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Combined Effect of Abutment Height and Restoration Emergence Angle on Peri-Implant Bone Loss Progression: A Retrospective Analysis

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ABSTRACT

Introduction: This study aimed to investigate the combined effect of trans-mucosal abutment height (TmAH) and restorative emergence angle (REA) on marginal bone loss (MBL) around bone-level implants.

Methods: Implant radiographs 12–18 months after crown placement (T0) and at least one year later (T1) were retrospectively analyzed. Sites were separated into four groups: Long/Narrow-Angle (LN) with TmAH ≥ 2 mm and REA $< 30°$, Long/Wide-Angle (LW) with TmAH ≥ 2 mm and REA $\geq 30°$, Short/Narrow-Angle (SN) with TmAH < 2 mm and REA $< 30°$, and Short/Wide-Angle (SW) with TmAH < 2 mm and REA $\geq 30°$. MBL was calculated, and multiple linear regression analysis was performed to control for patient-level and implant/prosthesis-level factors.

Results: 192 implants pertaining to 119 patients were included. Group significantly influenced MBL experience ($p < 0.001$). Group SW experienced on average 0.48 mm (95% CI: 0.25–0.71, $p < 0.001$), 0.43 mm (95% CI: 0.18–0.68, $p = 0.001$), and 0.25 mm (95% CI: 0.00–0.45, $p = 0.013$) greater MBL compared to Groups LN, LW, and SN, respectively. Group was also a significant factor impacting the development of peri-implantitis ($p = 0.041$), with Group SW displaying a roughly 4× greater likelihood of having peri-implantitis (PI) diagnosed compared to Groups LN (OR: 4.04; $p = 0.091$) and LW (OR: 4.19; $p = 0.013$). Every 1 mm increase in TmAH significantly decreased the likelihood of MBL > 0 mm (OR = 0.63; $p = 0.003$).

Conclusions: Abutment height $\geq$ 2 mm may play a role in reducing PI and MBL related to $\geq 30°$ REA around bone-level implants. REA was found to only be a significant factor when TmAH is less than 2 mm.

1 | Introduction

Establishing a stable peri-implant crestal bone level is a requirement to ensure the long-term success of dental implants (Misch et al. 2008). Crestal bone remodeling, which occurs following implant surface exposure to the oral environment, is recognized as a physiological rather than pathological process (Lang et al. 2011; Schwarz et al. 2018; Albrektsson et al. 1986). The formation of a biologic seal between soft tissues and implant components, known as the supracrestal tissue height (Avila-Ortiz et al. 2020) or supracrestal tissue adhesion (STAd) (Saleh et al. 2022; Misch, Monje, and Wang 2022), can be accompanied by marginal bone loss (MBL). This process is distinct from peri-implantitis, an otherwise pathological condition causing progressive bone loss (Schwarz et al. 2018).

Investigations into the factors that influence bone loss around dental implants have identified a significant impact from the height of the prosthetic abutment. When Galindo-Moreno et al. (2014) reported this in 2014, they noted that the abutment height (TmAH) was the variable with the most influence on the marginal bone loss at both 6 and 18 months [post-loading], with a TmAH of > 2 mm resulting in significantly less bone loss. Several clinical studies and randomized control trials have since supported the necessity of selecting an appropriate TmAH to accommodate the crown margin while providing sufficient space for STAd formation (Galindo-Moreno et al. 2014, 2022; Lee et al. 2018; Blanco et al. 2018; Spinato et al. 2019; Pico et al. 2019; De Siqueira et al. 2020; Borges et al. 2021). While a recent study argued that the vertical mucosal thickness can be a protective factor against a shorter abutment (Linkevicius et al. 2022), the majority of randomized control trials that have controlled for this factor and measured vertical tissue thickness before implant placement have reported that the establishment of STAd is influenced by TmAH regardless of vertical mucosal thickness (Blanco et al. 2018; Spinato et al. 2019; Muñoz et al. 2021).

Although initial bone loss is physiologically driven, its rate of progression has been identified as a significant predictor of peri-implantitis development (Galindo-Moreno et al. 2015; Windael et al. 2021) since excessive physiological remodeling may lead to the exposure of the implant's roughened surface and threads (Ravidà et al. 2021), facilitating plaque accumulation (Teughels et al. 2006; Berglundh et al. 2007; Carcuac et al. 2013).

Prosthetic factors, such as a restoration emergence angle (REA) of > 30°, have been recognized as risk factors for peri-implantitis due to their plaque-retentive nature (Katafuchi et al. 2018; Yi et al. 2020; Majzoub et al. 2021). A study by Katafuchi et al. (2018) reported a 2× greater prevalence of peri-implantitis for bone-level implants restored with emergence angles of > 30° than ≤ 30 degrees (Katafuchi et al. 2018); however, there is limited evidence that sugguests tissue-level implants may not be affected by the same correlation (Katafuchi et al. 2018; Yi et al. 2020).

The critical role of abutment height in peri-implant tissue response to restoration emergence angles necessitates further investigation. Apico-coronal implant platform positioning determines the space available for abutment height and influences crown emergence angle. Shallow placement requires shorter abutments and excessive crown emergence, while deeper placement allows for longer abutments and more gradual crown emergence. Considering both prosthetic factors is essential to determine whether the crown emergence or the use of a short abutment impacts disease onset.

Consequently, this study aims to investigate the impact of abutment height on peri-implant bone response to various restoration emergence angles around bone-level implants. By examining this relationship, we seek to provide valuable insights into the prosthetic factors influencing peri-implant bone level and contribute to the optimization of long-term implant stability.

2 | Methods

This retrospective radiographic study was conducted in alignment with the ethical standards of the Declaration of Helsinki and adhered to local and international regulations concerning the use of human subjects in research. Given its retrospective nature, this study utilized existing data that was anonymized and handled in compliance with the principles of confidentiality and privacy. This study was approved by the University of Michigan, School of Dentistry, Institutional Review Board for Human Studies (HUM00223052), which confirmed that all procedures performed in the study were in accordance with ethical standards.

