**Guided Bone Regeneration for Horizontal Maxillary Alveolar Ridge Augmentation Using Patient-Specific Solid Titanium Barriers: A Case Series**

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**Purpose:** To assess the radiographic and histomorphometric outcomes of horizontally augmented maxillary alveolar ridges using solid nonperforated customized titanium barriers. **Materials and Methods:** This case series study included patients who received guided bone regeneration treatment in the anterior maxillary esthetic zone (eight patients, 18 dental implants) using patient-specific solid titanium barriers loaded with a mix of autogenous and xenogenic particulate bone grafts. A radiographic comparison between three time periods (immediately postoperative, 4 months, and 10 months) included software-aided calibration of the linear changes in the horizontal dimensions on CBCT cross-sectional cuts after being standardized. Bone core specimens were retrieved for histomorphometric analysis by the time of implant insertion. **Results:** Wound healing was uneventful, except for two patients who showed soft tissue breakdown that did not affect the outcome. There was a statistically significant difference between the mean horizontal bone change at the different time intervals \((P < .001)\), with a 79.6% ± 29.2% mean area of newly formed bone. **Conclusion:** GBR using customized solid titanium barriers appears to be efficient and promising concerning the final horizontal bone gain and the quality of the augmented sites. Int J Oral Maxillofac Implants 2022 October 6. doi: 10.11607/jomi.9603. Online ahead of print.

**Keywords:** alveolar ridge, anterior maxilla, CAD/CAM, computer guided, guided bone regeneration (GBR), horizontal bone gain, nonperforated meshes, patient-specific barrier

The maxillary alveolar ridge is a tooth-dependent, stress-bearing area that usually flourishes with tooth eruption and diminishes with tooth removal. As a normal sequela of tooth extraction at the anterior maxilla, the alveolar bone resorbs horizontally and vertically, with a greater extent of horizontal deficiency mainly directed to the thin labial aspect; this relocates the alveolar ridge in a palatal direction and affects its capacity to receive root-form dental implants.\(^1\)\(^2\)

Various techniques have been adopted for reconstructing horizontal ridge deficiency of the anterior maxilla, including ridge splitting,\(^3\) autogenous block bone grafting,\(^4\) and guided bone regeneration (GBR). The GBR technique requires a biocompatible barrier that promotes volumetric stability and adequate vascularity and guards against the seepage of the fibrous tissue components into the concealed particulate graft, preserving its osteogenic capability.\(^5\)\(^6\)

Since expanded polytetrafluoroethylene (e-PTFE) was first introduced in 1969\(^7\) and was later sintered with pores between 5 and 20 mm to provide some periosteal blood infusion, several other barriers have been introduced, including high-density polytetrafluoroethylene (D-PTFE) and resorbable collagen and polymeric membranes. However, all showed mechanical hindrance, as the membrane collapses into the underlying soft tissue defect, leading to subsequent shrinkage of the underlying graft.\(^4\) Therefore, the commercially available titanium meshes in their classic forms were advocated as a gold standard for vertical, horizontal, or even 3D reconstruction of deficient alveolar ridges for their malleability and mechanical integrity, which maintains an unaltered graft space. The violated mesh does not impede the periosteal blood supply; however, it does not restrain fibrous tissue invasion, is difficult to remove surgically, and contributes to soft tissue dehiscence.\(^8\)\(^9\)

Hence, Van Steenberghe et al\(^10\) in 2003 utilized occlusive

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titanium barriers to completely conceal the underlying graft and safeguard the blood clot while simultaneously utilizing the titanium's osteoconductive capability and the high endosteal perfusion of the maxillary and calvarial bones to guide bone regeneration.

The present study employed computer-assisted surgical simulation technology for carrying prefabricated patient-specific solid grade IV titanium fixation devices into the operating room to secure execution of the preplanned virtual dimensions of the regenerated anterior maxillary alveolar ridges by incorporating an equal mix of autogenous cancellous particulate and xenogenic (1:1) bone into the device's occlusive fitting surface. Histomorphometric analysis of the consolidated, regenerated bone graft was conducted to evaluate the percent of newly formed bone, and radiographic analysis of the horizontal bone gain values at different time intervals was performed.

