within the first year following implant implantation" [1]. Early MBL results from bone remodeling because of trauma or injury to bone tissue and may predict ongoing bone loss, which could lead to peri-implant pathologies and ultimately implant failure [2]. Based on the consensus report of the 2017 World Workshop on the Classification of Periodontal and Peri-Implant Diseases and Conditions, the diagnosis of peri-implant health requires the absence of signs of inflammation, bleeding, or suppuration on gentle probing, no increase in probing depth over time, and the absence of bone loss beyond marginal bone level changes resulting from initial bone remodeling [3]. The amount of acceptable initial bone remodeling (early MBL) must not exceed 1.5 - 2 mm during the first year after functional loading [4-6]. Evidence also suggests that implants with high MBL rates in the early stages of healing (0.44 mm at six months post-loading) are more likely to experience more than 2 mm of MBL after the first year of loading, thus negatively affecting the outcomes and possibly leading to accelerated bone loss [7].

The stability of peri-implant hard and soft tissues is essential for the long-term success of implant therapy. Preclinical and clinical studies have shown that a soft tissue seal of approximately 3 to 4 mm will form following implant placement, corresponding to the supracrestal attached tissues [8, 9]. Changes in peri-implant bone levels may compromise the soft tissue seal, impairing the long-term success of implant therapy. Early MBL around dental implants may also be a risk factor for peri-implantitis [2]. After the first year of implant loading, MBL is most likely associated with inflammatory reactions leading to peri-implantitis [10]. Thus, minimizing early MBL is critical for peri-implantitis prevention.

Given the enormous diversity of local and systemic parameters, it is impossible to establish a universally applicable threshold for distinguishing between "physiologic" and "pathologic" early MBL [11]. Variables, such as the implant's position relative to the alveolar crest, depth of the implant-abutment connection [11], biologic width formation [12], and supracrestal soft tissue dimensions, [13] could contribute to early MBL.

The desired outcome of implant therapy extends beyond implant survival. A successful outcome requires optimal implant function and esthetics. This depends on alveolar ridge dimensions at the implant site, which dictate the ideal implant positioning and affect the quality of the future restoration and its emergence profile [14, 15]. To maintain alveolar ridge dimensions, alveolar ridge preservation (ARP) techniques using bone grafts and/or membranes have proven effective in minimizing horizontal and vertical ridge loss associated with tooth extraction [16-18]. Several modalities of ARP have been compared to tooth extraction alone, including the use of different bone grafts, membranes, collagen sponges, and autologous blood-derived products. A systematic review confirmed the efficacy of ARP in attenuating alveolar ridge dimensional reduction. More favorable radiographic outcomes were observed, when particulate bone graft material (allogenic or xenogenic) covered with a resorbable collagen material (membrane, matrix, or sponge) was used, compared to non-preserved sites, with a higher likelihood of reducing the need for bone grafting prior to or at the time of implant placement. However, no definite conclusions have been made regarding ARP's effect on implant-related outcomes such as MBL or implant survival [19]. Jung et al. [20] evaluated posterior sites treated with deproteinized bovine bone mineral combined with a bilayer collagen membrane and found significantly less horizontal and vertical ridge loss in the ARP group compared to the spontaneous healing group. For example, buccal bone height reduction was 2.31% in the ARP group compared to 13.11% in the control group ($P < 0.05$), and horizontal width loss at 1 mm below the crest was 17.1% in the ARP group compared to 32.5% in the control group ($P < 0.05$). Similarly, Walker et al. [21] found significantly less vertical buccal bone loss at ARP sites in a randomized trial utilizing CBCT imaging of molar sites: -1.12 ± 1.60 mm at mid-buccal compared to -2.60 ± 2.06 mm in spontaneously healed sites ($P = 0.01$). Although horizontal ridge width reduction was not significantly different, vertical height preservation in the ARP group was statistically significant in all buccal aspects.

The ability to limit alveolar ridge dimensional changes depends on the rate of resorption of the grafting material and its ability to encourage bone formation. Currently, xenografts and allografts are the most widely used materials; both are osteoconductive, and allografts can also demonstrate limited osteoinductive properties [22]. However, graft incorporation delays healing and may lead to different histologic characteristics compared to simple tooth extraction, often leaving varying amounts of residual graft material [23]. Cardaropoli et al. conducted a histological analysis comparing grafted sites following ARP using xenograft and a collagen membrane versus non-grafted sockets. They found osteoblasts adjacent to osteoid tissue, woven bone, and mature bone in grafted sockets with residual graft particles embedded in new bone and connective tissue. All sockets were filled with bone, with variations in the mineralized proportion between individuals [24]. Jo et al. conducted a clinical study on bone formation using three different graft materials (allograft with xenograft, xenograft alone, and autogenous bone) and concluded that there were no significant differences among the groups. All groups demonstrated new bone formation histologically, and the extraction sockets maintained their dimensions [25]. A systematic review assessing residual graft material percentages reported that xenografts and alloplasts exhibited the highest percentage (over 35% at seven months postoperatively) of residual particles, whereas allografts presented the lowest. Furthermore, the highest mean percentage of newly formed bone was found with allografts, whereas xenografts showed the lowest, even after five months [26].

Preclinical and clinical trials have extensively explored the sequence of healing events following simple tooth extraction and their histologic characteristics. In the early stages of healing, a blood clot occupies most of the extraction site. By two weeks, the woven bone starts to form. One month after extraction, mineralized bone occupies most of the socket volume. Thereafter, the bone matures and consolidates as woven bone is replaced with lamellar bone, bone marrow, and cortical bone formation at the socket entrance [27].

Differences in the histologic characteristics of bone healing between sites following ARP and non-preserved sites raise the question of whether early bone remodeling and long-term marginal bone stability differ after implant placement in grafted versus naturally healed bone [28]. In addition, in a recent clinical study, Kofina et al. identified that early soft tissue healing over grafted bone sites is characterized by delayed wound closure, persistent ischemia, and altered molecular content compared to non-grafted sites [29].

Salvi et al. investigated long-term biological complications and found no statistically significant difference between implants placed in regenerated bone compared to native bone in terms of peri-implant mucositis, peri-implantitis, or implant failures. However, there was greater variability and lower predictability of peri-implantitis in patients receiving implants in augmented sites compared to pristine sites. One limitation of this review was the lack of control over potential confounders, such as history of periodontitis and the type of graft material [30].

Details of studies comparing MBL and survival between implants placed in sites following ARP versus non-preserved sites are presented in Table 1 [15, 31-38]. Most available studies (six RCTs and three retrospective studies) have small sample sizes and short follow-up times, and xenografts are predominantly used as grafting material. Ramanauskaite et al., in a systematic review, concluded that after one to four years of follow-up, implants placed in grafted bone had a survival rate of 95 to 100%, and MBL was higher in implants placed in non-preserved sites [39]. However, the meta-analysis conclusions were influenced by one study [31] in which MBL was significantly higher in the control group (1.95 ± 0.07 mm) than in the test groups (1.14 ± 0.23 and 1.13 ± 0.29). In the other included studies, MBL was not significantly different between test and control sites [39]. Thus, evidence regarding clinical outcomes of implants inserted in sites following ARP compared to non-preserved sites remains limited and inconclusive, warranting further investigation.

Table 1 – Details of studies comparing MBL and survival between implants placed in sites following ARP with non-preserved sites following tooth extraction.

Authors and year	Study design	Number of subjects by groups	Group details	Ridge healing time	Maximum implant follow-up time post-loading	Mean MBL in mm	Implant survival
Marconcini et al. 2018 [31]	RCT Multi-arm	42 subjects for a total of 42 sockets Divided into three groups: - Control: n = 13 - Test 1: n = 15 - Test 2: n = 14	- Test 1: Xenograft (Collagenated cortico- cancellous porcine bone) - Test 2: Xenograft (cortical porcine bone) Both sockets sealed with resorbable collagen membrane for both groups	3 months	4 years	For the follow-up time of 4 years: - Control: 1.92 mm - Test 1: 1.13 mm - Test 2: 1.14 mm	100% for all groups
Cardaropoli et al. 2015 [32]	RCT Parallel arms	41 subjects for a total of 48 sockets Divided into two groups: - Control: n = 24 - Test: n = 24	- Test: Xenograft (Bovine bone particles) Socket sealed with resorbable collagen membrane	4 months	1 year	For the follow-up time of 1 year: - Control: 0.35 mm - Test: 0.33 mm	100% for both groups
Barone et al. 2012 [15]	RCT Parallel arms	40 subjects for a total of 40 sockets Divided into two groups: - Control: n = 20 - Test: n = 20	- Test: Xenograft (Cortico-cancellous porcine bone particles) Socket sealed with resorbable collagen membrane	4 months	3 years	For the follow-up time of 3 years: - Control: 1.02 mm - Test: 1.00 mm	95% for both groups
Patel et al. 2012 [33]	RCT Parallel arms	27 subjects for a total of 27 sockets Divided into two groups: - Control: n = 13 - Test: n = 14	- Control: synthetic bone substitute - Test: Xenograft (Bovine bone particles) Both sockets sealed with resorbable collagen membrane	8 months	1 year	For the follow-up time of 1 year: - Control: -- Mesial: 0.12 mm -- Distal: 0.35 mm - Test: -- Mesial: 0.20 mm	100% for both groups

						-- Distal: 0.13 mm	
Tabrizi et al. 2019 [34]	Prospective cohort	90 subjects for a total of 90 sockets - Group 1: n = 30 - Group 2: n = 30 - Group 3: n = 30	- Group 1: Control - Group 2: Control - Group 3: Xenograft (Bovine bone particles) Socket sealed with resorbable collagen membrane	- Group 1: 8 weeks - Group 2: 6 months - Group 3: 6 months	3 years	For the follow-up time of 3 years: - Group 1: 0.57 mm - Group 2: 0.52 mm - Group 3: 0.58 mm	N/A
Zhao et al. 2022 [35]	Prospective cohort	26 subjects for a total of 30 sockets Divided into two groups: - Control: n = 14 - Test: n = 16	- Test: Xenograft (Bovine bone particles) Socket sealed with resorbable collagen membrane	6 months	3 years	For the follow-up time of 3 years: - Control: 0.47 mm - Test: 0.12 mm	100% for both groups
Koutouzis and Lundgren 2010 [36]	Retrospect-ive record review	60 subjects for a total of 60 sockets Divided into two groups: - Control: n = 30 - Test: n = 30	- Test: Allograft (DFDBA) Socket sealed with resorbable collagen membrane	4 months	33 months	For the follow-up time of 1 year: - Control: 0.15 mm - Test: 0.15 mm	100% for both groups
Wu et al. 2019 [37]	Retrospect-ive record review	129 subjects for a total of 222 implants Divided into two groups: - Control: n = 117 - Test: n = 105	- Test: Xenograft (Bovine bone particles) Socket sealed with non-resorbable d-PTFE membrane	N/A	N/A	N/A	98.24% for the control 97.14% for the test
Apostolopoulos and Darby 2016 [38]	Retrospect-ive record review	42 subjects for a total of 51 implants	N/A	N/A	N/A	N/A	100%

1. AIM AND HYPOTHESIS

The primary aim of this study was to determine whether there is a difference in the following:

(a) early MBL (implant placement to prosthesis insertion), and

(b) MBL at least 5 years after functional loading

between implants placed in sites following ARP versus implants placed in non-preserved sites following tooth extraction.

The secondary aim was to identify possible risk indicators that could influence the MBL occurring during early healing (implant placement to prosthesis insertion) and at least 5 years after functional loading in sites following ARP versus non-preserved sites following tooth extraction.

Our hypothesis was that implants placed in sites following ARP would demonstrate the same radiographic MBL as implants placed in non-preserved sites following tooth extraction.

2. MATERIALS AND METHODS

2.1. Study Design

This study was a retrospective cohort study analyzing MBL on radiographs of implants placed in sites following ARP (test) and non-preserved sites (control) following tooth extraction in the Department of Periodontology at Tufts University School of Dental Medicine from January 1, 2006, to December 31, 2016. Up to 5,000 records were reviewed for the purposes of this study.

2.2. Radiographic Analysis

Periapical and bitewing radiographs of implants already present in patients' Axium records were collected. MBL was compared between the two groups for implants at implant placement and prosthesis insertion, or within 2 months maximum after prosthesis insertion, and at least 5 years after functional loading. For a possible additional secondary analysis, any available radiograph at the healing abutment connection was also collected.

Linear bone measurements were taken on the mesial and distal surfaces of each implant from reproducible reference points—the implant shoulder—to determine bone levels. A horizontal line was drawn through the shoulder of the implant, and the distance from this line to the first bone-to-implant contact was measured at the implant's mesial and distal sites. Radiographic bone level on periapical radiographs will be determined after calculating the distortion rate of radiographs using the known length of the implant, as shown in Figure 1. For bitewing radiographs, a line across three threads was drawn and measured, which was used to calculate the distortion rate based on the known distance between implant threads, as shown in Figure 2 [40].

Radiographic measurements were obtained using ImageJ (National Institutes of Health, USA), a widely utilized open-source image analysis software in biomedical research. Marginal bone levels were then recorded in an Excel spreadsheet. Negative values were used to indicate subcrestal implant placements. For instance, if the implant shoulder was 0.5 mm subcrestal, it was recorded as -0.5 mm to avoid using "0" and to maintain consistency in identifying the vertical implant position.

