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Wide Restorative Emergence Angle Increases Marginal Bone Loss and Impairs Integrity of the Junctional Epithelium of the Implant Supracrestal Complex: A Preclinical Study

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ABSTRACT

Aim: To assess the influence of the emergence angle on marginal bone loss (MBL) and supracrestal soft tissue around dental implants.

Materials and Methods: In six mongrel dogs, the mandibular premolars and molars were extracted. After 3 months of healing, four dental implants were placed in each hemimandible. The implants were randomly allocated to receive one of four customized healing abutments, each with a different value of the restorative emergence angle: 20°, 40°, 60° or 80°. Intra-oral radiographs were taken after placing the healing abutments and at 6, 9, 16 and 24 weeks of follow-up. Then, micro-CT and undecalcified histology and synchrotron were performed. MBL over time was analysed with generalized estimating equations (GEEs) and adjusted for baseline soft-tissue thickness.

Results: From implant placement to 24 weeks, GEE modelling showed that the MBL at mesial and distal sites consistently increased over time, indicating MBL in all groups ($p < 0.001$). The model indicated that MBL varied significantly across the different restorative angles (angle effect, $p < 0.001$), with 80° showing the greatest bone loss. Micro-CT, histology and synchrotron confirmed the corresponding trends and showed that wide restorative angles (60° and 80°) impaired the integrity of the junctional epithelium of the supracrestal tissue.

Conclusions: A wide restorative angle increases MBL and impairs the integrity of the junctional epithelium of the implant supracrestal complex.

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1 | Introduction

The influence of an implant-supported crown's restorative angle on peri-implant health has become a trending topic in the scientific literature. It is known from basic clinical principles that a suboptimal prosthetic design with poor cleansability contributes to peri-implant tissue inflammation (de Tapia et al. 2019). However, there are currently no evidence-based implant prosthetic guidelines for single crowns (Strauss et al. 2022). The individual customization of the transmucosal segment and the ensuing emergence angle of an implant prosthesis vary significantly for each clinical scenario. For this reason, there is no common consensus to guide clinicians on the restorative angle design.

The emergence or restorative angle is defined as, the angle between the average tangent of the transitional contour relative to the long axis implant (Glossary of Prosthodontic Terms 2023: 10th ed, Academy of Prosthodontics, 2023). It has been postulated that an emergence angle threshold above 30° may increase the risk of developing peri-implantitis (Katafuchi et al. 2018; Schwarz et al. 2021; Yi et al. 2020). Furthermore, prospective clinical studies have suggested that angles exceeding 40° could contribute to an increase in initial marginal bone loss (MBL; Strauss et al. 2022). This is crucial because MBL remains a major success criterion in implant dentistry (Galindo-Moreno et al. 2015). In cases of thread exposure, progressive vertical bone loss occurs in 50% of the cases (Jung et al. 2017) and may lead to mucosal recession and biological complications, such as bleeding on probing (BOP; Schwarz, Sahm, and Becker 2012).

It is interesting to note that most of the evidence on the topic of prosthetic design and peri-implant-related outcomes derives from cross-sectional or cohort studies (Katafuchi et al. 2018; Schwarz et al. 2021; Strauss et al. 2022; Yi et al. 2020). This poses a major limitation because these study designs inherently introduce confounding variables and can overestimate the effects, thereby preventing the generalization and clear interpretation of the data. The commonly cited thresholds of 30° or 40° have been arbitrarily chosen based on one preclinical study on tooth-supported crown s of 30° (Kohal, Gerds, and Strub 2003) or the mean implant restorative angle of 40° (Strauss et al. 2022). Histologically, there is a lack of studies investigating the role of the emergence angle on peri-implant hard and soft tissue, especially when considering the buccal aspect. The buccal area is arguably the most relevant for aesthetic outcomes and patient perceptions. This clearly shows a gap in understanding to what extent the prosthetic design influences the peri-implant hard and soft tissues including MBL.

To overcome the limitations of previous studies and thoroughly investigate a potential association between prosthetic design and MBL, both radiographically and histologically, including buccal sites, a longitudinal preclinical in vivo study is required. The aims, of the present study were, therefore (i) to test whether the emergence angle affects the initial MBL around dental implants and supracrestal soft tissue around dental implants and (ii) to determine an emergence angle threshold below which the MBL is attenuated.

2 | Materials and Methods

2.1 | Animals

Six male mongrel dogs (12–17 kg) were individually housed at normal room temperature and humidity (15°C–20°C and > 30%, respectively). The dogs were provided with a standardized diet during the entire breeding process until sacrificing. The '3Rs' principle (replacement, reduction and refinement) was applied in this in vivo study. The study design was based on the ARRIVE guideline (Percie du Sert et al. 2020), and the study protocol was approved by the Institutional Animal Care and Use Committee, Yonsei Medical Center, Seoul, South Korea (IRB No. 2022-0174). The workflow of this study is presented in Figure S1.

