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CAD/CAM and 3D-printing Applications for Alveolar Ridge Augmentation

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Abstract

Purpose of Review CAD/CAM and 3D-printing are emerging manufacturing technologies in dentistry. In the field of alveolar ridge augmentation, graft customization utilizing these technologies can result in significant reduction of surgical time. A review of the literature on materials, techniques, and applications of CAD/CAM and 3D-printing available for alveolar ridge augmentation was performed.

Recent Findings CAD/CAM applications for milling of customized block grafts of allogeneic, xenogeneic, and alloplastic origins have been reported, and currently only limited products are commercially available. 3D-printing applications are limited to alloplastic graft materials and containment shells, and have been mostly used in animal studies for optimizing biomaterials' properties.

Summary While current data support the potential use of CAD/CAM and 3D-printing for graft customization for alveolar ridge augmentation procedures, additional research is needed on predictability and long-term stability of the grafted sites.

Keywords CAD/CAM · 3D-printing · Ridge augmentation · Guided bone regeneration · Block graft

Introduction

Alveolar ridge augmentation refers to procedures designed to correct a deformed alveolar ridge, typically in preparation for dental implant placement. Different techniques and materials have been introduced, modified, and refined throughout the years; the current modalities of alveolar ridge augmentation include the following categories: guided bone regeneration (GBR), onlay block grafts, distraction osteogenesis, titanium mesh, and ridge split/expansion techniques. Each technique and material presents several advantages and disadvantages that need to be carefully considered by both the clinician and the patient. However, regardless of the specific technique or material of choice, a successful outcome in alveolar ridge augmentation is dependent upon common basic principles that include primary and passive flap closure, angiogenesis, space maintenance, and stability [1].

In terms of predictability, vertical ridge augmentation has been shown to be far more challenging than horizontal ridge augmentation [2], while in terms of complications, all techniques have their fair share of issues that can adversely affect the outcomes [2, 3]. Therefore, the main focus of contemporary alveolar ridge augmentation techniques and materials is to provide more predictable outcomes in vertical ridge augmentation in as minimally invasive manner as possible. Although the current consensus is that the most predictable technique for vertical ridge augmentation is distraction osteogenesis [2, 3], recently promising outcomes have also been reported for GBR [4–6].

With the increasing popularity of cone beam computed tomography (CBCT), intra- and extra-oral scanning, digital planning software for implant placement, and manufacturing of surgical guides for fully guided implant placement, the complete digital workflow is a reality in everyday clinical practice and is rapidly becoming the standard of care in implant dentistry. With regard to alveolar ridge augmentation in

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preparation for implant placement, the concept of preparing block graft materials extra-orally and pre-operatively has always been quite attractive due to the potential for reduction in surgical time and for more precise adaptation of graft materials. With the recent advances in planning and manufacturing software and hardware, graft customization can be integrated with the implant dentistry digital workflow with the potential to become part of everyday clinical practice.

Two routes of digital workflow in product manufacturing involve either a subtractive or additive process. Computer-aided design and computer-aided manufacturing (CAD/CAM) is a subtractive technique, in which material is subtracted from an initial block object to leave the desired shaped product. In contrast, three-dimensional printing (3D-printing) is an additive technique, in which the desired object is constructed in a layer-by-layer approach. In the context of bone graft manufacturing, CAD/CAM has the advantage that it can be applied on block grafts of different origin, while 3D-printing is limited to alloplastic materials. On the other hand, CAD/CAM offers customization of the graft shape and surface topography only, while 3D-printing provides the additional ability to customize the macroporous internal architecture of the graft. The main disadvantage of CAD/CAM, as a subtractive method, is the amount of material wasted, while with 3D-printing the waste is minimized.

3D-printing for Ridge Defect Sites

The concept of creating customized alveolar graft material that can be designed pre-operatively is not new. In 1991, Johnson et al. [7] introduced the idea of customized tissue spacers utilizing wax on dental casts to simulate the desired augmented alveolar ridge; silicone spacers were fabricated and used to expand the alveolar ridge via a tunneling approach, and particulate bone graft material was inserted into this newly expanded space 3–4 weeks after the insertion of the tissue spacer.

One of the earliest reports of utilization of 3D-printing technology to assist in fabrication of a customized bone block in humans was in 2006. In a clinical case report, Jacotti [8••] utilized a 3D-printed maxilla produced from autoclavable nylon polyamide material to allow for pre-operative manual milling and adaptation of an allogeneic corticocancellous iliac block graft (Puros block, Zimmer) for horizontal ridge augmentation. The advantages of this technique include improved visualization of the ridge defect, and significant reduction of intra-operative time. With the conventional technique, most of the time during surgery is spent shaping the bone block and adapting the graft to the recipient site; by having the pre-shaped bone block and fixation screws planned on the sintered model, the surgeon merely needs to transfer the sterile block graft and fixation screws to the patient's recipient site. In this case report, the remaining voids between the block grafts were filled with particulate allograft (Puros cancellous, Zimmer) and covered with an absorbable membrane (BioMend, Zimmer). Healing was evaluated radiographically and clinically at 6-month reentry surgery and dental implants were placed at that time.