In the present retrospective analysis, all patients treated with bone-level implants placed and restored at the University of Michigan Periodontics, Oral Surgery, and Prosthodontics dental clinics between January 2012 and December 2020 were screened for inclusion.

2.1 | Inclusion Criteria

- Partially edentulous patients receiving one or more bone-level implants.
- Presence of periapical radiographs (with a full view of the implant and crown being evaluated) taken at crown placement, between 12–18 months after crown placement (T0), and at least a one-year follow-up after T0 (T1).
- Implant characteristics related to implant length are available in-patient chart (for radiograph measurement calibration).
- Patient undergoing maintenance at the University of Michigan School of Dentistry.
- Presence of patient-related information on the presence of diabetes, smoking habits, and history of periodontitis.
- Presence of opposing dentition.

2.2 | Exclusion Criteria

- Implants placed/restored outside the University of Michigan.
- Full arch restorations.
- A portion of the implant/abutment/crown not visible in either T0 or T1 radiographs.
- Non-diagnostic/blurry/poorly angulated radiographs.
- Implants or patients with missing data related to implant brand/characteristics/fixture type/medical history/smoking status.
- Implant level-fixtures.

- Implants that had undergone reconstructive treatments for peri-implantitis.
- Tissue-level implants.

2.3 | Data Collection and Grouping

Four examiners screened and evaluated the physical and digital records that fell under the predetermined eligibility criteria (JM, SA, DL, OM). As part of the data collection process, relevant patient information was collected, including age (at the time of implant placement), gender, smoking status, diabetes (validated via the patient's medical records), number of maintenance visits, and history of periodontal disease. A positive history of periodontitis was assigned to patients who met the criteria for moderate (≥2 interproximal sites with attachment loss (AL) ≥4mm [not on the same tooth], or >2 interproximal sites with PD >5mm [not on the same tooth]) or severe (≥2 interproximal sites with AL >6mm [not on the same tooth] and >1 interproximal site with PD >5mm) disease according to the CDC-AAP case definitions (Eke et al. 2012) based on each patient's documented periodontal charts. Implant related data including the implant site, jaw, implant characteristics (length, diameter, connection type), type of crown retention (cement or screw retention), and splinted/non-splinted were also collected. Survival rate was calculated from the date of implant placement to last date seen in clinic. Finally, implant failure was defined as a removed, lost, mobile, or fractured implant (Chrcanovic, Albrektsson, and Wennerberg 2014).

2.4 | Peri-Implant Marginal Bone Loss, Peri-Implantitis, and Grouping

One calibrated examiner (JM) performed all measurements related to peri-implant MBL and prosthetic characteristics, including REA and TmAH. The examiner involved in performing radiographic analysis was calibrated in identifying alveolar bone levels (on both mesial and distal aspects of bone level implants) on digital images and trained to identify the crown-abutment margin and the position of the alveolar crest in relation to the implant platform (Pecoraro et al. 2005). The examiner was consistent in his inclusion of radiographs with clearly visible threads and absence of notable horizontal or vertical beam angulation. All measurements were performed using the MiPACS plugin (Medicore Imaging, Nashville, TN, USA) built on axiUm software (Henry Shien Inc., Melveille, NY, USA). The implant length listed in the patient's chart was used to calibrate measurements. Marginal bone levels were measured at two time points (12-18 months after crown placement (T0), and >1year following the T0 radiograph (T1)) on both mesial and distal aspects of the implant. MBL was calculated by taking the difference of these two measurements. MBL measurements were repeated 2 times, at least 30days apart, by the same examiner blinded to previous measurements to calculate the intra-class correlation coefficient. In the few cases that presented with a difference of >0.5mm between the first and second measurements, a final decision was taken after discussion with a second examiner (AR). Positive MBL calculations were assumed to be due to radiographic error, and these measurements were adjusted to reflect no MBL.

The definition of peri-implantitis (PI) proposed by the 2017 World Workshop on the Classification of Periodontal and Peri-Implant Diseases and Conditions is that PI is diagnosed when there is progressive bone loss >0.5mm, deepening probing depth (PD) in conjunction with clinical notes of inflammation related to bleeding on probing or suppuration (Berglundh et al. 2018) was used to classify implants into positive or negative for PI.

REA and TmAH were measured on the mesial and distal sides of each implant as shown in Figure 1.

Included cases were separated into four study groups based upon the radiographically measured TmAH and REA. Mesial

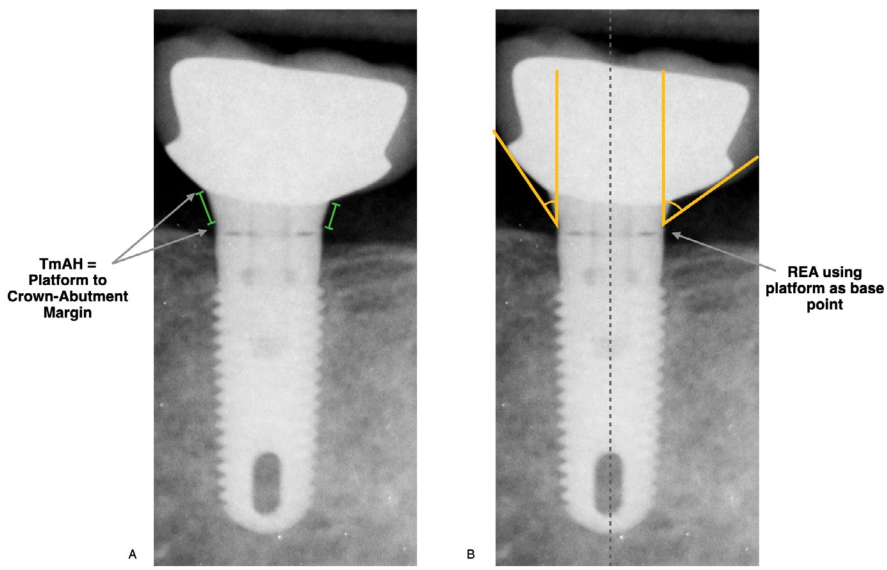

FIGURE 1 | Example of the assessment of transmucosal abutment height (TmAH) and restorative emergence angle (REA): (A) an example of the assessment of TmAH; (B) an example of the assessment of REA.

