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Vertical Ridge Augmentation of the Atrophic Posterior Mandible with Custom-Made, Computer-Aided Design/Computer-Aided Manufacturing Porous Hydroxyapatite Scaffolds

Michele Figliuzzi, DDS, Francesco Guido Mangano, DDS,† Leonzio Fortunato, MD, DDS, PhD,* Rossella De Fazio, DDS,* Aldo Macchi, MD, DDS,† Giovanna Iezzi, DDS, PhD,‡ Adriano Piattelli, MD, DDS,‡ and Carlo Mangano, MD, DDS†*

Abstract: The present study describes a new protocol for the manufacturing of custom-made hydroxyapatite scaffolds using computer-aided design/computer-aided manufacturing (CAD/CAM), to augment posterior mandibular bone and minimize surgery when severe atrophy is present. Computed tomographic images of an atrophic posterior mandible were acquired and modified into a 3-dimensional (3D) reconstruction model. This model was transferred as a stereolithographic file to a CAD program, where virtual 3D reconstructions of the alveolar ridge were performed, drawing 2 anatomically shaped, custom-made scaffolds. Computer-aided-manufacturing software generated a set of tool-paths for manufacture on a computer-numerical-control milling machine into the exact shape of the 3D projects. Clinically sized, anatomically shaped scaffolds were generated from commercially available porous hydroxyapatite blocks. The custom-made scaffolds well matched the shape of the bone defects and could be easily implanted during surgery. This matching of the shape helped to reduce the time for the operation and contributed to the good healing of the defects. At the 6-month recall, a newly formed and well-integrated bone was observed, completely filling the mandibular posterior defects, and implants were placed, with good primary stability. At the 1-year follow-up examination, the implant-supported restorations showed a good functional and esthetic integration. Although this is an interim report, this study demonstrates that anatomically shaped custom-made scaffolds can be fabricated by combining computed tomographic scans and CAD/CAM techniques. Further studies are needed to confirm these results.

Key Words: Alveolar bone augmentation, computer-aided-design/computer-aided-manufacturing (CAD/CAM), custom-made, scaffolds

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The lack of sufficient bone volume to place dental implants is a common problem in partially edentulous patients.[1] In particular, the posterior mandible may be challenging because of both insufficient height and width of the edentulous alveolar crestal bone. Augmentation of an insufficient bone volume is indicated, before or in conjunction with implant placement, to attain long-term functioning and an esthetic outcome.[1] Strategies used to overcome mandibular posterior atrophy include various techniques and materials developed to increase bone volume, such as onlay /inlay bone grafting,[2,3] guided bone regeneration,[4,5] distraction osteogenesis,[5] and nerve transposition. Although it has been shown that it is possible to augment bone vertically with all these different techniques, each of these options poses a risk of complications or potential for dimensional graft loss.[6] Autogenous bone block grafting is the accepted standard of care.[1,6,7] These tissue transplants, however, have limited availability and must be obtained in an accompanying procedure, which involves risks such as infection, bleeding, pain, swelling, and damage to nerves and blood vessels.[6,7] A variety of bone substitute materials, such as allogenic or xenogenic or synthetic materials, are available for ridge augmentation.[7] The ideals of bone substitutes are as follows: they should have biocompatibility, excellent osteoconductive properties, and appropriate strength, and they should be able to form a suitable shape easily and to ultimately replace the bone completely within a short period.[7] Calcium phosphate ceramics based on porous hydroxyapatite (HA) might meet all the mentioned criteria.[8,9] Calcium phosphate–based materials have been considered for use as bone graft substitutes in the treatment of bone defect for over 30 years, in orthopedic, dental, and maxillofacial surgery.[8] In particular, coralline HA is a calcium phosphate derived from a coral genus.[9] Using a replamineform process, the natural calcium carbonate skeleton is heated and by that transformed into HA.[9] In modern implant dentistry, priority should be given to those interventions that look simple, are less invasive, involve less risk of complications, and reach their goal within the shortest timeframe.[6] In the last few years, the application of digital technology in dentistry is becoming widespread, with the introduction of computed tomography (CT), and considerable progress has been made in the development of computer-aided-design/computer-aided-manufacturing (CAD/CAM) techniques.[10] There is a burgeoning interest in applying the principles of digital diagnostics, computerized treatment planning, and guided implant surgery together with CAD/CAM technology, for the fabrication of implant-supported fixed prosthesis.[10] More recently, attempts have been made to fabricate custom-made scaffolds, allowing bone grafts to be tailored for specific

applications or even for individual patients, using computer-assisted methods.[11]

