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ORIGINAL ARTICLE

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Effect of periodontal phenotype characteristics on post-extraction dimensional changes of the alveolar ridge: A prospective case series

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Abstract

Aim: This study was primarily aimed at assessing the effect that specific periodontal phenotypical characteristics have on alveolar ridge remodelling after tooth extraction.

Materials and Methods: Patients in need of extraction of a non-molar maxillary tooth were enrolled. Baseline phenotypical characteristics (i.e., mid-facial and mid-palatal soft tissue and bone thickness, and supracrestal soft tissue height [STH]) were recorded upon extraction. A set of clinical, digital imaging (linear and volumetric), and patient-reported outcomes were assessed over a 14-week healing period.

Results: A total of 78 subjects were screened. Forty-two subjects completed the study. Linear and volumetric bone changes, as well as vertical linear soft tissue and alveolar ridge volume (soft tissue contour) variations, were indicative of a marked dimensional reduction of the alveolar ridge over time. Horizontal facial and palatal soft tissue thickness gain was observed. Thin facial bone (≤1 mm) upon extraction, compared with thick facial bone (>1 mm), was associated with greater linear horizontal (−4.57 ± 2.31 mm vs. −2.17 ± 1.65 mm, $p = .003$) and vertical mid-facial (−0.95 ± 0.67 mm vs. −4.08 ± 3.52 mm, $p < 0.001$) and mid-palatal (−2.03 ± 2.08 mm vs. −1.12 ± 0.99 mm, $p = 0.027$) bone loss, as well as greater total (−34% ± 10% vs. 15% ± 6%, $p < 0.001$), facial (−51% ± 19% vs. 28% ± 18%, $p = 0.040$), and palatal bone volume reduction (−26% ± 14% vs. −8% ± 10%, $p < 0.001$). Aside from alveolar bone thickness, STH was also found to be a predictor of alveolar ridge resorption since this variable was directly correlated with bone volume reduction. Patient-reported discomfort scores progressively decreased over time, and the mean satisfaction upon study completion was 94.5 ± 0.83 out of 100.

Conclusions: Alveolar ridge remodelling is a physiological phenomenon that occurs after tooth extraction. Post-extraction alveolar ridge atrophy is more marked on the facio-coronal aspect. These dimensional changes are more pronounced in sites exhibiting a thin facial bone phenotype (Clinicaltrials.gov NCT02668289).

KEYWORDS
alveolar bone loss, bone resorption, digital imaging/radiography, phenotype, tooth extraction

Clinical Relevance

Scientific rationale for study: Facial bone thickness has been associated with the extent and magnitude of alveolar bone resorption after tooth extraction. However, there is a lack of evidence regarding the effect that other specific periodontal phenotypical characteristics have on the remodelling of the alveolar ridge after unassisted socket healing in non-molar sites.

Principal findings: Alveolar bone atrophy and horizontal soft tissue gain were observed after tooth extraction. These changes were more pronounced on the facio-coronal aspect of the ridge, mainly in the horizontal dimension, and in sites presenting thin facial bone (≤1 mm) upon extraction. The taller the supracrestal soft tissue height (STH) prior to tooth extraction, the greater the volumetric bone resorption.

Practical implications: Alveolar ridge atrophy is an inevitable physiological phenomenon that follows tooth extraction. Facial bone thickness and supracrestal STH are predictors of the extent and magnitude of alveolar ridge resorption. This information may be utilized to make clinical decisions for the effective management of non-molar extraction sites.

1 | INTRODUCTION

Dental extraction is frequently indicated when teeth cannot be maintained in adequate conditions of health, function, comfort, aesthetics, and/or for strategic reasons (Tonetti et al., 2000; Kao, 2008). Tooth extraction inescapably alters the homeostasis of the remaining tissues. The local trauma caused by the surgical intervention initiates a sequence of biological events, which ultimately leads to a variable degree of alveolar ridge atrophy. Pre-clinical and clinical studies have consistently shown that dimensional changes are more accentuated over the first few weeks, particularly on the facial aspect of the ridge (Schropp et al., 2003; Araujo & Lindhe, 2005; Chappuis et al., 2013; Discepoli et al., 2013).

Different therapies have been proposed to attenuate the extent of alveolar ridge atrophy after tooth extraction, including orthodontic forced eruption (González-Martín et al., 2020), partial extraction protocols (Hürzeler et al., 2010), and different alveolar ridge preservation modalities with or without immediate implant placement (Avila-Ortiz et al., 2019; Clementini et al., 2019; Saito et al., 2021; Couso-Queiruga, Mansouri, et al., 2022a; Couso-Queiruga, Weber, et al., 2022b). Whether any of these interceptive therapies is performed or not, predicting post-extraction dimensional changes can be extremely helpful to make clinical decisions when tooth extraction and future tooth replacement therapy are planned.

A recent meta-analysis which assessed the dimensional changes affecting alveolar ridge after unassisted socket healing in adult humans revealed that facial/buccal bone thickness upon extraction is strongly associated with the extent and magnitude of alveolar bone resorption (Couso-Queiruga, Stuhr, et al., 2021b). The prognostic value of this anatomical parameter has been validated by numerous clinical studies (Leblebicioglu et al., 2013; Chappuis et al., 2013; Chappuis et al., 2015; Avila-Ortiz, Gubler, et al., 2020b). However, other phenotypical features that could play a role in post-extraction healing dynamics, such as the supracrestal soft tissue height (STH), have not yet been fully characterized. This study was primarily aimed at assessing the effect that specific periodontal phenotypical characteristics (i.e., mid-facial and mid-palatal soft tissue and bone thickness, and STH) have on the remodelling of the alveolar ridge after non-molar tooth extraction. We hypothesized that phenotypical features of the alveolar bone and soft tissue impact ridge remodelling following the extraction of a maxillary non-molar tooth. Conversely, the null hypothesis was that phenotypical features of the alveolar bone and soft tissue do not impact ridge remodelling following the extraction of a maxillary non-molar tooth.

2 | MATERIALS AND METHODS

2.1 | Experimental design and centre

This prospective case series was designed and conducted in compliance with the Consolidated Standards of Reporting Trials (CONSORT) guidelines (Schulz et al., 2010). The clinical component of the study was managed in the Department of Periodontics at the University of Iowa College of Dentistry and Dental Clinics between February 2016 and June 2020. Details of the study timeline and events are depicted in Figure S1.

2.2 | Ethical approval and registration

Approval for the experimental protocol was obtained from the University of Iowa Institutional Review Board in January 2016 (HawkIRB #201510790). This human clinical trial was registered prior to initiation at clinicaltrials.gov (NCT02668289).