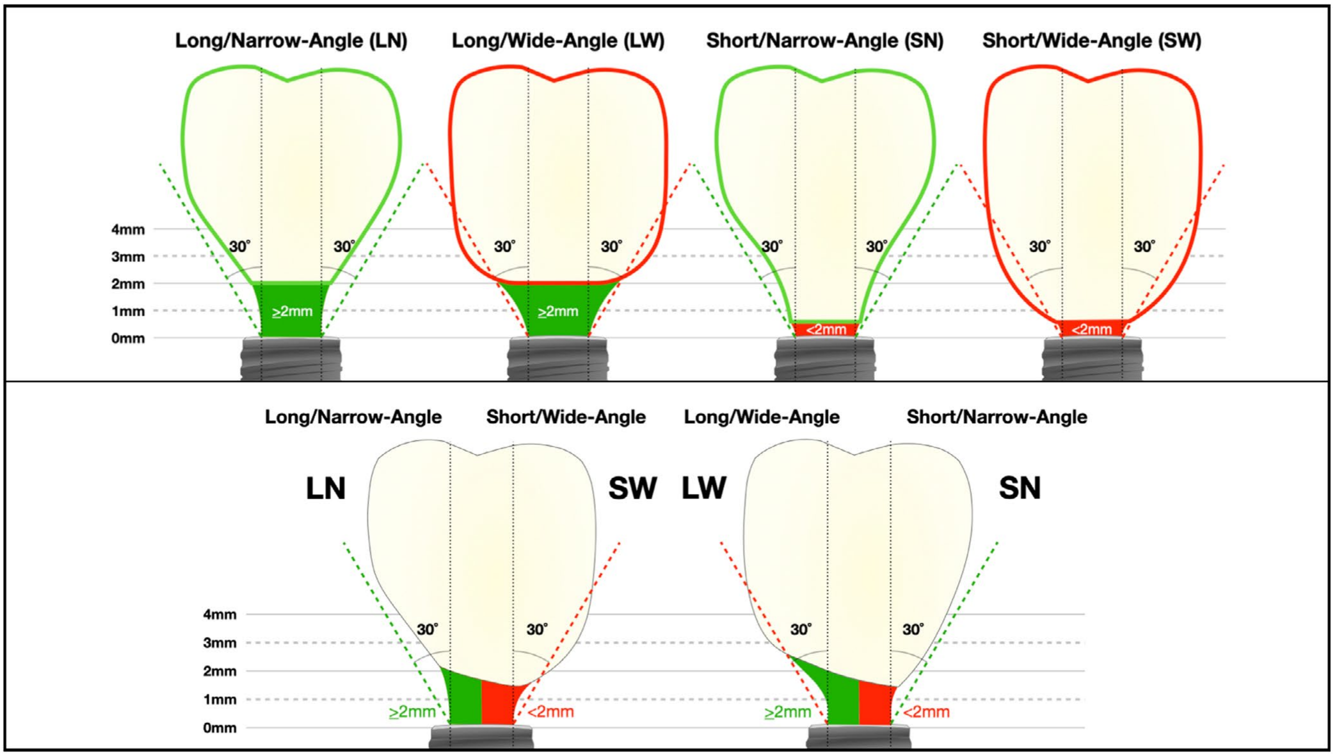

FIGURE 2 | Visual representation of groups. Groups were separated into: Long/Narrow-Angle (LN) (TmAH > 2 mm and REA < 30°), Long/Wide-Angle (LW) (TmAH > 2 mm and REA ≥ 30°), Short/Narrow-Angle (SN) (TmAH < 2 mm and REA < 30°), Short/Wide-Angle (SW) (TmAH < 2 mm and REA ≥ 30°). 1 implant would often present with mesial and distal sites belonging to separate groups.

and distal sites were grouped independently as follows (Galindo-Moreno et al. 2014; Katafuchi et al. 2018) (Figure 2):

- Long/Narrow-Angle (LN): TmAH > 2 mm and REA < 30°.
- Long/Wide-Angle (LW): TmAH > 2 mm and REA ≥ 30°.
- Short/Narrow-Angle (SN): TmAH < 2 mm and REA < 30°.
- Short/Wide-Angle (SW): TmAH < 2 mm and REA ≥ 30°.

2.5 | Statistical Analysis

The study's primary outcomes were mesial and distal MBL, assessed independently. Secondary outcomes included implant failure and peri-implantitis rates. Statistical analysis began with a descriptive assessment of variables, including absolute and relative frequencies for categorical and central tendency measures for continuous ones, carried out for the total sample and then stratified by group. Confounding variables were controlled by analyzing homogeneity across patient and implant profiles.

MBL changes from baseline to follow-up were analyzed using simple binary linear regression analysis using Generalized Estimating Equations (GEE) to evaluate group influences and other factors, adjusting for confounders. Peri-implantitis diagnosis was assessed using simple binary logistic regression with GEE, generating odds ratios and confidence intervals from the Wald's Chi2 statistic. We then performed multi-level models for each analysis to accommodate for potential confounding factors.

Significance for all analyses was set at a 5% level. For power analysis, a post hoc estimate determined a corrected sample size, accounting for the non-independence of implants due to multiple implants per patient and their moderate correlation, resulting in an adjusted power of 86.2% to detect significant MBL differences between groups with ANOVA.

2.6 | STROBE Statement

We have conducted this study in accordance with the STROBE guidelines for reporting observational studies. A detailed checklist has been completed and is available as Supporting Information to ensure transparency and reproducibility of our research methods and findings.

3 | Results

3.1 | Clinical Characteristics and Demographic Profiles

A total of 192 implants (pertaining to 119 patients, 54 males (45.4%) and 65 females (54.6%) averaging 64.1 ± 11.6 years of age through a range of 33-years to 91-years at baseline) were selected and mesial and distal sites were each subsequently divided into four study groups independently (384 sites; 78 in LN, 61 in LW, 83 in SN, and 162 in SW) for analysis (Figure S1). Patient-level variables are outlined in Table 1.

TABLE 1 | Demographic and clinical status of patients. Number of patients (%) or mean ± standard deviation.