MATERIALS AND METHODS

Case Description

A 43-year-old healthy woman was referred to the Oral and Maxillofacial Surgery Department, University of Catanzaro, Italy, for a fixed prosthetic rehabilitation of the atrophic posterior mandible due to severe periodontal disease. Clinical, radiographic evaluation with CT scan (Fig. 1A–C), and dental casts confirmed a class V (according to the Cawood and Howell classification)[12] posterior mandibular atrophy. In detail, preoperative mean residual bone height above the mandibular canal was less than or equal to 7 mm distal to the mental nerve foramen (7.9, 7, and 5.7 mm, respectively; 6, 12, and 18 mm from the mental nerve foramen, in both the right and left side of the mandible). In this situation, prosthetic rehabilitation was not possible without preprosthetic reconstructive surgery. For this reason, it was decided to carry out a custom-made regeneration technique using HA scaffolds, under local anesthesia. A written informed consent form was signed by the patient. The study was performed according to the principles outlined in the World Medical Association's Declaration of Helsinki on experimentation involving human subjects, as revised in 2008.

Custom-Made Scaffold Fabrication

Computed tomographic data sets of the mandible were acquired and subsequently loaded in the Digital Imaging and Communication in Medicine format into a specific 3-dimensional (3D) reconstruction software (Mimics; Materialise, Leuven, Belgium). The hard tissue threshold was selected so that only bone was reconstructed from the slices. With this software, it was possible to perform an accurate and complete 3D reconstruction of the mandible. This reconstruction was then transferred as a stereolithographic file to a 3D CAD program (Rhinoceros; Robert McNeel & Associates, Seattle, Wash). With this software, it was possible to virtually reconstruct the alveolar ridge defects (Fig. 2A–C), drawing 2 anatomically shaped custom-made scaffolds. The 3D geometry of these scaffolds was imported into a proprietary, CAM software, used to generate a set of tool-paths for fabrication on a proprietary computer-numerical-control (CNC) milling machine. Commercially available coralline HA blocks (Biocoral; Leader-Novaxa, Milan, Italy) were then placed in the CNC milling machine and milled into the exact shape of the 3D projects. In this way, 2 anatomically shaped custom-made HA scaffolds were manufactured. The scaffolds were sterilized before surgery.

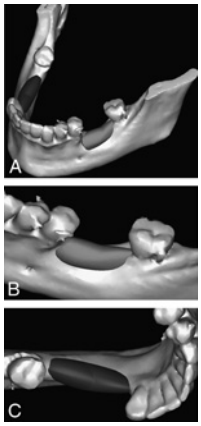

FIGURE 2. A to C, 3D reconstruction of the atrophied edentulous ridges with custom-made, CAD/CAM scaffolds.

Surgical Procedure

Local anesthesia was obtained by infiltrating articaine 4% containing 1:100.000 adrenaline. Wide exposure of the mandibular edentulous ridge was achieved with a crestal incision and with lateral releases. A mucoperiosteal flap was elevated; the mental neurovascular bundles were identified and protected with a retractor. The recipient mandibular sites were weakened with multiple microholes to enhance bleeding of the mandibular cortex. The clinically sized, anatomically shaped custom-made HA scaffolds were placed in position strictly overlapping the underlying alveolar crest and creating a kind of biological rigid fixation (Fig. 3A). Fixation of the scaffolds was obtained by means of titanium microscrews (Fig. 3B). Absolute surgical care is, finally, sought to obtain a tension-free suture above the scaffolds, to avoid ischemic damage to the mucosa and suture dehiscence (Fig. 3C). The patient was instructed to avoid hard food and received oral antibiotics, amoxicillin + clavulanic acid 2 g/d for 6 days (Augmentin; Glaxo-Smithkline Beecham, Brentford, United Kingdom). Postoperative pain was controlled by administering 100 mg of nimesulide (Aulin; Roche Pharmaceutical, Basel, Switzerland) every 12 hours for 2 days, and detailed instructions about oral hygiene were given, with mouth rinses with 0.12% chlorhexidine (Chlorexidine; OralB, Boston, Mass) administered for 7 days. The patient was seen on a weekly basis during the first 4 weeks. At the first control visit, 10 days after the surgery, a clinically healthy marginal area was present, and

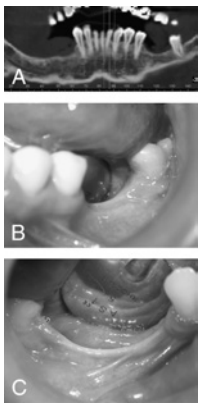

FIGURE 1. A, Computed tomographic scans of the atrophied posterior mandible. B and C, Clinical view of the atrophied residual mandibular ridges.

