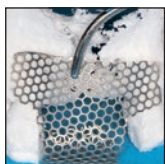# Treatment of Atrophic Ridges with Titanium Mesh: A Retrospective Study Using 100% Mineralized Allograft and Comparing Dental Stone Versus 3D-Printed Models

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This multicenter study retrospectively evaluated implant survival and bone growth in atrophic ridges that were augmented with titanium mesh and 100% mineralized solvent-dehydrated bone allografts (MSDBA). A secondary objective of this study was to evaluate differences in outcomes by diagnostic model type. Titanium mesh was shaped on a diagnostic wax-up of the patient's jaw: Twenty-three patients (Group 1) had wax-ups on dental stone models, and 16 patients (Group 2) had wax-ups on models fabricated with three-dimensional (3D) printing technology. Clinical and histologic data were analyzed. The average bone gain ranged from 5.94 to 6.91 mm horizontally and 5.76 to 6.99 mm vertically and was not significantly different between the two model groups (P > .05). Implant survival was 100% after 18 to 48 months. Although model type had no significant influence on outcomes, 3D-printed models allowed for faster surgery and served as visual aids for patient education. *Int J Periodontics Restorative Dent 2019;39:491–500. doi: 10.11607/prd.3733*

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Jawbone atrophy resulting from tooth loss and numerous other factors can complicate implant placement.[1] In severely atrophic ridges, bone regeneration procedures are necessary to restore adequate ridge dimensions before endosseous implants can be placed.[1] Techniques for vertical and horizontal ridge augmentation include guided bone regeneration (GBR), block grafting, and distraction osteogenesis.[1] Nearly 50 years ago, Boyne[2] first described the use of titanium mesh and autologous bone grafts for the advanced reconstruction of atrophic alveolar ridges. Numerous studies have reported successful vertical and horizontal bone regeneration using titanium mesh with a variety of autologous, allogenic, xenogenic, or alloplastic bone graft materials. Pellegrino et al[3] showed that the titanium mesh technique and computer-aided design/computer-assisted manufacturing (CAD/CAM) technology can be combined in the reconstruction of the totally edentulous maxilla. In contemporary practice, fabrication of stereolithographic anatomical models through three-dimensional (3D) printing can achieve highly accurate congruencies with the patient's anatomy, although some cautions still persist to ensure that the optimum computed tomography (CT) images are obtained.[4] Using a 3D-printed model

Table 1	Patient Selection Criteria
Inclusion	In need of implants to restore dental function and esthetics
	Proposed implant site with advanced horizontal and vertical deficiencies
	Good oral hygiene practices
Exclusion	Uncontrolled diseases, such as type 1 or 2 diabetes mellitus or periodontitis
	Physical or intellectual inability to maintain adequate oral hygiene and follow-up
	Heavy smokers (> 1 pack daily)
	Untreated dental or periodontal conditions

Fig 1 *An 18-year-old female presented with missing maxillary central incisors, shown here with a Pontic partial denture in place, and extensive vertical and horizontal ridge deficiencies resulting from a vehicular accident.*
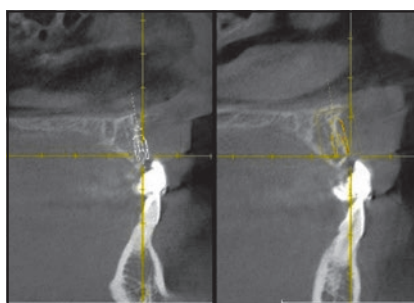
Fig 2 *Cross-cut tomographic scans show ridge deficiencies that required augmentation to accurately place dental implants.*

prior to surgery can allow preliminary preparation of titanium mesh[5] or allogenic block graft materials[6] to conform to the anatomical contours of the treated area.

While autogenous bone has been a preferred augmentation material because of its cellular viability and osteogenic capacity, its use requires two surgical sites, increases patient morbidity, and heightens intraoperative and perioperative risks.[7,8] Osmotic processing and solvent dehydration of allogenic bone tissues have been reported to retain the mineral content and structure of native bone while removing fats, killing bacteria, removing prions, and inactivating enveloped viruses.[9]

The resulting mineralized solvent-dehydrated bone allograft (MSDBA) materials have been extensively documented in the dental literature in both block[6,8] and particulate forms.[10] While particulate MSDBA materials have been used in tenting and sandwich techniques for ridge augmentation, their use with titanium mesh has not been previously reported.