N	119
Age (years)	64.1 ± 11.6
Gender	
Male	54 (45.4)
Female	65 (54.6)
Smoking	
Non-smoker	66 (55.5)
Former	41 (34.5)
Current	12 (10.0)
Diabetes	
No	99 (83.2)
Yes	20 (16.8)
History of periodontitis	
No	56 (47.1)
Yes	63 (52.9)
Follow up period (years)	7.43 ± 2.73

3.2 | Measurement Validation

The mean MBL from T0 to T1 for the initial measurement was 0.43 (SD = 1.09), and 0.44 (SD = 1.08) for the second measurement. The intraclass correlation coefficient (ICC) was calculated and found to be 0.95, demonstrating high reliability between the two sets of measurements.

3.3 | Homogeneity of Groups

An assessment of the homogeneity of the studied groups was conducted, with the distribution of the evaluated parameters shown in Table 2. The majority of factors showed no significant differences among the groups (Age, $p = 0.351$; Gender, $p = 0.370$; Smoking, $p = 0.337$; Diabetes, $p = 0.545$; History of Periodontitis, $p = 0.546$; Radiographic Follow-up, $p = 0.212$; Total Follow-up, $p = 0.651$; Diameter, $p = 0.086$; Retention, $p = 0.347$; Splinted, $p = 0.150$; Maintenance/year during Radiographic Follow-up, $p = 0.054$; Maintenance/year during Total Follow-up, $p = 0.083$). The sector of implant placement ($p = 0.049$), the arch in which the implant was placed ($p = 0.034$), length of the implants ($p = 0.014$), and the type of implant connection ($p = 0.001$) varied significantly across the groups (Table S1), and these variables were controlled for during the multiple analyses.

3.4 | Patient and Implant Level Factors Influencing Marginal Bone Loss

Both univariate (Table S2) and multivariate (Table 3) analyses were conducted. Factors found to have a significant impact on MBL were radiographic follow-up period, implant length, and study group. In addition, implants that were called in for > 3 maintenance visits/year had significantly more MBL.

3.5 | Impact of Group on the Amount of MBL

When comparing Mean MBL across the groups, generally, implants with Short TmAH had greater mean MBL compared to those with Long TmAH (Group SN and SW > Group LN and LW), and ≥ 30 REA greater mean MBL compared to those with < 30 REA and similar TmAH (Group SW > SN, and Group LW > LN). Mean MBL values by group were 0.26 ± 0.83 mm (95% CI 0.08–0.45), 0.27 ± 0.53 mm (95% CI 0.14–0.41), 0.46 ± 0.53 mm (95% CI 0.34–0.57), and 0.79 ± 1.02 mm (95% CI 0.63–0.94) in groups LN, LW, SN, and SW, respectively (Figure 3).

A linear regression using Generalized Estimating Equations (GEE) revealed a significant difference among groups in both univariate ($p < 0.001$) (Table S2) and multivariate ($p = 0.001$) (Table 3) models.

To assess the differences between all groups, re-estimation was performed using each group as a reference (Table 4). Specifically, Group SW experienced on average 0.48 mm (95% CI: 0.25–0.71, $p < 0.001$), 0.43 mm (95% CI: 0.18–0.68, $p = 0.001$), and 0.25 mm (95% CI: 0.00–0.45, $p = 0.013$) greater MBL compared to Group LN, Group LW, and Group SN, respectively. Group SN experienced, on average, 0.29 mm greater MBL compared to Group LN. No significant difference was found between Groups LN and LW.

3.6 | Patient and Implant Level Factors Influencing Failure and Peri-Implantitis

The failure rate was very low with only five cases, making inferential statistics inapplicable. All failed implants were associated with Group SW at mesial or distal sites, with 9/10 sites belonging to Group SW. The mean lifespan of failed implants was 7.93 years (Table S3), with severe peri-implantitis as the main failure cause. Results of the simple binary logistic regression analysis can be found in Table S4. After adjusting, analyses identified history of periodontitis, more maintenance visits, and study group as significant peri-implantitis predictors, while internal hex connections were protective compared to external hex (Table 5).

3.7 | Impact of Study Group on Peri-Implantitis Experience

At the final radiographic record, the prevalence of PI was 19.3% at the patient level (23/119 patients) and 18.8% at the implant level (36/192). Of the total cases of PI, Group LN made up 11.4%, Group LW 8.6%, Group SN 14.3%, and Group SW 65.7%. The intra-group rate of PI was 13.3%, 9.1%, 13.2%, and 25.6% for groups LN, LW, SN, and SW, respectively.

Simple (Table S4) and multiple (Table 5) logistic regression analyses were performed. Results of the multiple analyses revealed

TABLE 2 | Demographical and clinical status by implant group. Distribution of demographical and clinical parameters by study group.

