Buccal bone thickness adjacent to virtual dental implants following guided bone regeneration

by

Daniel J. Phillips, DMD

Thesis submitted to the Faculty of the
Oral Biology Graduate Program
Uniformed Services University of the Health Sciences
In partial fulfillment of the requirements for the degree of
Master of Science 2019

"Buccal bone thickness adjacent to virtual dental implants following guided bone regeneration"

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DISSERTATION APPROVAL SHEET

Buccal bone thickness adjacent to virtual dental implants following guided bone regeneration.

This thesis is submitted by Daniel J. Phillips and has been examined and approved by an appointed committee of the faculty of the Uniformed Services University of the Health Sciences.

The signatures that appear below verify the fact that all required changes have been incorporated and that the thesis has received final approval with reference to content, form, and accuracy of presentation. This thesis is therefore in partial fulfillment of the requirements for the degree of Master of Science.

04 June 2019
Date

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Major Advisor

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Department Chairperson

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Dedication

To Amber, my loving, and supportive wife.

Copyright statement

Abstract

Buccal bone thickness adjacent to virtual dental implants following guided bone regeneration.

Daniel J. Phillips, MS, 2019

Thesis directed by: Thomas M. Johnson, DMD, MS; LTC, DC, USA, Assistant Director, Periodontics Residency

Objective: This retrospective observational study sought to quantify the buccal bone thickness adjacent to virtual dental implants following guided bone regeneration (GBR) surgery and evaluate the influence of patient- and procedure-related variables on buccal bone thickness.

Materials and Methods: Cone-beam computed tomography (CBCT) images acquired from patients who had undergone GBR surgery between July 1, 2012, and November 7, 2016, were used for this analysis. In all cases, the GBR procedure involved a dense polytetrafluoroethylene (dPTFE) barrier membrane and a mineralized cortical particulate freeze-dried bone allograft (FDBA). Eighty-four virtual dental implants were placed at planned locations using CBCT images from 84 patients, and the adjacent buccal bone thickness was measured at each site. The effects of sex, age, estimated baseline ridge width, number of missing teeth in site, site type (tooth-bounded versus terminal position in arch), dental arch (mandibular or maxillary), arch location (anterior or posterior), smoking status, titanium reinforcement in the membrane, membrane fixation, and tenting screw use were assessed.

Results: The mean post-GBR buccal bone thickness adjacent to virtual dental implants was 2.24±1.01 mm. Fifty-nine of 84 virtual implants (70%) exhibited buccal bone thickness > 1.9 mm. GBR sites using membrane fixation produced significantly greater virtual implant buccal bone thickness than those without membrane fixation (2.31 ± 0.96 versus 1.15 ± 1.25 mm, $P = 0.012$). Virtual implant buccal bone thickness also exhibited moderate correlation with estimated initial ridge width ($r = 0.43$, $P < 0.0001$). The alveolar ridge at 81 virtual implant sites (96%) was classified as good or satisfactory, meaning dental implants were actually placed at these sites, with or without additional grafting at implant placement.

Conclusions: Observations in this study suggest GBR procedures using dPTFE membranes and FDBA result in favorable ridge dimensions for dental implant placement in most cases. However, additional augmentation at implant surgery may be necessary at ≈ 30% of sites, if buccal bone thickness > 1.9 mm is intended.

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INTRODUCTION

Two fundamental concerns in contemporary implant dentistry are 1) achieving and preserving osseointegration and 2) maintaining health and stability of peri-implant bone and mucosa over time. Patients have benefitted from the high implant survival and success rates achieved in the present era, and initial osseointegration failure occurs with acceptably low frequency.[1] Indeed, achieving osseointegration is usually not the clinical challenge. Comparatively higher proportions of implant patients experience biologic complications (peri-implant mucositis and peri-implantitis) after initial osseointegration.[2] Peri-implant bone loss can lead to midfacial recession, abutment or implant platform exposure, and loss of papilla height, compromising esthetics and impeding effective plaque removal.[3,4]

Peri-implant bone thickness is an important parameter impacting bone and mucosal stability. In a multicenter study investigating peri-implant bone loss between implant surgery and stage two uncovering, Spray and colleagues found an inverse relationship between baseline buccal bone thickness and bone resorption over the observation period. Patients with buccal bone thickness < 1 mm to 1.4 mm exhibited the largest horizontal bone loss. As the initial buccal bone thickness approached 1.8 to 2.0 mm, patients experienced significantly less bone loss, and in some cases, gained buccal bone.[5] Using cone-beam computed tomography (CBCT) images acquired after the restorative phase, Miyamoto and Obama determined that the likelihood of mucosal recession around 31 maxillary anterior implants (immediate or delayed placement in 18 patients) was reduced when labial bone thickness was > 1.2 mm at the platform level.[6] Interestingly, a similar critical bone thickness was observed in an animal model. After immediate implant placement and an eight-week healing period in a critical-sized, supra-alveolar, peri-implant defect model in dogs, buccal bone resorption was significantly greater when the baseline bone thickness was < 2 mm.[7] Thus, when augmenting a deficient alveolar ridge for subsequent implant placement, the best available evidence suggests peri-implant buccal bone thickness ≥ 1.8 to 2.0 mm should be a goal of GBR procedures.[5-7] Some experts prefer even greater peri-implant bone thickness for health and stability at the site.[8] Inadequate buccal bone thickness can unfavorably impact the treatment outcome.[5-10] Thin peri-implant bone may lead to mucosal recession, exposure of implant components, and poor cosmesis.[7-10]

Prior investigations and systematic reviews of GBR treatment outcomes have predominantly focused on 1) percentage of implants placed, 2) implant survival or success, 3) GBR complication rate, and 4) interproximal peri-implant radiographic bone level as primary clinical outcome measures.[11-17] Some studies have also reported mean gain in horizontal or vertical ridge dimension following GBR.[17-22] Few studies have sought to characterize the impact of GBR on buccal/labial peri-implant bone volume and buccal bone volume maintenance after function. Schneider and colleagues used digitally superimposed optical scans of cast models to evaluate alterations in labial peri-implant tissue contour following GBR and soft tissue augmentation.[23] In 12 patients receiving maxillary anterior GBR procedures, Block and coworkers evaluated augmentation stability by assessing CBCT images acquired at five different time points:

preoperatively, immediately after augmentation, three to six months following augmentation (before implant placement), immediately after implant placement, and at the longest available follow-up point.[24]

PURPOSE

The purpose of this retrospective study was to utilize a single CBCT image per patient, acquired after GBR for implant treatment planning and surgical guide fabrication, to assess a practical consideration for implant surgeons—the anticipated buccal bone thickness at the time of implant placement.