The purpose of this multicenter, retrospective study was to evaluate the clinical outcomes of bone growth and implant survival when using 100% particulate MSDBA with titanium mesh for vertical and horizontal ridge augmentation. The authors sought to evaluate clinical outcomes when 100% particulate

MSDBA was used as a grafting material, and to secondarily explore if the use of 3D-printed models would result in improved clinical outcomes compared to mesh prepared on dental stone models.

Materials and Methods

This nonrandomized multicenter retrospective study was based on a pooled population of patients treated by the authors in either a university dental clinic or in a private-practice clinical setting. Digital and physical searches of patient records were conducted in both locations to identify qualified subjects who had received treatment, based on the study's inclusion protocol (Table 1). The retrospective study period encompassed July 2010 to February 2018. Retrospective data from patient records were entered into electronic spreadsheets (Microsoft Excel, Microsoft) in a secure personal computer (Hewlett-Packard, HP) in accordance with ethical medical research principles[11] and patient privacy standards.[12]

Patient Evaluation

Medical records from previously treated partially edentulous patients with advanced horizontal and vertical alveolar ridge deficiencies were examined (Figs 1 and 2). As part of standard practices, after reviewing the patient's medical and dental histories, a clinical exam and a preoperative cone beam CT (CBCT) scan were taken to determine the volume

and shape of residual bone, the presence of anatomical landmarks, and the presence of any dental and/or periodontal conditions that needed to be treated before surgery. Patients who were deemed acceptable candidates for augmentation surgery provided informed consent, intraoral photographs were taken, and diagnostic models were fabricated. All procedures took place at two centers: the private practice of the principal investigator (E.E.) and the New York University dental clinic. Between the two centers, multiple operators performed the procedures.

Models and Mesh Preparation

Two types of diagnostic models of the patients' jaws were fabricated. In Group 1 (dental stone model), an impression of the edentulous area was made with alginate material and poured in dental stone. In Group 2, CBCT images were used to generate 3D digital images in a DICOM (Digital Imaging and Communications in Medicine) file format. These images were used to generate a model of the patient's jaw using 3D printing technology (Fig 3). In the present study, the DICOM file resulting from the CBCT scan was used by an open-source 3D software program (3D Slicer 4.6 for MacOS and Windows 10)[13] to assess the region of interest with its associated dentition, anatomical landmarks, and bone structure. Because of differences in scanners and patient anatomies, care was taken to inspect the appropriate Hounsfield unit range to include the alveolus and tooth structures but ex-


Fig 3 (right) *Model generated by 3D printing from a CBCT scan shows the extensive horizontal and vertical ridge deficiencies. The 3D-printed model is used to customize the titanium mesh according to the set goal of optimal implant placement for the planned prosthesis.*

Fig 4 (below) (a) *Dental stone model and* (b) *3D-printed model with waxed surgical areas and titanium mesh.*
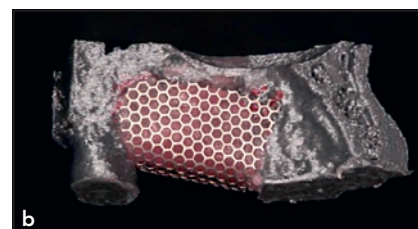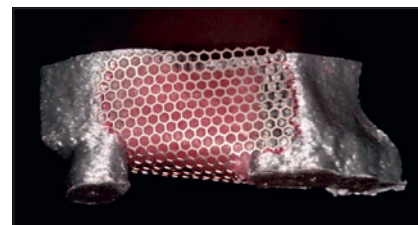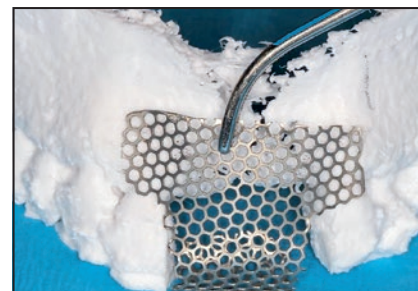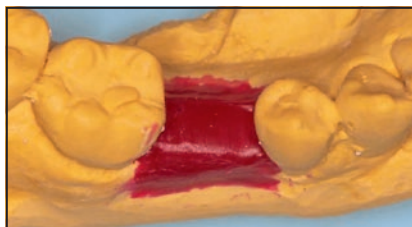
clude scatter from amalgam and ceramometal dental restorations. Data were saved in a stereolithographic (STL) file format that described the layout of the 3D data and communicated directly with 3D printer hardware. A heat extrusion printer (Ultimaker 2+, Dynamism) was used for 3D printing utilizing polylactic acid (PLA) as the material of choice. Once the model was printed, the clinician was able to physically examine the 1:1 model of the patient and define the surgical space.