	Long/narrow-angle (LN)		Long/wide-angle (LA)		Short/narrow-angle (SN)		Short/wide-angle (SA)		Total	
	Mean ± SD		Mean ± SD		Mean ± SD		Mean ± SD		Mean ± SD	
Mean age	61.2 ± 11.7		64.6 ± 11.3		65.3 ± 11.7		64.4 ± 11.1		64.0 ± 11.5	
Follow-up (years)										
Radiographic	4.76 ± 2.68		6.03 ± 3.42		5.95 ± 3.00		5.66 ± 2.65		5.6 ± 2.89	
Total	7.00 ± 2.08		7.70 ± 3.53		7.52 ± 3.07		7.17 ± 2.49		7.29 ± 2.75	
Maintenance visits/year										
Radiographic FU	2.04 ± 1.33		1.58 ± 1.09		1.60 ± 0.96		1.86 ± 1.29		1.80 ± 1.21	
Total FU	1.66 ± 0.74		1.38 ± 0.82		1.46 ± 0.71		1.78 ± 1.23		1.62 ± 1.00	
	n	**%**	***n***	**%**	***n***	**%**	***n***	**%**	***n***	**%**
Frequency										
n	78	20.3	61	15.9	83	21.6	162	42.2	384	100.0
Gender										
Male	44	56.4	23	37.7	40	48.2	77	47.5	184	47.9
Female	34	43.6	38	62.3	43	51.8	85	52.5	200	52.1
Diabetes										
Yes	9	11.5	14	23.0	15	18.1	28	17.3	66	17.2
No	69	88.5	47	77.0	68	81.9	134	82.7	318	82.2
Periodontitis										
Yes	48	61.5	33	54.1	39	47.0	86	53.1	206	53.6
No	30	38.5	28	45.9	44	53.0	76	46.9	178	46.4
Smoking										
Non-Smoker	43	55.1	38	62.3	38	45.8	79	48.8	198	51.6
Former	24	30.8	19	31.1	30	36.1	61	37.7	134	34.9
Current	11	14.1	4	6.6	15	18.1	22	13.6	52	13.5
Position										
Anterior	14	17.9	3	4.9	9	10.8	6	3.7	32	8.3
Posterior	64	82.1	58	95.1	74	89.2	156	96.3	352	91.7
Arch										
Maxilla	39	50.0	18	29.5	43	51.8	58	35.8	158	41.1
Mandible	39	50.0	43	70.5	40	48.2	104	64.2	226	58.9
Connection										
External Hex	8	10.5	17	27.0	15	18.5	26	15.9	66	17.2
Internal Hex	62	81.6	40	63.5	51	63.0	101	61.6	254	66.1
Morse Taper	6	7.9	1	1.6	3	3.7	7	4.3	17	4.4
Tri-lobe	0	0.0	5	7.9	12	14.8	30	18.3	47	12.2

(Continues)

TABLE 2 | (Continued)

	Long/narrow-angle (LN)		Long/wide-angle (LA)		Short/narrow-angle (SN)		Short/wide-angle (SA)		Total	
	Mean ± SD		Mean ± SD		Mean ± SD		Mean ± SD		Mean ± SD	
Length										
< 11 mm	20	25.3	31	50.0	20	24.4	56	34.8	127	33.1
11–12 mm	33	41.8	19	30.6	29	35.4	63	39.1	144	37.5
> 12 mm	26	32.9	12	19.4	33	40.2	42	26.1	113	29.4
Diameter										
< 4 mm	25	28.7	15	23.4	34	43.6	51	32.7	125	32.6
4–4.5 mm	22	25.3	18	28.1	20	25.6	27	17.3	87	22.7
> 4.5 mm	40	46.0	31	48.4	24	30.8	77	49.4	172	44.8
Retention										
Cement	64	84.2	44	69.8	61	77.2	114	68.7	283	73.7
Screw	12	15.8	19	30.2	18	22.8	52	31.3	101	26.3
Splinted										
Yes	16	21.1	22	35.5	36	43.9	63	38.4	137	35.7
No	60	78.9	40	64.5	46	56.1	101	61.6	247	64.3
Failure										
Yes	77	98.7	61	100.0	83	100.0	153	94.4	10	2.6
No	1	1.3	0	0.0	0	0.0	9	5.6	374	97.4

that the study group was a significant factor impacting the development of peri-implantitis ($p = 0.041$).

To assess the differences between all groups, re-estimation was performed using each group as a reference (Table 6). A significant difference was found when comparing LW vs. SW, with over 4× greater likelihood of Group SW being diagnosed with PI (OR: 4.19; $p = 0.013$). Group SW also displayed a roughly 4× greater likelihood of having PI diagnosed in comparison to group LN (OR: 4.04; $p = 0.091$).

3.8 | Impact of TmAH vs. REA on the Probability of MBL > 0 mm

The prevalence of MBL > 0 mm by group was 35.1%, 47.5%, 69.9%, and 67.7% in groups LN, LW, SN, and SW, respectively. A multiple binary logistic regression model (Table 7) was performed to identify what factor (REA or TmAH) had a more significant impact on the probability of MBL > 0 mm (pMBL > 0) It was found that TmAH was the only significant covariate ($p = 0.003$) with every 1 mm increase in TmAH reducing the odds of positive MBL by an average of 37% (OR = 0.63; $p = 0.003$).

The logistic equation for the current model is: $p/(1 - p) = 2.87 \times (0.99^{\text{Angle}}) \times (0.63^{\text{Height}})$, where p = estimated pMBL > 0. A similar model was estimated, including an interaction term between REA and TmAH, which did not reach statistical significance ($p = 0.276$). Graphical representation of p as a function of TmAH and REA is shown in Figure 4. It can be observed that the minimum pMBL ≥ 0 is reached at the largest level of TmAH and the smallest level of REA.

The results show that with an increase in TmAH, pMBL > 0 decreases with a steep slope. When TmAH is small, there is virtually no influence from REA, and pMBL > 0 is the worst possible. However, when the TmAH is large, while statistically insignificant, REA appears to influence pMBL > 0, and the lowest pMBL > 0 is reached when the TmAH is large and the REA is small.

4 | Discussion

The results of this retrospective radiographic study suggest that in regards to MBL, REA ≥ 30 only becomes a significant factor when TmAH is < 2 mm in bone-level implants. Additionally, implants with TmAH > 2 mm experienced roughly 4× less peri-implantitis, regardless of REA, with Group SW displaying an OR of 4.19 for PI in comparison to Group LW ($p = 0.013$) and 4.04 when compared to Group LN ($p = 0.091$). Finally, while REA was not found to have a significant effect on the prevalence of MBL > 0 mm, for every 1 mm increase in TmAH, the prevalence of MBL > 0 mm decreased by 37%.

TABLE 3 | MBL by group and clinical variables related to patient, implant, and prosthesis characteristics. Results of multiple linear regression using GEE (adjusted Beta, 95% confidence interval and *p*-value of Wald's test).