REVIEW OF THE LITERATURE

Normal extraction socket healing often results in substantial reduction in alveolar ridge volume.[25] Such untoward volumetric changes can preclude dental implant placement and commit patients to additional treatment or restrict the available restorative options. Thus, clinicians employ various ridge preservation techniques to minimize volumetric changes in the alveolar ridge after tooth extraction. With or without ridge preservation, clinicians often find residual alveolar bone dimensions suboptimal, particularly when the comprehensive treatment plan involves dental implant therapy. When implant therapy is planned, human and animal studies suggest that a minimum bone thickness of 2mm around the implant is necessary for stability of peri-implant tissues.[5-10] Specifically, an implant platform 5mm in diameter requires a minimum of 9mm in buccolingual ridge width. When the existing ridge width is inadequate, clinicians turn to a number of procedures for localized ridge augmentation. These techniques include guided bone regeneration (GBR) with particulate biomaterials and various membrane types, autogenous and allogeneic block grafts, ridge expansion (ridge split) techniques, osseoinduction using bioactive proteins such as bone morphogenetic protein-2 (BMP-2) therapy with acellular collagen sponge carrier, cellular allografts containing viable cells, and distraction osteogenesis. GBR represents one of the most widely utilized and most studied techniques for augmenting the alveolar ridge prior to or at the time of dental implant placement.

Guided bone regeneration is a well-studied procedure that reliably augments deficient alveolar ridges, and numerous studies suggest that dental implant survival in augmented sites is similar to implant survival in native bone.[12, 15, 28] However, numerous combinations of membranes, bone grafts, biomaterials, bone substitutes, and adjunctive materials are available for GBR procedures. For each specific combination, few studies provide insight into the magnitude of horizontal augmentation that clinicians can realistically expect, particularly with the biomaterials and membranes currently in widespread use. Precise information regarding dimensional changes in ridge volume following guided bone regeneration using specific materials would enhance communication between dental implant surgeons and restorative dentists and optimize the clinical decisions that ensue. Given the critical importance of precise treatment planning in implant dentistry, understanding the possibilities and limitations of implant site development is of clear value.

General description of guided bone regeneration procedures

In GBR, the surgeon typically makes a crestal incision in the area of a deficient alveolar ridge, although lateral incision designs are available.[18,28] Intrasulcular or submarginal incisions extended laterally to allow adequate access without undue intraoperative flap tension. The periosteum is carefully separated from the buccal cortex in a full thickness mucoperiosteal flap. Full thickness reflection extends several millimeters apical to the ridge deficiency. Intramarrow penetrations create discontinuities in the buccal cortical bone, allowing cells from the marrow into the GBR site. Optional tenting screws in the area of the deficiency support the membrane and maintain space in which bone regeneration may occur. A block or particulate autograft (cortical or cancellous) or a biomaterial (mineralized or demineralized allogenic bone, a xenograft, or a synthetic bone substitute) augments the deficient ridge and creates the desired ridge contour. A fitted and trimmed resorbable/absorbable or non-resorbable membrane covers the particulate biomaterial, and the surgeon often fixes the membrane in place using titanium tacks or screws. Some non-resorbable membranes possess titanium struts to enhance space maintenance. To accommodate the added volume of the biomaterial and membrane, one or two vertical incisions and a periosteal releasing incision is usually necessary to assure passive wound closure. In the periosteal releasing incision, a horizontal incision approximately 1.5mm deep through the fibrous layer of the periosteum allows ample flap advancement. The two margins of the incised periosteum (coronal and apical) are readily apparent on the internal aspect of the buccal flap. As the periosteal releasing incision proceeds, a several millimeter gap between apical and coronal periosteal margins appears, with distinct submucosa intervening between the two fibrous segments. Careful suturing assures passive wound closure and mucosal healing by primary intention.[18, 28]

Reported augmentation magnitude in guided bone regeneration procedures

Buser and coworkers performed ridge augmentation on 66 sites in 40 subjects using expanded polytetrafluoroethylene (ePTFE) membranes, membrane fixation screws, autogenous block grafts from the chin or ramus, block fixation/tenting screws, and bone chips. The surgeon intraoperatively used calibers to measure the ridge to the nearest quarter millimeter at a point 2mm apical to the osseous crest at the site of planned implant placement. The distance from the measurement site to the adjacent tooth was recorded in order to repeat the measurement upon re-entry. The mean horizontal augmentation attained was 3.53mm (range 1.0mm to 6.5mm).[18]

Von Arx and Buser augmented 58 deficient alveolar ridge sites in 42 patients using a combination of block grafts with anorganic bovine bone matrix (ABBM) and collagen membranes. Preoperative and postoperative ridge measurement locations were not standardized with a guide or template. For single-tooth edentulous sites, the middle of the edentulous span was utilized. A protocol was utilized to determine measurement locations for multiple adjacent missing teeth and distal extension situations. Measurements were recorded 1mm apical to the osseous crest using calipers to the nearest half millimeter. The calculated mean gain in horizontal ridge thickness was 4.6mm (range 2-7mm).[19]

Geurs et al. laterally augmented 98 potential dental implant sites in 51 patients using synthetic membranes and a combination of DFDBA and cortical cancellous chips in a thermoplastic biologic carrier. The alveolar ridge was measured at a single horizontal position along the deficient ridge both at the crest and 4mm apical to the crest before augmentation and at re-entry. The ridge width increased from 2.4mm to 5.2mm at the crest and from 4.4mm to 7.5mm at a vertical position 4mm apical to the crest.[20]

Beitlitum and coworkers performed GBR utilizing a ribose cross-linked collagen membrane and FDBA with or without the addition of autogenous bone chips in a bi-layered grafting technique. There were 27 subjects in the FDBA group and 23 subjects in the bi-layered graft group. Addition of autogenous bone chips did not statistically enhance horizontal or vertical ridge augmentation. The mean horizontal ridge augmentation was 5.0 mm and 3.6 mm for the FDBA and bilayered graft groups, respectively. During the GBR procedure, the minimum ridge width was measured clinically, and the point of measurement was indexed to the nearest tooth or implant for repeat measurement at the second surgery (implant placement or implant uncovering).[21]