All measurements were made by a single investigator (RA) and verified by another investigator (SS). A previously calibrated investigator (AP) measured the MBL on 10 randomly selected radiographs and compared them to the measurements by the two investigators in the same radiographs. To test intra-investigator variability, the MBL on another 10 randomly selected radiographs was measured twice, with a 1-week interval. The inter-investigator variability of the two investigators was evaluated using the same radiographs. The statistical significance of the differences between measurements was assessed using the paired t-test. Pearson correlation coefficients and Intraclass correlation coefficient (ICC) were calculated to analyze the correlation between the sets of measurements.

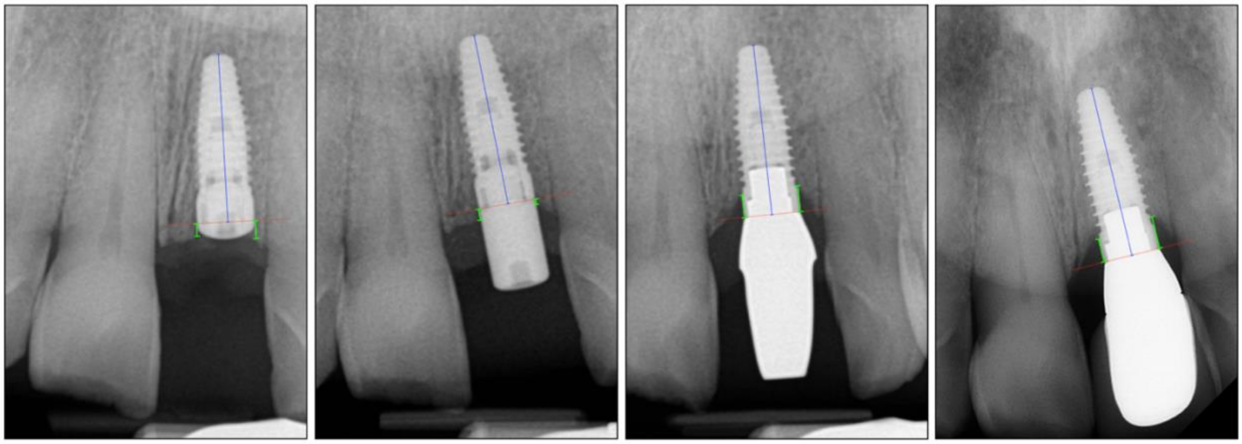
The different time points when radiographic measurements were conducted are as follows:

T1- Implant placement

T2- Healing abutment connection

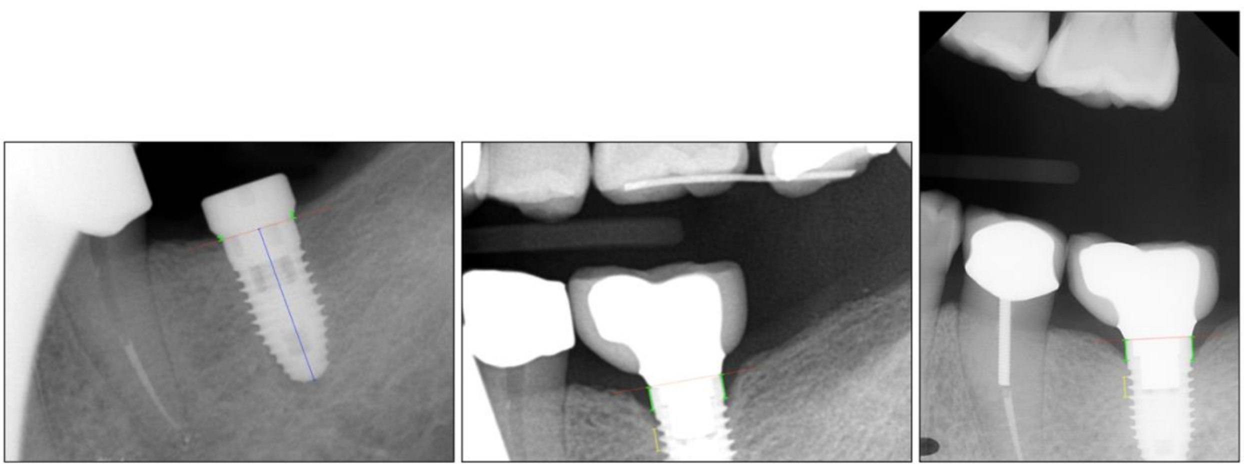
T3- Prosthesis insertion or within a maximum of 2 months after prosthesis insertion

T4- At least 5 years after loading (prosthesis insertion)



T1 -Implant placement | T2 -Abutment connection | T3 - Crown insertion | T4 - Nine years after crown insertion

Figure 1 – <u>Measurements recorded for dental implants on peri-apical radiographs.</u>
Red: Implant shoulder. Blue: Known length of the implant for peri-apical calibration. Green: Mesial and distal linear measurements from the implant shoulder to the first bone-to-implant contact.



T1 -Implant placement | T3 - Crown insertion | T4 - Six years after crown insertion

Figure 2 – <u>Measurements recorded for dental implants on peri-apical radiograph and, when applicable, bitewing radiographs.</u>
Red: Implant shoulder. Blue: Known length of the implant for peri-apical calibration. Yellow: Known distance between implant threads for bitewing calibration. Green: Mesial and distal linear measurements from the implant shoulder to the first bone-to-implant contact.

2.3. <u>Inclusion Criteria</u>

- Single or multiple non-adjacent implants in the maxilla or mandible.

- Single or multi-unit implant-supported restorations.

- Implant placement at least four months after tooth extraction (ARP or non-preserved site).
- Patients with periapical and bitewing radiographs that permit analysis of MBL around implants. For the primary analysis, radiographs at implant placement, prosthesis insertion, or within 2 months maximum after prosthesis insertion, and the most recent available at least 5 years after loading will be used, as derived from Axium records of each patient. All other radiographs available in Axium records between the above periods will also be collected and recorded for use in a possible secondary analysis.

2.4. Exclusion Criteria

Implants without periapical or bitewing radiographs at implant placement and prosthesis insertion, or within 2 months maximum after prosthesis insertion.

- Implants without implant-supported restoration within 12 months after implant placement.
- Implants with radiographs that do not permit analysis of MBL around implants (for instance, radiographs with a very high distortion or a poor diagnostic quality, or bitewing radiographs that don't capture the MBL).
- Implants are placed in combination with bone graft and/or guided bone regeneration.
- Implants with poorly fitted restorations.

2.5. Data Collection from Clinical Records

- All available information from Axium patients' records regarding subject- and implant-related factors and ARP-related factors that could be possible risk indicators for MBL was collected.

2.5.1. **Patient Factors**

- Gender, race.
- Age was based on T1.
- Systemic diseases (diabetes, hypertension, hypercholesterolemia) were based on the most recent patient records within one year of T1 and T4.
- Medications were based on the most recent records of the patient within one year of T1 and T4.
- Smoking habits (Current smoker, past smoker, non-smoker).
  - For current smokers, the number of cigarettes, duration, and frequency were based on the most recent records of the patient within one year of T1 and T4.
- History of periodontitis based on the most recent diagnosis on record of the patient within one year of T1 and T4.

2.5.2. **Implant Factors**

- Implant site (anterior or posterior, maxilla or mandible).
- One-stage or two-stage implants.
- Implant length and diameter.
- Implant brand and surface.
- Screw-retained or cement-retained implant-supported prosthesis.
- Height and width of a healing abutment.
- Single-unit prosthesis (crown), multi-unit prosthesis, or cantilever crown.

2.5.3. ARP Factors

- Type of bone graft used.
- Technique of ARP (flap or flapless).
- Primary closure vs. secondary healing.
- Type of socket seal or membrane (resorbable or non-resorbable, collagen matrix, or collagen sponge).
- Time of implant placement after ARP.

3. STATISTICAL ANALYSIS

3.1. Sample Size Calculation

Sample size was calculated using G Power* (Version 3.1). Assuming that the effect size is 0.69 based on a previous study [31], and the type I error rate is 5%, a power of 95% would be achieved with *n*=56 subjects per group (112 total).

3.2. Data Analysis

Means and standard deviations (SDs) for the continuous variables of mesial, distal, and total MBL were calculated for each group at the different time points. The normality of the data was assessed using the Shapiro-Wilk test. Then, a t-test was conducted to determine the statistical significance between the two groups. A univariable and multivariable mixed model analyses were performed after adjusting for significant patient and implant-related factors to determine the statistical significance within and between the two groups. This mixed model was also adjusted for multiple implants or sites per patient. The analyses were performed using the statistical program SAS Version 9.4 (SAS Institute, Cary, NC). A *P*-value of less than 0.05 was considered significant.

4. RESULTS

Our research protocol was reviewed and approved by Tufts University Health Sciences Institutional Review Board (IRB ID STUDY00003578). A total of 5,000 dental implant records were obtained from the Tufts IT department for the Department of Periodontology at Tufts University School of Dental Medicine from January 1, 2006, to December 31, 2016. Records were excluded based on missing radiographs at 3 time points (Tl, T3, T4), radiographs that could not be analyzed, and implants that did not have any prosthesis insertion. After reviewing the records, a final sample of 120 implants (60 per study group) from 111 patients fulfilled the inclusion criteria, 60 in the No ARP group and 60 in the ARP group (Figure 3).

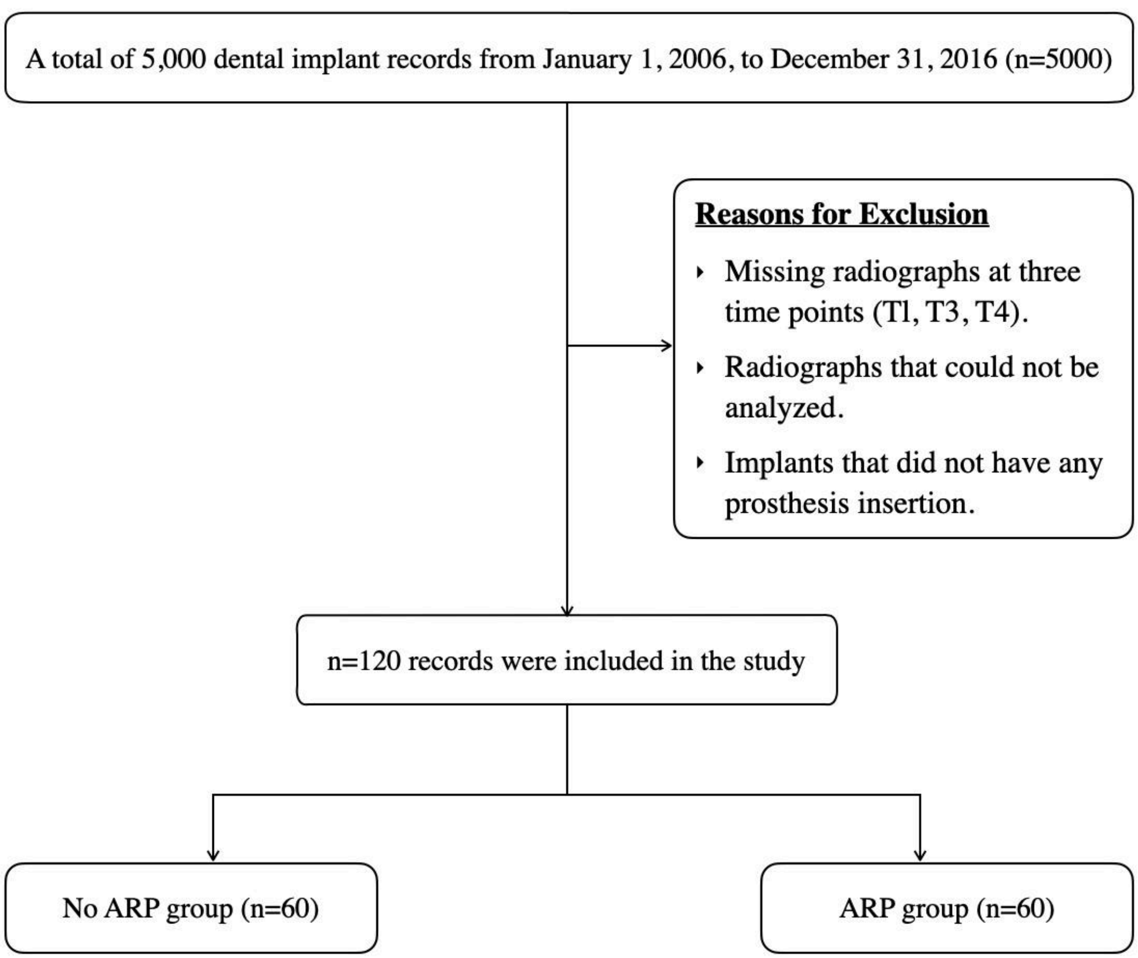


Figure 3 – Flow chart demonstrating the screening process

Radiographic calibration demonstrated excellent intra-rater reliability for mesial and distal MBL measurements, with ICC exceeding 0.98. Inter-rater reliability also showed high reproducibility, with measurement differences consistently within 0.2 mm across all samples and ICC over 0.90.