2.2 | Surgical Procedures

All surgical procedures were performed under general anaesthesia. General anaesthesia was induced by an intravenous injection of atropine (0.04 mg/kg), an intramuscular injection of a combination of xylazine (Rompun, Bayer) and ketamine (Ketara), followed by an enflurane inhalation anaesthesia (Gerolan). During the surgery, EKG monitoring was carried out by a certified veterinarian. The post-surgical management included daily irrigation with 0.2% chlorhexidine solution (Hexamedin) and intramuscular injections of antibiotics (20 mg/kg; cefazolin sodium). Pain control was achieved with morphine (0.3 mg/kg/i.m.) for 24 h and subsequently meloxicam (0.1 mg/kg/s.i.d/p.o.; Metacam, Boehringer Ingelheim) for 3 days.

2.2.1 | Surgery 1 (Tooth Extraction)

The mandibular premolars (P1, P2, P3, P4) and molars (M1) were extracted after hemisectioning the multi-rooted teeth (P2, P3, P4, M1) with fissure burs, using dental elevators and forceps. After tooth extraction, the ridge was flattened and primary intention wound healing was achieved.

2.2.2 | Surgery 2 (Implant Placement)

Three months after tooth extraction, for each hemimandible, a full-thickness flap was raised, soft tissue thickness was measured with a North Carolina Probe (UNC 15, Hu-Friedy, Chicago, USA) and four dental implants (Conelog screw-line, Camlog Biotechnologies GmbH, Basel, Switzerland) of 7 mm length and 3.8 mm diameter were placed. All implants were positioned at the bone level, with a minimum insertion torque of 15 N cm. Each implant was randomly allocated using an online random number generator (https://www.randomizer.org) to immediately receive one of four customized abutments, each with a different restorative angle: 20°, 40°, 60° or 80°. The flap was then sutured with 5.0 non-resorbable suture to obtain a primary intention healing of the wound.

2.2.2.1 | Post-surgical care. Post-surgical care involved administering an analgesic (0.2 mg/kg; meloxicam; Boehringer) and antibiotic (20 mg/kg; cefazolin sodium, Yuhan, Seoul, South

Korea) once daily for 7 days. Weekly checks of the wounds were conducted under sedation anaesthesia, but no oral prophylaxis was administered. Veterinary staff monitored the animals throughout the healing process, looking for any signs of pain or distress, implementing a humane endpoint if necessary.

2.2.3 | Surgery 3 (Sacrifice)

Twenty-four weeks after implant placement, all the animals were euthanized by an overdose injection of pentobarbital sodium (90–120 mg/kg). Implants and surrounding soft tissues were macroscopically inspected. Any local inflammation, necrosis, haemorrhage, dehiscence or any other lesion was recorded. Following dissection, the two hemimandibles were resected and fixed by immersion in 10% formaldehyde in phosphate buffer at pH 7.

2.3 | Two-Dimensional Radiographic Analysis (Periapical Radiographs)

Intra-oral radiographs of each implant were obtained using a paralleling technique and digital films (XCP dental film/PSP holder, Dentsply) at abutment insertion and at 6, 9, 16 and 24 weeks after implant placement. MBL was calculated at all time points by measuring the distance between the implant shoulder and the first bone-to-implant contact. For the calibration of the apical-coronal measurements, the inter-thread pitch distance (0.7 mm) was used. All the measurements were performed with the open-source software (ImageJ 1.50i; National Institutes of Health, Maryland, USA). All the measurements were performed by one calibrated examiner. Calibration was performed on the measurements of 10 randomly selected implants (https://www.randomizer.org). Around these implants, the MBL was measured on two different occasions, at least 1 month apart, and the intra-examiner reliability was calculated with the intra-class correlation coefficient (ICC). The mean ICC amounted to 0.99, confirming good intra-examiner reliability.

2.4 | Three-Dimensional Radiographic Analysis (Micro-CT)

Specimens were scanned using micro-computed tomography (micro-CT) (SkyScan 1072, SkyScan) at a resolution of 35 μm (100 kV and 100 μA). DICOM data were obtained, and the region of interest (ROI) was visualized with a 3D software (OnDemand3D, Cybermed). Cross-sectional micro-CT images were obtained through bucco-lingual and mesio-distal sectioning. The calibrated examiner measured the first bone-to-implant contact (fBIC) as the corono-apical distance between the implant shoulder and the most coronal contact point between bone and implant surface at mesial, distal and buccal sites.

2.5 | Clinical Parameters

Clinical parameters were recorded at one time point (24 weeks) before sacrifice. The clinical parameters, BOP and plaque control record (PCR) were measured dichotomously (yes/no) at four sites for all the implants (mesial-buccal, mid-buccal, distal-buccal, lingual) using the North Carolina Probe (UNC 15).

2.6 | Histological Analyses

Undecalcified histology was performed. The samples (48 implant sites) were immersed in 10% neutral-buffered formalin for 10 days, trimmed, dehydrated in ethanol and embedded in polymethyl methacrylate (Merck, Darmstadt, Germany). One central bucco-oral section of the implant site was prepared from each specimen. Sections with a thickness of 50–60 μm were obtained using a modified micro-cutting and grinding technique (Donath and Breuner 1982) and then stained with Toluidine blue. The histological slides were evaluated under a light microscope (Leica DM6 M, Leica Microsystems, Wetzlar, Germany) equipped with a digital camera. Images were captured digitally using the microscope software (LAS X, Leica Microsystems). fBIC was calculated as the distance between the implant shoulder and the most coronal aspect of bone in direct contact to the implant at the mesial, distal and buccal sites. Further, descriptive analysis of the buccal peri-implant soft tissues was performed. The distance between the apical termination of the thickest part of the inflammatory infiltrate and the fBIC was assessed. Briefly, a line parallel to the implant axis was drawn from the apical termination of the thickest part of the inflammatory infiltrate, identified by the accumulation of immune cells. This line intersected another line drawn perpendicular to the implant axis at the level of the fBIC.