MATERIALS AND METHODS

Patient Selection Criteria
Eight patients, four males and four females ranging in age from 18 to 40 (mean 28.3) years who had markedly deficient postextraction maxillary alveolar ridges, were selected from the outpatient clinic of the Department of Oral Implantology, Faculty of Dentistry, Cairo University. Clinical inspection and digital panoramic interpretation of the maxillary alveolar ridges of the patients indicated bone grafting before placement of root-form dental implants. Patients who smoked and those with a history of failed implants, previous maxillary grafting, local bone pathology, or systemic compromise that would jeopardize the quality of the consolidated graft were excluded. The eight selected patients consented after being comprehensively informed about the surgical intervention and the nature of the study.

Maxillary Ridge Criteria
Sagittal and axial views of the preoperative CBCTs were employed for mapping the height and width of the deficient maxillary ridges. Their exact dimensions were plotted, calibrating the horizontal width from the mid-palatal to midbuccal cortices and the vertical height from the alveolar crest to the basal bone. The selection criteria required ridges less than 3 mm in horizontal width. The clinical mapping of the alveolar ridges, aided by caliper measurement under local anesthesia, confirmed the horizontal dimension of the selected alveolar ridges, which was considered crucial for inclusion.

Study Design
This study represents a case series of eight patients with partial edentulism and atrophic anterior maxillary ridges. It was approved by the Cairo University Faculty of Dentistry's ethics and research committee and was registered on clinicaltrials.gov (no. NCT04049435). All procedures performed were per the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. The study was initiated in July 2019 and ended in June 2021. The selected patients were subjected to a virtual preplanned reconstruction of the deficient anterior maxillary ridges by incorporating an equal mix of autogenous cancellous particulates and xenogenic bone into a solid nonperforated concealing CAD/CAM fixtures titanium barrier. This was secured in place for 4 months, after which it was removed to allow for placement of root-form dental implants. Histologic and histomorphometric analysis of the regenerated graft was conducted by taking bone core specimens prior to implant insertion as well as a radiographic alveolar bone width analysis preoperatively, immediately postoperatively, at 4 months, and at 10 months (ie, 6 months postoperative implant placement).

Virtual Planning and Device Manufacture
Preoperative CBCT was imported in a DICOM file format with a slice thickness and distance of 0.5 mm and zero gantry tilt. This was imported to DICOM viewer software (Mimics Medical 19.0, Materialise) to show axial, coronoal, and sagittal views, producing a 3D model of the patient's skull. Virtual segmentation was then activated using the Exocad software (DentalCAD) by triggering the “Crop Mask” tool to split the maxilla from the whole mask, which isolated and separated the low maxillary alveolar ridges from the surrounding regions.

The virtual isolating concealment was designed to fashion ideal graft dimensions and the carrying capacity of its fitting surface, resulting in the preoperatively planned ridge dimensions. However, the thickness of the virtual barriers was standardized to a uniform thickness of 0.7 mm.

The customized barrier design process implemented virtual contouring of buccal and palatal sheets, creating a gap with ideal dimensions between their fitting surfaces and the deficient maxillary alveolar bone representing the graft confinement space. The virtual augmentation of the device's fitting surface was adopted to justify the prospective ridge proportions after connecting the sheets to establish a solid barrier (Fig 1).

The locations of the devices' fixation screws were virtually selected based solely on cortical, buccal, and palatal bone sufficiency. The screw holes were designed to match the screw heads.

The fabrication of the concealment devices utilized a five-axis milling machine (Coritec 250i, Imes-Icore) with titanium alloy grade IV blocks (Fig 2). The machined
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devices were chemically sterilized before surgery by immersing them in a 2.4% glutaraldehyde solution (Cidex, Johnson & Johnson) for 12 hours, followed by steam sterilization.