4.1. Descriptive Statistics for Subject-Level Characteristics

A total of 65 implants (54.2%) were placed in male patients, and 55 implants (45.8%) in female patients. The mean age of the study population was 59.15 ± 11.12 years, with no significant difference between the ridge-preserved (ARP) group (58.6 ± 10.33 years) and the non-ARP group (59.7 ± 11.91 years; *P* = 0.412).

A significant difference was noted in the gender distribution between the two groups, with a greater proportion of male patients in the non-ARP group (32.5%) compared to the ARP group (21.7%). Conversely, females were more represented in the ARP group (28.3%) compared to the non-ARP group (17.5%; *P* = 0.038). Race distribution also varied significantly, with a higher percentage of White patients in the non-ARP group (18.35%) compared to the ARP group (9.15%; p = 0.045). The prevalence of diabetes was significantly higher in the non-ARP group (8.35%) compared to the ARP group (3.35%) at T1 (*P* = 0.032). However, by T4, this difference was no longer significant (*P* = 0.402). The prevalence of hypertension and hypercholesterolemia did not differ significantly between groups at either time point.

Smoking status was comparable between groups, with 13.3% of patients being former smokers and 2.5% identified as current smokers. A history of periodontitis was highly prevalent in both groups (77.5% at T1 and 84.2% at T4), with no significant difference between the groups (*P* > 0.05) (Table 2).

Table 2 – Overall subject-level descriptive statistics

Co-variants	Total		No ARP		ARP		*P*-value
	Frequency (n)	Percent (%)	Frequency (n)	Percent (%)	Frequency (n)	Percent (%)	
Age (mean ±SD)	59.15±11.12		59.7 ±11.91		58.6±10.33		0.412
Gender:							
Male	65	54.2	39	32.5	26	21.7	0.038*
Female	55	45.8	21	17.5	34	28.3	
Race:							
Not Reported	79	65.8	35	29.15	44	36.65	0.045*
White	33	27.5	22	18.35	11	9.15	
Black	3	2.5	1	0.85	2	1.65	
Asian	5	4.2	2	1.7	3	2.5	
Medical History at Baseline (T1):							
Diabetes	14	11.7	10	8.35	4	3.35	0.032*
Hypertension	41	34.2	19	15.85	22	18.35	0.601
Hypercholesterolemia	33	27.5	18	15.0	15	12.5	0.512
Medical History at Final Follow-up (T4):							
Diabetes	20	16.7	12	10.0	8	6.7	0.402
Hypertension	52	43.3	23	19.2	29	24.1	0.098
Hypercholesterolemia	52	43.3	22	18.3	30	25.0	0.091
Smoking Status:							
Current smokers	3	2.5	1	0.83	2	1.67	0.712
Former smokers	16	13.3	8	6.65	8	6.65	
Non-smokers	101	84.2	51	42.5	50	41.7	
History of Periodontitis:							
At T1	93	77.5	47	39.2	46	38.3	0.819
At T4	101	84.2	50	41.7	51	42.5	0.921

Statistical comparison performed using Chi-square test. * P-value < 0.05. ARP: Alveolar Ridge Preservation.

4.2. Descriptive Statistics for Implant-Level Characteristics

This study analyzed 120 dental implants. Of these, 66 implants (55.0%) were placed in the maxilla and 54 (45.0%) were placed in the mandible; there was no significant difference between the ARP and non-ARP groups regarding arch location ($P = 0.712$). The ARP group showed a trend toward a higher number of anterior implants (23.35%) compared to the non-ARP group (16.65%; P=0.056).

Regarding the implant placement protocol, 74 implants (61.7%) were placed using a two-stage protocol, and 46 implants (38.3%) were placed using a single-stage protocol. ARP-treated sites were more often managed with a two-stage approach compared to non-ARP sites (33.35% and 28.35%, respectively; $P = 0.048$).

When assessing implant dimensions, 63 implants (52.5%) had a diameter of less than 5.0 mm, whereas 57 implants (47.5%) had a diameter of 5 mm or greater. The majority (89 implants, 74.2%) were 10 mm or less in length, whereas 31 implants (25.8%) were longer than 10 mm. Implant diameter and length did not differ significantly between groups.

In terms of prosthetic rehabilitation, screw-retained prostheses were used for 74 implants (61.7%), whereas cement-retained prostheses were used for 46 implants (38.3%; $P = 0.598$). Among prosthetic designs, 94 implants (78.3%) were restored with a single crown, 23 implants (19.2%) with a fixed partial denture (FPD), and three implants (2.5%) with a cantilever crown. In ARP sites, single crown restorations were more common (43.3%) than FPD restorations (4.2%). In contrast, non-ARP sites have a lower prevalence of single crowns at approximately 35.0% ($P = 0.039$; Table 3).

Table 3 – Overall implant-level descriptive statistics

Co-variants	Total		No ARP		ARP		*P*-value
	Frequency (n)	Percent (%)	Frequency (n)	Percent (%)	Frequency (n)	Percent (%)	
Arch Location:							
Maxilla	66	55.0	34	28.35	32	26.65	0.712
Mandible	54	45.0	26	21.65	28	23.35	
Implant Location:							
Anterior	48	40.0	20	16.65	28	23.35	0.056
Posterior	72	60.0	40	33.35	32	26.65	
Implant Stage:							
One-stage placement	46	38.3	26	21.65	20	16.65	0.048*
Two-stage placement	74	61.7	34	28.35	40	33.35	
Implant Diameter:							
< 5.0 mm	63	52.5	31	25.85	32	26.65	-
≥ 5.0 mm	57	47.5	29	24.15	28	23.35	
Implant Length:							
≤ 10.0 mm	89	74.2	41	34.2	48	40	-
> 10.0 mm	31	25.8	19	15.8	12	10	
Prosthesis:							
Screw-retained	74	61.7	36	30	38	31.7	0.598
Cement-retained	46	38.3	24	20	22	18.3	
Prosthesis Type:							
Crown	94	78.3	42	35	52	43.3	0.039*
Fixed Partial Denture (FPD)	23	19.2	18	15	5	4.2	
Cantilever Crown	3	2.5	-	-	3	2.5	

Statistical comparison performed using Chi-square test. * *P*-value < 0.05. ARP: Alveolar Ridge Preservation.

4.3. Materials and Surgical Characteristics of ARP

In cases where ARP was performed, freeze-dried bone allograft (FDBA) was the most frequently used grafting material, employed in 85% of sites. Other graft types included demineralized FDBA (DFDBA) in 8.3% of cases and xenograft in 6.7% of cases.

Regarding membranes used during ARP procedures, resorbable membranes were utilized in most cases (88.3%), whereas non-resorbable membranes and collagen matrices were each used in 5% of cases. A single case (1.7%) involved the use of a collagen sponge as a membrane substitute.

In terms of surgical approach, the flap technique was more prevalent, employed in 73.3% of cases, whereas flapless procedures accounted for 26.7%.

Regarding flap management, flap repositioning procedures were the most common approach, accounting for 88.3% of cases. In contrast, one-stage primary closure was performed in only 11.7% (Table 4).

The average healing time between ARP and implant placement was 8.70 months (±5.52 SD).

Table 4 – Materials and surgical characteristics of ARP

Variables		Frequency (n)	Percent (%)
Type of Graft	Allograft FDBA	51	85.0
	Allograft DFDBA	5	8.3
	Xenograft	4	6.7
Type of Membrane	Resorbable	53	88.3

	Non-resorbable	3	5.0
	Collagen matrix	3	5.0
	Collagen sponge	1	1.7
Technique of ARP	Flap	44	73.3
	Flapless	16	26.7
Closure/ Healing	Primary closure	7	11.7
	Flap repositioning	53	88.3
Healing time between ARP and implant placement (mean ±SD)		8.70 months	SD ± 5.521

FDBA: Freeze-Dried Bone Allograft. DFDBA: Demineralized Freeze-Dried Bone Allograft. ARP: Alveolar Ridge Preservation.

4.4. Marginal Bone Loss Analysis

MBL was assessed at T1, T2, T3, and T4.

At T1, average MBL values were noticeably lower in the ARP group (-0.07 ± 0.64 mm) compared to the non-ARP group (0.25 ± 0.48 mm), with the difference being statistically significant ($P < 0.05$). By T2, this trend continued, as the ARP group still showed lower MBL (0.50 ± 0.59 mm) than the non-ARP group (0.81 ± 0.64 mm), although the difference was not statistically significant ($P > 0.05$).

At T3, MBL increased in both groups, but the ARP group maintained lower values (1.06 ± 0.74 mm) compared to the non-ARP group (1.31 ± 0.70 mm; $P > 0.05$).

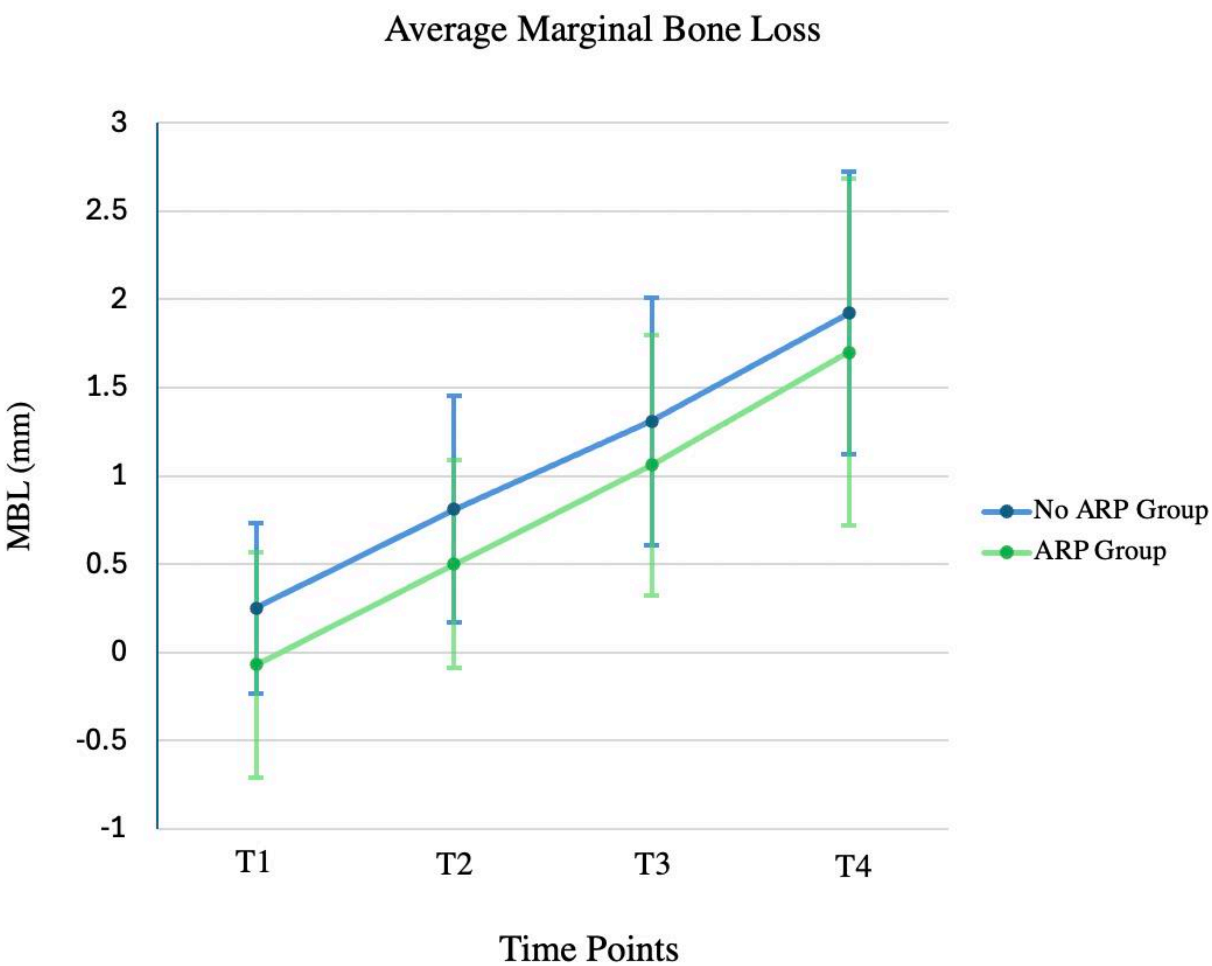
By T4, the total average MBL was 1.81 ± 0.90 mm. Although the non-ARP group experienced slightly greater bone loss (1.92 ± 0.80 mm) compared to the ARP group (1.70 ± 0.98 mm), the difference was not statistically significant (*P* > 0.05; Table 5).

Figure 4 demonstrates the average MBL of the non-ARP and ARP groups from T1 to T4. Both groups showed increasing MBL over time; however, the ARP group consistently had less MBL at each time point.