Urban and colleagues published a prospective GBR case series utilizing a resorbable polymer membrane and particulate autogenous bone with or without addition of anorganic bovine bone. Twenty-five surgical sites were evaluated in 22 subjects, with 58 implants placed after GBR healing. Intrasurgical initial (at GBR surgery) and final (prior to implant placement) horizontal ridge width was recorded using calipers at a single point, 2mm apical to the osseous crest. The mean gain in ridge width following GBR was 5.56mm. The implant survival rate was 100 percent after an average of 45.88 months of follow-up.[17]

Block and coworkers evaluated a series of 12 patients who received GBR procedures in the anterior maxilla using particulate bovine xenograft and resorbable membranes. Eight patients received collagen membranes placed under the flap (not fixed with tacks). Four patients received polyglyolic acid/polylactic acid (PGA/PLA) foils fixed with PGA/PLA tacks. The width of the alveolar ridge was measured at three vertical positions from the osseous crest (designated as crestal, midway, and apical ridge thickness) using an iCAT CBCT scanner (Imaging Sciences International). CBCT images were acquired at 5 time points (pre-operatively, immediately after augmentation, 3 to 6 months after augmentation, immediately after implant placement, and after osseointegration). At the crest, the mean change in ridge with was minimal (< 1mm) at all postoperative time points. At the longest postoperative time point, the mean changes in ridge width at the midway and apical vertical positions were 2.69mm and 2.75mm, respectively.[24]

Summary

Previous research has established that buccal peri-implant bone thickness of at least 1.9 mm is required for peri-implant tissue stability.[5-10] GBR is a widely accepted technique in augmenting atrophic ridges prior to implant placement. Most authors reporting GBR treatment outcomes have focused on dental implant survival and success rates, radiographic crestal bone stability, or complication rates associated with GBR procedures.[3, 12, 13, 14] Data characterizing the anticipated buccal peri-implant bone thickness following GBR are lacking.

Materials and Methods

Ethical guidelines

This protocol was reviewed and approved by the Regional Health Command Central (Provisional) Human Research Protections Office, Fort Sam Houston, Texas, United States (Ref. #C.2017.006e) and was determined to be exempt from regulatory requirements of 32CFR§219.

Inclusion and exclusion criteria

CBCT images acquired from patients undergoing GBR procedures at Tingay Dental Clinic, Fort Gordon, Georgia, United States, from July 1, 2012, to November 7, 2016, were assessed in this study. All images were acquired using a single CBCT scanner (3D Accuitomo 170, J. Morita, Kyoto, Japan) in the routine course of treatment planning for dental implant placement and surgical guide fabrication. CBCT field of view (FOV) was ø 40 x height 40 mm (isotropic 80-µm voxel), ø 60 x height 60 mm (isotropic 125-µm voxel), or ø 100 x height 100 mm (isotropic 250-µm voxel). All scans utilized a 360-degree arc of rotation, peak tube potential 90 kV, current 5 mA, and exposure time 17.5 seconds. The surgeon was a periodontics resident in every case, and all patients were active duty military personnel or eligible military retirees. GBR sites were included in the study if the surgical goal was primarily horizontal ridge augmentation in preparation for dental implant placement and the procedure utilized a dPTFE membrane, with or without titanium reinforcement (Cytoplast, Osteogenics Biomedical, Lubbock, TX) and a mineralized cortical particulate freeze-dried bone allograft (OraGRAFT, Lifenet Health, Virginia Beach, VA). Sites were excluded if no implant was planned, the surgical goal was primarily vertical ridge augmentation, the surgeon employed materials other than a dPTFE membrane and mineralized cortical particulate FDBA, or more than one ridge augmentation procedure had been completed. Patient records were reviewed to confirm the treatment plan and record patient- and procedure-related variables: gender, age, number of missing teeth in site, site type (tooth-bounded versus terminal position in arch), dental arch (mandibular or maxillary), arch location (anterior or posterior), smoking status, titanium reinforcement in the membrane, membrane fixation, and tenting screw use. The timing of CBCT image acquisition varied considerably due to patient military responsibilities and the clinical judgement of the individual staff periodontist covering the case.

Virtual implant placement

A tapered bone-level implant system (OSSEOTITE Tapered Certain, Zimmer Biomet, Warsaw, IN) was selected to establish virtual implant fixture dimensions, which were entered into the CBCT system software [i-Dixel (version 2.3.0.3), J. Morita, Kyoto, Japan)]. Maxillary central incisor sites and all cuspid and bicuspid sites received virtual fixtures with 4.1-mm platform diameter. All molar sites received virtual implants with 5.0-mm platform diameter (Table 1). Mandibular incisor and maxillary lateral incisor sites received virtual implants with 3.4-mm platform diameter. Implant length (8.5 mm, 10 mm, 11.5 mm, or 13 mm) was selected based on proximity to adjacent structures utilizing a 2-mm safety margin. A single examiner (DJP) positioned virtual implants in the intended positions. Care was taken to place virtual fixtures according to defined constraints. Platform depth was established 3 mm apical to adjacent cementoenamel junctions (CEJ). The proper faciolingual implant position was selected based on individual patient occlusion (typically centered on a line connecting the central grooves of adjacent posterior teeth or oriented between the incisal edge and cingulum of adjacent anterior teeth). Mesiodistally, virtual fixtures were placed at least 2 mm from adjacent teeth and 3 mm from adjacent implants. The examiner did not perform any of the GBR procedures included in this study and was blind to surgeon identity.

Table 1: Standardized virtual implant platform diameters for various tooth types

<table>
<tr><th colspan="3">Implant platform diameter</th></tr>
<tr><th>3.4 mm</th><th>4.1 mm</th><th>5.0 mm</th></tr>
<tr><td>Mandibular incisors</td><td>Canines</td><td rowspan="3">Molars</td></tr>
<tr><td>Maxillary lateral incisors</td><td>Premolars</td></tr>
<tr><td></td><td>Maxillary central incisors</td></tr>
</table>

CBCT image evaluation

CBCT images were analyzed using the capture station measurement tools. The method of positioning CBCT images prior to measurement described by Block and colleagues was adapted for use in this study.[24] Landmarks such as the occlusal plane, the nasal spine, the floor of the maxillary sinus, the inferior border of the mandible, the mandibular canal, the mental foramen, adjacent teeth, and dental restorations were used to place images in anatomic position and set the spline of the alveolar ridge. The fixed metric scale included in the CBCT system software was used to determine the vertical level of measurement. Baseline ridge width was estimated by measuring the distance between external buccal and lingual cortical surfaces 2 mm apical to the osseous crest in the mesiodistal center of the GBR site. Cross-sectional CBCT images of the ridge (perpendicular to the arch form) at the centers of virtual implants were selected for assessment, and virtual implant buccal bone thickness was measured horizontally 1 mm apical to the platform. The zoom feature in the CBCT system software was used to enlarge images to 400 percent in order to confirm start and end points of linear measurements. Example measurements and the associated clinical photos at implant surgery are shown in Figure 1. The examiner recorded zero buccal bone thickness at sites where the standardized platform depth (3 mm apical to adjacent CEJs) resulted in > 1 mm supracrestal platform position (Figures 1E and 1F). Ten sites were randomly selected for repeat measurement by the primary examiner in order to conduct intra-examiner reliability analysis. A second investigator (DTS) measured virtual implant buccal bone thickness using a separate sample of ten randomly selected sites in order to conduct inter-examiner reliability analysis.

