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Process chain for the fabrication of a custom 3D barrier for guided bone regeneration

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Abstract

Guided Bone Regeneration (GBR) is a surgical procedure that consists in the use of barrier membranes to cover bone defects caused by trauma, periodontal disease and other pathologies. These barriers allow the proliferation of bone cells, and prevent the invasion of the defect by non-osteogenic cells (connective and epithelium) in patients with a lack of horizontal and/or vertical bone. This process is essential for the successful dental implant placement. Additive manufacturing (AM) is emerging as an important tool for biomedical applications, especially for regenerative medicine and tissue engineering. This paper proposes a process chain for the fabrication of a custom barrier from cone beam computed tomography (CBCT) as Digital Imaging and Communication in Medicine (DICOM) files obtained from a patient with vertical bone resorption of the anterior maxilla. DICOM files have been processed with Invesalius 3.0 to obtain the tridimensional (3D) anatomy of the region of interest. This 3D model was cleaned, fixed, and smoothed. The prototyped model of the patient's bone defect was further processed in Rhinoceros to offer a 3D architecture for cell growth. To obtain information of the thermal and mechanical properties a finite element method (FEM) was assessed. The prototype obtained was produced with fused deposition modeling (FDM) an additive manufacturing technology.

Keywords: Additive Manufacturing; Guided bone regeneration; Process chain; Fused Deposition Modelling

1. Introduction

New procedures in dental implant therapy have been implemented using bone regeneration engineering. The overall success of dental implant therapy not only depends on the presence of adequate bone volume, long-time stability and health of peri-implant tissues, but also an appropriate amount of buccal bone thickness (2mm) is needed before dental implant placement, especially in the anterior maxilla [1]. Guided bone regeneration (GBR) is used in the reconstruction of alveolar ridge with the purpose of reestablishing the bone volume for the subsequent placement of dental implants [2].

GBR is a studied procedure that tries to solve the problems of (1) reconstructing large osseous defects in the jaws, or (2) the treatment of the atrophic maxilla or mandible [3]. The

procedure consists in achieving bone tissue formation at the expense of a barrier which produces and establishes an environment where bone cells could be active. These barriers must exclude the epithelium tissue, prevent the flow of non-osteogenic cells, and provide a space where bioactive cells and molecules interact on the formation of bone tissue and also allow the primary wound closure [4].

The conventional GBR technique is based on the use of resorbable (collagen) [5], and the use of non-resorbable Polytetrafluoroethylene (PTFE) membranes to establish the environment necessary for bone regeneration. Bone grafting can sometimes be placed to support the membrane and comply with osteoconduction function because space is required for the fibrin clot to promote the formation of bone tissue.

The current technique most used for bone regeneration in vertical defects is based on the use of PTFE membranes sometimes reinforced with a titanium structure [6]. Although the predictable results of the use of PTFE barriers are significantly associated with the exposure and consequent microbial infection; and due to their non-resorbable nature, a second surgery is required to remove them, with an increased cost and patient discomfort [7].

The objective of this project was to generate a process chain for a custom designed barrier produced by additive manufacturing (FDM) for GBR. The purpose was to fabricate a biodegradable barrier with optimal mechanical properties to maintain the space, avoiding its collapse during the bone augmentation, insurance the patient comfort, and reducing the surgery time. The initial patient model was obtained using cone-beam computed tomography (CBCT) imaging and DICOM files and processed with Invesalius and Meshmixer. After that, the barrier was designed in Rhinoceros, a superficial modeling software, to have a smooth and custom barrier. To evaluate the mechanical and thermal properties of the custom three-dimensional (3D) barrier designed, Finite Element Method (FEM) method was assessed. The barrier was prototyped using ABSM30 in a Fortus 400MC.

2. Literature overview

GBR was first suggested in 1959 by the placement of mechanical barrier membrane to contain blood clots and isolate bone defects surrounded by connective tissues [8]. Some studies have suggested the preservation of the alveolar bone immediately after tooth extraction, by the use of materials that can act as barriers to providing a close space for the access of bone-forming cells [4].