2.3 | Outcomes of interest

2.3.1 | Clinical outcomes

- Mid-facial keratinized mucosa width (KMW) change (in mm) from baseline to 14 weeks.
- Visual assessment of wound healing at 2 and 14 weeks post-operatively using a 3-point wound healing index as follows: 1. Uneventful wound healing with no or minimal mucosal edema or erythema, and no suppuration; 2. Uneventful wound healing with slight gingival edema, erythema, or discomfort but no suppuration; and 3. Poor wound healing with severe mucosal edema, erythema, and suppuration (Avila-Ortiz, Gubler, et al., 2020b).
- Incidence of complications during the study period.

2.3.2 | Digital imaging outcomes

- Horizontal facial and palatal soft tissue thickness change (in mm) from baseline to 14 weeks.
- Vertical mid-facial STH change (in mm) from baseline to 14 weeks.
- Vertical mid-palatal STH change (in mm) from baseline to 14 weeks.
- Horizontal alveolar bone width changes (in mm) from baseline to 14 weeks.
- Vertical mid-facial crestal bone height change (in mm) from baseline to 14 weeks.
- Vertical mid-palatal crestal bone height change (in mm) from baseline to 14 weeks.
- Alveolar ridge volume (soft tissue contour) change (in mm^3) from baseline to 14 weeks.
- Alveolar bone volume change 9 (in mm^3) from baseline to 14 weeks.

2.3.3 | Patient-reported outcome measures (PROMs)

- Self-reported discomfort at 2 and 14 weeks post-operatively.
- Overall satisfaction upon completion of the study.

2.4 | Eligibility criteria and recruitment

Adult patients between 18 and 75 years of age who expressed an interest to participate in the study were pre-screened. Patients who required the extraction of a tooth-bound non-molar tooth in the maxilla were eligible to participate in the study. The exclusion criteria were as follows: (1) any periodontal attachment loss greater than 2 mm affecting the tooth of interest or the interproximal aspect of neighbouring teeth; (2) severe haematological disorders (i.e., haemophilia or leukaemia); (3) active infectious diseases that may compromise normal healing; (4) liver or kidney dysfunction/failure; (5) currently under cancer treatment or within 18 months from completion of radiotherapy or chemotherapy; (6) long-term history of oral bisphosphonate use (i.e., 10 years or more) or a history of IV bisphosphonates; (7) uncontrolled diabetes mellitus, defined as HbA1c > 7.0; (8) severe metabolic bone diseases; (9) pregnancy at the time of screening or trying to conceive; (10) current heavy tobacco use, defined as >10 cigarettes per day; (11) intake of medications known to largely influence bone or soft tissue metabolism; (12) mental disabilities that may interfere with reading, understanding, and signing the informed consent and/or with following study-related instructions; (13) any other non-specified reason that from the point of view of the investigators would make the candidate non-suitable for the study. All patients were required to read, understand, and sign the consent form. During the screening visit, prior to the clinical and radiographic examination, patients were informed of the purpose, design, and timeline of the study, as well as the expected benefits and possible risks associated with their participation.

2.5 | Clinical procedures

Before the baseline surgical intervention, a cone beam computed tomographic (CBCT) scan (i-CAT Next Generation, Imaging Sciences International Inc., Hatfield, PA, USA) of the maxillary arch was taken. The field of view was approximately 6 cm at 0.3 mm voxel size, and the exposure factor settings were fixed at 120 kVp and 18.66 mAs for all scans. Additionally, an intra-oral impression was obtained using a polyvinyl siloxane material (Penta Quick VPS; 3M, St. Paul, MN, USA) and stone casts were subsequently made (Microstone, Whip Mix Corp., Louisville, KY, USA). All surgical procedures were performed under local anaesthesia. Prior to tooth extraction, probing depths (PD), gingival recession (GR), and bleeding on probing (BOP) were assessed at six sites (mid-facial, mesio-facial, disto-facial, mid-palatal, mesio-palatal, and disto-palatal) around the tooth to be extracted and on the adjacent teeth to verify their periodontal status. Supracrestal STH (i.e., the distance from the gingival margin to the crestal bone) was also measured at six sites around the tooth of interest via vertical transmucosal probing using a periodontal probe (UNC-15; Hu-Friedy, Chicago, IL, USA). The mucogingival junction was demarcated using Schiller's iodine solution (Maurer et al., 2000). Mid-facial KMW was then measured using a UNC-15 periodontal probe. All clinical parameters were obtained by a calibrated examiner. At baseline, flapless tooth extraction was performed with care to minimize trauma to the periodontal structures. All alveolar sockets were gently curetted and inspected. Any site that did not exhibit complete alveolar bone integrity was excluded from the study. No additional intervention that could have influenced the outcomes of interest was performed (e.g., collagen plug, bone graft materials, autologous blood-derived products, immediate removable mucosa-supported prosthesis, sutures). All patients received detailed verbal and written post-operative instructions, as well as prescriptions for anti-inflammatory medication (ibuprofen 600 mg TID for 3–5 days, as needed), unless contraindicated for medical reasons. Patients were recalled at 2 and

14 weeks. At 2 weeks, wound healing score (WHS) of the extraction site was recorded. At 14 weeks, mid-facial KMW and WHS were recorded, and a second CBCT scan and an impression were obtained according to the same protocol followed at baseline. Patients who were interested in tooth replacement were scheduled in the appropriate clinic at the University of Iowa College of Dentistry and Dental Clinics for further treatment.

2.6 | Digital imaging assessments

To ensure data quality, the same independent calibrated examiner (ECQ) repeated all linear and volumetric measurements in 10 random patients, verifying that an inter-class correlation coefficient of at least 0.9 was achieved, after which data collection ensued.

2.7 | Bone and soft tissue linear measurements

Cast models were scanned using a laboratory scanner (D2000, 3Shape, Copenhagen, Denmark) to obtain high-resolution standardized tessellation language (STL) files. Both baseline and 14-week STL and CBCT-derived Digital Imaging and Communication in Medicine (DICOM) files were imported to a software package (Romexis, Planmeca v.5.2.1., Hoffman Estates, IL, USA) and superimposed by matching at least eight points using anatomical landmarks to allow the visualization of soft and hard tissue structures beneath the overlying surface, as described elsewhere (Couso-Queiruga, Tattan, et al., 2021c; González-Martín et al., 2014). A sagittal section at the middle of each region of interest was made for further analysis. At baseline, facial and palatal bone and soft tissue thickness were measured at 1 mm apical to the crest and the mucosal margin, respectively. Horizontal alveolar bone and soft tissue linear changes were quantified in millimetres at three pre-determined reference points located at 1, 3, and 5 mm from the highest baseline mid-facial or mid-palatal crestal points. Additionally, mid-facial and mid-palatal vertical bone changes between baseline and 14 weeks were measured using reproducible landmarks (i.e., a horizontal line connecting the cemento-enamel junction of the adjacent teeth) for consistency and reliability between measurements, as shown in Figure 1.