Table 5 – Mesial, distal, and average MBL at all time points (T1, T2, T3, and T4)

	Total			No ARP			ARP		
Time Point	Mesial MBL	Distal MBL	Average MBL	Mesial MBL	Distal MBL	Average MBL	Mesial MBL	Distal MBL	Average MBL
Implant Placement (T1)	0.19 ± 0.65*	0.19 ± 0.65*	0.09 ± 0.59*	0.36 ± 0.59	0.36 ± 0.59	0.25 ± 0.48	0.02 ± 0.68	0.02 ± 0.68	-0.07 ± 0.64
Second Stage (T2)	0.57 ± 0.64	0.73 ± 0.74*	0.65 ± 0.63	0.69 ± 0.72	0.93 ± 0.73	0.81 ± 0.64	0.46 ± 0.54	0.54 ± 0.71	0.50 ± 0.59
Prosthesis Insertion (T3)	1.12 ± 0.75*	1.25 ± 0.79	1.19 ± 0.72	1.26 ± 0.72	1.36 ± 0.79	1.31 ± 0.70	0.98 ± 0.75	1.15 ± 0.79	1.06 ± 0.74
Final Follow-Up (T4)	1.75 ± 0.87*	1.87 ± 1.01	1.81 ± 0.90	1.91 ± 0.81	1.93 ± 0.90	1.92 ± 0.80	1.58 ± 0.91	1.81 ± 1.11	1.70 ± 0.98

Data are presented as mean ± standard deviation. Statistical comparison performed using independent t-test. * *P*-value < 0.05 between ARP and No ARP. ARP: Alveolar Ridge Preservation.



<u>Figure 4 – Mean MBL ± SD of No ARP and ARP groups from T1 to T4</u>

4.5. Proportion of Implants with ≥2 mm MBL

A total of 48 implants (40%) exhibited ≥2 mm of MBL at T4, with a higher percentage in the non-ARP group (45.0%) compared to the ARP group (35.0%; $P = 0.190$). However, there were no statistically significant differences at any time point.

At T1, only one implant in each group (ARP and non-ARP) exhibited MBL ≥ 2 mm. At T2, an additional implant in the non-ARP group showed MBL ≥ 2 mm, whereas the ARP group remained the same, with only one implant with MBL ≥ 2 mm.

The overall trend shows that more implants developed MBL between T3 and T4, with a slightly greater increase in the non-ARP group. The number of implants with MBL ≥ 2 mm in the non-ARP group increased from 14 (23.3%) at T3 to 27 (45%) at T4, a difference of 13 implants. In the ARP group, the number increased from 9 (15%) at T3 to 21 (35%) at T4, a difference of 12 implants. Overall, the number of implants with MBL ≥ 2 mm increased from 23 (19.2%) at T3 to 48 (40.0%) at T4, a difference of 25 implants. However, no statistically significant differences were observed between the non-ARP and ARP groups at all time points (*P*>0.05; Table 6). Figure 5 illustrates the findings reported in Table 6 using a bar chart.

Table 6 – Number of implants with MBL ≥ 2 mm in No ARP and ARP groups at each time point

Time Point	Total		No ARP		ARP		*P*-value
	Frequency (n)	Percent (%)	Frequency (n)	Percent (%)	Frequency (n)	Percent (%)	
Implant Placement (T1)	2	1.7	1	1.7	1	1.7	0.499
Second Stage (T2)	3	2.5	2	3.3	1	1.7	0.271
Prosthesis Insertion (T3)	23	19.2	14	23.3	9	15.0	0.256
Final Follow-Up (T4)	48	40.0	27	45.0	21	35.0	0.190

Statistical comparison performed using Chi-square or Fisher's exact test. **P*-value < 0.05. ARP: Alveolar Ridge Preservation.

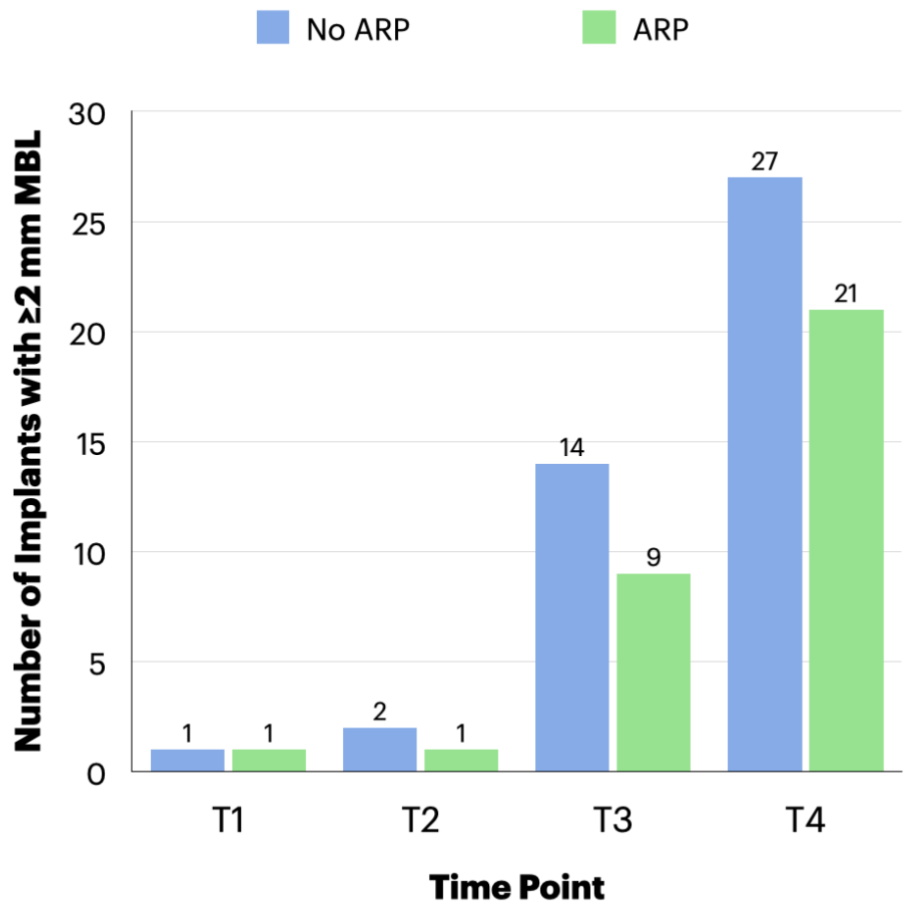


Figure 5 – Number of implants with MBL ≥ 2 mm in No ARP and ARP groups at each time point

4.6. MBL Changes Between T1–T3 and T3–T4

During the initial phase of healing (T1-T3), the ARP group experienced slightly greater bone loss (- 1.13 mm) than the non-ARP group (-1.06 mm); however, the difference was not statistically significant ($P = 0.596$).

After prosthesis insertion (T3-T4), bone loss continued at a decreased rate compared to the T1-T3 phase. Both groups exhibited very similar bone loss rates between the ARP (-0.63 ± 0.63

mm) and non-ARP (-0.61 ± 0.52 mm) groups, with no statistically significant difference observed (*P* = 0.842; Table 7).

Table 7 – MBL Changes Between T1-T3 and T3-T4

Time Point	Total	No ARP	ARP	*P*-value
Implant Placement (T1) - Prosthesis Insertion (T3)	-1.09±0.61	-1.06±0.60	-1.13±0.62	0.596
Prosthesis Insertion (T3) - Final Follow-Up (T4)	-0.62±0.58	-0.61±0.52	-0.63±0.63	0.842

Data are presented as mean ± standard deviation. Statistical comparison performed using paired t-test. **P*-value < 0.05. ARP: Alveolar Ridge Preservation.

4.7. Multivariable Linear Regression Analysis

The multivariable linear regression analysis was conducted to investigate the factors that contributed to MBL from T1 to T3 and from T3 to T4.

It demonstrated that both the arch location of the implant and the type of prosthesis were predictors of early MBL (T1 to T3). Maxillary implants experienced significantly higher MBL compared to mandibular implants, by 0.281 mm (*P* = 0.010). Additionally, FPDs had significantly higher MBL than single crowns, by 0.275 mm (*P* = 0.014). The group, whether Non-ARP or ARP, did not show any significance regarding early MBL (T1 to T3) (*P* = 0.300), as shown in Table 8.

Table 8 - Multivariable linear regression analysis showing the factors that contributed to MBL from T1 to T3

	Unstandardized Coefficients		Standardized Coefficients		
Model	B	Beta	Beta	t	Sig.
(Constant)	-1.103	0.095		-11.612	<.001
Group	-0.111	0.107	-0.092	-1.042	0.300
Arch	0.281	0.107	0.232	2.637	0.010
Crown vs FPD	-0.275	0.110	-0.220	-2.486	0.014

a. Dependent Variable: T1-T3dif
Statistical comparison performed using multiple linear regression test.

For long-term MBL (T3 to T4), results showed that as age increased, the MBL between T3 and T4 decreased by 0.014 mm ($P = 0.004$). Similarly, the group did not show any significance regarding long-term MBL (T3 to T4) ($P = 0.725$), as shown in Table 9.

Table 9 - Multivariable linear regression analysis showing the factors that contributed to MBL from T3 to T4

	Unstandardized Coefficients		Standardized Coefficients		
Model	B	Beta	Beta	t	Sig.
(Constant)	0.208	0.286		0.726	0.469
Group	-0.036	0.103	-0.032	-0.353	0.725
Age	-0.014	0.005	-0.264	-2.958	0.004

a. Dependent Variable: T3-T4dif
Statistical comparison performed using multiple linear regression test.

5. DISCUSSION

The hypothesis of this retrospective study was that implants placed in sites following ARP would show similar radiographic MBL over time compared to implants placed in non-preserved sites following tooth extraction. The results partially supported the stated hypothesis. In both study groups, progressive MBL occurred throughout the different time points. However, implants in the ARP group exhibited lower average MBL at all measured time points compared to implants placed at non-ARP sites. Although these differences were not statistically significant at later follow-up points, including five years after loading, early-phase outcomes and overall clinical patterns suggest a potential benefit of ARP in maintaining marginal bone stability.

5.1. ARP Characteristics and Techniques

In most ARP-treated cases, grafting was combined with membrane placement and allowed to heal by secondary intention. FDBA was used in the majority of sites (85%). FDBA has been extensively documented for its osteoconductive properties and predictable resorption profile, making it an ideal material for maintaining ridge volume in post-extraction sockets [41, 42]. DFDBA and xenografts were used less frequently in 8.3% and 6.7% of sites, respectively. DFDBA is considered to have some osteoinductive potential because of exposed bone morphogenetic proteins; however, clinical evidence supporting superior outcomes remains limited [43]. Xenografts, such as deproteinized bovine bone, have been described as having slower resorption rates and possible advantages for achieving better long-term socket volume [44, 45].

Regarding barrier membranes, resorbable membranes were utilized in most cases (88.3%). Resorbable membranes, often made of collagen, are typically preferred because they are biocompatible, easy to handle, and eliminate the need for secondary membrane removal surgery [46]. Non-resorbable membranes and collagen matrices, such as Mucograft, were each used in 5% of sites. A collagen sponge was used in one case (1.7%), reflecting its limited adoption and uncertain evidence in ridge preservation. In terms of surgical approach, flap elevation was completed in 73.3% of ARP cases. Flap elevation remains a common practice in regenerative procedures because it provides visibility of the surgical field and accuracy in graft placement; however, it has been associated with increased disruption of the periosteal blood supply, which may impair healing [47]. Alternatively, flapless techniques were used in 26.7% of cases. Flapless approaches have been advocated for preserving soft tissue contours and keratinized mucosa while minimizing postoperative morbidity [48].

Flap repositioning without primary closure was the dominant closure method (88.3%), allowing healing by secondary intention. This method is particularly suitable for use with resorbable membranes and particulate bone grafts, which can integrate with transmucosal exposure [49]. Primary closure was achieved in only 11.7% of cases. Although traditionally regarded as essential for barrier function, recent evidence suggests that complete closure may not be necessary with appropriate material selection and could compromise mucogingival architecture [50]. The mean healing time between ARP and implant placement was 8.7 ± 5.5 months, consistent with recommendations for allowing complete soft and hard tissue maturation, especially when slowly resorbing graft material is used [51].

5.2. MBL at Each Time Point

Implants placed in ARP sites consistently resulted in less MBL at each time point compared to implants placed in spontaneously healed (non-ARP) sites. At the time of implant placement (T1), the ARP group showed almost no detectable marginal bone loss (- 0.07 ± 0.64 mm), whereas the non-ARP group exhibited a positive MBL value of 0.25 ± 0.48 mm. Although statistically significant, this difference is likely attributable to differences in implant placement depth rather than bone remodeling. Implants in the ARP group were likely placed flush with, or slightly below, the crestal bone, accounting for the negative average measurement. In contrast, implants in the non-ARP group tended to exhibit more supracrestal positioning, with an average placement about 0.25 mm above the bone crest. Ridge morphology at the time of placement, since grafted sites generally have more preserved ridge volume and better-defined crestal contours, allowing for sub-crestal or flush placement with greater confidence [19, 52]. Because these measurements reflect placement depth rather than bone loss, they should be interpreted cautiously when evaluating MBL at T1.