In a more recent clinical case series, Venet et al. [9] utilized similar methodology to shape allogeneic corticocancellous block grafts (TBF, Mions, France) for horizontal ridge augmentation in the anterior maxilla. The pre-shaped bone blocks were delivered to the recipient sites via a minimally invasive subperiosteal tunneling technique, and stabilized with a fixation screw without a barrier membrane; voids were filled with particulate material recovered from the initial block. Healing was evaluated radiographically and clinically at 6 months, at which time implants were placed and allowed to heal for 4 months prior to prosthetic restoration. A total of six patients were treated utilizing a total of 11 bone blocks, and 12 implants were placed, without any complications reported. Both reports by Jacotti [8••] and Venet et al. [9] utilized 3D-printed models of a defect site in order to manually mill a customized block extra-orally and pre-operatively; they demonstrated the clinical feasibility of this technique and its advantages with regard to surgical time reduction and ease of graft adaptation; however, no histologic evaluation was performed in any of the cases.

Draenert [10] introduced a slightly different approach by 3D-printing a model of the desired defect augmentation outcome in order to manually bend a customized shell extra-orally and intra-operatively. In a clinical case report, an open-source software (3D Slicer and Autodesk Meshmixer) was utilized to perform a virtual ridge augmentation of a maxillary defect, and subsequently the STL data generated was used to create a 3D-printed bending model of the desired augmentation outcome. This model was then utilized chair-side for extra-oral thermic bending and trimming of an absorbable shell graft (poly-D, L-lactic acid polymer; KLS Matin Resorbx). The shell was delivered via a tunnel approach and fixed with osteosynthesis screws, and a meshgraft of autologous bone chips and xenograft (BioOss, Geistlich) was placed. Healing was only evaluated radiographically but no information was provided on graft survival and augmentation outcome.

CAD/CAM for Customized Block Grafts

In the digital workflow era, the need to have a physical alveolar ridge defect model is completely eliminated. The reconstruction of alveolar ridge dimensions can be performed digitally, and the graft digitally designed and digitally manufactured.

As early as 1994, Eufinger [11] demonstrated in vitro the application of digital workflow to create a CAD/CAM onlay block graft. Helical computed tomography (CT) was utilized to create a 3D model of an atrophic edentulous mandible, and geometric modeling was then used to generate a model of the onlay graft to be milled. This modeling procedure predicted the dimensions of the graft by subtracting the atrophic mandible geometry from the idealized geometry derived from dentate dried skulls.

In 2013, Schlee et al. [12••] published a proof-of-concept case series utilizing CAD/CAM milled allogeneic cancellous bone blocks derived from the head of the tibia (Tutoplast-protocol, Tutogen Medical, Germany) for vertical and horizontal ridge augmentation in posterior mandibular defects. A total of two patients and three sites were treated, and average surgical time for the ridge augmentation procedure was 41 min. The block graft was fixated with osteosynthesis screws, and the peripheral areas were filled with particulate allograft (Navigraft, Tutogen) and covered with an absorbable membrane (BioGide, Geistlich). Core biopsies were performed at the 6-month reentry surgery that showed almost complete new bone formation with few graft remnants that were surrounded by newly formed bone. One out of three sites exhibited a partial graft exposure 2-months post-operatively that was successfully managed, however resulted in approximately 2 mm graft resorption measured at the level of fixation screws at reentry; all other sites exhibited no resorption at 6 months. A total of 9 implants were placed, with an average crestal bone loss of 1.69 and 1.64 mm at 6 and 12 months post-placement.

In another case report in 2013, Figliuzzi et al. [13] used a similar approach for bilateral mandibular vertical ridge augmentation on one patient, with the choice of grafting material being a CAD/CAM milled coralline porous hydroxyapatite block (Biocoral; Leader-Novaxa, Milan, Italy); no particulate graft or barrier membrane was used in this case. Core biopsies were performed at 6 months reentry and histomorphometric analysis showed 34.5% new bone, 35.6% marrow spaces and 29.9% residual biomaterial. No information on graft resorption was provided; however, dental implants were placed and followed up to 1 year with no complications reported. A similar surgical technique was utilized in a prospective cohort study for vertical and horizontal ridge augmentation in the anterior and posterior maxilla, with similar histomorphometric outcomes reported at 8 months. In this study, two types of complications were noted, graft fracture during fixation and graft exposure 2 months post-operatively, that were both managed [14].