2.7 | Synchrotron

Synchrotron images were developed from 24-week samples (Beamline 6C Bio Medical Imaging of the Pohang Light Source-II). The beamline uses a multi-pole wiggler as its photon source and provides a monochromatic x-ray beam between 10 and 50 keV. The resulting 3D images were processed using Amira 2019.2 (Thermo Fisher Scientific, Hillsboro, OR).

2.8 | Statistical Analysis

Descriptive statistics of continuous variables are presented with mean, standard deviation, median and interquartile range (IQR) values. All test assumptions were evaluated visually using graphical representations of residuals, including q–q plots. If the residuals were not normally distributed, non-parametric tests were applied. To evaluate the reliability of the primary outcome (MBL), the two-way mixed, single rater and absolute agreement ICC was used. For MBL comparisons between groups, general linear models under the generalized estimating equations (GEEs) adjusted for soft-tissue thickness were constructed with the Bonferroni correction. This methodological approach was used to control the intra-subject correlation of the measurements (e.g., the MBL was measured at different time points). For histomorphometry comparisons, the Kruskal–Wallis test with Dunn's multiple comparison correction was performed. Categoric variables were compared with χ^2 and the Fisher test. The significance level α was set to 5%. All the analyses were performed with two statistical software packages (Stata v18.0; Stata Corp, College Station, TX and GraphPad Prism version 10.0 Boston, USA).

3 | Results

All implants osseointegrated successfully, and all experimental sites healed uneventfully. There were no implant losses or technical complications, such as abutment loosening, during the 24-week follow-up period.

3.1 | Influence of Restorative Angle on Marginal Bone Level

3.1.1 | Radiographic Analysis

MBL measurements are presented in Figure 1 and Table 1.

From baseline to 24 weeks, unadjusted GEE modelling showed that the MBL consistently increased over time (time effect, $p < 0.001$) in all groups, indicating bone loss (Table 1). Moreover, the model indicated that MBL varied significantly across the different values of the emergence restorative angle (angle effect, $p < 0.001$), with 80° showing the greatest bone loss (Table 1). Expressed differently, the wider the restorative angle, the greater the MBL. Furthermore, an interaction (time × angle, $p < 0.001$) was observed, indicating that MBL across the different values of the angle differed significantly (Table 1). When adjusting for soft tissue thickness at baseline, the GEE model revealed similar findings with no significant influence of the soft tissue thickness ($p = 0.915$).

After 24 weeks, the mean MBL was comparable around implants restored with 20° and 40° (0.07 ± 0.20 mm and 0.11 ± 0.27 mm,

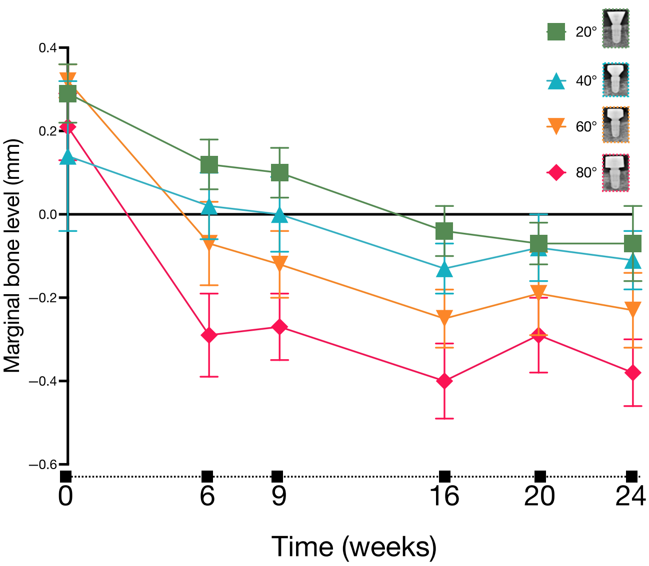

FIGURE 1 | Line chart indicating the mean marginal bone level at each time points for the different angle groups. Error bars indicate standard error. Differences were tested using a linear model under the generalized estimating equations with angle, time and their interaction and adjusted for soft tissue thickness at baseline (implant placement). Bonferroni correction was applied for the multiple comparisons.

TABLE 1 | Mean marginal bone level at each time point at different angle groups.