2.8 | Alveolar bone and ridge volume assessments

The magnitude of volume reduction of the alveolar ridge from baseline to 14 weeks, both at the bone and alveolar ridge contour (superficial soft tissue) levels, were measured (in mm^3). For the volumetric bone assessment, DICOM files were imported into a software package (Romexis, Planmeca, v.5.2.1. Hoffman Estates, IL, USA). The grey-scale value and region of interest in a two-dimensional sagittal section were standardized between both datasets (i.e., baseline and 14 weeks). Manual segmentation was used to define the volume of interest (VOI) using reproducible landmarks. The VOI was confined by two sagittal planes located at the interproximal height of contour of the adjacent teeth, a horizontal plane at the apical end of the root or a guiding landmark at an equivalent location when the tooth was not present, the most coronal point of the alveolar crest, and the most prominent aspect of the facial and palatal plates of the alveolar bone. Facial and palatal volumetric bone assessments were made separately by dividing the VOI with an additional plane, using the middle aspect of the mesial and distal alveolar bone peaks at baseline as a reference, as shown in Figure 1. Subsequently, the percent of reduction of facial and palatal alveolar bone volume that took place from baseline to 14 weeks post-extraction was calculated. For the assessment of alveolar ridge volume changes (i.e., soft tissue contour), STL files were analysed using two specialized software packages (González-Martín et al., 2014; González-Martín & Veltri, 2017). For each patient, the baseline and 14-week STL files were superimposed for best fit alignment. To verify the alignment, the average error between STL files in areas where no treatment was performed and no changes were expected was established at ±0.15 mm (Geomagic Control X, 3D Systems, Rock Hill, SC, USA). Aligned raw STL files were exported to another software (Meshmixer, Autodesk Inc., San Francisco, CA, USA). In each baseline file, the dental crown was virtually removed at the level of the gingival margin. Subsequently, the superimposed STL files were trimmed to obtain the VOI, which was confined by two sagittal planes that contacted with the most proximal point of the adjacent teeth, a horizontal plane at the shallowest level of the vestibulum in the two scans, the crest of the ridge on the coronal aspect, and the most prominent facial and palatal aspect of the alveolar ridge. The VOIs were exported back into the first software package (Geomagic Control X, 3D Systems) to quantify the total volumetric difference between baseline and 14 weeks. Facial and palatal volumetric alveolar ridge changes were quantified separately by dividing the VOI with an additional plane, using the middle aspect of the mesial and distal papillae at baseline as a reference, as shown in Figure 2.

2.9 | Patient-reported outcome measures

Patients were asked to rate their level of discomfort at 2 and 14 weeks post-operatively and overall satisfaction upon study completion using a 100-point visual analogue scale. This was done prior to the clinical examination to minimize observer effect bias.

2.10 | Statistical analyses

Mean and standard deviation values were calculated for all the variables. Data from different sites (e.g., mid-facial and mid-palatal) were treated independently. Intra-rater reliability of digital measurements was assessed using intra-class correlation coefficient (ICC) for a single,

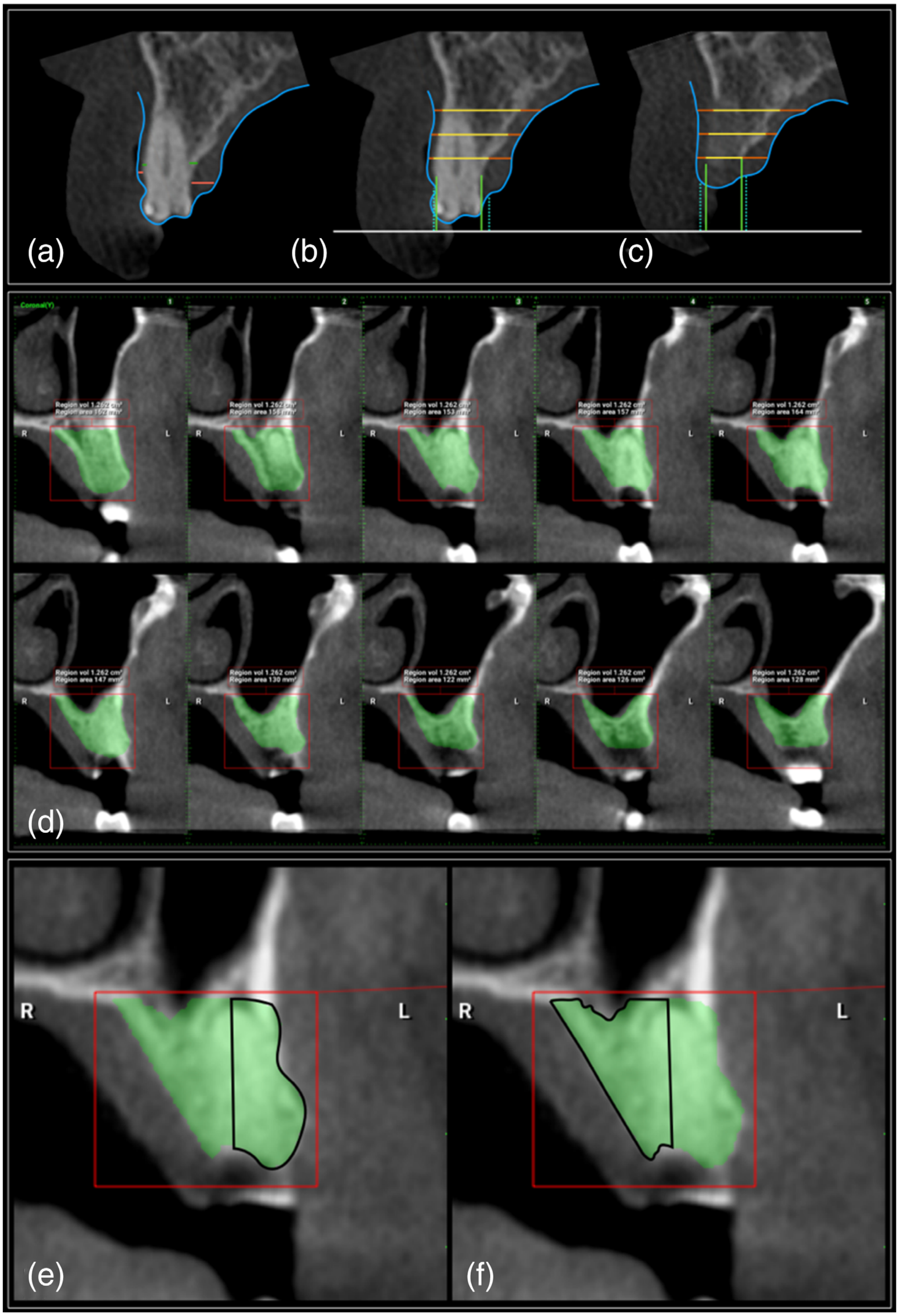

FIGURE 1 Multi-panel illustrating linear and volumetric measurements. A sagittal section was made in the middle of the tooth/region of interest to perform linear measurements. The blue line represents the surface of the mucosa after superimposition of the standardized tessellation language and Digital Imaging and Communication in Medicine files. The white line represents a horizontal reproducible landmark. Facial and palatal bone/soft thickness measurements at baseline (a), vertical and horizontal bone/soft tissue measurements prior to (b), and 14 weeks after tooth extraction at the predetermined reference points (c). Manual segmentation was used to determine the total bone (d) and facial (e) and palatal (f) volume of interest utilizing reproducible landmarks between different time points. [Colour figure can be viewed at wileyonlinelibrary.com]