Although the difference in MBL between groups was not statistically significant at later time points, the ARP group maintained a consistent trend of lower bone loss. At T2, T3, and T4, MBL values remained lower in the ARP group by approximately 0.2 - 0.3 mm on average. These results are consistent with previous studies, which observed that implants placed in ridge-preserved sites tend to experience more favorable long-term bone stability than those in non-preserved sites, even when differences do not always reach statistical significance [15, 31]. Marconcini et al. [31] examined clinical outcomes for implants placed in ARP and non-ARP (spontaneously healed) sites. After four years of follow-up, the mean MBL was 0.38 ± 0.20 mm in the ARP group compared to 0.68 ± 0.30 mm in the non-ARP group. Although the difference did not reach statistical significance (*P* > 0.05), the trend favored ridge preservation. The authors further noted that implants in the ARP group maintained a more stable soft tissue profile and experienced less vertical resorption, suggesting a potential clinical advantage for long-term peri-implant stability. Barone et al. [15] conducted an RCT comparing implants in ridge-preserved versus non-preserved sites over a three-year follow-up period. The mean MBL for the ARP group was 0.95 ± 0.37 mm, compared to 1.16 ± 0.40 mm in the non-preserved group. Although the difference was not statistically significant (*P* > 0.05), it again demonstrated a trend favoring ridge preservation. Furthermore, the ARP group required fewer simultaneous bone augmentation procedures at the time of implant placement, suggesting that ridge preservation may provide a more consistent implant site condition and potentially improve long-term outcomes.

In contrast, other studies have demonstrated statistically significant differences favoring ridge preservation [20, 21, 53]. Cinquini et al. [53] retrospectively compared MBL changes around implants placed in ridge-preserved versus spontaneously healed sites. After healing, the median MBL was 0.40 mm in the ARP group and 1 mm in the non-preserved group, a difference that reached statistical significance (*P* = 0.032). Their regression model identified ARP as the only statistically significant predictor of MBL, independent of other patient- or prosthesis-related factors.

5.3. MBL Changes Between T1–T3 and T3–T4

The most significant bone loss was recorded during T1–T3, suggesting that most crestal remodeling occurs before prosthetic loading. MBL was slightly greater in the ARP group (−1.13

mm) compared to the non-ARP group (−1.06 mm), although this difference was not statistically significant (*P* = 0.596). This finding is not surprising considering the biologic processes following implant insertion, including surgical trauma, biologic width formation, metallic leakage from the dental implant, or the foreign body reaction evoked by the implant [54]. In our study, a greater proportion of implants (61.7%) were placed using a two-stage protocol, compared to 38.3% with a single-stage approach. This means that the T2 time point (healing abutment connection) was not applicable for implants placed using a one-stage protocol. The timing of healing abutment connection, whether at the time of implant placement or after a healing period, can influence the amount of MBL. This may be explained by the biologic width formation at the time of abutment insertion. As demonstrated by Hermann et al., [55] bone remodeling occurs rapidly during the early healing phase for non-submerged implants and after abutment connection for submerged implants [55]. Another factor contributing to the higher rate of MBL from T1–T3 or T2–T3 may be the abutment connection and disconnection frequency until final prosthesis loading, a phenomenon commonly observed in clinical practice. Studies suggest that immediate connection of the definitive abutment leads to less marginal bone remodeling compared to protocols involving multiple abutment disconnections and reconnections [3, 56]. For instance, Canullo et al. [57] found that placing the definitive abutment at the time of surgery resulted in significantly less bone loss after 12 months compared to repeated disconnection and reconnection. Similarly, Koutouzis et al. [58] reported that implants receiving the final abutment at placement showed MBL of only 0.13 mm at six months, compared to 0.28 mm in implants subjected to two abutment disconnections [58]. A meta-analysis further confirmed that abutment disconnection and reconnection can affect peri-implant MBL by 0.19 mm or greater, with the greatest mean differences observed when the abutment disconnected more than three to four times [59]. Berglundh et al. [12] and Abrahamsson et al. [8] have presented evidence that the peri-implant tissue complex establishes a zone of approximately 2 mm of vertical bone to promote biologic sealing, which may also account for this early resorption phase. Furthermore, poor plaque control, limited patient compliance, or prolonged healing abutment retention before prosthesis delivery may contribute to increased MBL [60].

In the T1–T3 interval, the ARP group demonstrated slightly greater bone loss (–1.13 mm) compared to the non-ARP group (–1.06 mm). Although this difference was not statistically significant, it may also be explained by the delayed timing of implant placement in ARP-treated sites. The average healing time before implant placement in the ARP group was approximately 8.7 months, potentially allowing partial resorption of the graft material. Supporting this, Tan et al. [52] and De Risi et al. [26] reported that delayed implant placement following ARP may lead to increased remodeling and volume reduction. Similarly, Jo et al. [25] observed reduced bone volume in grafted sites with extended healing times.

Moreover, newly formed bone may differ biologically from native bone. Araujo et al. [61] suggested that grafted bone, especially with slowly resorbing materials such as deproteinized bovine bone mineral, may possess distinct remodeling characteristics, contributing to early bone resorption during implant site preparation or the initial healing phase.

Although occlusal stress and overload following prosthesis insertion (T3) have been proposed as potential contributors to MBL, definitive evidence establishing a direct causal relationship remains limited [62]. Bone remodeling slowed markedly in the T3–T4 period, with both groups showing nearly identical levels of bone loss. Specifically, the ARP group had a mean loss of -0.63 ± 0.63 mm, and the non-ARP group had a loss of -0.61 ± 0.52 mm. This finding aligns with the stabilization phase described by Albrektsson et al. [4], who proposed that most MBL occurs within the first year after loading. Galindo-Moreno et al. [7] and Linkevicius et al. [13] also emphasized that tissue thickness and biologic width dynamics influence crestal bone stability. Our data support these findings, suggesting that peri-implant tissues enter a more stable state once functional loading is achieved, although they remain susceptible to age- and load-related remodeling.

5.4. Proportion of Implants with ≥2 mm MBL

Although there is general agreement in the literature regarding a safe range of 1.5 - 2 mm of MBL during the first year after functional loading, wide variation exists in how studies define success. Albrektsson et al. [4] provided criteria that have remained influential, defining success as ≤ 1.5 mm bone loss during the first year, and thereafter ≤ 0.2 mm annually. Similar parameters were established in the ICOI Pisa Consensus [5], where implant success includes < 2 mm bone loss combined with clinical stability without symptoms or pathosis. In a systematic review, Papaspyridakos et al. [6] found that many studies considered MBL greater than 1.5 mm to be outside of the acceptable range for determining implant success.

At T4, representing at least five years and an average of 8.83 ± 2.67 years of functional loading, 40% of implants demonstrated MBL of at least 2 mm. Although no statistically significant differences were found between groups, the non-ARP group showed a higher proportion of implants with ≥2 mm MBL (45%) compared to the ARP group (35%). The clinical implications of this finding become clearer when considering that MBL ≥2 mm typically serves as a threshold for identifying implants at risk of biological complications, including peri-implantitis. Although MBL alone is not diagnostic for peri-implantitis, exceeding this threshold after years of functional loading may suggest biological changes leading to chronic inflammation or bone instability [3, 7]. Recent work from Ko et al. [63] contextualizes these findings. In their preclinical study, they indicated that peri-implantitis progression was not significantly different between ARP and non-ARP sites, even when extraction sockets exhibited inflammation or residual infection. Similarly, Sayardoust et al. [64] found that implants placed in ARP-treated sites using deproteinized bovine bone mineral exhibited comparable marginal bone levels and peri-implantitis rates to implants in non-grafted sites after five years. Importantly, in both studies, patients received regular supportive therapy, allowing a more straightforward interpretation of biological remodeling independent of hygiene factors. Their results suggest that while ARP structurally benefits implant placement, it does not fundamentally alter the long-term biological behavior of peri-implant tissues. Thus, although ARP enhances early bone volume and aids in prosthetically driven implant placement, long-term peri-implant health appears to be more influenced by host response, plaque management, and maintenance rather than by socket grafting alone[63]. This finding sends a clear clinical message that ARP should not be viewed as a sole intervention for preventing peri-implant bone loss; rather, it should be considered part of a broader approach to oral health care that includes patient education, risk management, and maintenance. Ridge preservation clearly enhances dimensional stability in the short term and assists in prosthetically driven implant placement; however, its biological outcomes, such as MBL and peri-implantitis, appear to plateau over time.

Although grafted and non-grafted sites heal differently histologically, evidence suggests that residual graft material does not interfere with bone remodeling or increase the risk of inflammation-related bone loss [65]. Histologic studies showed only minor differences in bone resorption, inflammatory infiltration, and connective tissue composition between groups. Deeper histomorphometry and immunohistochemical analyses revealed comparable inflammatory responses and bone-to-implant contact rates. These findings suggest that ARP does not create a biologically distinct or compromised environment under experimentally induced peri-implantitis [63].

Buonocunto et al. [66] also reported that while the overall prevalence of peri-implantitis across sites treated with ARP was low (8.2%), mandibular sites and compromised extraction sockets were susceptible to disease. This matches our observation, as significant MBL was statistically associated with arch location, primarily in earlier phases of healing. However, unlike their findings, which highlighted mandibular susceptibility, our results showed more MBL in the maxillary arch. Despite these variations, ARP did not create additional biologic complications in either study. This supports the conclusion that ridge preservation does not predispose implants to longer-lasting peri-implant disease, even when sites may have been more anatomically or structurally vulnerable.

Furthermore, Chou et al. [67] investigated implants placed in ARP-treated sites in patients with and without a history of periodontitis. Their results reported no statistically significant difference in peri-implantitis prevalence between these two groups, despite periodontitis being a well-recognized risk indicator for peri-implant disease. The observation that ARP-treated sites did not show an increased disease prevalence, even among higher-risk patients, strengthens the conclusion that ridge preservation procedures do not predispose sites to biologic failure over time. Chou et al.'s findings [67] are also consistent with results from our secondary analysis, which found that a history of periodontitis was not significantly related to MBL outcomes, perhaps due to the high prevalence of periodontitis in our study population compared to T1, which could have masked differences between groups.

A substantial increase in implants exceeding the 2 mm threshold occurred between T3 and T4, suggesting that functional loading, host response, and maintenance factors could play a role in long-term bone loss beyond the influence of surgical techniques [4, 13]. The slightly lower proportion of implants with ≥2 mm MBL in the ARP group supports the idea that ridge preservation may play a modest protective role over time. This is consistent with findings from Marconcini et al. [31], who reported more favorable bone levels in grafted sites, and with Avila-Ortiz et al. [19], whose systematic review showed that ARP can reduce ridge resorption, even if its long-term impact on implant survival and disease progression remains uncertain. Araujo et al. [61] similarly noted that while grafting stabilizes ridge dimensions, grafted sites are subject to biological remodeling after implantation.

5.5. Secondary Analysis

As a secondary analysis, the association of all the patient-related and implant-specific factors with MBL was explored during the two distinct phases: T1–T3 and T3–T4. Variables examined included patient demographics (age, gender, race), systemic health conditions (diabetes, hypertension, hypercholesterolemia), smoking habits, and history of periodontitis. Implant-related factors such as implant location (anterior/posterior, maxilla/mandible), surgical protocol (one-stage vs. two-stage), implant length and diameter, prosthetic retention type (screw- vs. cement-retained), and type of restoration (single unit vs. multi-unit) were also included. Although all of these factors were initially entered into the models, only those displayed in the final tables were statistically significant predictors of MBL in each phase.

5.5.1. Early Phase Predictors (T1-T3)

- **Arch Location**

In our study, maxillary implants showed significantly greater MBL during the early healing phase (T1–T3) compared to mandibular implants. This finding is in agreement with Salvi et al. [30] , who reported that maxillary implant sites display an increased pattern of remodeling due to generally lower bone density and poorer cortical anchorage in the maxilla, potentially compromising initial stability and leading to greater bone remodeling. Other studies have similarly reported that implants placed in the maxilla are more susceptible to early MBL, particularly within the first year after placement [4, 36]. Galindo-Moreno et al. [7] also emphasized that factors such as bone quality, implant placement depth, and crestal positioning can affect marginal bone changes and often differ between the maxilla and mandible. Ko et al. [63] further noted that peri-implant bone stability may be less predictable at maxillary sites, particularly when grafting has been performed or implant placement is delayed.

- **Prosthesis Type**

Patients restored with fixed partial dentures (FPDs) experienced significantly greater MBL during the early healing phase (T1-T3) compared to those restored with single-unit crowns.

Although this might seem unexpected, given that prosthetic loading typically begins at T3, several factors could explain this early difference. One possible reason is that implants planned for FPDs were more often placed in posterior or maxillary regions, where bone tends to be less dense and offers reduced initial stability. These anatomical differences may lead to greater early remodeling, even when ARP has been performed [30, 64].

Additionally, certain aspects of surgical staging for multi-unit restorations may influence early bone response. Wider flap designs [12], the use of taller healing abutments to accommodate soft tissue contours [13], and implant positioning within the available ridge [7] have been associated with early crestal bone remodeling prior to prosthetic loading. Implant depth and its relationship to the alveolar crest can significantly affect marginal bone changes, both of which may vary more in cases planned for FPDs [7]. Taken together, these findings suggest that early marginal bone remodeling may be influenced not only by surgical and anatomical factors but also by the anticipated prosthetic design, even before functional forces are applied.