Group	Mean marginal bone level (mm)										
	20°		40°		60°		80°				
Time point (weeks)	Mean (SD)	Median (Q1, Q3)	Mean (SD)	Median (Q1, Q3)	Mean (SD)	Median (Q1, Q3)	Mean (SD)	Median (Q1, Q3)	*p* (angle effect)	*p* (time effect)	*p* (angle × time interaction)
0	−0.29 (0.24)	−0.29 (−0.40, −0.17)	−0.14 (0.65)	−0.25 (−0.39, −0.10)	−0.32 (0.15)	−0.40 (−0.42, −0.21)	−0.21 (0.27)	−0.28 (−0.43, −0.08)	< 0.001	< 0.001	< 0.001
6	−0.12 (0.21)	−0.11 (−0.21, −0.04)	0.02 (0.27)	−0.05 (−0.28, 0.16)	0.07 (0.35)	0.06 (−0.16, 0.34)	0.29 (0.33)	0.24 (0.07, 0.51)			
9	−0.10 (0.22)	−0.15 (−0.27, 0.04)	0.00 (0.32)	−0.05 (−0.17, 0.33)	0.12 (0.28)	0.11 (−0.16, 0.35)	0.27 (0.28)	0.25 (0.01, 0.55)			
16	0.04 (0.21)	0.02 (−0.13, 0.21)	0.13 (0.24)	0.06 (−0.02, 0.33)	0.25 (0.27)	0.20 (0.06, 0.42)	0.40 (0.34)	0.40 (0.14, 0.65)			
20	0.07 (0.18)	0.08 (−0.08, 0.23)	0.08 (0.28)	0.01 (−0.14, 0.37)	0.19 (0.36)	0.16 (−0.02, 0.41)	0.29 (0.32)	0.28 (0.07, 0.57)			
24	0.07 (0.20)	0.09 (−0.12, 0.23)	0.11 (0.27)	0.38 (0.09, 0.27)	0.23 (0.31)	0.30 (−0.09, 0.42)	0.38 (0.27)	0.32 (0.13, 0.61)			

Note: Differences were tested using a linear model under the generalized estimating equations with angle, time and their interaction and adjusted for soft tissue thickness at baseline (implant placement). Bonferroni correction was applied for the multiple comparisons. *p*-values are indicated.
Abbreviations: SD, standard deviation; Q1, first quartile; Q3, third quartile.

respectively). It was more than double in the 60° abutment group (0.23 ± 0.09 mm) and almost 4 times higher around implants restored with 80° abutments (0.38 ± 0.27 mm) (Table 1).

3.1.2 | Micro-CT Analysis

The fBIC measurements are reported in Table 2. At the mesial-distal sites, fBIC values were comparable to MBLs, further confirming the results of the two-dimensional analysis. While the 20° group showed the lowest fBIC value (Table 2), the 80° group showed the highest fBIC value, with significant differences between the groups ($p < 0.0001$) (Figure 2). At buccal sites, fBIC values tended to exhibit an increase with increase in the restorative angle (Table 2).

3.1.3 | Synchrotron Imaging

Figure S2 shows a representative 3D reconstruction of each group using synchrotron imaging, displaying the surrounding bone. A video of the 3D reconstructions for each group is provided in Video S1. The advantage of synchrotron over micro-CT is the minimization of artefacts, which improves the depiction of the MBL, particularly buccal bone loss, as the emergence angle increases.

3.2 | Influence of Restorative Angle on the Clinical Parameters

3.2.1 | Clinical Parameters

At the 24-week timepoint, the BOP amounted to 14% in group 20°, 25% in group 40°, 31% in group 60° and 25% in group 80°. As for plaque accumulation, this tended to increase according to the restorative angle, amounting to 66.6% in group 20°, 66.6% in group 40°, 91.7% in group 60°, and 100% in group 80°.

3.3 | Influence of Restorative Angle on Marginal Soft-Tissue Level

3.3.1 | Histological Analyses

3.3.1.1 | Histomorphometric Analysis. All histological cross-sections ($N = 48$) were available for histomorphometric analysis and are presented in Figure S3. Histomorphometric analysis showed that the median fBIC at buccal sites amounted to 0.44 mm (IQR, 0.13–1.4) in the 20° group, 0.84 mm (IQR, 0.41–1.32) in the 40° group, 0.90 mm (IQR, 0.46–1.25) in the 60° group and 0.97 mm (IQR, 0.34–1.46) in the 80° group,

TABLE 2 | First bone implant contact (fBIC) based on micro-CT at the different angle groups.

Group	20°		40°		60°		80°		
fBIC (mm)	Mean (SD)	Median (Q1, Q3)	Mean (SD)	Median (Q1, Q3)	Mean (SD)	Median (Q1, Q3)	Mean (SD)	Median (Q1, Q3)	Inter-group *p*
Mesial/distal sites	0.10 (0.25)	0.00 (−0.10, 0.15)	0.13 (0.33)	0.17 (0.00, 0.37)	0.20 (0.35)	0.15 (0.00, 0.52)	0.40 (0.33)	0.30 (0.15, 0.60)	< 0.0001
Buccal sites	0.99 (1.20)	0.51 (0.23, 1.63)	2.09 (2.28)	0.92 (0.01, 4.74)	1.16 (0.86)	1.22 (0.01, 4.74)	1.66 (1.42)	1.06 (0.43, 2.76)	0.637

Note: Differences were tested using the Kruskal–Wallis test with the Dunn's test for multiple comparison adjustments. *p*-values are indicated.
Abbreviations: SD, standard deviation; Q1, first quartile; Q3, third quartile.