Surgical Procedure
All patients’ surgeries were performed under local anesthesia (articaine 4%, 1:100,000 epinephrine, Septodont), applying strict aseptic conditions, with standard scrubbing and draping using povidine-iodine (Betadine, Purdue Products) surgical scrub.

Chin bone harvest. Bilateral mental nerve blocks, as well as field infiltration anesthesia, were administered for homeostasis. A vestibular mucosal incision was made from canine to canine along the mucosa of the lower lip, leaving sufficient labial mucosa attached to the gingiva. After mucosal reflection, the mentalis muscle was sharply incised perpendicular to the symphyseal bones, which were exposed after stripping, elevating, and retracting the muscle fibers. Using an Auto Chip Maker bur (ACM, NeoBiotech), the corticocancellous autogenous particles were collected from the chin and mixed with xenogenic bone graft (UBGEN, granules 0.25 to 1 mm) in a 1:1 ratio. This was loaded into the fitting surface of the machined device (Fig 2a), followed by layered closure of the donor site with Vicryl 000 sutures (Ethicon).

Maxillary bone augmentation. Buccal local anesthetic infiltration and nasopalatine nerve block were administrated. A full-thickness three-line pyramidal mucoperiosteal buccal flap was elevated to expose the labial cortical plate and the palatal plate of bone after severing of the nasopalatine nerve (Fig 3a). Bleeding pinpoints were gently drilled with a small round bur to expose the underlying marrow; for better graft vascularization and consolidation, the device was fixed in place using four to six mini-screws into the planned buccal and palatal invents after being loaded with the graft mix (Fig 3b).

Horizontal periosteal scoring ensured a tension-free closure of the buccal flap in a layered fashion with Vicryl 000 (Ethicon) periosteal sutures and Prolene 0000 (Ethicon) mucosal interrupted sutures.

Second-stage surgery. Four months postoperatively, all the patients were subjected to CBCT scans that revealed the dimensions of the consolidated bone graft and illustrated the suitable size of the prospective dental implants.

Full-thickness buccal and palatal mucoperiosteal flaps were raised under local anesthesia, allowing for removal of the customized barrier, retrieval of bone core specimens from the anterior segments of the reconstructed maxillae utilizing a 3-mm diameter trephine drill (Freiatec), and placement of the implants (Figs 3c and 3d). Finally, the mucosal flap was sutured.

The dental implants (Dual Implant, Titan Industries) were preserved for an additional 6 months to osseointegrate before being uncovered (Fig 3e). A 10-month postoperative CBCT of each reconstruction was taken.

Sample Preparation and Histomorphometric Analysis
The core biopsy specimens were fixed in formalin for 1 week and then decalcified using a combination of ethylenediaminetetraacetic acid (EDTA) and formic acid. After softening, the specimens were longitudinally embedded in paraffin blocks. Three 4-μm-thick sections were cut from each block, mounted on glass slides,
and stained with routine hematoxylin and eosin (H&E). The stained sections were examined using low- and high-power light microscopy (Leica). Quantitative measurements were done with Leica Qwin 500 LTD (Leica Microsystems). Eight of the most representative fields were selected for each specimen, and the bone area percent was measured using a magnification of 200×. The bone area percent was recorded and tabulated.

**Standardizing Radiographic Interpretation and Measuring Bone Gain**

The radiographic calculation of the horizontal bone gain employed the superimposition of the STL files of the preoperative and the immediate, 4-, and 10-month postoperative CBCT cross-sectional cuts. Standardization was achieved by adjusting the long cross-sectional axis at the center of the region of interest and bisecting it. The authors implemented a fixed-reference registration point superimposition protocol on the CBCT by considering the nasal floor as a fixed anatomical reference at each implant site and selecting the anterior nasal spine and the canine tip as set comparative references between the preoperative and postoperative CBCT scans, implementing a software superimposition of both images aided by the reference points. The horizontal distance between the regenerated area postoperatively and the preoperative ridge was recorded, tabulated, and submitted to statistical analysis.