5.5.2. Late Phase Predictors (T3-T4)

- **Age**

Age was significantly associated with MBL during the late phase (T3–T4), with older patients demonstrating greater bone loss over time. This observation is consistent with Wu et al., [37] who found that age was an important variable affecting implant outcomes. Biologically, impaired regenerative capacity with aging and the potential for more chronic, low-grade inflammation may impair bone remodeling and peri-implant stability. Although our regression model did not find significant associations between MBL and systemic conditions such as diabetes or hypertension, previous studies by Moy et al. [68] and Monje et al. [69] have noted that medically compromised patients show more complications or less predictable osseointegration.

Most patients included in our study had a reported history of periodontitis noted at baseline (T1) and again at the final follow-up (T4), demonstrating long-term exposure to the chronic effects of the disease. It is likely that many of these patients, particularly older individuals, had been managing periodontitis for years. In many cases, this may have involved inconsistent maintenance visits or poor disease control, further increasing their risk for peri-implant bone loss [70]. Periodontitis is known to promote an inflammatory environment, elevate bacterial load, and interfere with normal bone metabolism. These factors can accelerate marginal bone remodeling or contribute to the early development of peri-implant disease [70]. These findings are consistent with previous reports [71, 72] that noted greater MBL and higher rates of peri-implantitis among patients with a history of periodontal disease. Therefore, in addition to careful surgical and prosthetic planning, long-term implant success in this population depends on regular maintenance care, supportive periodontal therapy, and strong patient adherence to oral hygiene routines.

5.6. Subject Level Characteristics

We examined several demographic and systemic factors to evaluate their potential effects on MBL. Although several of these factors did not show statistically significant associations with MBL in the secondary analysis, their distribution among groups may provide valuable insight based on existing literature.

5.6.1. Gender

A statistically significant difference in gender distribution was noted between groups, with males comprising a greater proportion of the non-ARP group (65%) compared to the ARP group (43.3%; $P = 0.038$). Although gender was not significantly associated with MBL in our study population, the unequal distribution may reflect patient demographics, treatment selection, or referral patterns. Some studies suggest that women, particularly when esthetic zone areas are involved, may be more willing to undergo ARP procedures than men. In terms of MBL, Mumcu et al. [73] reported no apparent differences between males and females, whereas Negri et al. [74] proposed that postmenopausal bone changes may increase remodeling in women aged 50–60 years. Our findings did not reveal a gender-based MBL pattern; however, the observed imbalance in group composition should be considered for broader interpretation.

5.6.2. Age

The age distribution was comparable across groups, averaging 59.15 ± 11.12 years. No significant age difference was observed between the ARP group (58.6 ± 10.3 years) and the non-ARP group (59.7 ± 11.9 years) ($P = 0.412$). Additionally, age was significantly associated with late-phase MBL (T3–T4), indicating that older participants experienced more bone loss. This finding aligns with Wu et al. [37], who reported that aging is associated with reduced regenerative capacity and increased susceptibility to inflammation. Although some systematic reviews, such as Bryant et al. [75], did not find a direct impact of age on implant outcomes, they proposed that age might interact with overall health status to affect bone stability.

5.6.3. Systemic Conditions

Regarding systemic conditions, diabetes was present in a significantly greater proportion of non-ARP patients at baseline (16.7% vs. 6.7%; $P = 0.032$); however, this difference was not sustained at T4. Although diabetes was not significantly associated with MBL in our analysis, prior evidence remains mixed. For example, studies have shown that diabetic patients with glycemic control do not experience an increase in peri-implant diseases [76]. Moreover, Moy et al. [68] and Monje et al. [69] demonstrated an increased incidence of complications following implant placement among diabetic patients, particularly those with poorly controlled diabetes and comorbidity issues.

Hypertension and hypercholesterolemia were common in both groups but did not differ significantly and showed no association with MBL. These findings are consistent with current literature, which has not found strong or consistent evidence that these health issues affect peri-implant bone loss or implant health [77].

5.6.4. Smoking

In our sample, only a small number of participants reported smoking, with 2.5% identified as current smokers and 13.3% as former smokers. Considering the small number of smokers, our inability to demonstrate a significant association between smoking and MBL was anticipated. However, our results should not be interpreted as evidence that smoking poses no risk. Extensive literature documents that cigarette smoking is significantly associated with greater MBL and poor implant outcomes [78, 79]. The low prevalence of smokers in our cohort likely limited our ability to detect such an effect. Nonetheless, from a clinical perspective, smoking continues to represent a significant risk factor for impaired healing and long-term peri-implant complications, and practitioners should exercise caution when treating implant patients with a known history of tobacco use [70].

5.6.5. History of Periodontitis

One notable finding in our population was the high prevalence of periodontitis, with 77.5% of patients affected at T1 and 84.2% at T4. No significant differences were observed between the ARP and non-ARP groups. Although our secondary analysis did not show a statistically significant association between history of periodontitis and MBL, this may be due to the high baseline prevalence across the study population. The literature strongly supports the role of periodontal history as a risk factor for peri-implant bone loss and peri-implantitis [71, 72, 80], emphasizing the need for implant procedures to include maintenance protocols tailored to patients with periodontal conditions.

5.7. Implant Level Characteristics

This section reviews the distribution of implant-level characteristics between groups to provide context and insight based on relevant literature. Although some of these variables were discussed earlier as potential predictors of MBL, this section highlights their distribution patterns between the two groups.

5.7.1. Arch Location

Sixty-six implants (55%) were placed in the maxilla and 54 (45%) in the mandible, with no significant difference in distribution between the ARP and non-ARP groups ($P = 0.712$).

The maxilla often presents a more complicated site for implant placement due to its unique anatomy. These anatomic features include lower bone mineral density, larger proportions of trabecular bone, and greater porosity compared to the mandible, all of which decrease primary stability and subsequently increase the risk of early MBL [5, 81]. In addition, the cortical plates of the maxilla are typically thinner, which may compromise implant anchorage and increase the potential for early bone remodeling [82]. These features may partially explain our finding that implants in the maxilla were associated with significantly greater MBL during the early healing period (T1–T3). Previous studies have also indicated higher complication and failure rates for implants placed in the maxilla, particularly in posterior sites, compared to the mandible [83, 84].

5.7.2. Implant Location (Anterior vs. Posterior)

Anterior implants made up 40% of the sample, with a higher proportion in the ARP group (23.35%) compared to the non-ARP group (16.65%) ($P = 0.056$). Although MBL did not differ significantly between anterior and posterior sites, anatomical and esthetic demands in anterior regions may influence grafting decisions, implant depth, and long-term stability [85].

5.7.3. Implant Placement Protocol (One- vs. Two-Stage)

The ARP group had more two-stage procedures (66.7%) compared to the non-ARP group (56.7%; $P = 0.048$). This may reflect a preference for more conservative healing in grafted sites. Although surgical staging was not directly associated with MBL in our secondary analysis, it is known to influence tissue response and early bone remodeling, especially in complex cases [86].

5.7.4. Implant Dimensions (Diameter and Length)

Implants were evenly distributed based on diameter; 52.5% of had a diameter of less than 5 mm, and 47.5% were 5 mm or greater. Regarding implant length, most implants (74.2%) were 10 mm or less. Although no notable differences in implant diameter were observed between groups, it is crucial to consider the influence of implant size. Within a standard diameter range (≥4.0 mm), factors such as bone quality [87], implant-to-bone contact [88], and stress distribution at the crestal level may influence the behavior of MBL [89]. Although all implants used in this study were appropriately sized, selecting implants based on the anatomic site and anticipated prosthetic loads remains important for minimizing MBL and ensuring long-term stability [89].

5.7.5. Screw vs. Cement-Retained Prostheses

Screw-retained prostheses were used more frequently (61.7%) compared to cement-retained restorations (38.3%), with no significant differences between groups ($P = 0.598$). Although cement-retained prostheses have been linked to a higher risk of peri-implant disease due to residual subgingival cement [90], our study did not find an association between the type of prosthesis retention and MBL.

5.7.6. Prosthesis Type (Crown vs. FPD)

Single-unit crowns were significantly more common in the ARP group (43.3%), whereas FPDs were more frequent in the non-ARP group (15% vs. 4.2%; $P = 0.039$). The difference in restoration type may reflect the clinical context in which ARP is typically performed on future single-tooth replacements, particularly in anterior or esthetic zones [19, 52]. Conversely, the greater frequency of FPDs in non-ARP sites may be associated with more complex edentulous spans, or posterior segments where esthetics are less of a concern and multi-unit restorations are more practical.

5.8. Strengths

A significant strength of this study was its relatively large sample size, which provided adequate statistical power to detect differences in MBL. Access to a comprehensive electronic health record with detailed subject-level and implant-level data allowed for the examination of various clinical, surgical, and prosthetic factors in conjunction with MBL, leading to a better overall understanding of the many factors influencing MBL. Although not all these factors were thoroughly addressed in the current study, the available data offer a basis for future research and hypothesis generation. Further studies could explore additional factors to enhance our understanding of long-term implant success.

Another notable strength is the long follow-up period; the average time between prosthesis insertion (T3) and final evaluation (T4) was 8.83 ± 2.67 years. Studies with similar or extended follow-up durations are uncommon in the literature, making our findings more meaningful. This follow-up allowed us to examine both the initial stages of bone remodeling and the subsequent phases of bone stability, as well as detect excessive MBL that may arise years after implant loading. Short-term studies might not capture these delayed changes or might overlook patient-related factors over time. By monitoring implants over a more extended period and under real-life conditions, we provided an accurate account of peri-implant bone behavior over time, offering meaningful insights to expand existing knowledge on long-term implant health.

5.9. Limitations

This study also has several limitations that should be acknowledged. Radiographic assessment was based on periapical radiographs, which may vary due to angulation and distortion, particularly in the anterior maxilla. Although MBL values were calibrated using the known length of the implant to minimize distortion effects, the lack of standardized radiographic protocols may have introduced some variability in measurements. If peri-apical radiographs were unavailable, bitewing radiographs were used instead. In those cases, distortion was adjusted based on the known distance between at least three implant threads, following established methods [40]. We could argue that bitewing radiographs might actually offer clearer visualization of the crestal bone. Bitewing radiographs have been shown in periodontal literature to provide better reproducibility and diagnostic accuracy for detecting interproximal bone levels, and their application in implant research may offer similar advantages when used appropriately.

Although we analyzed a variety of patient and implant-related factors, including age, gender, systemic health, surgical protocol, and prosthetic design, the inclusion of numerous covariates may have diminished the ability to identify statistically significant associations. Retrospective studies are helpful in identifying trends; however, they cannot determine causality. Moreover, some patient-level data, such as smoking status and periodontitis history, were sourced from existing records and may be subject to reporting bias. For example, smoking status may be underreported by patients, particularly in institutional settings. Similarly, although periodontitis was documented, inconsistencies may exist in recording the disease's severity and treatment history.

It is important to acknowledge that all surgical and restorative procedures in this study were performed by postgraduate residents with varying levels of training. Although all cases were supervised by faculty, and residents likely received the same education, differences in clinical experience, such as the number of surgeries performed, the duration of surgeries, and techniques, could have influenced outcomes during the crucial early healing phase. Extended surgical times or prolonged flap elevation may unintentionally affect peri-implant healing. As a result, this study's findings may not fully represent outcomes in private practice settings, where procedures are often performed under more standardized conditions.

Finally, although the long follow-up period is a strength of the study, the length of follow-up was not identical for all implants. These slight differences in follow-up duration may have influenced the detection of MBL progression in some instances. Despite these challenges, our findings contribute valuable insights into the behavior of marginal bone in clinical situations and hopefully will influence future work to enhance evidence-based protocols for implant therapy, improving long-term results.

CONCLUSIONS

1. Implants placed in ARP sites consistently demonstrate lower average MBL at every measured time point compared to implants in non-preserved sites. Although not statistically significant at long-term follow-up, the trend suggests that ARP may improve early peri-implant bone preservation.
2. In both groups, the most substantial MBL occurred between implant placement and prosthesis delivery (T1–T3), reflecting biological responses such as surgical trauma, abutment manipulation, and the establishment of the peri-implant seal.
3. A higher proportion of implants in the ARP group remained below the 2 mm MBL threshold during long-term follow-up (T4), indicating a possible modest protective effect of ARP against excessive bone loss over time.
4. Arch location and prosthesis design were significantly associated with early bone remodeling. Maxillary implants and multi-unit restorations (FPDs) exhibited greater MBL between T1 and T3, likely due to biomechanical and anatomical differences.
5. Age was the only variable significantly associated with late-phase bone loss (T3–T4), with older patients exhibiting more MBL, possibly due to reduced regenerative capacity and increased susceptibility to inflammation.
6. Despite histologic differences between ARP and non-ARP sites, long-term bone stability was similar, indicating that residual graft particles do not interfere with remodeling or increase the risk of progressing MBL when patients are well-maintained.

APPENDIX A

Table 1 – Details of studies comparing MBL and survival between implants placed in sites following ARP with non-preserved sites following tooth extraction.