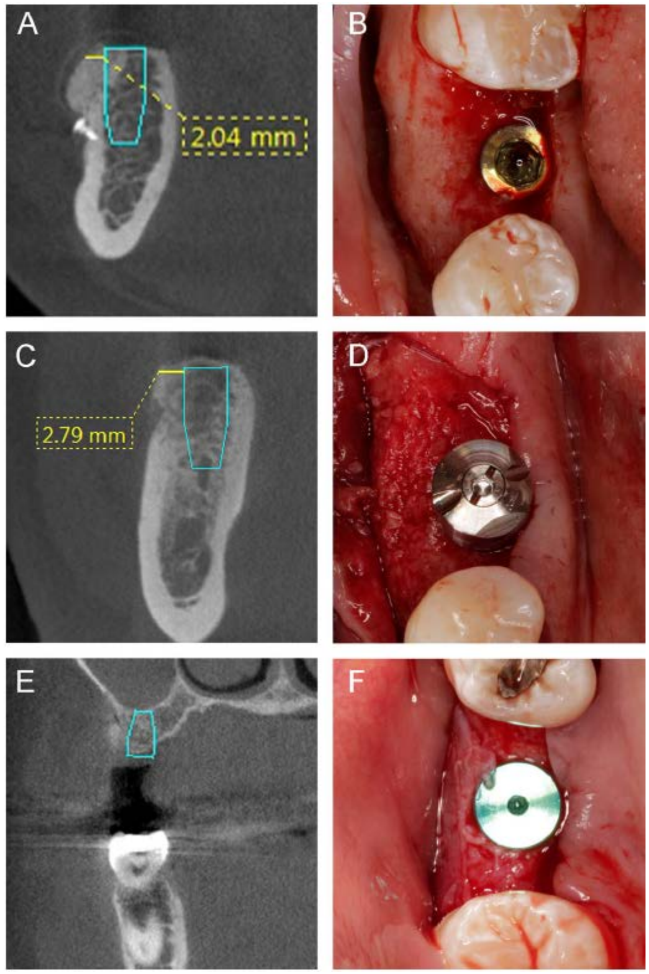

Figure 1. A and B: Virtual implant buccal bone thickness measurement and corresponding clinical photo at re-entry surgery (patient S2, tooth #30 area, FOV Ø 100 × height 100 mm, 250 μm voxel). The barrier membrane and fixation screw are apparent in the CBCT image. The membrane remained in place until implant placement ≈ five months following GBR. C and D: Virtual implant buccal bone thickness measurement and corresponding clinical photo at re-entry surgery (patient S52, teeth #30 and #31 area, FOV Ø 60 × height 60 mm, 125 μm voxel). The GBR site was in the terminal position in the mandibular arch. The barrier membrane in this case was removed before implant placement. Implant surgery occurred ≈ four months following GBR. E and F: Virtual implant with corresponding clinical photo at re-entry surgery (patient S57, tooth #3 area, FOV Ø 100 × height 100 mm, 250 μm voxel). The standardized virtual implant platform position resulted in > 1 mm supracrestal placement, with conspicuous palatal deficiency. Zero buccal bone thickness was recorded 1 mm apical to virtual implant platform. Ridge assessment was “satisfactory” (implant actually placed, additional augmentation performed at implant surgery ≈ five months following GBR).

Alveolar ridge assessment

Based on review of patient records, an alveolar ridge classification was assigned for each of the 84 virtual implant sites: good (no additional augmentation required at implant surgery), satisfactory (able to place the implant with additional augmentation at implant surgery), or unsatisfactory (inadequate post-GBR ridge volume for dental implant placement). This portion of the study relied upon documentation of actual implant placement, with or without additional grafting at the time of implant surgery, rather than virtual implant assessment on the CBCT image.

Statistical analyses

Descriptive and inferential statistical analyses for all qualitative and quantitative variables were performed using statistical software (SAS 9.4, SAS Institute, Cary, NC). An alpha level of 0.05 was used to assess statistical significance. Two-sample t-tests were performed to evaluate differences in post-GBR buccal bone thickness adjacent to virtual dental implants for each dichotomous patient- and procedure-related variable. Where three or more categories were present, a one-way analysis of variance (ANOVA) was used. If the overall ANOVA was significant, a Tukey multiple comparisons test was used to determine which pairwise groups were different. Fisher's exact test was used to examine associations between categorical variables. Pearson's correlation coefficient was calculated to examine associations between quantitative variables. Lin's concordance correlation coefficient (CCC) was used to assess inter-examiner reliability, and an intra-class correlation coefficient (ICC) was calculated to assess intra-examiner reliability.

Results

Characteristics of study population

Eighty-four individuals met inclusion criteria for this study. No patient had more than one GBR site. In total, the identified GBR sites comprised 111 planned implant locations. Twenty-three patients had two planned implant locations, and two patients had three planned implant locations within the GBR site. For individuals with multiple planned implant sites, one implant location was randomly selected for inclusion in this analysis. Thus, each patient contributed only one virtual implant. Characteristics of the study population, CBCT images, and virtual dental implants placed are summarized in Table 2.