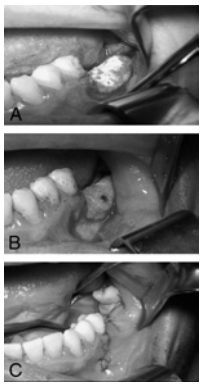

FIGURE 3. A, The scaffold is put in receiving site. B, Fixation of the scaffolds by means of titanium microscrews. C, Sutures.

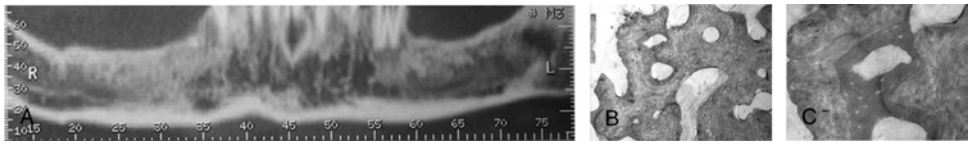

FIGURE 4. A, Computed tomography of control 6 months after surgery. B and C, Histologic samples taken from the augmented areas.

no postoperative pain or swelling was reported. There was no bleeding or wound infection. Sutures were removed. No removable prosthesis was allowed for 6 months. Professional plaque control supplemented this healing phase every month, during 6 months.

Implant Placement and Biopsies Retrieval

Six months after augmentation, under local anesthesia, miniscrew were removed, and the implants were inserted. Screw-shaped implants (Tixos; Leader-Novaxa, Milan, Italy) were placed, with good primary stability. Primary wound closure was achieved with horizontal mattress sutures alternated with interrupted sutures. Bone core biopsies were retrieved using a 2.0 × 10-mm trephine bur under sterile saline solution irrigation; the dimension of the bone cores was almost 2 × 6 mm. The bone core biopsies were immediately stored in 10% buffered formalin and were subsequently processed (Precise 1 Automated System; Assing, Rome, Italy) to obtain thin ground sections. The specimens were dehydrated in an ascending series of alcohol rinses and were embedded in glycol methacrylate resin (Technovit; 7200 VLC, Heraeus Kulzer GmbH & Co, Wehrheim, Germany). After polymerization, the specimens were sectioned lengthwise along the larger axis of the specimens, using a high-precision diamond disk, to approximately 150 μm and ground down to about 30 μm. Two slides were obtained from each specimen. The slides were stained with basic fuchsin and toluidine blue.

Histologic and Histomorphometric Evaluation

Histologic and histomorphometric evaluation of the augmented bone retrieved with a trephine bur at implant placement was performed. Histomorphometry of newly formed bone, marrow spaces, and residual graft material were carried out for each case on the whole sample at a low magnification (×25). Histomorphometry was carried out using a light microscope (Laborlux S; Ernst Leitz GmbH, Wetzlar, Germany) connected to a high-resolution video camera (3CCD, JVC KY-F55B; JVC, Yokohama, Japan) and interfaced to a monitor and personal computer (Intel Pentium III 1200 MMX; Intel Corp, Santa Clara, Calif). This optical system was linked to a digitizing pad (MatrixVision GmbH, Oppenweiler, Germany) and a histometry software package with image-capturing capabilities (Image-Pro Plus Version 4.5; Media Cybernetics, Inc, Silver Spring, Md). The values for marrow spaces/soft tissues, residual graft material, and newly formed bone were recorded exactly 1 mm distant from the preexisting bone, and the mean percentage values were calculated.

RESULTS

No clinical complications were observed during the 6-month healing period. At the 6-month recall, a clinically available newly formed and well-integrated bone was observed (Fig. 4A) completely filling the mandibular posterior defects. Representative examples of the histologic sections are illustrated in Figure 4B and C. The specimens were made of preexisting, compact mature bone undergoing remodeling, newly formed trabecular bone, and some biomaterial particles (Fig. 4B). The bone was well organized, with several osteon in evidence. Inside the porous HA structure, new bone formation was observed, with newly formed osteoid matrix undergoing mineralization (Fig. 4C). Implants were placed (Fig. 5A). At the 1-year follow-up control, the implant-supported prosthetic restorations showed a good functional and esthetic integration (Fig. 5B–C).