In both groups, the intended surgical area was waxed to simulate the desired regenerated ridge contours (Fig 4). Titanium mesh was adapted to fit the area of wax-up. Because Group 1 models lacked accurate reference points in relation to anatomic landmarks and the exact limits of the defect, the mesh was trimmed slightly in excess of the defect to enable final adjustment during the surgery. Since the STL models in Group 2 included anatomical structures, fixation points
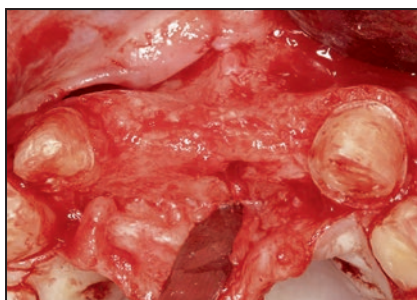
Fig 5 *Clinical view of the surgical site prepared according to the study protocol.*

Study group	Model type	Titanium mesh	No. used	Bone screws
Table 2	**Titanium Mesh and Bone Screws Used in This Study**			
Group 1	Dental stone	MatrixNeuro Reconstruction Mesh[a]	13	BioHorizons Bone Screw Kit[b]
		TriStar TRIM4060 Mesh[c]	10	TriStar Self-Drilling Screws[c]
Group 2	3D printed	OsteoForm Mesh[d]	17	Auto-Drive Self-Drilling Screws[d]

[a]DePuy Synthes.
[b]BioHorizons.
[c]Impladent.
[d]OsteoMed.

were defined, and the titanium mesh was trimmed and polished with metal burs along the margins to prevent operator injury and flap perforation (Fig 3). In both groups, the titanium mesh was removed from the model and placed in a pouch and sterilized.

Antibiotic Prophylaxis and Analgesics

All patients were prescribed a 1-week regimen of 500 mg amoxicillin three times daily, or 500 mg ciprofloxacin twice per day for those allergic to penicillin, commencing at least 1 hour prior to the surgical procedure. Postoperative analgesic coverage was provided by either 800 mg ibuprofen every 6 hours as necessary, or a combination of the latter with acetaminophen ES (500 mg) alternating every 4 to 6 hours as necessary.

Surgical Procedures

Incision and flap design were standardized across all cases. Profound anesthesia was achieved via local infiltrations and nerve blocks according to the defined surgical field. A full-thickness flap, with a buccally biased crestal incision, was opened and extended past the mucogingival junction to visualize and expose the full apical extent of the ridge deficiency. Lateral extension on the buccal aspect of the flap was accomplished by including the adjacent one to two teeth distal and mesial to the defect by way of papilla-sparing (or papilla-slicing) incisions with serial buccal sulcular incisons.[14] On the lingual aspect of the flap, minimal lateral extension was required due to performance of an intrasulcular incision up to the distal transitional line angle of the adjacent tooth on each side of the respective area, and the flap was reflected (Fig 5).

In defects of the anterior maxilla, the incisive foramen and nasopalatine nerve were identified and dissected to aid in lateralization and provided a more natural ridge contour after augmentation. In defects of the posterior mandible, the same approach was used to identify and dissect the mental foramen and mental nerve, respectively.