Authors and year	Study design	Number of subjects by groups	Group details	Ridge healing time	Maximum implant follow-up time post-loading	Mean MBL in mm	Implant survival
Marconcini et al. 2018 [31]	RCT Multi-arm	42 subjects for a total of 42 sockets Divided into three groups: - Control: n = 13 - Test 1: n = 15 - Test 2: n = 14	- Test 1: Xenograft (Collagenated cortico- cancellous porcine bone) - Test 2: Xenograft (cortical porcine bone) Both sockets sealed with resorbable collagen membrane for both groups	3 months	4 years	For the follow-up time of 4 years: - Control: 1.92 mm - Test 1: 1.13 mm - Test 2: 1.14 mm	100% for all groups
Cardaropoli et al. 2015 [32]	RCT Parallel arms	41 subjects for a total of 48 sockets Divided into two groups: - Control: n = 24 - Test: n = 24	- Test: Xenograft (Bovine bone particles) Socket sealed with resorbable collagen membrane	4 months	1 year	For the follow-up time of 1 year: - Control: 0.35 mm - Test: 0.33 mm	100% for both groups
Barone et al. 2012 [15]	RCT Parallel arms	40 subjects for a total of 40 sockets Divided into two groups: - Control: n = 20 - Test: n = 20	- Test: Xenograft (Cortico-cancellous porcine bone particles) Socket sealed with resorbable collagen membrane	4 months	3 years	For the follow-up time of 3 years: - Control: 1.02 mm - Test: 1.00 mm	95% for both groups
Patel et al. 2012 [33]	RCT Parallel arms	27 subjects for a total of 27 sockets Divided into two groups: - Control: n = 13 - Test: n = 14	- Control: synthetic bone substitute - Test: Xenograft (Bovine bone particles) Both sockets sealed with resorbable collagen membrane	8 months	1 year	For the follow-up time of 1 year: - Control: -- Mesial: 0.12 mm -- Distal: 0.35 mm - Test:	100% for both groups

						-- Mesial: 0.20 mm -- Distal: 0.13 mm	
Tabrizi et al. 2019 [34]	Prospective cohort	90 subjects for a total of 90 sockets - Group 1: n = 30 - Group 2: n = 30 - Group 3: n = 30	- Group 1: Control - Group 2: Control - Group 3: Xenograft (Bovine bone particles) Socket sealed with resorbable collagen membrane	- Group 1: 8 weeks - Group 2: 6 months - Group 3: 6 months	3 years	For the follow-up time of 3 years: - Group 1: 0.57 mm - Group 2: 0.52 mm - Group 3: 0.58 mm	N/A
Zhao et al. 2022 [35]	Prospective cohort	26 subjects for a total of 30 sockets Divided into two groups: - Control: n = 14 - Test: n = 16	- Test: Xenograft (Bovine bone particles) Socket sealed with resorbable collagen membrane	6 months	3 years	For the follow-up time of 3 years: - Control: 0.47 mm - Test: 0.12 mm	100% for both groups
Koutouzis and Lundgren 2010 [36]	Retrospect-ive record review	60 subjects for a total of 60 sockets Divided into two groups: - Control: n = 30 - Test: n = 30	- Test: Allograft (DFDBA) Socket sealed with resorbable collagen membrane	4 months	33 months	For the follow-up time of 1 year: - Control: 0.15 mm - Test: 0.15 mm	100% for both groups
Wu et al. 2019 [37]	Retrospect-ive record review	129 subjects for a total of 222 implants Divided into two groups: - Control: n = 117 - Test: n = 105	- Test: Xenograft (Bovine bone particles) Socket sealed with non-resorbable d-PTFE membrane	N/A	N/A	N/A	98.24% for the control 97.14% for the test
Apostolopoulos and Darby 2016 [38]	Retrospect-ive record review	42 subjects for a total of 51 implants	N/A	N/A	N/A	N/A	100%

Table 2 – Overall subject-level descriptive statistics

Co-variants	Total		No ARP		ARP		*P*-value
	Frequency (n)	Percent (%)	Frequency (n)	Percent (%)	Frequency (n)	Percent (%)	
Age (mean ±SD)	59.15±11.12		59.7 ±11.91		58.6±10.33		0.412
Gender:							
Male	65	54.2	39	32.5	26	21.7	0.038*
Female	55	45.8	21	17.5	34	28.3	
Race:							
Not Reported	79	65.8	35	29.15	44	36.65	0.045*
White	33	27.5	22	18.35	11	9.15	
Black	3	2.5	1	0.85	2	1.65	
Asian	5	4.2	2	1.7	3	2.5	
Medical History at Baseline (T1):							
Diabetes	14	11.7	10	8.35	4	3.35	0.032*
Hypertension	41	34.2	19	15.85	22	18.35	0.601
Hypercholesterolemia	33	27.5	18	15.0	15	12.5	0.512
Medical History at Final Follow-up (T4):							
Diabetes	20	16.7	12	10.0	8	6.7	0.402
Hypertension	52	43.3	23	19.2	29	24.1	0.098
Hypercholesterolemia	52	43.3	22	18.3	30	25.0	0.091
Smoking Status:							
Current smokers	3	2.5	1	0.83	2	1.67	0.712
Former smokers	16	13.3	8	6.65	8	6.65	
Non-smokers	101	84.2	51	42.5	50	41.7	
History of Periodontitis:							
At T1	93	77.5	47	39.2	46	38.3	0.819
At T4	101	84.2	50	41.7	51	42.5	0.921

Statistical comparison performed using Chi-square test. * *P*-value < 0.05. ARP: Alveolar Ridge Preservation.

Table 3 – Overall implant-level descriptive statistics

Co-variants	Total		No ARP		ARP		*P*-value
	Frequency (n)	Percent (%)	Frequency (n)	Percent (%)	Frequency (n)	Percent (%)	
Arch Location:							
Maxilla	66	55.0	34	28.35	32	26.65	0.712
Mandible	54	45.0	26	21.65	28	23.35	
Implant Location:							
Anterior	48	40.0	20	16.65	28	23.35	0.056
Posterior	72	60.0	40	33.35	32	26.65	
Implant Stage:							
One-stage placement	46	38.3	26	21.65	20	16.65	0.048*
Two-stage placement	74	61.7	34	28.35	40	33.35	
Implant Diameter:							
< 5.0 mm	63	52.5	31	25.85	32	26.65	-
≥ 5.0 mm	57	47.5	29	24.15	28	23.35	
Implant Length:							
≤ 10.0 mm	89	74.2	41	34.2	48	40	-
> 10.0 mm	31	25.8	19	15.8	12	10	
Prosthesis:							
Screw-retained	74	61.7	36	30	38	31.7	0.598
Cement-retained	46	38.3	24	20	22	18.3	
Prosthesis Type:							
Crown	94	78.3	42	35	52	43.3	0.039*
Fixed Partial Denture (FPD)	23	19.2	18	15	5	4.2	
Cantilever Crown	3	2.5	-		3	2.5	

Statistical comparison performed using Chi-square test. * *P*-value < 0.05. ARP: Alveolar Ridge Preservation.

Table 4 – Materials and surgical characteristics of ARP

Variables		Frequency (n)	Percent (%)
Type of Graft	Allograft FDBA	51	85.0
	Allograft DFDBA	5	8.3
	Xenograft	4	6.7
Type of Membrane	Resorbable	53	88.3
	Non-resorbable	3	5.0
	Collagen matrix	3	5.0
	Collagen sponge	1	1.7
Technique of ARP	Flap	44	73.3
	Flapless	16	26.7
Closure/ Healing	Primary closure	7	11.7
	Flap repositioning	53	88.3
Healing time between ARP and implant placement (mean ±SD)		8.70 months	SD ± 5.521

FDBA: Freeze-Dried Bone Allograft. DFDBA: Demineralized Freeze-Dried Bone Allograft. ARP: Alveolar Ridge Preservation.

Table 5 – Mesial, distal, and average MBL at all time points (T1, T2, T3, and T4)

Time Point	Total			No ARP			ARP		
	Mesial MBL	Distal MBL	Average MBL	Mesial MBL	Distal MBL	Average MBL	Mesial MBL	Distal MBL	Average MBL
Implant Placement (T1)	0.19 ± 0.65*	0.19 ± 0.65*	0.09 ± 0.59*	0.36 ± 0.59	0.36 ± 0.59	0.25 ± 0.48	0.02 ± 0.68	0.02 ± 0.68	-0.07 ± 0.64
Second Stage (T2)	0.57 ± 0.64	0.73 ± 0.74*	0.65 ± 0.63	0.69 ± 0.72	0.93 ± 0.73	0.81 ± 0.64	0.46 ± 0.54	0.54 ± 0.71	0.50 ± 0.59
Prosthesis Insertion (T3)	1.12 ± 0.75*	1.25 ± 0.79	1.19 ± 0.72	1.26 ± 0.72	1.36 ± 0.79	1.31 ± 0.70	0.98 ± 0.75	1.15 ± 0.79	1.06 ± 0.74
Final Follow-Up (T4)	1.75 ± 0.87*	1.87 ± 1.01	1.81 ± 0.90	1.91 ± 0.81	1.93 ± 0.90	1.92 ± 0.80	1.58 ± 0.91	1.81 ± 1.11	1.70 ± 0.98

Data are presented as mean ± standard deviation. Statistical comparison performed using independent t-test. * *P*-value < 0.05 between ARP and No ARP. ARP: Alveolar Ridge Preservation.

Table 6 – Number of implants with MBL ≥ 2 mm in No ARP and ARP groups at each time point

Time Point	Total		No ARP		ARP		*P*-value
	Frequency (n)	Percent (%)	Frequency (n)	Percent (%)	Frequency (n)	Percent (%)	
Implant Placement (T1)	2	1.7	1	1.7	1	1.7	0.499
Second Stage (T2)	3	2.5	2	3.3	1	1.7	0.271
Prosthesis Insertion (T3)	23	19.2	14	23.3	9	15.0	0.256
Final Follow-Up (T4)	48	40.0	27	45.0	21	35.0	0.190

Statistical comparison performed using Chi-square or Fisher's exact test. **P*-value < 0.05. ARP: Alveolar Ridge Preservation.

Table 7 – MBL Changes Between T1-T3 and T3-T4

Time Point	Total	No ARP	ARP	*P*-value
Implant Placement (T1) - Prosthesis Insertion (T3)	-1.09±0.61	-1.06±0.60	-1.13±0.62	0.596
Prosthesis Insertion (T3) - Final Follow-Up (T4)	-0.62±0.58	-0.61±0.52	-0.63±0.63	0.842

Data are presented as mean ± standard deviation. Statistical comparison performed using paired t-test. **P*-value < 0.05. ARP: Alveolar Ridge Preservation.

Table 8 - Multivariable linear regression analysis showing the factors that contributed to MBL from T1 to T3

	Unstandardized Coefficients		Standardized Coefficients		
Model	B	Beta	Beta	t	Sig.
(Constant)	-1.103	0.095		-11.612	<.001
Group	-0.111	0.107	-0.092	-1.042	0.300
Arch	0.281	0.107	0.232	2.637	0.010
Crown vs FPD	-0.275	0.110	-0.220	-2.486	0.014

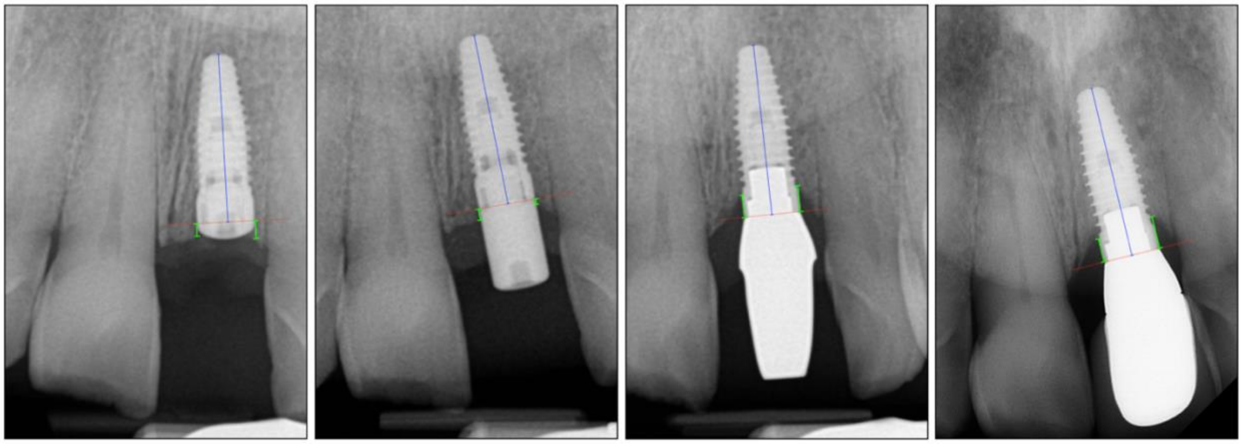
a. Dependent Variable: T1-T3dif
Statistical comparison performed using multiple linear regression test.