fixed rate (Koo & Li, 2016). Correlations between outcomes and variables of interest were assessed using Pearson correlation and univariate linear regression analyses. Spearman correlation was used instead when appropriate, in case of monotonic relationships. Student's *t*-tests and Wilcoxon rank-sum tests were used in the sub-analyses, which compared thick and thin facial bone phenotypes. All analyses were conducted using a specific software package (R version 4.0, www.r-project.org).

2.11 | Sample size calculation

Data from a previous study in which the reported change in volumetric bone resorption in the USH group was normally distributed with standard deviation of 69.35 mm^3 for the USH group were used (Avila-Ortiz, Gubler, et al., 2020b). Sample size calculation was performed using a software package (G*Power 3.1). This analysis indicated that, at a 95% significance level with an 80% power, a

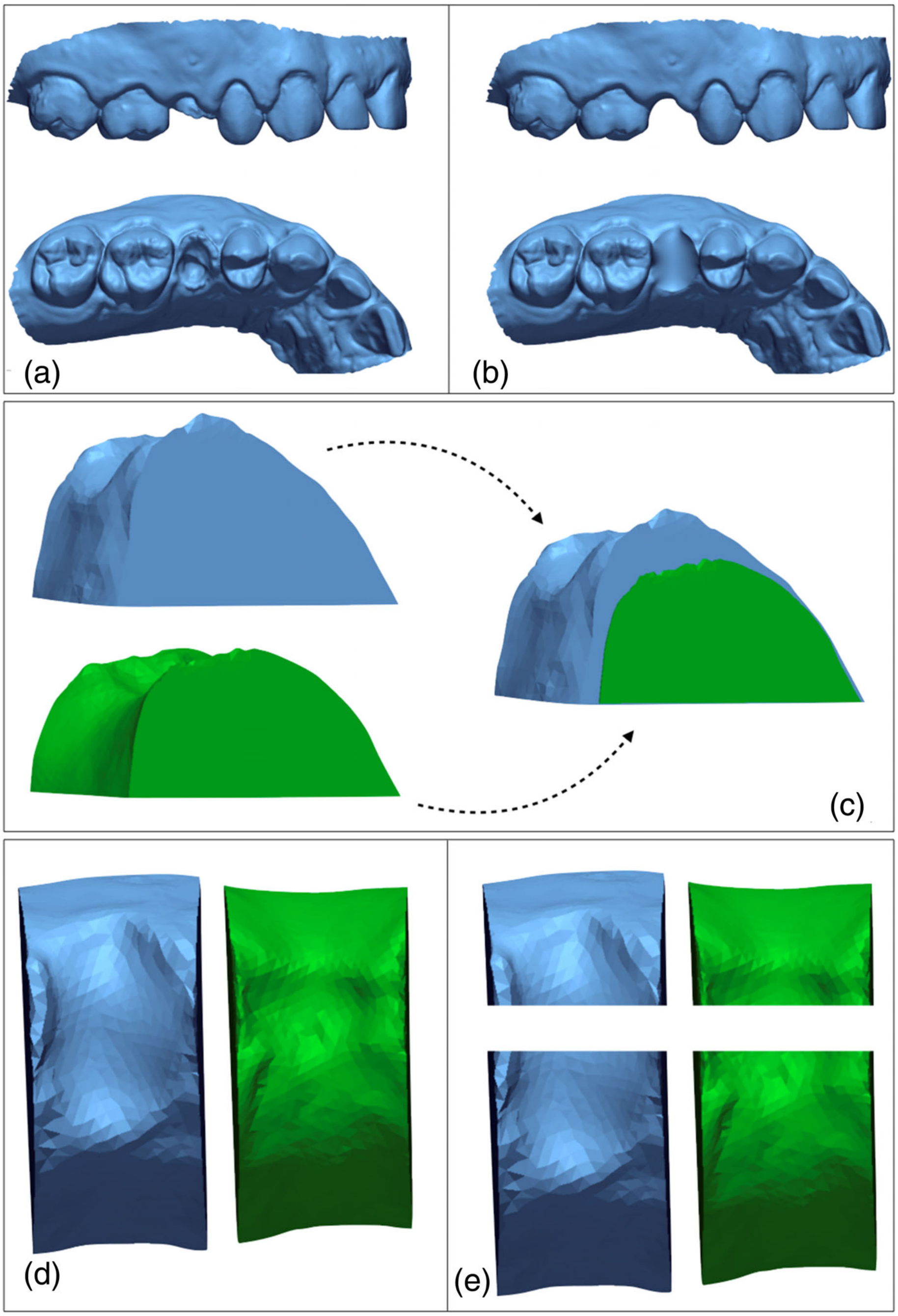

FIGURE 2 Baseline standardized tessellation language (STL) files before (a) and after digital tooth removal (b), superimposition of volume of interests obtained from the segmentation of STL files representing the alveolar ridge contour at baseline (blue) and 14 weeks after tooth extraction (green) (c), total alveolar ridge volume at baseline (blue) and 14 weeks after tooth extraction (green) (d), and facial and palatal alveolar ridge volume at baseline (blue) and 14 weeks after tooth extraction (green) (e). [Colour figure can be viewed at wileyonlinelibrary.com]

minimum of 27 subjects would be required to reject the null hypothesis with a type I error probability of .05 associated with the test of this null hypothesis.

3 | RESULTS

3.1 | Population

A total of 78 patients were screened. Eighteen patients were not eligible upon initial screening, nine were excluded owing to problems related to COVID-19, five were excluded because of a patent lack of integrity of the alveolar bone at the time of tooth extraction, and four were lost to follow-up after the baseline intervention. Therefore, the final sample was constituted by 42 patients who completed the study. None of the included patients had a diagnosis of periodontitis. Post hoc analysis showed a total power of 94% with an α-error probability of .05. This population included 22 males (52.4%) and 20 females (47.6%) between 23 and 77 years of age, with a mean age of 55.5 ± 15.73 years. Except for four light smokers (<10 cigarettes/day), all patients were non-smokers. The mean overall body mass index of the total population was 30.1 ± 5.19.

TABLE 1 Linear bone changes in millimetres.