To increase blood supply and promote recruitment of osteogenic progenitor cells into the graft, the recipient bone bed was decorticated with a surgical-length, round #2 bur (Core Bur, Stryker) in a high-speed handpiece. In Group 1 patients, a try-in of the titanium mesh was made to determine its relationship with adjacent anatomical landmarks and the residual bone, then the mesh was removed, trimmed, and polished with metal burs along the margins to prevent flap perforation and injury to the surgeon. Composite cortical (Puros Cortical Particulate Allograft, Zimmer Biomet), and cancellous (Puros Cancellous Particulate Allograft, Zimmer Biomet) MSDBA materials were individually hydrated according to the manufacturer's instructions. In the posterior mandible, the titanium mesh was placed over the defect site and affixed to the residual ridge buccally and lingually with bone screws (Table 2). From the mesial and distal sides of the stabilized titanium mesh, cancellous particulate allograft was layered on the bone bed, then a layer of a 50:50 cancel-
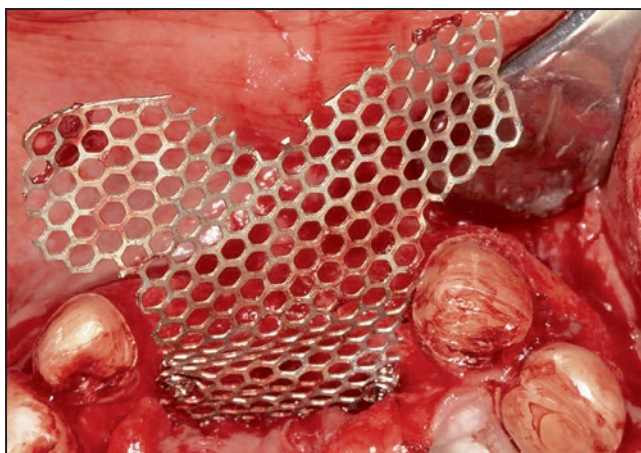
Fig 6 (above) *The titanium mesh was initially stabilized with two screws placed on the lingual aspect.*
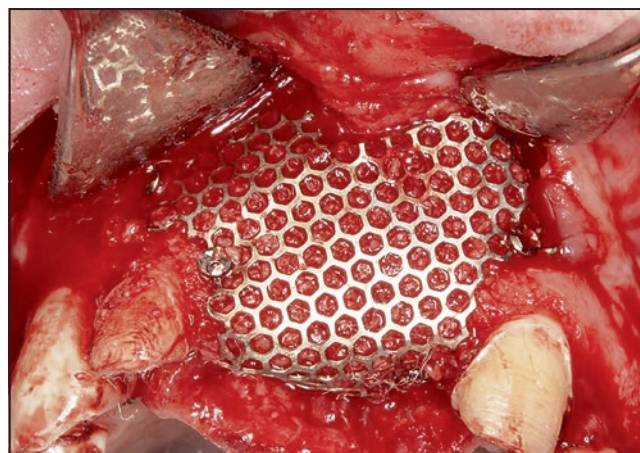
Fig 7 (top right) *The defect site was filled with layers of cancellous and cortical MSDBA materials, then the titanium mesh was folded over the graft site and stabilized by additional bone screws.*

Fig 8 (right) *Primary closure was achieved by coronally stretching and making passive the surgical flap without vertical incisions or cutting the inner layer of the tissue.*


lous cortical mixed placed over the first layer of cancellous allograft, and a third layer of cortical particulate allograft was placed in a sandwich technique,[15] designed to mimic the cortical and cancellous layer of anatomical bone. In all other locations, the titanium mesh was initially attached to the lingual/palatal aspect of the residual ridge (Fig 6), the MSDBA materials were layered on the bone bed, and then the mesh was folded over the graft materials and affixed to the buccal aspect of the residual ridge with bone screws (Table 2, Fig 7). In all cases, any remaining voids in the mesh were filled with remaining MSDBA material. No barrier membranes were placed over any of the titanium meshes.