	Beta	95%CI	*p*
Group			0.001**
Group 1	0		
Group 2	0.08	−0.13 to 0.30	0.444
Group 3	0.29	0.09 to 0.49	0.004**
Group 4	0.48	0.25 to 0.71	< 0.001***
Gender			
Male	0		
Female	−0.15	−0.33 to 0.04	0.121
RX time period (years)	0.06	0.03 to 0.10	< 0.001***
Sector			
Anterior	0		
Posterior	−0.14	−0.45 to 0.17	0.376
Arch			
Maxilla	0		
Mandible	−0.01	−0.22 to 0.20	0.906
Connection			0.831
External Hex	0		
Internal Hex	0.02	−0.36 to 0.40	0.932
Internal Tri-lobe	0.11	−0.31 to 0.53	0.600
Length			0.122
< 11 mm	0		
11–12 mm	−0.25	−0.48 to −0.01	0.040*
> 12 mm	−0.22	−0.51 to 0.07	0.138
Diameter			0.487
< 4 mm	0		
4–4.5 mm	0.00	−0.27 to 0.27	0.986
> 4.5 mm	0.13	−0.11 to 0.36	0.295
Maintenances per year during RX period			0.079
≤ 1	0		
1–2	0.13	−0.14 to 0.39	0.356
2–3	0.15	−0.19 to 0.49	0.390
> 3	0.50	0.11 to 0.88	0.011*

*$p < 0.05$.
**$p < 0.01$.
***$p < 0.001$.

There have been many efforts to evaluate the impact of these prosthetic characteristics on crestal bone levels and disease experience; however our study has shown that the added sub-grouping of TmAH with REA is an important consideration.

Majzoub et al. (2021) reported on the significant association between REA and MBL on bone-level implants affected by peri-implantitis, with implants having > 30 REA presenting with significantly more MBL at the time of diagnosis. Similar findings were reported by Yi et al. (2020), who found a mean of 0.56 mm greater MBL in bone-level implants with ≥ 30 REA; however, these findings did not reach significance in the tissue-level group. While their sample of tissue-level implants was small, these findings could potentially support our results that REA only plays a significant role in MBL severity when TmAH is < 2 mm. These findings may be due to the increased space available to establish STAd with tissue-level implants and longer TmAH or from the control over transmucosal emergence that each of these provide. Further studies evaluating transmucosal contours as well as restorative margin positioning would confirm the findings presented in the current study.

Strauss et al. (2022) contribute to this conversation by suggesting that REA may have a time-dependent effect on MBL. Their prospective study indicated a significant correlation between REA and both the severity and probability of MBL within the first year post-loading ($p < 0.05$). However, this relationship was no longer present at the 5-year follow-up (Strauss et al. 2022). While the results of our study agree that REA does not significantly affect the incidence of MBL after the first year as shown in our logistic models ($p = 0.991$), they deviate in our finding a significant impact in the severity of MBL experienced outlined in our linear models. This discrepancy may be due to the subgrouping presented in our study, which allowed for a more nuanced understanding of the impact of REA on the amount of MBL, identifying that the significant impact of REA is only associated with shorter abutments (< 2 mm) ($p = 0.013$).

While REA did not exhibit a significant impact on the presence of MBL when considered alongside TmAH, our further explorations provide deeper insights. The graphical representation of pMBL > 0 suggests that the dynamic between TmAH and REA and their impact on MBL probability is complex. For instance, when TmAH is small, the impact of REA is substantially overshadowed by TmAH, leading to the worst recorded pMBL > 0. It can be observed that in the short abutment groups, roughly 70% of implants presented with MBL > 0 mm regardless of the REA, with 69.9% and 67.7% in groups SN and SW, respectively (Table S5). Conversely, with longer TmAH, REA's impact seemed to gain prominence, with 35.1% in Group LN and 47.5% in Group LW encountering MBL > 0 mm. This highlights that while TmAH typically holds greater significance over the presence of MBL, reducing its likelihood by an average of 37% for every 1 mm increase, the role of REA should not be entirely discounted. While the interaction term between TmAH and REA (ANGLE × HEIGHT) was not statistically significant ($p = 0.276$), their interaction is still important

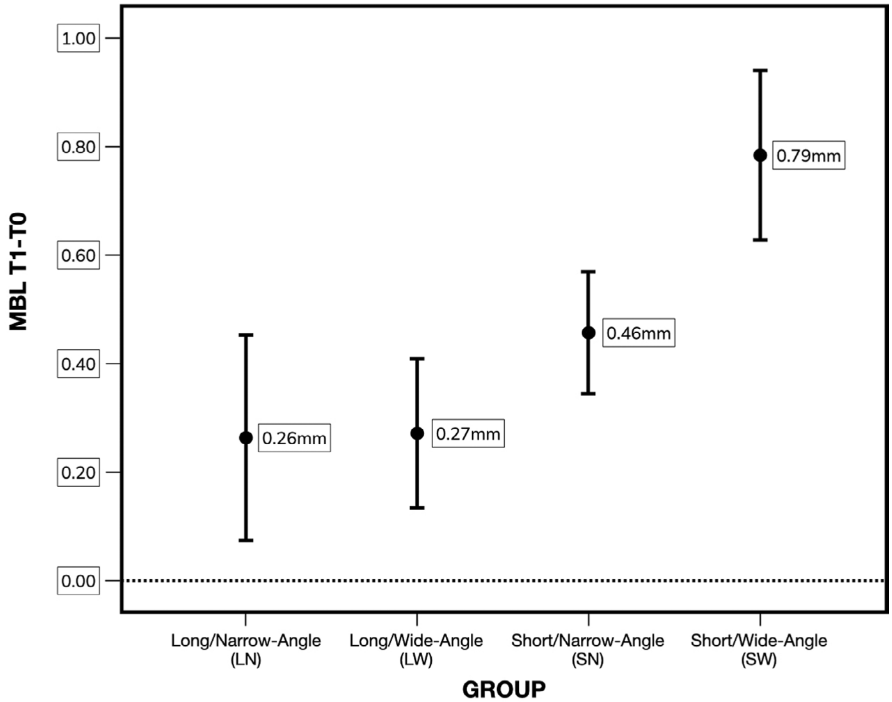

FIGURE 3 | Mean (±95% CI) Marginal Bone Loss by Group. Mean MBL values by group were 0.26 ± 0.83 mm (95% CI 0.08–0.45), 0.27 ± 0.53 mm (95% CI 0.14–0.41), 0.46 ± 0.53 mm (95% CI 0.34–0.57), and 0.79 ± 1.02 mm (95% CI 0.63–0.94) in groups LN, LW, SN, and SW, respectively.