DISCUSSION

Augmentation of the alveolar ridge is necessary for patients with extensive mandibular resorption to perform esthetic and prosthetic rehabilitation and enable implant insertion. Vertically increasing alveolar crest by means of block grafts is indicated when the height of the residual crest is less than 5 mm (Cawood and Howell class IV, V, and VI), and horizontal increase is indicated when the width of the alveolar ridge is less than 4 mm, or less than 5 mm in esthetic areas with high labial line.[6,12] Mandibular bone reconstructions often involve autogenous tissue grafting, a method limited by harvesting difficulties, donor site morbidity, the clinicians' ability to contour delicate 3D shapes and the steady resorption of the graft after augmentation.[6,7] The edentulous posterior mandible, in fact, suffers from the presence of a compact cortical layer, which tends to limit graft osteogenesis, because of a low permeability to the osteogenic elements (microvessels and cells). To obtain favorable results, the procedure of bone grafting needs few fundamental requisites: a suitable vascular support, a valid interface between graft and the osteogenetic cell lines, and the mechanical stability of the graft.[7] Because the osteoblasts necessitate high oxygen tension for bone matrix production, a high permeability of the graft to the vascular network is needed for an effective new bone formation.[7] Calcium phosphate–based materials such as coralline HA have been widely used for hard tissue repair in clinical settings because of their good biocompatibility and osteoconductivity, mechanical strength, and biodegradability.[8,9,13,14] Several researchers have explored the micropore size and interconnectivity of ceramic materials for osteoconductivity, and an optimal pore size of 150 to 400 μm has been established as the most important criteria for continued bone ingrowth into a porous scaffold.[8,9,15] Despite the use of commercially available HA blocks for being manually cut, bent, and adapted during surgical intervention, obtaining the final shape for the

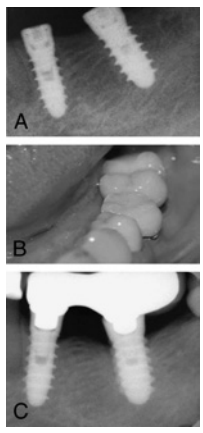

FIGURE 5. A, 6 months after augmentation, implants are placed. B, 1-year clinical picture of implant-supported prosthetic restoration. C, 1-year radiographic control of implant-supported restoration.

scaffold is still a complex practice for bone regeneration of the mandible. At present, advancements in CAD/CAM technologies for scaffold fabrication provide a valuable alternative to bone replacement based on autograft and allograft procedures.[10] In our present study, clinically sized, anatomically shaped scaffolds were generated from commercially available HA blocks by using digitized clinical images and a single-piece, CNC milling machine. Precise adaptation of the scaffolds was achieved in a considerably short operation time. Scaffold handling in the operating theater was minimal, thus preserving its strength. Other benefits that should be mentioned include reduced volume to augment, as the custom-made scaffold was designed on the planned implant positions (ie, final prosthesis demands), minimizing the quantity of harvested or synthetic graft material, and improved intervention quality, with shorter wound exposure time. No fracture or deformation of the custom-made scaffold was evident during the healing period. Six months after the augmentation procedures, screw-shaped implants were placed in the augmented area, with good primary stability. At the 1-year control, finally, the implant-supported prosthetic restorations showed optimal functional and esthetic integration. According to the planned position of the prosthesis and of the osseointegrated implants, the design of the anatomically shaped, custom-made HA scaffold allows one to obtain reduced surgery time and improved quality.[11] The custom-made approach may thus become a viable and reproducible method with the support of CAD/CAM technologies, for supporting minimal intervention reconstructive surgery.[13–16] This is particularly true for reconstruction of mandibular defects, where the 3D external geometry of the flap or scaffold that fits the anatomical defect holds an important role both in establishing the stress distribution at the bone-implant interface and in maintaining esthetic structure. Further studies with a larger sample size and histologic evaluation of the new bone formation could lead to a best interpretation of this preliminary case report. The ability to engineer anatomically correct pieces of biomaterials, however, can have tremendous potential for alveolar bone reconstructions. In the future, the addition of stem cells[17] or bioactive agents[18] to the custom-made scaffolds could accelerate the vascular invasion and bone regeneration.

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