After the mesh was tightly and rigidly fixed, a large surgical spoon was placed apical to the mucogingival junction and used to stretch the elastic fibers of the buccal mucosa to allow for passive primary closure of the buccal flap. Mattress sutures were placed at future papilla sites and at the midpoint of the edentulous area, while interrupted sutures were placed intermediately to ensure closure and approximation of the buccal and lingual flaps (Fig 8).

For all patients, a second CBCT scan was taken at 6 months (Fig 9) and the surgical site was exposed at 8 months postoperative. Height and width measurements were taken from the CBCT scan to determine the amount of bone gain.

Incisions were made approximating the margins of the mesh, a flap was carefully elevated to avoid perforations, and the bone screws and titanium mesh were removed (Fig 10). In all cases, a 0.5- to 1-mm–thick layer of firm connective tissue had formed between the mesh and underlying bone, which was left as part of the elevated flap. In order to increase the thickness of the gingiva, an acellular dermal matrix (Puros Dermis, Zimmer Biomet or AlloDerm, Allergan) was tacked (AutoTac System Kit, BioHorizons) in place. After 4 weeks of healing, bone core samples were taken from the augmented sites and dental implants were placed in prosthetically driven positions.
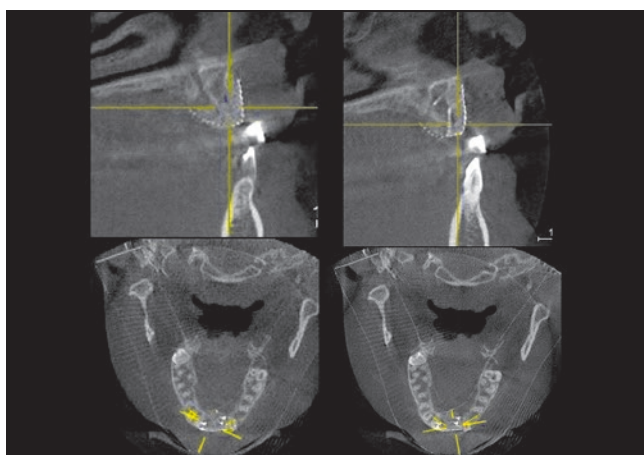
Fig 9 *CBCT scans show the amount of vertical and horizontal bone gain at 6 months postoperative.*
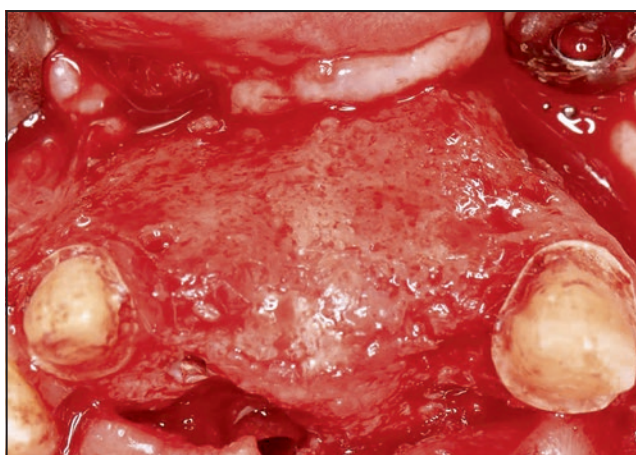
Fig 10 *Increased horizontal and vertical dimensions of the regenerated ridge are clinically evident 8 months after grafting.*
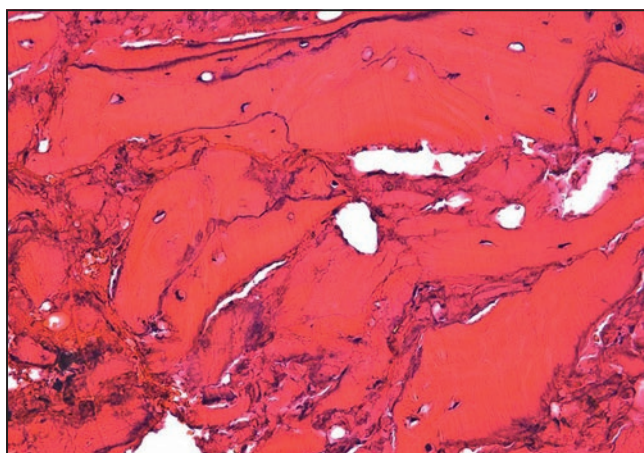
Fig 11 *Histologic slide of a bone biopsy sample collected at the time of implant placement shows active remodeling with reversal lines, filled lacunae with osteocytes, and a minimum amount of residual graft material.*
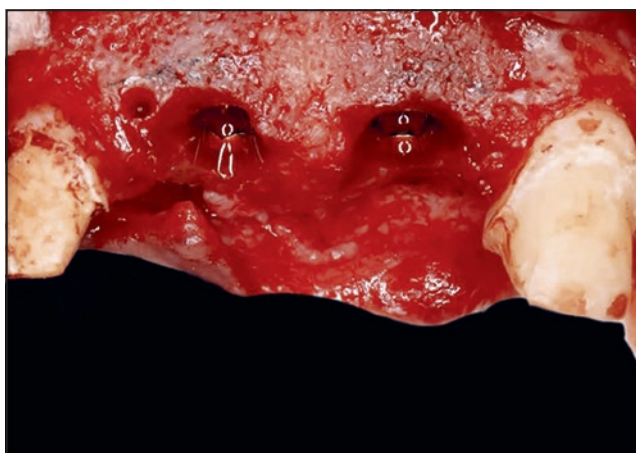
Fig 12 *The regenerated bone was scalloped along the margins of the surgical guide to ensure adequate prosthetic space, then implants (4.1 × 11.5 mm; Trabecular Metal, Zimmer Biomet) were placed in the maxillary central incisor locations.*