This designation was plotted on the selected preoperative and immediate, 4-, and 10-month postoperative views, hoping to compute the exact positions at different time intervals (Fig 4). The horizontal bone gain values were recorded, tabulated, and submitted to statistical analysis.

**Statistical Analysis**

An independent investigator performed the statistical analysis using IBM SPSS software for Windows (Version 2.0). The data were presented as mean and standard deviation. The significance level was set at $P \leq .05$. Kolmogorov-Smirnov and Shapiro-Wilk tests were used to assess data normality. The horizontal bone changes at the different follow-up periods were compared using repeated measures ANOVA.

**RESULTS**

**Clinical Results**

Intraoperatively, although the surgical insertion of three devices required extended mucoperiosteal elevation and reflection, all the holding devices demonstrated adequate adaptation to the maxillary ridges and considerable graft holding capacity. The holding devices were firmly interlocked to their recipient sites and were further stabilized by the compressing effect of the screw heads by the drilling procedure. On the other hand, the expanse of the constructed assembly yielded the soft tissue closure, which required extensive periosteal scoring and extending the mucosal vertical releasing incisions.

All the patients showed mild to moderate postoperative edema, which resolved after 5 to 7 days. Although two of the patients demonstrated flap dehiscence, no patients revealed any infection with routine follow-up, strict oral hygiene measures, and daily warm saline irrigation.

By the end of the graft consolidation period (4 months), the surgical removal of all barriers was uneventful. All the appliances were easily retrieved; none
of them showed fibrous invasion or soft tissue adhesion. Furthermore, all the alveolar ridges were consolidated, with generous horizontal dimensions and uniform contour, for successful placement of 18 dental implants of adequate diameter (Figs 3c and 3d).

**Radiographic Results**

**Alveolar bone width at different follow-up periods.**

There was a statistically significant difference between the mean alveolar bone width at different follow-up periods ($P < .001$). The mean alveolar bone width was significantly lowest at baseline (2.56 ± 0.69 mm), significantly highest at immediate postoperative (7.55 ± 0.70 mm), followed by 4 months postoperative (6.93 ± 0.68 mm), and 10 months postoperative (6.58 ± 0.82 mm) (Fig 5).

**Horizontal bone changes at different time intervals.**

There was a statistically significant difference between mean horizontal bone change at different time intervals ($P < .001$). The mean ridge gain measured immediately postoperative was significantly highest (4.84 ± 0.65 mm), followed by 4 months postoperative (4.22 ± 0.73 mm), 10 months postoperative, and 6 months postoperative (3.89 ± 0.78 mm). The significantly highest mean ridge reduction was detected from immediate to 6 months postoperative (0.95 ± 0.49 mm); this was followed by immediate to 4 months postoperative (0.62 ± 0.19 mm) and 4 months to 10 months postoperative (0.33 ± 0.38 mm), which did not differ significantly.

**Histomorphometric Results**

**Histologic analysis.** Histopathologic examinations of the H&E stained sections showed variable results. In general, bone formation ranged from large to thin mature lamellar and woven bone areas. Trabeculae of lamellar bone were identified by parallel lamellae, marked reversal lines, and established fibro-fatty marrow formation, while woven bone trabeculae lacked the previous signs. One case showed slight signs of inflammation, and residual areas of the graft material were also evident in some cases despite bone formation being detected (Fig 6).

![Figures and graphs related to the study results](image-url)
al13 demonstrated that the porous membranes yielded metabolic demands of the bone graft. In 2009, Gutta et al demonstrated blood perfusion and the nutritional supply and rations in the bone-carrying devices essential for ad-
tensive design, which impeded fibrous tissue invasion, facilitated the device removal, and protected the graft even in cases demonstrating mucosal dehiscence and device exposure. On the other hand, the metal device's bulk and weight seem to compromise the mucosal soft tissue coverage integrity, precipitating postoperative wound dehiscence. Therefore, careful soft tissue han-
dling and relaxed wound closure seem crucial.