Table 9 - Multivariable linear regression analysis showing the factors that contributed to MBL from T3 to T4

	Unstandardized Coefficients		Standardized Coefficients		
Model	B	Beta	Beta	t	Sig.
(Constant)	0.208	0.286		0.726	0.469
Group	-0.036	0.103	-0.032	-0.353	0.725
Age	-0.014	0.005	-0.264	-2.958	0.004

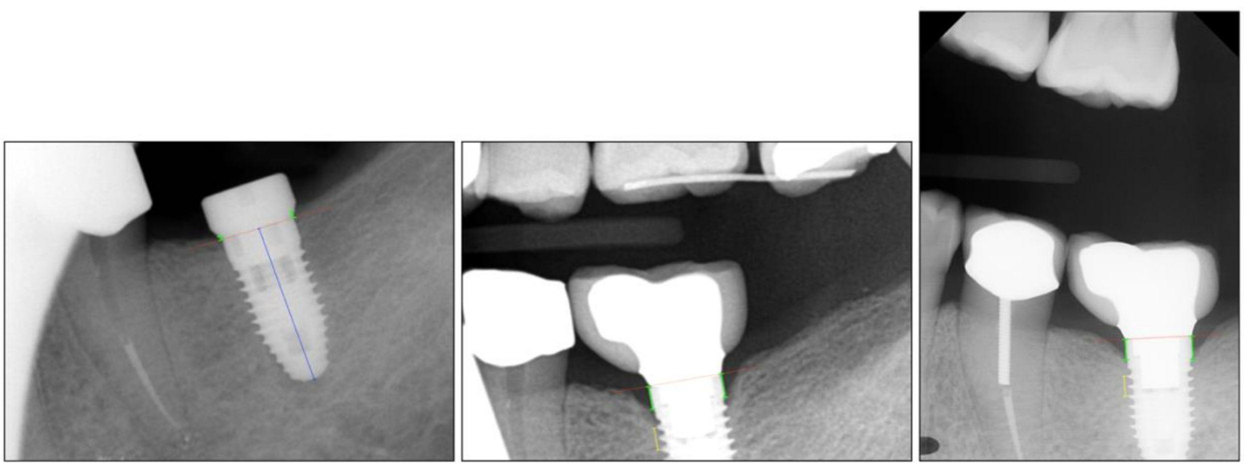
a. Dependent Variable: T3-T4dif
Statistical comparison performed using multiple linear regression test.

APPENDIX B



T1 -Implant placement T2 -Abutment connection T3 - Crown insertion T4 - Nine years after crown insertion

Figure 1 – <u>Measurements recorded for dental implants on peri-apical radiographs.</u>
Red: Implant shoulder. Blue: Known length of the implant for peri-apical calibration.
Green: Mesial and distal linear measurements from the implant shoulder to the first bone-to-implant contact.



T1 -Implant placement T3 - Crown insertion T4 - Six years after crown insertion

Figure 2 – <u>Measurements recorded for dental implants on peri-apical radiograph and, when applicable, bitewing radiographs.</u>
Red: Implant shoulder. Blue: Known length of the implant for peri-apical calibration.
Yellow: Known distance between implant threads for bitewing calibration. Green: Mesial and distal linear measurements from the implant shoulder to the first bone-to-implant contact.

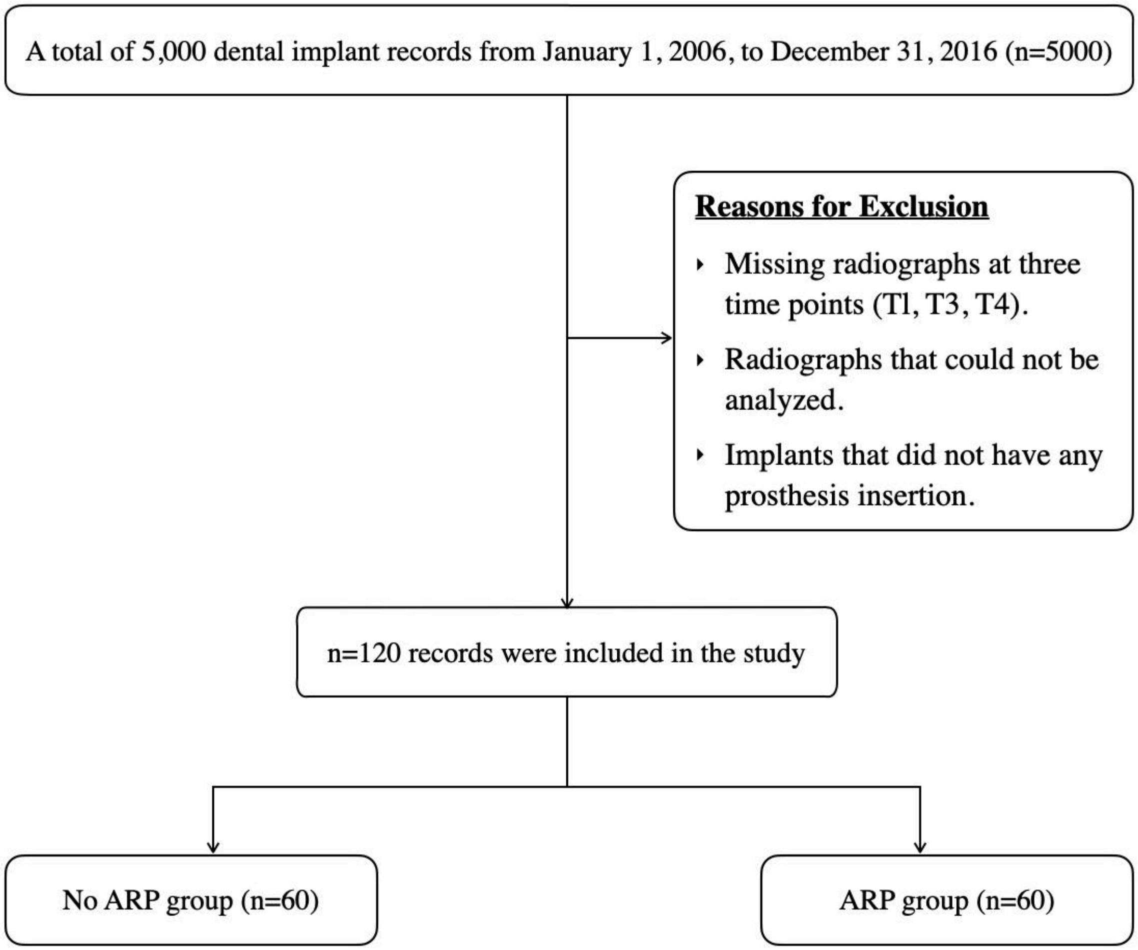


Figure 3 – Flow chart demonstrating the screening process

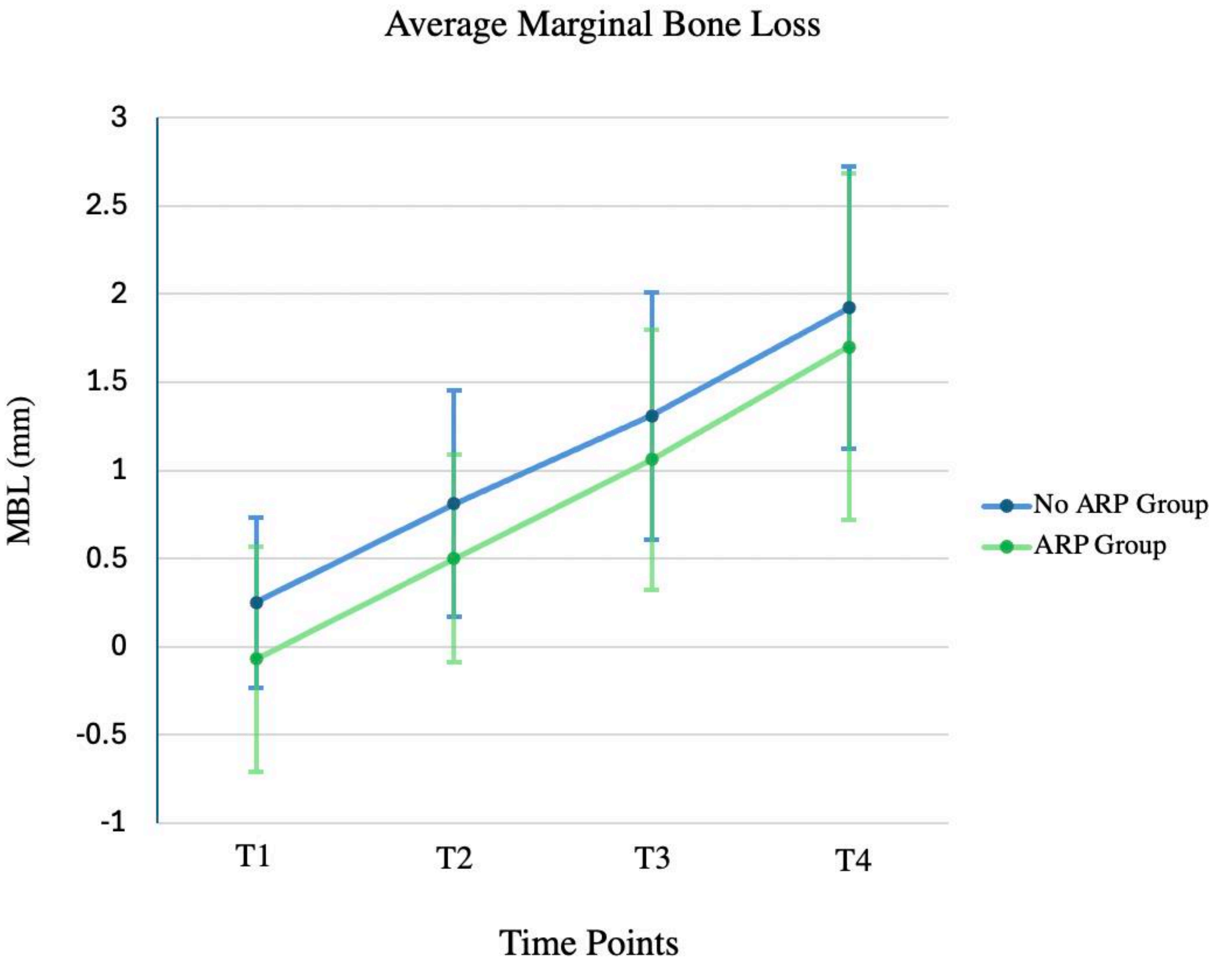


Figure 4 – Mean MBL ± SD of No ARP and ARP groups from T1 to T4

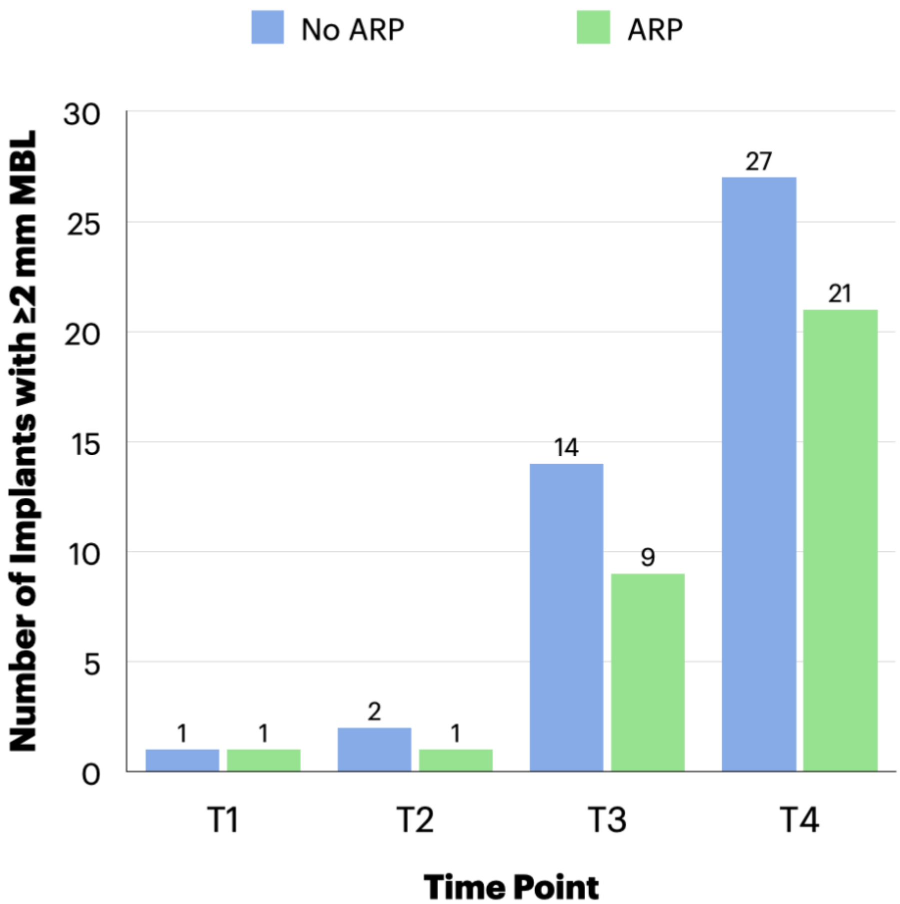


Figure 5 – Number of implants with MBL ≥ 2 mm in No ARP and ARP groups at each time point

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