Histologic Assessments

Immediately before implant placement, trephine burs (08.910.03, Brasseler USA) with a 2.8-mm interior diameter and 3.3-mm exterior diameter were randomly used to biopsy the regenerated bone from planned implant sites. The bone core was retrieved inside the trephine drill and sent to the laboratory for histologic processing and analysis (Fig 11). The biopsy site was further prepared for implant placement according to the manufacturer's instructions (Fig 12).

Statistical Analyses

Descriptive statistics were used to describe the demographics of the study population and to calculate overall implant survival. To compare bone gain levels between Groups 1 and 2, t tests (Sattherthwaite procedure) were used. Mean differences with 95% confidence intervals were recorded. For the categorical variables used to collect data on adverse events, Fisher exact test was used to compare Group 1 and Group 2.

Table 3   Distribution of Treatments by Location
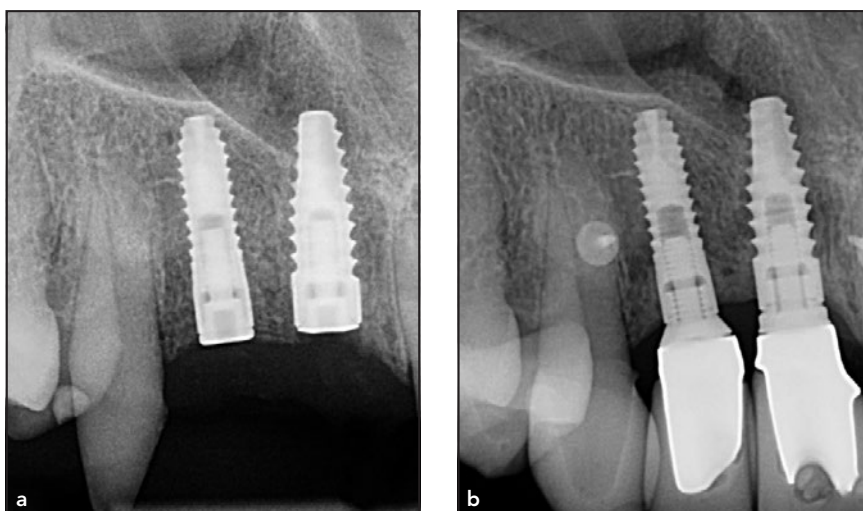
| Group no.	Model type	No. of patients	Augmentation locations (n)				Random biopsy locations (n)			
			Mandible		Maxilla		Mandible		Maxilla	
			Anterior	Posterior	Anterior	Posterior	Anterior	Posterior	Anterior	Posterior
1	Dental stone	23	4	14	3	2	2	2	5	1
2	3D-printed	17	–	3	11	3	–	1	6	1

Results

A total of 39 patients (26 females, 13 males) with an average age of 53.9 years (range: 17 to 88 years) presented with 40 horizontal and/ or vertical ridge deficiencies that were reconstructed using titanium mesh and 100% MSDBA materials in a layered bone grafting technique. The distribution of treatments by jaw location is summarized in Table 3.