Table 2. Characteristics of study population

Sex	54 Male (64%)	30 Female (36%)
Age	Mean 39.3 ± 10.6, range 21 to 66	
Smoking status	3 undetermined (4%)	81 non-smokers (96%)
Site type	13 anterior (15%)	71 posterior (85%)
Dental arch	22 maxillary (26%)	62 mandibular (74%)
GBR site terminal position in arch	26 sites in terminal position (31%)	58 sites bounded by teeth (69%)
Number of missing teeth at GBR site	55 single missing tooth (65%)	29 multiple missing teeth (35%)
Tenting screw use	20 sites utilized tenting screws (24%)	64 sites did not use tenting screws (76%)
Membrane fixation	79 sites with membrane fixation (94%)	5 sites not using membrane fixation (6%)
Membrane reinforcement	52 Ti-reinforced membranes (62%)	32 non-reinforced membranes (38%)
Membrane removal before implant placement	32 membranes removed before implant (38%)	52 membranes removed at implant surgery (62%)
Interval between GBR and CBCT image (months)	Mean 6.2 ± 6.1, range 1.2 to 52.0	
Estimated baseline ridge width (mm)	Mean 5.6 ± 1.7, range 1.7 to 11.7	
FOV Ø 40 × height 40 mm CBCT images	6 (7%)	
FOV Ø 60 × height 60 mm CBCT images	74 (88%)	
FOV Ø 100 × height 100 mm CBCT images	4 (5%)	

FOV: field of view; CBCT: cone-beam computed

Factors influencing post-GBR buccal bone thickness at virtual dental implant sites

Individual patient data are presented in table 5. Mean buccal bone thickness adjacent to virtual dental implants was 2.24 ± 1.01 mm in this study population. Virtual implant buccal bone thickness fell in the 2 to 3 mm range for the majority of sites (Figure 2).

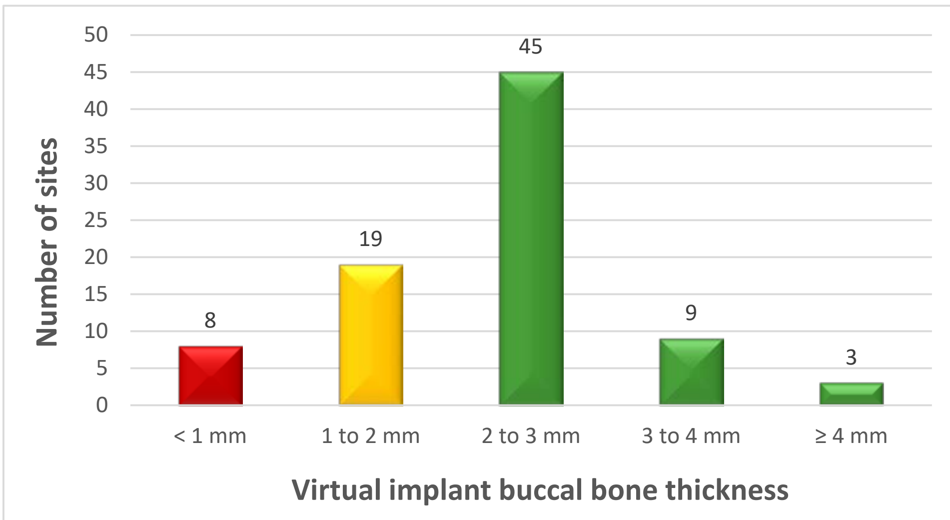

Figure 2. Frequency analysis of buccal bone thicknesses observed at virtual dental implant sites following GBR surgery

Analyses of qualitative patient- and procedure-related variables are presented in Table 3. Sites with membrane fixation had significantly greater virtual implant buccal bone thickness than those without membrane fixation (2.31 ± 0.96 versus 1.15 ± 1.25 mm, $p = 0.012$). Additionally, virtual implant buccal bone thickness was significantly correlated with the estimated initial ridge width ($r = 0.43$, $p < 0.0001$).

Table 3. Influence of qualitative patient- and procedure-related variables on buccal bone thickness adjacent to virtual dental implants following GBR surgery

Variable	N	Mean	SD	Min	Max	df	t	p-value[1]
Sex						82	0.04	0.970
Male	54	2.24	1.07	0	5.06			
Female	30	2.25	0.90	0	3.97			
Distal Extension						79.38	-0.71	0.480
Yes	26	2.33	0.61	1.22	3.8			
No	58	2.20	1.14	0	5.06			
Site						82	-1.03	0.305
Anterior	13	1.97	1.30	0	4.77			
Posterior	71	2.29	0.95	0	5.06			
Tent Screw Use						82	-1.39	0.169
Yes	20	2.51	0.79	1.66	4.77			
No	64	2.15	1.06	0	5.06			
Titanium Struts						82	1.23	0.222
Yes	52	2.13	0.98	0	5.06			
No	32	2.41	1.04	0	4.77			
Membrane Fixation						82	-2.58	0.012
Yes	79	2.31	0.96	0	5.06			
No	5	1.15	1.25	0	2.82			
Premature Membrane Removal						82	1.61	0.112
Yes	32	2.02	0.93	0	3.97			
No	52	2.38	1.03	0	5.06			

[1] *Two-sample t-test*

Age, gender, number of missing teeth in GBR site, site type (tooth-bounded versus terminal position in the arch), dental arch (maxillary or mandibular), arch location (anterior or posterior), tenting screw use, titanium strut reinforcement, and membrane removal prior to implant placement were not significantly associated with virtual implant buccal bone thickness in this population. The interval between GBR surgery and CBCT image acquisition ranged from 1.2 to 52.0 months with a mean of ≈ six months (Appendix 1 and Table 2). Two-thirds of the CBCT images were acquired between three and seven months following GBR surgery. No significant correlation was found between maturation time (interval between GBR surgery and CBCT image acquisition) and virtual implant buccal bone thickness ($r = -0.136$, $p = 0.708$).

Intra-examiner and inter-examiner reliability analysis

Strong agreement was noted comparing repeated primary-examiner buccal bone thickness measurements and comparing primary- to secondary-examiner measurements. The calculated CCC was 0.973 (substantial inter-examiner reliability), and the ICC was 0.930 (excellent intra-examiner reliability).

Alveolar ridge assessment

Over 96% of the dental implant sites were categorized as "good" or "satisfactory," indicating the GBR procedures resulted in actual dental implant placement with high frequency (Figure 3).