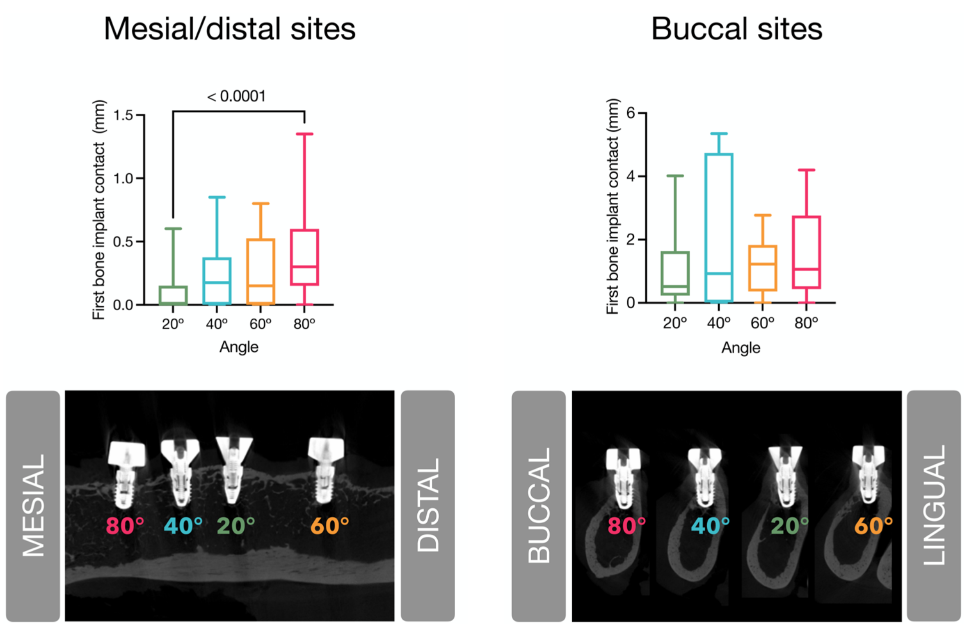

FIGURE 2 | First bone-to-implant contact (fBIC) values in the different groups at different sites (mesial/distal and buccal) based on micro-CT analysis. Differences were tested using the Kruskal–Wallis test with the Dunn's test for multiple comparison adjustments.

with no statistically significant difference between the groups ($p = 0.588$) (Figure 3).

3.3.1.2 | Descriptive Histology. Figure 4 shows representative histological cross-sections of the buccal soft tissue aspect for each group. All samples displayed a keratinized oral epithelium which stopped at the peri-implant mucosal margin. Nevertheless, the continuity and integrity of the junctional epithelium varied based on the emergence angle of the abutments: most of the samples restored with 20° and 40° abutments presented a continuous and intact junctional epithelium and a well organized connective tissue around the abutment surfaces (Figure 4). In contrast, samples from the 60° and 80° groups showed a disorganized connective tissue containing more cellular content including inflammatory cell infiltrates (Figure 4). This different aspect was often accompanied by a partial or lack of junctional epithelium formation.

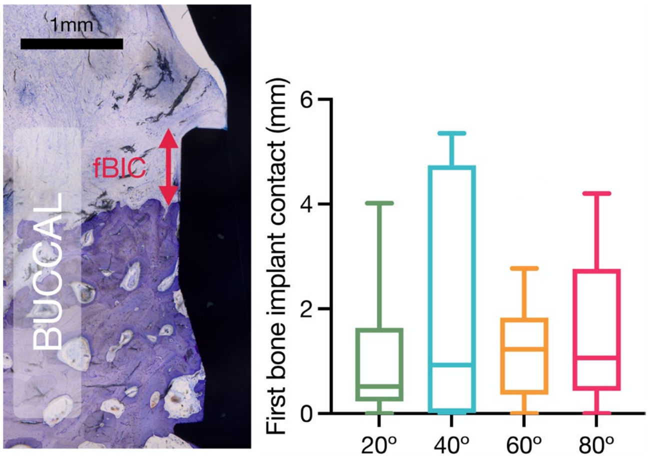

FIGURE 3 | First bone-to-implant contact (fBIC) values at the different groups based on histomorphometric analysis (scale bars indicate 1 mm). Differences were tested using the Kruskal–Wallis test.