Histologic Findings

A total of 18 bone core samples were obtained from anterior and posterior regions of both maxillae and mandibles and were histologically analyzed (Table 3). All specimens exhibited new bone formation with numerous osteocytes in different stages of remodeling and maturation. Secondary osteons with central capillaries and osteoblasts that deposited bone in concentric lamellae were observed. Residual graft particles were surrounded by newly formed bone and bridged gaps between the newly deposited bone. Minimal to no inflammation was present in the connective tissue. The apical area demonstrated a greater amount of new bone formation, while in the coronal area, dense connective tissue was more visible (Figs 13 and 14).

Fig 13 *Radiographs of a patient treated with titanium mesh over MSDBA in the anterior maxilla. Views of* (a) *initial implant placement and* (b) *follow-up at 6.5 years.*
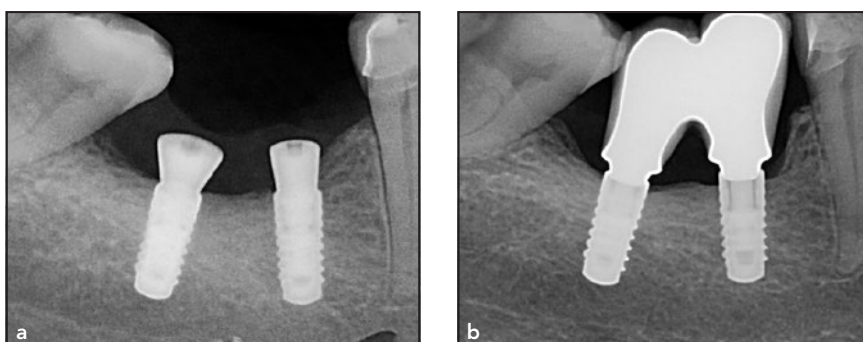
Fig 14 *Radiographs of a patient treated with titanium mesh over MSDBA in the posterior mandible. Views of* (a) *initial implant placement and* (b) *follow-up at 4.3 years.*

Treatment Outcomes

The distribution of adverse events and treatment outcomes is summarized in Table 4. Cumulative mesh

Table 4   Distribution of Adverse Events and Treatment Outcomes

Group no.	Adverse events				Cumulative results					
	Mesh exposure		Mesh infection		Mesh		Mean bone gain (mm)		Implants	
	Early[a]	Late[b]	Early[a]	Late[b]	Failure (n)	Survival (%)	Horizontal	Vertical	Placed (n)	Survival (%)
1	7	5	1	1	2	91.67	6.91	5.76	35[c]	100[c]
2	4	2	2	–	2	88.24	5.94	6.99	28[d]	100[d]

[a]Within 2 weeks postoperative.
[b]Within 2 months postoperative.
[c]At 24 months of follow-up.
[d]At 18 months of follow-up.

Table 5   Comparison of Bone Growth by Model-Type Group

Bone growth (mm)	Group 1 (mean)	Group 2 (mean)	Difference (Group 2 – Group 1)	95% Confidence interval of difference	P
Horizontal gain	6.91	5.94	–0.974	(–2.10, 0.15)	.087
Vertical gain	5.76	6.99	1.225	(–1.49, 3.94)	.356