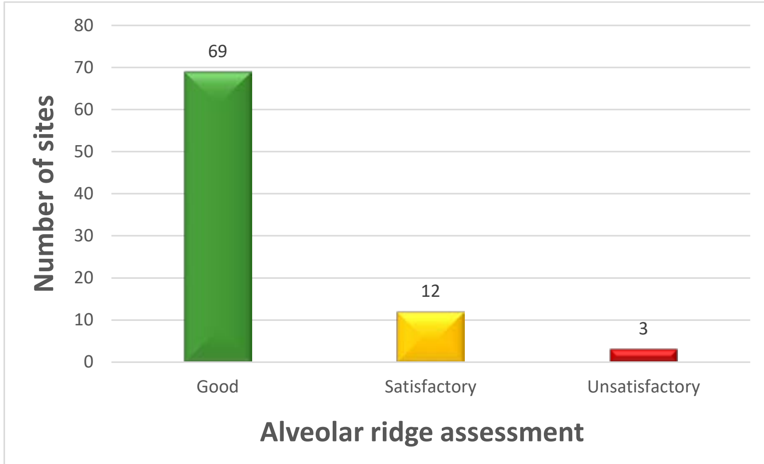

Figure 3. Number of sites assessed as good, satisfactory, and unsatisfactory

Eighty-one of 84 planned implants were actually placed. Three planned implants (< 4%) were not placed due to insufficient ridge augmentation following GBR. At 12 sites (14%), additional grafting was performed at implant surgery. Alveolar ridges assessed as "good" had significantly higher virtual implant buccal bone thickness compared with those assessed as "satisfactory" or "unsatisfactory" (Table 4). These sites also exhibited significantly larger estimated initial ridge width values compared with other sites. Additionally, ridge assessment was significantly associated with membrane fixation ($p = 0.026$). In particular, ≈ 85% of sites with membrane fixation received ridge assessment of "good," while only 40% of sites without membrane fixation received the "good" assessment. Age, gender, number of missing teeth in GBR site, site type (tooth-bounded versus terminal position in the arch), dental arch (maxillary or mandibular), arch location (anterior or posterior), tenting screw use, titanium strut reinforcement, and membrane removal prior to implant placement were not significantly associated with ridge assessment in this population.

Table 4. Analysis of ridge assessment with quantitative variables

Variable	RIDGE ASSESSMENT GOOD (N = 69) Mean	GOOD (N = 69) SD	SATISFACTORY (N = 12) Mean	SATISFACTORY (N = 12) SD	UNSATISFACTORY (N = 3) Mean	UNSATISFACTORY (N = 3) SD	df	F	p-value[1]
Age	40.07	10.17	35.92	12.63	35.00	12.17	2	1.04	0.357
Baseline ridge width	5.85	1.64	4.52	1.21	3.16	2.16	2	7.03	0.002
Missing teeth in site	1.49	0.72	1.25	0.62	1.33	0.58	2	0.65	0.524
Virtual implant buccal bone thickness	2.55	0.77	0.91	0.72	0.48	0.84	2	31.7	<.0001

[1]*One-way ANOVA test*

Table 5. Individual subject data

Subject	Sex [M/F]	Age [Integer]	Terminal position in arch [Y/N]	Anterior (A), Posterior (P)	Maxilla (Mx), Mandible (Mn)	Number of missing teeth in site [#]	Tenting screw [Y/N]	Titanium struts [Y/N]	Membrane fixation [Y/N]	Premature membrane removal [Y/N]	Healing time at post-GBR image [days]	Ridge Assessment [Good/Satisfactory/Unsatisfactory]	Virtual Implant buccal bone thickness [mm]
S1	F	30	N	P	Mn	1	N	N	N	Y	341	SATISFACTORY	0.9
S2	M	42	N	P	Mn	1	N	N	Y	N	51	GOOD	2.04
S3	F	37	N	P	Mn	2	Y	Y	Y	N	80	GOOD	1.66
S4	F	37	Y	P	Mn	1	N	Y	Y	N	121	GOOD	2.49
S5	M	49	N	P	Mn	1	N	Y	Y	N	208	GOOD	2.71
S6	M	48	N	P	Mn	1	N	Y	Y	N	132	GOOD	0
S7	M	40	N	P	Mn	1	N	Y	Y	N	170	GOOD	2.41
S8	F	47	Y	P	Mn	2	N	Y	Y	N	263	GOOD	2.7
S9	M	44	N	P	Mn	1	N	Y	Y	N	124	GOOD	2.56
S10	M	21	N	A	Mn	1	N	N	N	N	205	UNSATISFACTORY	0
S11	M	26	N	P	Mn	1	N	N	N	Y	136	GOOD	2.02
S12	M	43	N	A	Mn	2	N	Y	Y	N	78	UNSATISFACTORY	0
S13	M	49	N	P	Mn	1	Y	Y	Y	N	152	SATISFACTORY	1.66
S14	M	21	N	P	Mn	1	N	N	Y	N	140	GOOD	3.07
S15	F	27	Y	P	Mx	1	N	Y	Y	N	110	GOOD	1.81
S16	F	27	Y	P	Mn	1	N	Y	Y	N	199	GOOD	2.8
S17	M	55	Y	P	Mn	1	N	Y	Y	N	72	GOOD	1.66
S18	M	55	Y	P	Mn	2	N	Y	Y	Y	39	GOOD	2.39
S19	F	26	N	P	Mn	1	N	Y	Y	N	54	GOOD	2.82
S20	F	25	N	P	Mn	1	N	Y	Y	Y	84	GOOD	2.5
S21	M	43	N	P	Mn	1	Y	N	Y	N	215	GOOD	2.61
S22	M	42	N	A	Mx	1	Y	N	Y	N	160	GOOD	4.77
S23	M	44	N	P	Mn	1	N	N	Y	N	257	GOOD	2.47
S24	M	37	N	A	Mx	1	N	N	Y	N	168	GOOD	2.43
S25	M	36	Y	P	Mx	1	N	Y	Y	N	291	GOOD	2.05
S26	M	31	N	A	Mn	1	Y	N	Y	N	150	GOOD	2.75
S27	M	34	Y	P	Mx	1	N	Y	Y	N	187	GOOD	3.01
S28	M	41	N	P	Mn	1	N	Y	Y	N	257	UNSATISFACTORY	1.45
S29	F	58	Y	P	Mx	3	N	Y	Y	N	140	GOOD	3.46
S30	M	38	Y	P	Mn	1	N	Y	Y	N	370	GOOD	1.22
S31	F	28	N	P	Mx	2	N	Y	Y	Y	420	SATISFACTORY	1.45
S32	M	39	N	P	Mn	1	N	Y	Y	N	55	GOOD	5.06
S33	M	56	N	A	Mn	3	Y	Y	Y	Y	415	GOOD	2.3
S34	M	56	N	A	Mn	3	Y	Y	Y	Y	415	GOOD	2.28
S35	F	63	N	P	Mn	2	N	N	Y	Y	239	GOOD	2.72
S36	M	37	N	A	Mn	4	N	N	Y	N	141	GOOD	3.15
S37	M	34	N	P	Mn	1	Y	Y	Y	N	152	GOOD	2.31
S38	M	25	N	A	Mx	1	N	N	Y	Y	146	SATISFACTORY	1.13
S39	M	52	Y	P	Mx	2	N	N	Y	Y	165	GOOD	1.73
S40	M	33	N	p	Mx	1	N	N	Y	Y	94	GOOD	3.61
S41	M	49	N	P	Mn	2	N	N	Y	Y	178	GOOD	2.22
S42	M	39	N	P	Mn	1	N	Y	Y	N	94	GOOD	2.34