Mangano et al. [15] utilized the same grafting material, a CAD/CAM milled coralline porous hydroxyapatite (Biocoral; Leader-Novaxa, Milan, Italy) block graft, for the application of bilateral sinus elevation in five patients. In addition to CAD/CAM milling of the block graft, custom-milled lateral sinus window preparation guides were fabricated as well. The grafts were allowed to heal for a period of 6 months and no complications were reported. A total of 19 implants were placed and followed for 2 years; all implants survived with no clinical or prosthetic complications.

In a case report in 2015, Mangano et al. [16] introduced the use of a new alloplastic material for CAD/CAM block graft milling, biphasic calcium phosphate (mixture of 70% β-tricalcium phosphate and 30% hydroxyapatite) for horizontal and vertical ridge augmentation in the anterior mandible. In this case report, the block graft milling design incorporated a hole in the center of graft for fixation screw placement, and platelet-rich-in-growth-factors (PRGF) was used during surgery. Core biopsies were performed at the 12-month reentry surgery and revealed compact mature bone undergoing remodeling, marrow spaces, and newly formed trabecular bone surrounded by residual graft particles; no histomorphometric analysis was performed. In a case series of vertical and/or horizontal ridge augmentation performed with the same CAD/CAM milled biphasic calcium phosphate block graft and an absorbable collagen membrane [17], three out of 15 sites had early graft exposure, and one graft was lost completely. CBCT evaluation at 8 months revealed mean vertical bone gain of 2.1 mm and mean horizontal bone gain of 3.0 mm. A total of 14 implants were placed survival was 100% with a mean follow-up time of 4.7 years.

Other applications of the CAD/CAM milling process for alveolar ridge augmentation procedures include the use of block grafts of bovine origin [18], as well as the fabrication of milled surgical guides for autogenous bone block harvesting [19]. Clearly, one of the major advantages of CAD/CAM technology for block grafts over 3D-printing is its potential application on a wide range of grafting materials, including alloplastic, allogeneic and xenogeneic.

3D-printing for Customized Alloplastic Block Grafts

In contrast to the CAD/CAM milling process, 3D-printing technology for block grafts is currently applicable to alloplastic materials only. Critical aspects of biomaterial properties for alveolar ridge augmentation include biocompatibility, absorption rate, ease of handling, and cost. Specifically for alloplastic materials, the macro- and micro-porosity is a determining factor for angiogenesis and cell adhesion, and research is ongoing to identify the optimal architecture.

In an animal study, Tamimi et al. [20•] compared 3D-printed monolithic monetite (dicalcium phosphate anhydrous) block grafts to autogenous onlay block grafts for vertical bone augmentation on the calvaria of New Zealand rabbits after

8 weeks of healing. The 3D-printed monetite was shown to be osteoconductive, as evidenced by new bone formation on graft sites in contact or close proximity to native bone. Although no significant differences between materials were observed with regard to vertical bone height gain, the mean bone volume gain was significantly higher for the autogenous group and the mean residual graft volume was significantly higher in the monetite group. These results indicate that 3D-printed monolithic monetite block grafts have the potential to be used as an alternative to autogenous block grafts; however, the different healing and resorption patterns need to be taken into consideration. In a follow-up animal study [21] utilizing similar methodology and comparing two different heights of 3D-printed monolithic monetite block grafts of 4 and 3 mm, the authors concluded that a maximum height of 4 mm bone gain is possible on the lateral side of the graft where a higher vascular supply is present. The block grafts in general resulted in more new bone formation on the lateral, medial, and inferior surfaces and least on central-superior surfaces where it is furthest from native bone. Histomorphometric analysis revealed 40 and 37% mean new bone formation and 50 and 55% mean residual graft for the 3- and 4-mm group respectively.

In order to evaluate the effect of macroporous architecture on new bone formation in 3D-printed monetite blocks, Tamimi et al. [22•] tested four different designs utilizing the same animal model. In addition, dental implants were placed to evaluate if osseointegration of titanium implants on monetite is possible. The amount of mean new bone formation within the monetite blocks ranged from 35.7 to 46.9%, while the mean residual graft ranged from 43.1 to 57.7%; mean bone height gain ranged from 3.1 to 3.7 mm; mean bone-to-implant contact (BIC) ranged from 20.9 to 37.8%. The results of this study indicate that different macrogeometry designs can influence the bone formation pattern, with designs that allow for blood diffusion from high metabolic areas to low metabolic areas providing superior outcomes. Furthermore, the authors concluded that, although osseointegration is possible, additional research is required to improve BIC.