	Thick ($n = 26$)	Thin ($n = 16$)	Total ($n = 42$)	p-Value
Vertical mid-facial				
n-Miss	1	0	1	<.001
Mean mm (SD)	−0.95 (0.67)	−4.08 (3.52)	−2.17 (2.70)	
Vertical mid-palatal				
n-Miss	1	0	1	.027
Mean mm (SD)	−1.12 (0.99)	−2.03 (2.08)	−1.48 (1.56)	
Horizontal at 1 mm				
n-Miss	2	3	5	.003
Mean mm (SD)	−2.17 (1.65)	−4.57 (2.31)	−3.02 (2.20)	
Horizontal at 3 mm				
n-Miss	1	1	2	.006
Mean mm (SD)	−1.40 (0.92)	−3.11 (2.21)	−2.04 (1.73)	
Horizontal at 5 mm				
n-Miss	1	1	2	.008
Mean mm (SD)	−1.15 (0.80)	−2.59 (2.12)	−1.69 (1.58)	

3.2 | Baseline data

Three maxillary central incisors, 7 maxillary lateral incisors, 1 maxillary canine, 15 maxillary first premolars, and 16 maxillary second premolars were extracted because of deep horizontal or oblique root fracture ($n = 19$), extensive caries ($n = 17$), prosthetic reasons ($n = 4$), and endodontic problems ($n = 2$). Mean PD and GR, including all sites, were 2.55 ± 0.41 mm and −2.33 ± 0.45 mm, respectively. About one-quarter (23.8%) of sites did not present BOP at baseline. Mean STH of the six sites/spots measured per tooth was 4.03 ± 0.60 mm (range 2–7 mm). All sites exhibited an adequate width of mid-facial keratinized mucosa at baseline with a mean value of 4.6 ± 1.17 mm (range 2.5–6.5 mm). Mean facial bone thickness was 1.15 ± 0.59 mm (range 0.3–2.2 mm). Mean palatal bone thickness was 1.35 ± 0.40 mm (range 0.5–2.2 mm). Mean facial soft tissue thickness was 1.35 ± 0.33 mm (range 0.8–2.1 mm). Mean palatal soft tissue thickness was 2.13 ± 0.61 mm (range 1.2–3.9 mm). Baseline clinical parameters are displayed in Table S1. No relationship was observed between soft tissue thickness and bone thickness prior to tooth extraction.

3.3 | Clinical outcomes

Uneventful healing throughout the study period was generally observed in all sites. Only one patient reported slightly altered sensation in the lip adjacent to the extraction site, which was resolved within 2 weeks. KMW change between baseline and 14 weeks was +0.07 ± 1.26 mm. Mean WHS decreased from 2 weeks to 14 weeks post-operatively (1.27 ± 0.45 and 1.05 ± 0.22, respectively).

3.4 | Digital imaging outcomes

ICC for the calibrated examiner demonstrated excellent intra-rater reliability agreement for linear (0.98), bone volume (0.98), and alveolar ridge volume (0.97) assessments.

3.4.1 | Linear outcomes

Mean horizontal bone width reduction between baseline and 14 weeks was −3.02 ± 2.20 mm, −2.04 ± 1.73 mm, and −1.69 ± 1.58 mm at 1, 3, and 5 mm apical to the bone crest, respectively. Mean vertical mid-facial and mid-palatal bone reduction were −2.17 ± 2.70 mm and −1.48 ± 1.56 mm, respectively. Mean facial soft tissue thickness gain was 0.9 ± 2.1 mm, 0.35 ± 0.98 mm, and 0.65 ± 2.64 mm at 1, 3, and 5 mm apical to the bone crest, respectively. Mean palatal soft tissue gain was 0.78 ± 1.85 mm, 0.18 ± 0.64 mm, and 0.35 ± 1.19 mm at 1, 3, and 5 mm apical to the bone crest, respectively. Mean vertical mid-facial and mid-palatal soft tissue reduction was −1.59 ± 1.30 mm and −2.05 ± 1.17 mm, respectively, as shown in Tables 1 and 2. Linear regression analyses revealed an inverse relationship between facial bone thickness at baseline and linear horizontal ($p < .001$), vertical mid-facial ($p < .001$) and mid-palatal ($p = -.1$) alveolar bone resorption. Facial bone thickness at baseline also had an inverse relationship with facial ($p = .05$) and palatal ($p = .99$) soft tissue width changes, while a potential inverse relationship with mid-facial ($p = .17$) and mid-palatal ($p = .11$) STH reduction was noted. An inverse relationship was also observed between palatal bone thickness at baseline and vertical mid-palatal bone reduction ($p = .06$), as well as an inverse relationship with facial STH reduction nearing statistical significance ($p = .08$). These results indicate that the thicker

TABLE 2 Linear soft tissue changes in milli metres.

	Thick ($n = 26$)	Thin ($n = 16$)	Total ($n = 42$)	p-Value
Vertical mid-facial				
n-Miss	6	4	10	.640
Mean mm (SD)	−1.45 (1.32)	−1.83 (1.29)	−1.59 (1.30)	
Vertical mid-palatal				
n-Miss	6	4	10	.293
Mean mm (SD)	−1.84 (0.66)	−2.40 (1.70)	−2.05 (1.17)	
Facial soft tissue at 1 mm				
n-Miss	6	6	12	.151
Mean mm (SD)	0.70 (2.25)	1.30 (1.82)	0.90 (2.10)	
Facial soft tissue at 3 mm				
n-Miss	12	5	17	.602
Mean mm (SD)	0.11 (0.6)	0.65 (1.30)	0.35 (0.98)	
Facial soft tissue at 5 mm				
n-Miss	17	8	25	.228
Mean mm (SD)	−0.11 (0.65)	1.51 (3.71)	0.65 (2.64)	
Palatal soft tissue at 1 mm				
n-Miss	6	6	12	.260
Mean mm (SD)	0.48 (1.67)	1.36 (2.13)	0.78 (1.85)	
Palatal soft tissue at 3 mm				
n-Miss	8	6	14	.279
Mean mm (SD)	0.11 (0.66)	0.32 (0.62)	0.18 (0.64)	
Palatal soft tissue at 5 mm				
n-Miss	7	7	14	.402
Mean mm (SD)	0.12 (0.65)	0.83 (1.86)	0.35 (1.19)	

the facial bone at baseline, the less the horizontal and vertical bone resorption, and the less the soft tissue width gain. On the other hand, the thicker the palatal bone at baseline, the less the bone height reduction.