Table 5. Continued

Subject	Sex [M/F]	Age [Integer]	Terminal position in arch [Y/N]	Anterior (A), Posterior (P)	Maxilla (Mx), Mandible (Mn)	Number of missing teeth in site [#]	Tenting screw [Y/N]	Titanium struts [Y/N]	Membrane fixation [Y/N]	Premature membrane removal [Y/N]	Healing time at post-GBR image [days]	Ridge Assessment [Good/Satisfactory/Unsatisfactory]	Virtual Implant buccal bone thickness [mm]
S43	M	35	Y	p	Mn	1	N	N	Y	N	151	GOOD	2.17
S44	M	29	N	P	Mn	1	N	Y	Y	Y	148	SATISFACTORY	0
S45	M	49	N	P	Mx	2	N	Y	Y	N	35	GOOD	2.95
S46	M	39	Y	p	Mn	1	N	Y	Y	N	167	SATISFACTORY	1.69
S47	M	39	Y	p	Mn	1	N	N	Y	N	110	GOOD	2.93
S48	M	37	N	P	Mn	1	Y	N	Y	N	152	GOOD	4.1
S49	M	33	N	P	Mn	1	N	Y	Y	Y	96	SATISFACTORY	1.69
S50	F	64	N	A	Mn	1	Y	N	Y	N	1559	GOOD	1.93
S51	M	38	N	P	Mn	1	Y	Y	Y	N	140	GOOD	3.34
S52	F	47	Y	p	Mn	2	N	Y	Y	Y	180	GOOD	2.79
S53	M	48	N	A	Mn	1	N	Y	Y	N	123	GOOD	2.49
S54	M	22	Y	P	Mn	2	N	Y	Y	Y	96	GOOD	2.68
S55	M	22	Y	P	Mx	2	N	Y	Y	Y	205	GOOD	2.03
S56	F	42	N	P	Mn	3	N	Y	Y	N	161	GOOD	2.56
S57	F	66	N	P	Mx	1	N	Y	Y	Y	105	SATISFACTORY	0
S58	M	36	N	P	Mx	1	N	Y	Y	N	131	SATISFACTORY	0
S59	F	27	Y	P	Mx	1	N	Y	Y	N	110	SATISFACTORY	1.41
S60	F	41	Y	P	Mn	2	N	Y	Y	Y	240	GOOD	1.98
S61	F	44	N	P	Mx	2	N	Y	Y	N	143	GOOD	2.92
S62	F	33	N	P	Mn	1	N	Y	Y	Y	182	GOOD	3.97
S63	F	33	N	P	Mn	1	N	Y	Y	N	194	GOOD	2.96
S64	M	30	N	P	Mn	1	N	Y	Y	N	176	GOOD	2.32
S65	M	30	N	P	Mn	2	Y	Y	Y	Y	110	GOOD	1.68
S66	M	40	N	P	Mn	1	Y	Y	Y	Y	153	GOOD	2.1
S67	F	38	Y	P	Mn	1	Y	Y	Y	Y	287	GOOD	2.35
S68	M	43	Y	P	Mn	3	N	Y	Y	Y	115	GOOD	2.28
S69	F	47	N	P	Mn	2	N	Y	Y	Y	700	GOOD	2.39
S70	M	22	N	A	Mn	1	N	N	Y	Y	210	SATISFACTORY	1.01
S71	F	44	N	P	Mx	2	Y	Y	Y	Y	166	GOOD	2.37
S72	F	41	N	P	Mx	1	N	Y	Y	Y	109	GOOD	1.47
S73	M	23	N	A	Mx	2	N	Y	Y	N	223	GOOD	1.43
S74	F	24	N	P	Mx	1	N	N	Y	N	132	GOOD	3.33
S75	F	24	N	P	Mn	1	Y	N	Y	N	63	GOOD	2.76
S76	M	32	N	P	Mn	1	N	N	N	Y	100	GOOD	2.82
S77	M	56	Y	P	Mn	1	Y	N	Y	N	118	GOOD	2.39
S78	M	41	N	P	Mn	1	N	N	Y	N	161	GOOD	2.54
S79	F	47	N	P	Mn	3	N	N	N	Y	126	SATISFACTORY	0
S80	F	47	Y	P	Mx	2	Y	N	Y	N	217	GOOD	2.25
S81	F	47	Y	P	Mn	3	Y	N	Y	Y	172	GOOD	2.76
S82	F	47	Y	P	Mn	2	Y	N	Y	N	142	GOOD	1.84
S83	M	46	N	P	Mn	1	N	N	Y	Y	109	GOOD	2.91
S84	M	44	Y	P	Mx	2	N	N	Y	N	42	GOOD	3.8

Discussion

Results of any retrospective observational study must be placed in context of the limitations present. The sample in the present report consisted of active duty and retired military personnel. Surgeons in all cases were periodontics residents, and a specific membrane/biomaterial combination was used. Observations under the conditions described may not be generalizable to other patient populations treated with different biomaterials by experienced periodontists in private practice settings. Additionally, the primary outcome variable in this study—virtual implant buccal bone thickness—is a surrogate endpoint. Perfect maintenance of alveolar ridge volume and buccal bone thickness after implant function would not be anticipated. Moreover, obtaining serial CBCT images of each site would provide much more information and allow more impactful conclusions. Even so, retrospective observational studies are worth the effort. In the present investigation, the examiner was able to make a relatively large number of observations and assess a parameter of practical importance without any additional radiation exposure to patients.