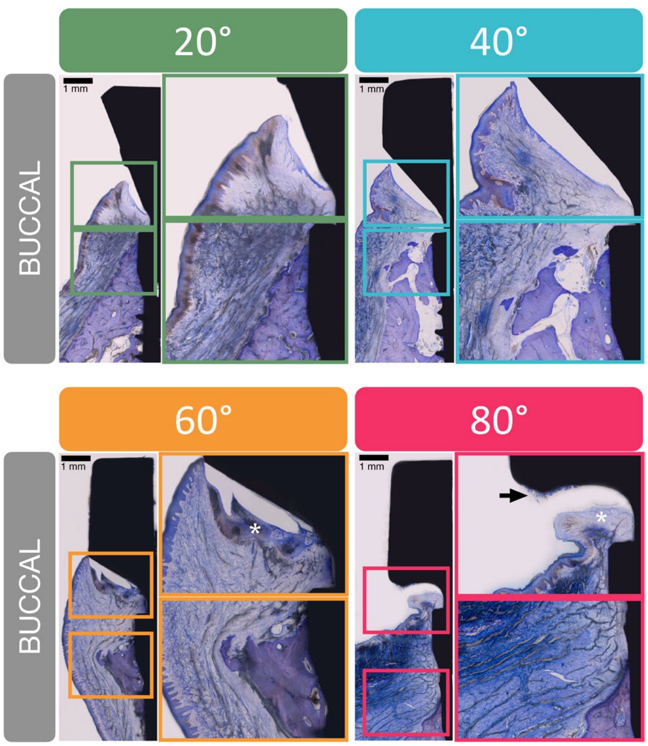

FIGURE 4 | Histological images of the buccal soft tissue surrounding the customized abutments for each group. For each group, a representative image and two magnifications focused on the supracrestal soft tissue and crestal bone at buccal sites are shown (scale bars indicate 1 mm). The white asterisk shows the disorganized or lacking junctional epithelium. The black arrow indicates the presence of bacterial biofilm against the abutment surface.

The linear distance from the thickest area of the inflammatory infiltrate to the fBIC varied across the groups (Figure 5).

The mean distance from the inflammatory infiltrate to fBIC at the buccal sites amounted to 1.69 ± 0.57 mm in the 20° group, 1.67 ± 0.78 mm in the 40° group, 1.09 ± 0.63 in the 60° group and 1.00 ± 0.86 in the 80° group, with a trend towards differences between the 20° and 80° groups ($p = 0.065$) (Figure 5).

4 | Discussion

The present study aimed at investigating the influence of the emergence angle on MBL and supracrestal soft tissue around dental implants. This study predominantly revealed the following:

- The emergence angle significantly affects the initial MBL over time;
- A wider emergence angle leads to increased MBL;
- Wider angles favour plaque accumulation and BOP;
- A wider emergence angle (60° and 80°) impairs the integrity of the junctional epithelium of the implant supracrestal tissue;
- A narrow emergence angle (20°) attenuates MBL and preserves the integrity of the junctional epithelium at the supracrestal soft tissue.

Stability of peri-implant bone has always been a crucial factor for long-term implant success (Albrektsson et al. 1986). However, only in recent years has the influence of the restorative emergence angle been considered a relevant factor (Katafuchi et al. 2018; Schwarz et al. 2021; Strauss et al. 2022). This study found a positive association between MBL and the emergence angle. In other words, the wider the angle, the greater the marginal bone resorption, particularly with 80° at buccal sites. These findings are in line with previous reports suggesting that geometric implant-abutment designs can influence the degree of MBL (Bernabeu-Mira et al. 2023; Caram et al. 2014; Cochran et al. 2009; Finelle et al. 2015; Koutouzis, Adeinat, and Ali 2019; Perez-Sayans et al. 2022; Souza et al. 2018). It is plausible that an emergence angle > 40° might limit the self-cleansability, resulting in plaque accumulation. The current study revealed a tendency towards higher plaque accumulation with increasing restorative angles. These observations may in turn explain the trend towards higher BOP as the angles were increased. However, it should be noted that 60° showed more BOP than 80°. This might be due to the inability to probe adequately, likely causing less trauma upon

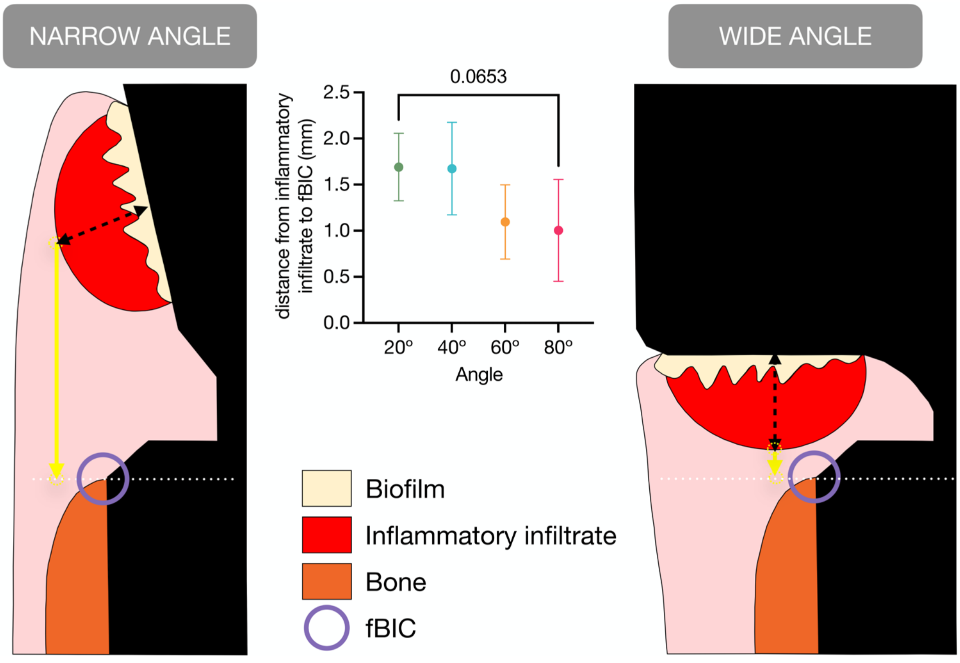

FIGURE 5 | Distance from inflammatory infiltrate to fBIC. The distance between the apical termination of the thickest part of the inflammatory infiltrate (red) and the fBIC (purple) was measured (yellow arrow). One line parallel to the implant axis was drawn from the apical termination of the thickest part of the inflammatory infiltrate (identified by the accumulation of immune cells). This line intersected another line drawn perpendicular to the implant axis at the level of the fBIC (purple). Differences were tested using the one-way ANOVA test with the Dunnet test for multiple comparison adjustments.

probing, leading to an underestimation of clinical inflammation (Monje et al. 2021).