3.4.2 | Volumetric outcomes

Total, facial, and palatal mean alveolar bone volume at baseline was 1075.17 ± 208.67 mm^3, 393.73 ± 131.59 mm^3, and 681.45 ± 189.91 mm^3, respectively. Total, facial, and palatal mean alveolar bone volume at 14 weeks was 834.12 ± 209.09 mm^3, 254.40 ± 127.56 mm^3, and 579.73 ± 185.42 mm^3, respectively. These results translate into a volumetric reduction between both time points of −22% ± 12%, −37% ± 21%, and −15% ± 15%, respectively, as shown in Table 3. Linear regression analyses revealed an inverse relationship between facial bone thickness at baseline and total bone volumetric reduction ($p < .0001$). Evidence of an inverse relationship between facial bone thickness and facial bone volumetric reduction ($p = .008$) was also observed. Additionally, a direct relationship between STH and total ($p = .1$), facial ($p = .05$), and palatal ($p = .13$) volumetric bone resorption was noticed. These results indicate that the thicker the facial bone at baseline, the smaller the volumetric bone reduction at 14 weeks. Conversely, the shorter the STH at baseline, the smaller the alveolar bone resorption. Furthermore, these findings corroborate that alveolar bone resorption after tooth extraction mainly occurs on the facio-coronal aspect of the ridge. Scatter plots derived from linear regression analyses showing the correlation between facial bone thickness and STH and bone volumetric changes are displayed in Figures S2 and S3.

Total, facial, and palatal mean alveolar ridge volume at baseline was 1049.78 ± 331.78 mm^3, 377.11 ± 141.34 mm^3 and 672.65 ± 232.2 mm^3, respectively. Total, facial, and palatal mean alveolar ridge volume at 14 weeks was 859.63 ± 297.06 mm^3, 260.94 ± 123.23 mm^3, and 598.69 ± 227.26 mm^3, respectively. These results translate into a volumetric reduction between both time points of −19% ± 8%, −33% ± 14%, and −12% ± 8%, respectively, as shown in Table 4. Linear regression analysis revealed that none of the phenotypical variables recorded in this study had a significant effect on alveolar ridge volume changes (i.e., soft tissue contour alterations). Scatter plots derived from linear regression analyses showing the correlation between facial bone thickness and alveolar ridge volumetric changes are displayed in Figure S2.

TABLE 3 Bone volume changes in cubic metres and relative percentages.

	Thick ($n = 26$)	Thin ($n = 16$)	Total ($n = 42$)	p-Value
Total bone volume				
n-Miss	1	0	1	<.001
Mean mm^3 (SD)	−167.60 (77.15)	−348.44 (123.15)	−238.17 (131.28)	
Mean percentage (SD)	15 (6)	34 (10)	22 (12)	
Facial bone volume				
n-Miss	2	0	2	.040
Mean mm^3 (SD)	−114.67 (65.76)	−176.31 (98.88)	−139.32 (85.12)	
Mean percentage (SD)	28 (18)	51 (19)	37 (21)	
Palatal bone volume				
n-Miss	2	0	2	<.001
Mean mm^3 (SD)	−54.79 (70.36)	−172.12 (84.98)	−101.72 (95.32)	
Mean percentage (SD)	8 (10)	26 (14)	15 (15)	

TABLE 4 Alveolar ridge volume changes in cubic metres and relative percentages.

	Thick ($n = 26$)	Thin ($n = 16$)	Total ($n = 42$)	p-Value
Total alveolar ridge volume				
n-Miss	0	0	0	.969
Mean mm^3 (SD)	−195.44 (95.74)	−181.54 (82.22)	−190.15 (90.05)	
Mean percentage (SD)	18 (8)	20 (9)	19 (8)	
Facial alveolar ridge volume				
n-Miss	0	0	0	.376
Mean mm^3 (SD)	−111.55 (55.59)	−123.71 (52.63)	−116.18 (54.16)	
Mean percentage (SD)	29 (11)	40 (17)	33 (14)	
Palatal alveolar ridge volume				
n-Miss	0	0	0	.076
Mean mm^3 (SD)	−83.89 (47.93)	−57.83 (52.51)	−73.96 (50.73)	
Mean percentage (SD)	13 (7)	10 (10)	12 (8)	

3.5 | Stratification of patients according to facial bone thickness at baseline

According to available clinical evidence (Chappuis et al., 2013; Avila-Ortiz, Gubler, et al., 2020b), sites were stratified as a function of baseline facial bone thickness. Sixteen extraction sites presented thin facial bone (≤1 mm) and 26 sites presented thick facial bone (>1 mm). Mean facial bone thickness was 0.50 ± 0.22 mm and 1.53 ± 0.34 mm in the thin and thick bone phenotype group, respectively.

3.5.1 | Linear outcomes

Significant differences were observed between bone phenotypes in terms of mean bone width changes. In the thick bone group, a linear reduction of −2.17 ± 1.65 mm, −1.40 ± 0.92 mm, and −1.15 ± 0.80 mm was observed at 1, 3, and 5 mm apical to the crest, respectively, versus −4.57 ± 2.31 mm, −3.11 ± 2.21 mm, and −2.59 ± 2.12 mm in the thin bone group ($p = .003$, $p = .006$, and $p = .008$, respectively). In the thick bone group, mean facial soft tissue thickness gain was 0.7 ± 2.25 mm and 0.11 ± 0.6 mm at 1 and 3 mm apical to the crest, respectively, while a reduction of −0.11 ± 0.65 mm was observed at 5 mm. In the thin bone group, mean facial soft tissue thickness gain was 1.3 ± 1.82 mm, 0.65 ± 1.3 mm, and 1.51 ± 3.71 mm at 1, 3, and 5 mm apical to the crest, respectively. The difference between groups was only statistically significant at the 5-mm level ($p = .028$). Mean palatal soft tissue thickness gain in the thick bone group was 0.48 ± 1.67 mm, 0.11 ± 0.66 mm, and 0.12 ± 0.65 mm at 1, 3, and 5 mm apical to the crest, respectively, versus 1.36 ± 2.13 mm, 0.32 ± 0.62 mm, and 0.83 ± 1.86 mm in the thin bone group. However, the difference between groups was not statistically significant at any level: 1, 3, or 5 mm apical to the crest ($p = .260$, $p = .279$, and $p = .402$, respectively). Mean vertical mid-facial and mid-palatal bone loss in the thick bone group was −0.95 ± 0.67 mm and −1.12 ± 0.99 mm, respectively, whereas these values were −4.08 ± 3.52 mm and −2.03 ± 2.08 mm in the thin bone group. The difference between groups was statistically significant on both facial ($p < .001$) and palatal ($p = .027$) sites. Mean mid-facial and mid-