Seiler et al16 utilized a lattice-shaped structure to cus-
tomize the reconstruction of 3D mandibular defects, in-
dicating that a printed titanium mesh for alveolar bone reconstruction presented a possible improvement on hand-configured mesh graft techniques. Furthermore, the study found that a customized product aided in providing a precise fit and high stability after screw fixation and it shortened the duration of surgery. In 2020, Hartmann and Seiler17 demonstrated that although their customized patient-specific titanium meshes widely overlayed significant jaw defects, a high rate of mesh exposures was detected. In the current study, the patient-specific occlusive devices offered a time-saving, easy, and precise concealment of the graft with proper contour integrity and acceptable soft tissue response.

In agreement with the findings of Eufinger and Wehmöller,18 Eufinger et al,19 and Scholz et al,20 the

**DISCUSSION**

The appropriate reconstructive technique of the hori-

zontally deficient maxillary alveolar ridge usually de-

pends on the pattern of alveolar ridge deficiency, the di-

mensions of the maxillary ridge, and the soft tissue cov-

erage.11

The current study was conducted to assess the hori-

zontal bone gain of the consolidated bone graft after loading a 1:1 mixture of autogenous and xenogenic bone particles into the fitting surface of patient-specific occlusive titanium smooth barriers, which guided the surgical execution of the virtual reconstructive plan. The chin bone was selected as a donor site due to the abundance of corticocancellous bone and its proximity to the recipient site. The donor site morbidity was minimal in this study. The autogenous bone was harvested using a minimally invasive protocol by auto-chip maker (ACM) bur to take advantage of the high osteogenic po-

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riers implemented in this study provided ample pro-
tection and sealing of the particulate graft, molded the particles into a 3D construct according to the vir-

tual plan, and afforded a dense consolidated bone graft with proper vertical height. This is in accordance with Toscano et al,14 who found that occlusive titanium membranes to enhance the stiffness and adaptability of the underlying recipient site's graft. The authors of Toscano et al are referring to the highly qualitative and quantitative character of the consolidated graft to the endosteal perfusion of the maxillary bones that over-
came the detaching of the bone graft from its periosteal blood supply.

According to Louis et al,15 the perforated design of the titanium mesh induces an intervening layer of fi-

brous tissue between the bone graft and the mesh that can contribute to graft loss and difficult mesh removal. This was overcome in the present study by the occlu-
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**Histomorphometric analysis.** Five bone core speci-

dens were retrieved from three patients, from areas between the prepared osteotomies of the dental im-

plants and parallel to the graft at 4 months of healing. The mean bone area percent was 69.26% ± 32.66% for patient 1, 92.59% ± 13.10% for patient 2, and 77.04% ± 37.15% for patient 3, with an overall mean of 79.6 ± 29.2. The grafted autogenous particles demonstrated ongoing remodeling and residual xenogenic bone graft material with an interconnecting network of newly formed bone of various degrees of maturation. There was perfusion of the marrow spaces with blood vessels in all the specimens, and small signs of inflammation were detected in one sample.

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patient-specific titanium occlusive titanium sheets can properly camouflage the integrity and contour of even large facial and cranial bony defects with favorable esthetics and soft tissue response. Although the authors of this study experienced two cases of soft tissue dehiscence, neither clinical signs of soft tissue infection nor radiographic findings of graft volume loss were detected, which could be attributed to the sealing capability of the customized titanium barrier. This lower titanium surface free energy reduces the incidence of gingival inflammation, the metal’s well-established biocompatibility, and its exposure survival tolerance. This matches what was demonstrated by Buser et al., Maiorana et al., and Roccuzzo et al.—that the e-PTFE membrane, when exposed, results in graft infection that usually compromises the regenerative outcome of the treatment. In contrast, the exposure of the titanium mesh, although it would trigger 15% to 25% graft resorption, does not usually precipitate significant complications or graft failure.