These findings are well in line with those of a recent cross-sectional study, which found that increasing angles were more likely to show increased BOP (Rungtanakiat et al. 2023). Furthermore, the present results appear to be consistent with those of a recent RCT in which two interventions were compared to reduce mucosal inflammation in patients with peri-implant mucositis. The authors found that a prosthesis with suboptimal cleansability (with presumably wide restorative angles) was more prone to the recurrence of BOP after the peri-implant mucositis intervention (de Tapia et al. 2019).

A plausible explanation for the increased resorption at wide restorative angles is the radius of action of the plaque, as proposed by Waerhaug (1979). According to this hypothesis, plaque can trigger bone loss or other destructive events within a mean radius of approximately 1 mm. Beyond this radius, plaque has no effect (Waerhaug 1979). To mimic and explore this hypothesis in the present study, we measured the distance from the thickest part of the inflammatory infiltrate to the first bone–implant contact. We found that this distance tended to decrease as the restorative angle increased. In practice, a wider restorative angle would favour plaque accumulation and the ensuing inflammatory response closer to the bone, which may partly explain the trend towards more resorption at wider angles. A schematic of this potential mechanism is provided in Figure S1. However, it should be noted that this remains speculative, as Waerhaug's hypothesis has not been further investigated.

The 'cuff-like' soft tissue barrier has been the driving philosophy regarding the stability of the marginal bone height to maintain osseointegration (Berglundh et al. 1991; Klinge, Meyle, and Working 2006). The soft tissue forms a continuous barrier that 'seals' the transmucosal segment from bacteria and other microorganisms, leading to a reduced number of inflammatory markers in this region (Tomasi et al. 2016). Following implant placement, a mature barrier epithelium typically forms in dogs within 6–8 weeks of healing (Berglundh et al. 2007). In the present study, that phenomenon occurred consistently with narrow angles (20°–40°) but not with wider angles (60°–80°). In other words, an increase in the emergence angle prevented the formation of a continuous junctional epithelium and impaired its integrity. This was often accompanied with a progressive disorganization of the supracrestal connective tissue. This compromised integrity is likely to affect the barrier properties of the epithelium and the essential seal around the implant, hindering its ability to cope with the bacterial challenge and potentially contributing to increased MBL. Existing evidence indicates the crucial basement membrane integrity in protecting the underlying connective tissue (Fischer and Aparicio 2022; Ivanovski and Lee 2018). Immunological studies in medicine have clearly highlighted the critical role of the epithelium in preventing and coping with pathogenic infections (Larsen, Cowley, and Fuchs 2020). Based on present findings, one might speculate that the lack of integrity of the epithelium barrier could increase the susceptibility to peri-implant diseases. Conversely, narrow angles may support the formation of a continuous junctional epithelium, making it less susceptible to such diseases. This improved its structural integrity and barrier qualities so that it would be better prepared to cope with the bacterial challenge and ensuing inflammation (e.g., peri-implant mucositis), thereby reducing the risk of developing peri-implantitis.

From a clinical standpoint, it is conceivable that a weaker seal may partially explain why implant-supported restorations with a convex profile (resembling wide emergence angles) exhibit mucosal recessions more frequently than those with a concave profile (resembling narrow emergence angles), as recently shown in an RCT (Siegenthaler et al. 2022). The present study may provide histological support for those clinical findings.

4.1 | Clinical Implications

Is it possible to recommend a specific restorative angle for optimal prosthetic design? Based on the current findings, it seems reasonable to maintain an angle as narrow as clinically possible (20°–40°). A restorative -driven implant position (Belser et al. 1998) should always be prioritized to establish an optimal relationship between implant depth and angulation in relation to the prosthetic–gingival margin (Chantler et al. 2023; Gonzalez-Martin et al. 2020). However, when applying these findings in a clinical context, it is important to recognize that emergence angles are inherently dictated by the implant position (Steigmann et al. 2014) and the desired shape and form of the restoration: if the implant is slightly labial, the initial abutment-crown profile should be concave. If it is centred on the crest, the profile should be slightly concave (Siegenthaler et al. 2022) or flat. For a palatal position, a convex profile is optimal (Steigmann et al. 2014).

The ability to maintain a favourable contour of the prosthesis with a narrow emergence angle contour is directly related to the available height between the implant platform and the apical margin of the implant crown. Thus, shallow implant placement is a difficult problem to address prosthetically, as such cases would require prosthesis with a wide emergence angle or ridge lap to satisfy the essential aesthetics. In the anterior region, most clinicians tend to focus on aesthetics, prioritizing on the cervical margin contour (Chu et al. 2019; Mattheos et al. 2021). This emphasis can result in markedly wider emergence angles. For example, a narrow emergence angle would require more vertical distance between the implant platform and the crown margin to achieve the desired transition to an aesthetic contour. If less vertical height is available, the prosthodontist would be forced to use a wider contour angle. It is important to note that not all clinical scenarios will have an ideal implant diameter, angulation and depth. This reality calls clinicians to apply clinical judgement—understanding the importance of all elements can help clinicians to assess individual risks and make well-informed choices if compromise of certain features is needed. Further research on the impact of the transmucosal segment of the implant prosthesis (Mancini et al. 2023) on MBL and marginal mucosal changes (Siegenthaler et al. 2022; Strauss et al. 2022) will eventually provide guidance to clinicians on understanding which confounding factors can be appropriately addressed and managed when designing an implant-supported restoration.