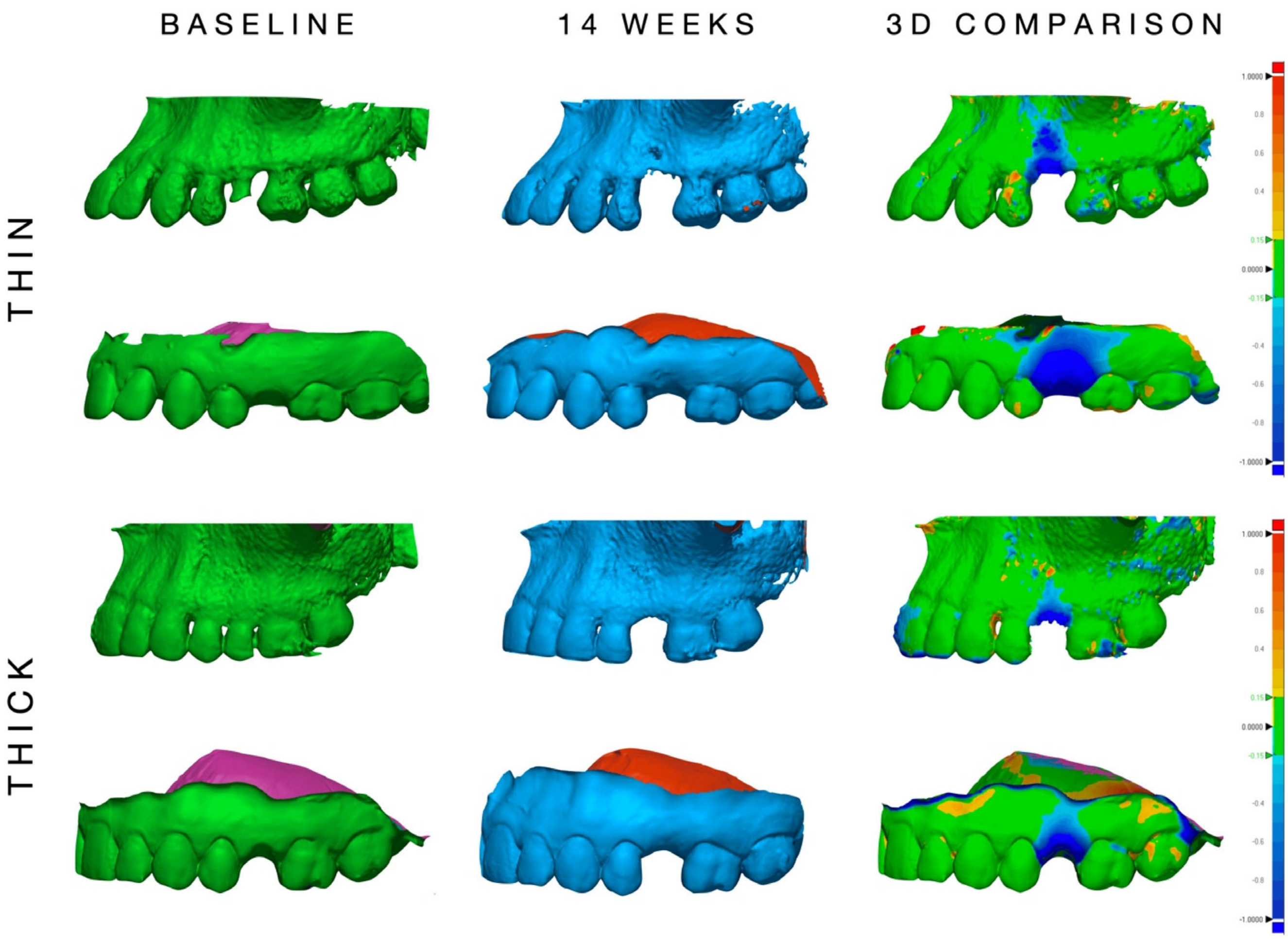

FIGURE 3 Alveolar bone volume and soft tissue contour differences between thin (≤1 mm) and thick (>1 mm) bone phenotypes and a three-dimensional (3D) colour map comparison indicating areas of adequate alignment and areas of negative discrepancies (blue) between baseline and 14 weeks after tooth extraction. The colorimetric scale represents mm. [Colour figure can be viewed at wileyonlinelibrary.com]

palatal STH reduction in the thick bone group was −1.45 ± 1.32 mm and −1.84 ± 0.66 mm, respectively, versus −1.83 ± 1.29 mm and −2.4 ± 1.7 mm in the thin bone group. These differences were not statistically significant, as shown in Tables 1 and 2.

3.5.2 | Volumetric outcomes

In the thick bone group, mean total, facial, and palatal bone volume loss was −15% ± 6%, −28% ± 18%, and −8% ± 10%, respectively, whereas in the thin bone group these values were −34% ± 10%, −51% ± 19%, and −26% ± 14%, respectively. These differences were statistically significant (p < .001, p = .040, and p < .001, respectively).

In the thick bone group, mean total, facial, and palatal alveolar ridge volume loss was −18% ± 8%, 29% ± 11%, and −13% ± 7%, respectively, whereas in the thin bone group these values were −20% ± 9%, −40% ± 17%, and −10% ± 10%, respectively. These differences were not statistically significant (p = .969, p = .376, and p = 0.076, respectively), as shown in Tables 3 and 4.

An example of a three-dimensional colour map comparison of alveolar bone and alveolar ridge volume changes between thin and thick bone phenotypes is shown in Figure 3.

3.6 | Patient-reported outcome measures

Mean patient-reported discomfort scores were very low at 2 weeks (2.1 ± 1.63) and decreased even further at 14 weeks (1.02 ± 1.37). Mean overall satisfaction upon study completion was high (94.5 ± 0.83 out of 100).

4 | DISCUSSION

To our knowledge, this case series represents the most comprehensive analysis to date of the effect that specific periodontal phenotypical characteristics have on the remodelling of the alveolar ridge after unassisted socket healing in non-molar tooth sites.

4.1 | Main findings

Analysis of alveolar bone changes from baseline to 14 weeks revealed higher alveolar bone resorption in the horizontal dimension, followed by vertical mid-facial and mid-palatal. Linear regression analyses showed that the thinner the facial bone at baseline, the greater the horizontal and vertical alveolar bone resorption. It was also observed that the thinner the palatal bone at baseline, the greater reduction in palatal bone height. Analysis of bone volume changes also showed that the thinner the facial bone at baseline, the greater total and facial bone volume loss. Additionally, a correlation between STH and bone resorption was found, meaning that the shorter the STH at baseline, the less the volumetric bone resorption.

An increase in facial and palatal soft tissue thickness and a reduction in height were observed. From a topographical perspective, the resorptive pattern was similar to that observed in the bone compartment, affecting mainly the facio-coronal aspect of the ridge. Linear regression analyses revealed that the thicker the facial bone at baseline, the less the soft tissue thickness gain, and the less the reduction in STH. Interestingly, either bone or soft tissue thickness at baseline did not show a significant association with alveolar ridge volume (soft tissue contour) changes.