TABLE 4 | MBL by group and clinical variables related to patient, implant, and prosthesis characteristics. Results of multiple linear regression using GEE. Numbers represent the amount of mean MBL experienced in each group, after adjustment, in comparison to the reference group, with 95% CIs and *p*-values of Wald's test.

	Reference category			
	Group LN	**Group LW**	**Group SN**	**Group SW**
Group LN	Reference			
Group LW	0.08 mm (−0.13–0.30) $p = 0.444$	Reference		
Group SN	0.29 mm (0.09–0.49) $p = 0.004$**	0.18 mm (−0.04–0.39) $p = 0.108$	Reference	
Group SW	0.48 mm (0.25–0.71) $p < 0.001$***	0.43 mm (0.18–0.68) $p = 0.001$**	0.25 mm (0.00–0.45) $p = 0.013$*	Reference

Note: *p*-values are raw *p*-values. They have not been corrected by Bonferroni.
*$p < 0.05$.
**$p < 0.01$.
***$p < 0.001$.

to consider according to the model. As REA increases, the protective effect of a longer TmAH is diminished. Specifically, when REA is 20°, a 1 mm increase in TmAH reduces pMBL > 0 mm by 41%. But at an REA of 40°, it only reduces pMBL > 0 mm by 30%, and at an REA of 60°, the reduction is 16%. In addition, it should be noted that this impact of TmAH is multiplicative rather than additive.

This is not the first study to find an increased risk of disease for implants with TmAH < 2 mm. In a study of a Swedish population, it was noted that a ≤ 1.5 mm distance from the prosthetic margin to crestal bone at baseline resulted in a 2.3× greater prevalence of moderate-to-severe peri-implantitis (Derks et al. 2016). The association found in the present study was much more dramatic, with Group SW displaying a 4× greater prevalence of peri-implantitis in comparison to both groups with TmAH > 2 mm (Group LN: OR 4.04, $p = 0.091$; Group LW: OR 4.19, $p = 0.013$). Once again, a likely reason for this discrepancy is the added subgrouping based on REA in our study. A possible explanation for this common finding is that the presence of a short abutment does not allow a sufficient space for supracrestal tissue height establishment. This leads to increased

TABLE 5 | PI by Clinical variables related to patient, implant and prosthesis characteristics. Results of multiple binary logistic regression using GEE (adjusted OR, 95% confidence interval and *p*-value of Wald's test).

	OR	95%CI	*p*
New group			0.041*
Group 1	1		
Group 2	0.96	0.16 5.81	0.967
Group 3	3.22	0.28 36.5	0.345
Group 4	4.04	0.80 20.3	0.091
History of PD			
No	1		
Yes	4.81	1.31 17.7	0.018*
RX time period (years)	1.21	0.96 1.54	0.110
Sector			
Anterior	1		
Posterior	2.23	0.28 17.8	0.450
Arch			
Maxilla	1		
Mandible	0.63	0.17 2.31	0.487
Connection			0.072
External Hex	1		
Internal Hex	0.17	0.04 0.79	0.024*
Internal Tri-lobe	0.15	0.02 1.12	0.064
Length			0.825
< 11 mm	1		
11–12 mm	1.25	0.34 4.58	0.734
> 12 mm	0.81	0.27 2.46	0.711
Splinted			
No	1		
Yes	1.05	0.33 3.32	0.932
Maintenances per year during RX period	2.64	1.44 4.84	0.002**

*$p < 0.05$.
**$p < 0.01$.
***$p < 0.001$.

MBL (Lee et al. 2018; Blanco et al. 2018; Spinato et al. 2019; Pico et al. 2019; Muñoz et al. 2021), exposure of the rough surface of the implants (Berglundh et al. 2007; Carcuac et al. 2013; Albouy, Abrahamsson, and Berglundh 2012), and possibly exposure of the implant's threads, all of which become a local factor for plaque accumulation and place the implant at a greater risk for periimplantitis (Ravidà et al. 2023).

A narrower emergence angle has been postulated to decrease plaque accumulation and the consequent inflammation arising from bacterial aggregation (Katafuchi et al. 2018; Yi et al. 2020; Majzoub et al. 2021). In a recent cross-sectional study, implant REAs were evaluated by removal of the crown and scanning with an intraoral scanner and also using periapical radiographs. The authors reported that there was a high degree of correlation between the mesial and distal REAs when comparing the two methods and found that with increasing emergence angle there was a significant increase in both plaque accumulation and BOP (Pelekos et al. 2023). In this context, the use of a tissue-level implant or a bone-level implant with a long transmucosal abutment may offer protection through the improved soft tissue adaptation and increasing the distance from the bone crest to the restorative margin. This additional space is essential in restricting the impact of plaque-associated inflammation, as inflammatory lesions localized to the sub-epithelial space are less likely to cause damage to the crestal bone (Graves, Li, and Cochran 2011). This concept aligns with the principles of bone coupling, where the proximity of the inflammatory lesion to the bone surface can stimulate the recruitment of osteoclast precursors, osteoclastogenesis, and subsequent bone resorption (Graves, Li, and Cochran 2011).

Investigations into the implant or restoration transmucosal design, regardless of the level of the abutment-crown junction, have also shed light on plausible explanations for the current study findings. Several studies have identified that less peri-implant bone loss occurs around implants with straight or convergent collars than around those with divergent collars (de Praça, Teixeira, and Rego 2020). In a study on tissue-level implants comparing convergent and divergent transmucosal morphology, implants with convergent contours had significantly less marginal bone loss after 24 months of loading (Agustín-Panadero et al. 2019). As it pertains to the present study, this

TABLE 6 | PI by Clinical variables related to patient, implant, and prosthesis characteristics. Results of multiple binary logistic regression using GEE. Numbers represent the adjusted ORs for PI with 95% CIs and *p*-values of Wald's test regarding new group changing the reference category.