4.2 | Strength and Limitations

The major strength of the present study lies in the standardization of conditions typically considered as clinical confounding factors. This approach enabled us to focus specifically on the influence of the restorative angle on the peri-implant hard and soft tissues not only at mesial and distal sites like most of the available evidence (Lops et al. 2022; Majzoub et al. 2021; Strauss et al. 2022; Yi et al. 2020) but also at buccal sites.

Another strength of our study is the use of synchrotron technology, a powerful and increasingly popular tool in dental research to evaluate bone (Han et al. 2021; Park et al. 2024). Synchrotron radiation offers several advantages over conventional x-ray sources. Its higher brightness enables the detection of very low concentrations of elements and compounds, allowing for more sensitive and detailed analyses of the bone around the implant (C. T. Chantler and Creagh 2022). The small beam size and high collimation of synchrotron radiation provide high-resolution imaging and microanalysis, which is particularly useful for examining the fine structure and composition of oral tissues and dental materials (C. T. Chantler and Bourke 2022). Additionally, synchrotron-based infrared spectroscopy can map chemical compositions, providing insights into molecular structure and organization while minimizing metal artefacts around dental implants.

Conversely, the present study is limited by the preclinical design, the impossibility of blinding, lack of customized film holders for x-rays, the inherent limited sample size and power, short follow-up time and the lack of implant loading with conventional implant-supported crowns using common restorative materials (e.g., zirconia). Additionally, the random allocation of the different abutments was done per hemi-mandible because of the limited sample size. This inherently led to a slight imbalance, with more 40° abutments positioned at P2, which tends to have a narrower ridge. This may partly explain why the 40° abutments presented some outliers (e.g., sites that showed more buccal bone resorption than 80°). Moreover, the possibility that the impairment of the junctional epithelium could be attributed to an artefact cannot be dismissed. For example, even a slight compression of the tissue due to limited space by wider angles could lead to tearing during the histological preparation. The statistical differences found do not necessarily imply clinical relevance. Nevertheless, the minimal clinically important differences in implant-related outcomes have yet to be established.

4.3 | Future Perspective

Would we observe the same increased MBL and soft-tissue impairment if the wide angle were placed 1–2 mm more coronal to the implant platform (i.e., tissue-level implant)? Based on Waerhaug's plaque front hypothesis, these complications could be avoided by increasing the distance between the plaque and bone, beyond 1 mm, thereby relocating the abutment inflammatory infiltrate (Abrahamsson, Berglundh, and Lindhe 1998; Ericsson et al. 1995; Lazzara and Porter 2006) tissue barrier and limiting away from the crestal bone. This would allow for adequate soft tissue healing forming a 'cuff-like' soft marginal bone loss. Although this remains to be fully elucidated, this hypothesis provides a potentially new explanation for why tall, straight crestal emergence zone profiles show less bone resorption than shorter ones and why abutment shape influences MBL clinically (Bernabeu-Mira et al. 2023; Perez-Sayans et al. 2022). Conversely, the present findings cannot dismiss the hypothesis that the onset of bone loss is an aseptic phenomenon due to the establishment of the supra-crestal connective tissue height and then perpetuated/aggravated by the presence of plaque. Future studies should validate these hypotheses with the new tools (Strauss et al. 2024) and analyses (Mancini et al. 2023) currently available.

5 | Conclusion

Wide restorative angles induce more MBL and impair the integrity of the junctional epithelium at implant sites. In contrast, narrow restorative angles comparatively attenuate MBL and facilitate the formation of a continuous junctional epithelium, thereby limiting mucosal inflammation. It seems reasonable to maintain the angle as narrow as clinically possible (< 40°).

Author Contributions

Franz J. Strauss: conception/design of the work, funding acquisition, investigation, interpretation and writing, statistical analysis, original draft preparation and editing. **Jin-Young Park:** funding acquisition, conception/design of the work, analysis, interpretation and critical revision. **Jung-Seok Lee:** conception/design of the work, analysis, interpretation, critical revision. **Lucia Schiavon:** analysis, interpretation and critical revision. **Rawen Smirani:** analysis, interpretation and critical revision. **Sonja Hitz:** analysis, interpretation, critical revision. **Jennifer G. M. Chantler:** analysis, interpretation, writing – original draft preparation. **Nikos Mattheos:** analysis, interpretation, critical revision. **Ronald Jung:** funding acquisition, interpretation, critical revision. **Dieter Bosshardt:** analysis, interpretation, critical revision. **Jae-Kook Cha**: funding acquisition, conception/design of the work, critical revision. **Daniel Thoma:** interpretation, critical revision and final approval of manuscript.

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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.