Compared with thick facial bone (>1 mm), thin facial bone (≤1 mm) at baseline was associated with greater horizontal and vertical linear bone reduction, greater gain in horizontal soft tissue thickness, and greater reduction in STH. Additionally, greater bone volume reduction was observed in sites presenting a thin bone phenotype, whereas no significant soft tissue volume changes were observed as a function of baseline facial bone thickness.

It must be pointed out that no significant association was observed between soft tissue features (i.e., soft tissue thickness and KMW) and post-extraction bone dimensional changes after tooth extraction.

4.2 | Agreements and disagreements with existing evidence

Alveolar ridge resorption patterns observed in this study are in accordance with the existing body of high-level evidence (Couso-Queiruga, Stuhr, et al., 2021b). Facial soft tissue thickness gain was 0.9 ± 2.1 mm at the most coronal level, which is higher than the 0.4–0.5 mm reported by a previous systematic review on this topic (Tan et al., 2012). Total and soft tissue volumetric changes are in agreement with a previous study (Avila-Ortiz, Gubler, et al., 2020b), although higher total bone volume loss was observed in this study, which could be explained by the differences in the methodology followed or by larger the sample size.

Mean values for alveolar ridge volume changes were smaller than the alveolar volume bone reduction. This can be explained as due to the assessment of soft tissue contour being dependent on site-specific characteristics of each subject and it being limited to the vestibular depth and the extent of the analog impressions obtained at baseline and at 14 weeks. To the best of our knowledge, this is the first study reporting volumetric changes at the level of the bone and soft tissue contour on facial and palatal regions after unassisted tooth extraction.

The association between facial bone thickness and bone and soft tissue remodelling is in accordance with previous publications (Chappuis et al., 2013; Spinato et al., 2014; Chappuis et al., 2015; Avila-Ortiz, Gubler, et al., 2020b). After stratification according to the facial bone thickness, alveolar ridge remodelling was observed in both groups. However, those changes were more pronounced in the thin bone phenotype group (≤1 mm). In the thick bone phenotype group (>1 mm), more bone height loss was observed on the palatal side compared with the facial side. This difference could be explained by the fact that those sites presented with a thinner palatal bone thickness upon extraction compared with the facial sites. Some of the results observed in this study differ from those reported in a previous publication on this topic (Chappuis et al., 2013). Interestingly, in the study by Chappuis et al. (2015), only dimensional changes were observed for the thin bone phenotype group, whereas no horizontal bone loss was observed in the thick bone phenotype group. In another publication by the same group, a 7.5-fold increase in facial soft tissue thickness at the most facio-coronal aspect of the ridge at 8 weeks post extraction was reported for the thin phenotype group. However, these investigators found greater facial soft tissue thickness gain in the thin group at the most apical sites compared with the most coronal level, with 15.7-, 6.5-, and 2-fold increase at 5, 3, and 1 mm apical to the crest, respectively. The differences between studies could be explained by selection criteria, by the different follow-up time, and by the methodology followed by Chappuis and co-workers to analyse bone and soft tissue changes in DICOM files, which may have been insufficient for detecting immature bone formation in early stages of healing.

To the best of our knowledge, this is the first study that analysed the association between STH and post-extraction dimensional changes affecting the alveolar ridge. Although STH is not included in the most recent consensus derived from the 2017 World Workshop (Jepsen et al., 2018), we believe that it should be considered an integral component of the periodontal phenotype. Contrary to the taller STH typically observed around dental implants (Avila-Ortiz, Gonzalez-Martin, et al., 2020a), periodontal STH tends to be shorter and, based on our observations, is associated with less bone volume resorption. Finally, PROMs after tooth extraction, specifically the perceived discomfort and overall satisfaction, are similar to those in other studies on this topic (Machtei et al., 2019; Avila-Ortiz, Gubler, et al., 2020b).

4.3 | Limitations

Despite having adhered to the highest methodology standards, this study is not exempt from limitations. First, only tooth-bound non-molar teeth presenting CAL ≤2 mm and post-extraction sockets exhibiting integrity of the alveolar bone were included, which represents a narrow clinical situation that prevents complete extrapolation of our findings to other scenarios (e.g., molar sites or sockets presenting extensive bone damage). Nevertheless, it could also be considered a strength, as this decision was made to homogenize the study sample with the purpose of avoiding the influence of socket size and morphology variations on the healing outcomes (Couso-Queiruga, Ahmad, et al., 2021a). Second, the follow-up time was 14 weeks and, although it is well known that most of the resorptive events occur within the first 6–8 weeks after tooth extraction, further dimensional changes may occur over time. Third, tooth extraction was performed as non-traumatic as possible without flap elevation, which could also have influenced the outcomes of this study (Saleh et al., 2022). Fourth, the findings of the present study should be interpreted with caution, as further studies focused on analysing the fate of the alveolar ridge after tooth extraction in anterior maxillary sites as a function of periodontal phenotype features using precise methodological assessments are needed to validate the conclusions of this investigation. Fifth, it is possible that some of the examined correlations failed to reach statistical significance because of the relatively small sample size. There is a need for further clinical studies evaluating the effect of other local (i.e., gingival architecture), systemic, and surgical variables on post-extraction dimensional changes after unassisted socket healing. Future studies in this area of research should be properly designed and incorporate well-described and reproducible outcome assessment methods, as well as utilize digital technology, which can be considered the current gold standard for the assessment of post-extraction dimensional changes and the outcomes of different treatment modalities related to the management of the extraction site.

5 | CONCLUSIONS

This study provides valuable insights regarding the effect of periodontal phenotypical characteristics on alveolar ridge resorption patterns after maxillary non-molar tooth extraction and unassisted healing. The main findings were as follows:

- Alveolar ridge resorption is more pronounced on the facio-coronal aspect, mainly in the horizontal dimension.
- Independently of the baseline facial bone thickness, alveolar ridge dimensional changes should be expected after tooth extraction. However, these changes are more pronounced in sites exhibiting a thin facial bone phenotype: the thinner the facial bone, the greater the extent and magnitude of alveolar bone resorption.
- Thin facial bone thickness is also associated with greater facial and palatal soft tissue gain.
- The shorter the STH, the smaller the bone volume reduction.

AUTHOR CONTRIBUTIONS

Gustavo Avila-Ortiz contributed to the conception, design, data acquisition, analysis, and interpretation of data. Emilio Couso-Queiruga contributed to the design, data acquisition, analysis, and interpretation of data. Zachary A. Graham contributed to data acquisition, analysis, and interpretation of data. Tabitha Peter contributed to the analysis and interpretation of data. Emilio Couso-Queiruga and Gustavo Avila-Ortiz led the writing. Oscar Gonzalez-Martin and Pablo Galindo-Moreno critically reviewed the manuscript and provided feedback. All authors gave final approval and agreed to be accountable for all aspects of the scientific work.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflict of interest to report pertaining to the conduction of this clinical trial

DATA AVAILABILITY STATEMENT

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

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