Requirements for bone regeneration include wound closure with primary intention healing, maintenance of a space in which regeneration may occur, and wound stability.[26] With adequate space provision, bone regeneration is possible in membrane-protected defects without need of any graft or biomaterial.[11,27-29] When a graft or biomaterial is used in GBR, autogenous bone is considered the gold standard.[30,31] Additionally, bone morphogenetic protein-2 (BMP-2) has been shown to support robust bone formation in a variety of procedures.[32] In animal models, application of BMP-2 and space provision has been shown to produce a regenerate histologically similar to immediately adjacent native bone.[33,34] On the contrary, histologic assessments of GBR and ridge preservation procedures utilizing autogenous grafts as well as allogeneic or xenogeneic bone derivatives predominantly exhibit a mixture of new vital bone, residual graft/biomaterial, and scar-like connective tissue.[35-43] The present study did not include histologic assessment and provides no information on the composition of the augmented ridge or cellular events during healing. Neither does this report provide any insight into temporal stability of the augmented ridge dimensions.

Lack of standardization in the timing of CBCT image acquisition is another study limitation. Most of the CBCT images were acquired three to seven months following GBR. Reasons for unusually short or long intervals between GBR and implant surgery were not always apparent. Some patients in the treated population have limited time remaining at Fort Gordon prior to reassignment, and some patients need to complete dental treatment in relatively brief periods between extended intervals without access to care. Accommodation of dynamic patient schedules probably accounted for most of the variation in timing of CBCT image acquisition. GBR sites imaged early may have contained more residual FDBA particles and less new vital bone, although histologic analyses were not included in this study. Sites imaged late were subject to resorption for a longer period, presumably reducing horizontal alveolar ridge dimensions. However, no significant correlation between maturation time and virtual implant buccal bone thickness could be identified under the described conditions.

Virtual dental implant placement is not an exercise free of subjectivity. However virtual implants in this study were placed using defined parameters for three-dimensional positioning. Virtual fixtures were placed for each individual patient in the same manner by which implants are typically planned in the course of patient care, with strict attention to the described constraints. Since virtual implants were carefully positioned 3 mm apical to adjacent CEJs, platforms remained supracrestal in sites with vertical ridge deficiency. The vertical level of measurement was 1 mm apical to the virtual implant platform, and zero buccal bone thickness was recorded if the platform remained > 1 mm supracrestal. Zero buccal bone thickness was recorded at seven of 84 sites (8%). This measurement protocol avoided artificially inflating virtual implant buccal bone thickness by increasing the platform depth but reduced the mean virtual implant buccal bone thickness reported. Because of the relatively large number of observations, excluding sites with zero buccal bone thickness raises mean thickness to 2.44 ± 0.78 mm, an increase of only 0.2 mm.

The membrane was removed prior to actual dental implant placement at 38% of sites evaluated. Early membrane removal was not identified as a factor influencing virtual implant buccal bone thickness in this population under the described conditions. Membrane exposure can lead to bacterial contamination of the site, infection, and treatment failure.[44] However, the presence of a post-GBR CBCT image suggests the treating practitioner planned to place a dental implant. Thus, the study may have been biased toward clinically successful procedures. Failed GBR sites would be unlikely to receive CBCT imaging in preparation for implant placement. The reason for early membrane removal was not discernible in all cases. In some situations, the surgeon may have elected to remove the membrane before implant placement because the patient would have no access to follow-up for an extended period. Additionally, exposed dPTFE membranes have been shown to adequately protect regenerative biomaterials for up to four weeks.[45-47] Inability of bacteria to penetrate the 0.2-micron pores in the membrane may partially explain the lack of influence of early membrane removal observed in this study.[48]

The ridge assessment analysis in this study may indicate that practitioners can anticipate greater buccal bone thickness at the time of implant placement when the initial ridge deficiency is less severe. This possibility seems intuitive. However, estimated baseline ridge width is a crude measure of the amount of augmentation needed. Some alveolar ridges are wide, even though most of the ridge volume is positioned toward the lingual/palatal. Also, remodeling of the native cortical bone following GBR may have produced variance between estimated and “true” initial ridge width values.

The appropriateness of CBCT imaging for linear alveolar bone measurements is well-established. The CBCT scanner utilized in the present study was shown to have a mean absolute linear measurement error of 0.14 ± 0.07 mm in performance testing using a standardized anthropomorphic target (human skull surrounded by polyurethane material to simulate soft tissue).[49] This mean error, the third lowest among eight tested CBCT scanners, was determined while utilizing FOV ø 170 x height 120 mm (250-µm voxel) and 360-degree arc of rotation.[49] Anteroposterior and mediolateral distances measured in the study were ≈ 120 mm, and superoinferior distances were ≈ 25 mm.[49] Every measurement error involving this scanner represented a slight underestimation of the accepted value.[49] Tendency toward consistent underestimation or overestimation of linear distances may be related to the scanner manufacturer and model as well as the acquisition parameters utilized.[49] Spatial resolution is diminished with large voxel size, and excessively reducing the number of basis projections has been associated with deteriorated image quality and diagnostic performance for some purposes.[50] Cook and colleagues found strong agreement between CBCT and direct linear measurements on cadaver heads irrespective of voxel size (200 µm or 300 µm), scan time (4.8 seconds, 8.9 seconds, or 28.9 seconds), and number of basis projections (180- or 360-degree rotation; 169, 309, or 619 pulses).[51] Mean CBCT measurements were not statistically different than mean direct measurements, regardless of acquisition parameters.[51] Over the range of settings utilized in the present study, FOV and voxel size appear to have little effect on linear measurement accuracy and standard deviation.[49-51] The practitioners performing GBR in this study selected scan settings based on individual patient treatment needs. Limiting the analysis to a particular FOV did not appear necessary.

The present study suggests GBR procedures utilizing dPTFE membranes and mineralized cortical particulate FDBA produce adequate bone volume for dental implant placement with high reliability, and in the majority of cases, favorable buccal bone thickness can be anticipated at the time of implant placement. However, the analysis implies additional bone augmentation at implant surgery may be necessary at ≈ 30% of implant sites in order to achieve predictable stability of peri-implant tissues.[8-11] Only 14% of sites analyzed actually received additional bone augmentation. At least two phenomena may account for this variance. In some CBCT images, the alveolar ridge presented a robust horizontal dimension if the implant could be placed slightly deeper than 3 mm from adjacent CEJs. Indeed, some patients exhibited a "satisfactory" ridge (implant actually placed, additional grafting needed) even though the recorded virtual implant buccal bone thickness was zero (measured 1 mm apical to the virtual implant platform). Some practitioners may have compromised by placing the fixture slightly deeper or accepting > 1-mm supracrestal platform position. Additionally, some practitioners may have elected not to perform additional augmentation in borderline cases, particularly when the fixture was not in the esthetic zone and the peri-implant mucosa was of favorable quality.

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