Materials such as polytetrafluoroethylene (e-PTFE) reinforced with titanium have been studied for GBR [9, 10, 11]. These barrier membranes have shown an excellent behavior due to their low immunological effect and stability [12]. However, they must be surgically removed, with the risks mentioned before. Also, resorbable collagen barriers have been promoted for GBR because their rapid degradation (8-18 weeks) and that may enhance bone regeneration [13], but its limitations include low mechanical properties and early loss of barrier function [14]. Recently, with the advances in additive

manufacturing, researchers have been innovating in the fabrication of barriers [15]. For these manufacturing technologies, biodegradable polymers have been used. Outcomes of PCL in hard tissue regeneration have been well-documented, especially in the field of orthopedics [16]. Shim et al. proposed a system of polymers base on polycaprolactone (PCL)/poly (lactic-co-glycolic acid), (PLGA)/tricalcium phosphate (β-TCP) to manufacture barriers. The results showed great adhesion and cell proliferation, and a compressive strength in comparison with the use of each material separately [17].

Modeling of the physical phenomena associated with manufacturing [18] and biological process [19] has been recognized as one of the most significant tasks in the research of this fields. FEM, as a numerical simulation technique, has been extensively used in the field of dental biomechanics to evaluate engineering and biomechanical problems.

The modern development of computer technologies has converted to the FEM in a powerful technique for dental and implant biomechanics because of its versatility in calculating stress distribution within complex structures. Bone remodeling using FEM have the potential to generate specific tools to help dentists in the pre-operational planning and to evaluate the effectiveness of operational practices, as well as assist bioengineers in the design and manufacturing process to optimize solutions for the improvement of an implant [20]. The FEM applications in dentistry have increased the last years, becoming a powerful tool for the prediction of the implant behavior and its surrounding bone. The success or failure of a dental implant depends on the manner in which stresses are transferred to the surrounding bone. Load transfer from the implant to its surrounding bone depends on the type of loading, the bone implant interface, the dimensions of the implants, the shape and characteristics of the implant surface, the morphology of the implant, the prosthesis type, and the quality of the surrounding bone [21]. FEM allows researchers to predict the stress influence due to the contact of the implant/graft with cortical bone or trabecular bone. The adaptive response of the surrounding bone occurs under the effect of stress. Implant features causing excessive high or low stresses can contribute to pathologic bone resorption or bone atrophy [22]. The complexity of the mechanical characterization of bone and its interaction with implant/grafts systems have forced researchers to make major simplifications and assumptions to make the modeling and solving process possible.

Some other researchers have been used image-based 3D-printed barriers with promising results in periodontal regeneration [23, 24]. They have found that with the use of different polymer structures as scaffolds, they can achieve bone regeneration in alveolar sockets with little or no residual material, these findings were proved with histologic evidence in a human model [25]. This process chain has also been used in regeneration of periodontal defects with excellent result in the regeneration of periodontal tissues even with the absence of bone graft material [26].

3. Methods

3.1. Clinical Evaluation

Case: A healthy 26-year-old female patient, who suffered a car accident 10 years ago, with the loss of the dental organs 1.1, 2.1 and 2.2. Also, this trauma resulted in a Class III bone defect, extended vertically and horizontally in the upper anterior region [27].

3.2. CBCT examination

The CBCT scanning was performed using a Promax 3D® CBCT device (Planmeca Oy, Helsinki, Finland). The occlusal plane of the jaws was positioned horizontally to the scan plane (parallel to the floor), and the mid-sagittal plane was centered (perpendicular to the floor). The beam height at the surface of the image receptor (CMOS flat panel) was adjusted and set to visualize the entire jaws comprising a field of view (FOV) in an arc of 180º (80-mm width and 80-mm height). Image size consisted out of 401×401×251 isotropic pixels. A total number of 534 slices of 200 μm isotropic voxel edge length was obtained. For image acquisition, the dose protocol was 90 kV and 8 mA using pulsed scanning time of 12.002 s.