Another alloplastic material that was recently introduced for 3D-printing is biphasic calcium phosphate (70% β-tricalcium phosphate and 30% hydroxyapatite). In an animal study, Mangano et al. [23] utilized a sheep maxillary sinus model to evaluate healing of a 3D-printed biphasic calcium phosphate block graft at 45 and 90 days. The results indicate that there is complete integration of the scaffold within the sinus cavity, the amount of newly formed bone increases over time, and the periphery of the scaffold shows bone tissue in different amount and maturation compared to the core that mainly consists of connective tissue.

Although currently the evidence available on 3D-printed alloplastic block grafts for ridge augmentation is limited to animal studies, this concept can be very promising. Such a technique for graft manufacturing combines the advantages of an alloplastic material, unlimited availability, no risk for disease transmission, and high patient acceptance, with the advantages of the 3D-printing technology, reduced waste of biomaterial, ability to optimize surface topography and macroporous architecture; and reduction of intra-operative time. Additional research is required in order to manufacture 3D-printed grafts that have regeneration and implant success outcomes similar to those of conventional materials and techniques.

3D-printing for Customized Containment Shells

Another application of 3D-printing for alveolar ridge augmentation is the manufacturing of a 3D-printed containment shell. The only material that has been used to date for this application is titanium, for the manufacturing of a Ti-mesh, while no true 3D-printed absorbable alloplastic shell materials have been manufactured.

Ciocca et al. [24••] presented a case report demonstrating a step-by-step procedure for digital alveolar ridge reconstruction to facilitate prosthetically driven implant placement. Based on the digital design, a Ti-mesh was 3D-printed to provide the shell needed to contain particulate bone graft; implants were later placed in a fully guided manner into desired positions, and prosthetic frameworks were milled and restored.

More recently, Connors et al. [25] published a case series of a 3D-printed custom titanium ridge augmentation matrix (CTRAM) used for particulate graft material containment in three mandibular posterior sites. The main grafting material used was freeze-dried bone allograft (FDBA, LifeNet Health); in addition, an absorbable membrane (Dynamatrix, Keystone Dental) and platelet-rich plasma (PRP) were used in two sites, while enamel matrix derivative (Emdogain, Straumann) without membrane was used in the third site. Furthermore, in one case, a traditional mesh-like design was used for the CTRAM that is similar to the commercially available Ti-meshes, while on the second case, a modified design was employed to facilitate access for graft placement. Surgical reentry was performed at 8 months and 4 dental implants were placed at the appropriate pre-planned position. One out of three sites exhibited an early partial mesh exposure that was successfully managed, and resulted in less than anticipated bone fill that did not, however, negatively affect implant placement; no other complications were noted. This case series demonstrated the potential application of 3D-printing for the fabrication of a custom-fit Ti-mesh, but also for individual design modifications that can improve all aspects of ridge augmentation procedures.

Conclusion

The utilization of CAD/CAM and 3D-printing for digital reconstruction and graft manufacturing for alveolar ridge augmentation procedures can present significant benefits for the patient and the clinician. First, it allows for detailed pre-operative planning, design of the desired final grafting outcome, and virtual evaluation of the desired outcome relative to the final prosthetic reconstruction. Second, it has the potential to produce customized grafts with optimal adaptation and stability, both crucial factors for success in ridge augmentation procedures. Third, it allows for significant reduction of intra-operative time; less surgical time typically results in less complications, more uneventful healing, less patient discomfort, and overall improved patient experience. Fourth, the CAD/CAM milling process can be applied to a wide range of grafting materials, including alloplastic, and those of allogeneic and xenogeneic origin; this allows the clinician to utilize the material of choice based on its properties for each clinical scenario. Finally, the 3D-printing process, although currently limited to alloplastic materials, has the potential to aid in optimizing the surface topography and microporous architecture of these materials, thus significantly improving their regenerative potential and success.

Based on this review of the literature on CAD/CAM and 3D-printing applications for alveolar ridge augmentation, it is evident that this is a promising technology; however, research is at its infant stages and the level of evidence is low, limited to animal studies, or, at best, case series. The animal studies utilize models that are not always realistic or the most appropriate. The human studies include short-term data on implant survival and stability of the augmented ridge. Well-designed randomized controlled clinical trials and longer follow-up of dental implants placed on augmented sites are necessary to assess the predictability and long-term stability of these techniques and materials. Furthermore, additional research and focus on developing optimal alloplastic graft materials would provide clinicians with more choices and flexibility to allow for truly customized treatment options that can best serve individual patient needs.

Currently, one allogeneic block graft produced with a CAD/CAM block milling technique is commercially available in the USA (Straumann Allograft Custom Block, LifeNet Health). However, an estimated 6-week delivery time is required and the cost is significantly higher compared to other commercially available non-custom block grafts. Since CAD/CAM and 3D-printing technologies present with significant potential advantages, it is anticipated that as manufacturing time and cost are reduced, customized block grafts will be widely accepted and utilized and will become the future in alveolar ridge augmentation.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflicts of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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