Table 6   Comparison of Adverse Events by Model-Type Group

Adverse events	Group 1 vs Group 2 (P)
Early exposure	.7298
Late exposure	.677
Removal	1
Infection	.6235

survival was 91.7% in Group 1 and 88.2% in Group 2. Overall, a total of 63 implants placed in accordance with preplanning goals exhibited 100% survival after 18 months of follow-up. In Group 1, 23 patients were treated for 23 ridge deficiencies and achieved an average of 6.91 mm in horizontal and 5.76 mm in vertical bone gain. In Group 2, 16 patients were treated for 17 ridge deficiencies and achieved an average of 5.94 mm in horizontal and 6.99 mm in vertical bone gain (Table 5). There were no significant differences in horizontal and vertical bone gains between Groups 1 and 2 (P > .05

for both; Table 5). Group 1 achieved slightly greater (0.97 mm) horizontal bone gain than Group 2, whereas Group 2 achieved slightly greater (1.23 mm) vertical bone gain than Group 1, though these differences were not significant (Table 5). Evaluation of adverse events (exposure status, removals, and infections) did not show a significant difference between the two groups (Table 6). Across the study population, patient medical history and the presence of comorbidities did not affect clinical outcomes (data not shown). Additionally, the authors' internal data showed that patients who were

treated with the use of a 3D-printed model had surgery times that were an average of 25 minutes less than those with dental stone models.

Discussion

The present study demonstrated that the use of 100% MSDBA with titanium mesh achieved mean bone gains of 5.94 to 6.91 mm in the horizontal and 5.76 to 6.99 mm in the vertical dimensions. Bone quality, quantity, and stability were also adequate to enable the placement and restoration of dental implants, which achieved 100% survival over 18 to 48 months of follow-up. Bone core samples showed new bone formation, and the quality of the bone that was achieved with the allograft material allowed for osseointegration. These positive clinical outcomes appeared to be correlated with the technique and materials that were used, suggesting that the therapy under evaluation may be appropriate for a diverse patient population, though further confirmatory studies are warranted.

While there were no significant differences in clinical outcomes between patients who had received

a dental stone model (Group 1) vs a 3D model (Group 2), there were observed benefits to using the 3D model. The 3D-printed models enabled accurate adaptation of the titanium mesh before surgery and were also effective diagnostic tools for communicating treatment plans and surgical procedures to patients, which reduced surgical time by an average of 25 minutes.

In addition to the native crestal bone housing, the mucogingival buccal flap is one of the main sources of blood supply to the alveolar ridge, requiring careful management. Failure to achieve and maintain primary closure can lead to delayed healing and graft failure.

The use of vertical or periosteal incisions is a common technique for both flap advancement and accessibility. These methods can compromise the available blood supply to the graft. Mörmann et al[16] showed that the blood supply to the surgical site was reduced by 50% when vertical incisions were used and remained reduced for 4 days, which is the most critical period for revascularization and survivability of graft and flap. Periosteal incisions may also compromise blood supply and can lead to postoperative complications, such as paresthesia, infection, and continued discomfort.[17] To provide accessibility, in this study the flap was extended laterally by slicing the papilla buccally, as described by Zucchelli et al.[14] The mucosal lamina propria richness in elastic fibers[16] allowed for passive primary closure by stretching of the flap coronally.[18,19] The graft material was thus secured without compromising the blood

supply. If fibrous scar tissue was present on the intaglio surface of the flap, it was excised from the inner aspect of the buccal flap prior to stretching.

Limitations

This retrospective analysis was based on data points that were originally collected for routine clinical care rather than research. Additionally, although the authors found no significant differences in clinical outcomes between the two model-type groups, this finding may have been influenced by the small sample sizes of the cohorts. Also, different mesh materials and different screws were used within the study population, though the present findings showed a high success rate across the population. Potential confounders (ie, advanced age) were not accounted for, though this study population had a diverse range of ages.

Conclusions

This study demonstrated that the use of 100% MSDBA with titanium mesh achieved clinically meaningful bone gains. Bone quality, quantity, and stability were also adequate to enable the placement and restoration of dental implants, which achieved 100% survival over 18 to 48 months of follow-up. Bone core samples showed new bone formation. The use of 100% MSDBA may obviate the need for autogenous bone grafting, though further

studies are warranted. Additionally, the authors found no significant differences in clinical outcomes by type of diagnostic model, but 3D-printed models allowed for faster surgery and served as visual aids for patient education.

Acknowledgments

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