	Reference category			
	Group LN	**Group LW**	**Group SN**	**Group SW**
Group LN	1			
Group LW	0.96 (0.16–5.81) $p = 0.967$	1		
Group SN	3.22 (0.28–36.5) $p = 0.345$	3.35 (0.63–17.7) $p = 0.155$	1	
Group SW	4.04 (0.80–20.3) $p = 0.091$	4.19 (1.35–13.0) $p = 0.013$*	1.25 (0.21–7.43) $p = 0.804$	1

Note: p-values are raw *p*-values. They have not been corrected by Bonferroni.
*$p < 0.05$.
**$p < 0.01$.
***$p < 0.001$.

would indicate that the length of the abutment played a role only in elevating the initial crown emergence from the crestal bone, and the crown-abutment margin was not the primary influence on marginal bone levels.

This would fall under one of the limitations of the present study, as the level of the initial crown emergence was not documented. Future studies should control for this factor and include it in their investigation. Furthermore, paradoxically, the results of our study indicated that implants that went through increased maintenance visits per year showed greater MBL ($p = 0.011$) and a higher risk of PI ($p = 0.002$) compared with those with fewer visits. We hypothesize that this occurs retroactively, akin to the situation observed in patients with periimplantitis or periimplant mucositis, where individuals with more significant bone loss necessitate a more rigorous maintenance recall during the follow-up period (Ravidà et al. 2021). In simpler terms, excessive bone loss leads to the patient being enrolled in more maintenance visits, not the other way around (Hujoel et al. 2000).

As with all radiographic analyses, this study shares the limitation of error due to radiographic beam angulation. While some studies have shown that this can cause up to 4 mm deviations in crestal bone measurements (Jenkins, Dummer, and Addy 1992), others have shown that by selecting "well-matched" pairs of radiographs, this deviation can be reduced to as low as 0.3 mm (Carpio et al. 1994). In the present study, all radiographs were taken with Rinn-type film holders shown to reduce error from vertical and horizontal beam angulation (Cascante-Sequeira et al. 2022), and only well-matched radiographic pairs were included in the study. Further studies with a prospective design using customized radiographs and 3D imaging should be conducted to further evaluate the findings of this study.

TABLE 7 | MBL (no/yes) by REA and TmAH. Results of multiple binary logistic regression using GEE (adjusted OR, 95% confidence interval and *p*-value of Wald's test).

	OR	95%CI	*p*
Constant	2.87	0.94–8.77	0.064
REA	0.99	0.98–1.02	0.991
TmAH	0.63	0.46–0.85	0.003**

$^{*}p < 0.05$.
$^{**}p < 0.01$.
$^{***}p < 0.001$.

In addition, all negative changes in marginal bone level were considered to be MBL; therefore, despite having an excellent intra-class correlation coefficient, MBL due to measurement error cannot be dismissed. This limitation, however, is compensated by strictly selecting only high-quality radiographs, resulting in more reliable and reproducible marginal bone level measurements evidenced by the ICC of 0.95, albeit with a reduced sample size. It should also be noted that this limitation should not be applied to the analysis of PI, as this diagnosis was strictly made based on the recommendations of the World Workshop (Berglundh et al. 2018) using radiographic measurements beyond 0.5 mm, in conjunction with deepening probing depths and clinical notes of inflammation, and the analysis was performed in a logistic fashion (yes/no) rather than linear.

5 | Conclusion

Within the limitations of the present study, abutment height greater than 2 mm plays a significant role in reducing the experience of PI and MBL related to ≥ 30° REA around bone-level implants. Additionally, REA becomes a significant factor only when TmAH is less than 2 mm. The probability of marginal bone loss > 0 mm was found to have an inverse relationship with TmAH and have no significant relationship with REA.

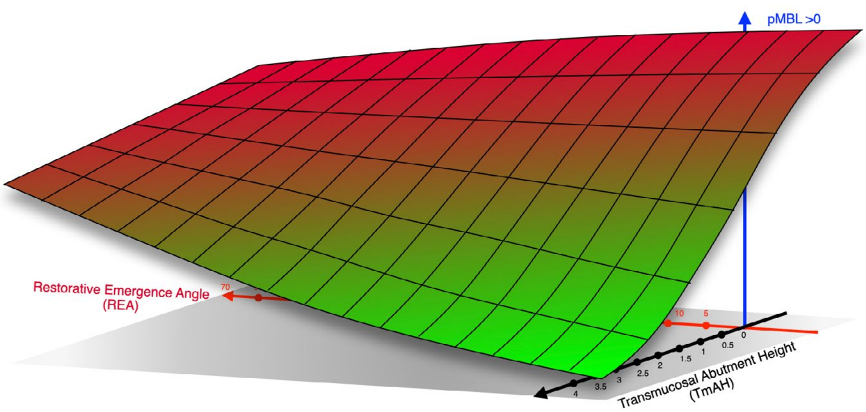

FIGURE 4 | Graphical representation of *p* as a function of TmAH and REA. This three-dimensional surface plot illustrates the estimated probability of marginal bone loss greater than 0 mm (pMBL > 0) based on varying levels of TmAH and REA. The graph is derived from the logistic equation described in Section 3.8. The *x*-axis represents the REA (in degrees), the *y*-axis represents the TmAH (in mm), and the *z*-axis represents the probability of MBL > 0 mm. The color gradient indicates the probability levels, with green areas representing lower probabilities of MBL > 0 mm and red areas indicating higher probabilities.

Author Contributions

Jonathan Misch: conceptualization, investigation, writing – original draft, writing – review and editing, formal analysis, data curation, visualization, resources. **Sawsan Abu-Reyal:** investigation. **Danyal Lohana:** investigation. **Obada Mandil:** investigation. **Muhammad H. A. Saleh:** conceptualization, methodology, writing – review and editing, project administration, supervision, resources. **Junying Li:** methodology, writing – review and editing, supervision. **Hom-Lay Wang:** methodology, supervision, writing – review and editing, project administration, resources, formal analysis. **Andrea Ravidà:** conceptualization, formal analysis, methodology, project administration, supervision, writing – review and editing, data curation.

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Ethics Statement

The IRBMED has reviewed the study and determined that it is exempt from ongoing IRB review, per the following exemption category: EXEMPTION 4(iii) at 45 CFR 46.104(d). Study eResearch ID: HUM00223052.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

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