The outcomes of the current study recorded a statistically significant difference between mean horizontal bone changes at different time intervals. The final horizontal bone gain measured from baseline to 6 months postoperative was 3.89 mm, which corresponds with the findings of Rasia et al., where the mean horizontal bone gain of the titanium mesh group ranged between 3.75 and 5.65 mm, with an exposure rate of 16.1%, and those of Atef et al., who reported a mean horizontal gain of 3.4 mm and an exposure rate of 40%.

The graft mixture ratio in the current study was 50:50, which is the current standard mixture ratio for guided bone regeneration according to Urban et al. However, there are other studies with different proportions and different bone gain results. In 2014, Mordenfeld et al. compared a 90:10 ratio with that of 60:40. The mean horizontal bone gain was 4 and 4.5 mm for both groups, respectively. Pieri et al. showed a mean of 4.16 mm horizontal bone gain with a 70:30 graft mixture ratio.

For bone core specimens of adequate dimension to facilitate manipulation and examination, and to best simulate the bone layers of the host site, the authors retrieved the specimens vertically, parallel to the estimated locations of the proposed implants. The authors believed that a 3-mm core specimen from the implant osteotomy sites would jeopardize implant stability, which limited the selection of the cores to three alveolar ridges with a span that allowed for a safe retrieval.

Histopathologic examinations of the H&E stained sections showed variable results. In general, bone formation ranged from large to thin mature areas of lamellar bone, woven bone, and calcification. Trabeculae of lamellar bone were identified by parallel lamellae, marked reversal lines, and established fibro-fatty marrow formation, while woven bone trabeculae lacked the previous signs. Only one case showed signs of inflammation, although bone formation was still evident.

The results of our study were similar to those of Cucchi et al., who reported the histologic and histomorphometric outcomes of augmentation via GBR using Ti-PTFE or Ti-mesh, and showed that there were similar proportions of regenerated bone, residual biomaterial, and soft tissue. A 50:50 mixture was used to graft the areas in their study, and this was done to employ a one-stage protocol according to Simion et al., who used a Ti-PTFE membrane in combination with a 50:50 mixture of autogenous bone and deproteinized bovine bone mineral (DBBM).

Our results also followed those of Urban et al., who evaluated bone augmentation afforded by Ti-PTFE and a 50:50 combination of autogenous bone and DBBM; the mean proportions of newly formed bone, residual material, and soft tissue were 36.6%, 16.6%, and 46.8%, respectively.

Other studies also suggested that GBR using non-resorbable membranes, or a Ti-mesh with resorbable membranes, afforded similar extents of bone augmentation, as revealed by histologic and histomorphometric analyses.

Our study measured the area percent of the newly formed bone, as did other studies such as Urban et al. and Gutta et al. However, we did not measure the intervening soft tissue or the residual material.

Achievement of infection-free zones during the entire study period was one of the criteria that predicted success in regenerating the horizontal bony defects. The overall tissue under the membranes was similar, except for denser and thicker connective tissue in the titanium-treated sites.

It was proven that it was impossible to interfere with the connective tissue penetration through the microholes for the porous titanium membrane. This finding emphasizes the importance of pore size in the outcome of the regenerative procedure. In one of the sections, connective tissue ingrowth also appeared at the titanium membrane periphery but did not proceed to the core of the grafted sites. This may indicate that the titanium barrier apical to the fixation screw could have established a seal to the bone surface that was tight enough to prevent the ingrowth of soft tissue. The implants were then inserted in the second stage of surgery following the removal of the titanium barriers and screws.

The authors relate the short consolidation period and the histologic absence of residual xenogenic particles to limiting the reconstructed defects into short-span areas, with a maximum of three teeth missing and high maxillary endosteal perfusion. It seems that the maxillary endosteal blood supply was enough for these
short-span defects to consolidate in a relatively short period despite being sealed.

CONCLUSIONS

GBR using customized solid titanium barriers appears to be efficient and promising concerning the final horizontal bone gain and the quality of the augmented sites.

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