3.3. Digital processing

The data were recorded using the digital imaging CBCT and (DICOM) protocol. The axial plan was adjusted parallel to the occlusal plane, and the slice sections obtained in 0.15 mm of thickness. To study the patient case, DICOM files were first analysed in 2D images and measured the missing bone tissue on the upper incisors.

Afterward, the maxillofacial information obtained through CBCT as DICOM files was processed by InVesalius 3.0 software (CTI, Campinas, SP, Brazil) by selecting compact bone and generated a stereolithography file (STL). The file was processed into Netfabb (Autodesk, Inc., San Rafael, USA) to reduce noise and redundant data. Then the 3D model was smoothed out using a free software called Meshmixer (Autodesk, Inc., San Rafael, USA), used for editing 3D models, also to obtain the part of interest and where the implant for the bone regeneration will be suited.

3.4. Design of the custom barrier

The custom barrier was designed using Rhinoceros 5.2.4 (Mc Neel & Associates, Seattle, USA) modeling software. The patient model information contributed to creating the surface from edges of the jaws and lack of bone on the upper incisors. Smoothing and curves manage performed using control points (Gumball) and cut to the correct size. The barrier was exported as a solid in STL.

3.5. Finite Element Method

3.5.1. Implant loading

Barriers were thermally loaded in their faces. A variation of the temperature of 35°C was applied to the internal and external surface. The inner surface will be in contact with a filler material in an early stage, and after some weeks this surface will be in contact with regenerated alveolar bone (hard tissue). The outer surface will be in touch with the gum (soft tissue). The inner buccal zone is sensible to extreme changes of temperature. This abrupt changes of temperature can cause mechanical stress in the implants inside of the maxilla. The ends of the barrier were fixed in the three principal axis (x, y, and z) due to the permanent contact with the surrounding bone.

3.5.2. Thermomechanical analysis

The governing equations used to simulate this model were the transient energy equation and the elastic equation. The material considered in this study was polylactic acid (PLA), and its behavior was assumed as linear.

The transient energy equation is given:

$$\rho \left(\frac{\partial H(T)}{\partial t} \right) = \nabla \cdot (k(t)\nabla T) \tag{1}$$

Where ρ is density, k is isotropic temperature-dependent thermal conductivity, H is the temperature dependent enthalpy

The mechanical behavior when temperature changes are controlled largely by the strains, which must remain lower than a few percent to avoid cracking. Assuming small strain, the linearized strain tensor is:

$$\epsilon = \frac{1}{2}[\nabla u + (\nabla u)^T] \tag{2}$$

Where u is the displacement vector.

3.5.3. Software and evaluation

The finite element method (Fig. 1) was applied to the analysis of a barrier used in the process of bone regeneration of the maxilla (alveolar) area. The meshing of the barrier was using GMSH [28]. The mesh was built using the TetGen algorithm applying solid tetrahedral elements with a global seeding size of 0.15 mm. The numerical simulations were performed in an open-source finite element software (FEBio) and Elmer GUI (http://www.csc.fi/elmer). For the numerical computation of the von Mises stress, a transient thermomechanical analysis was applied to the barrier. The material was considered as Hookean material.
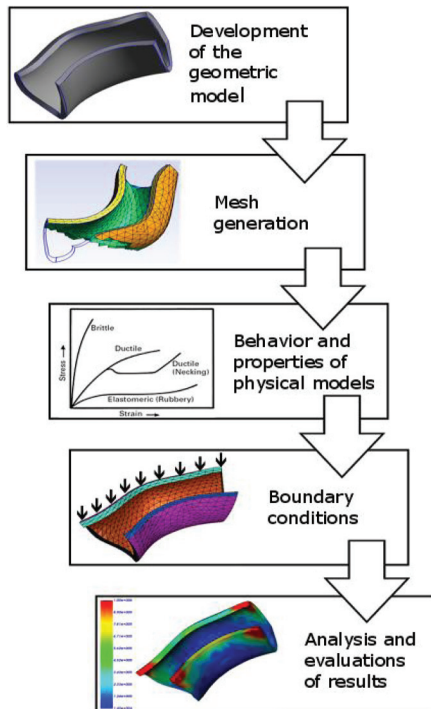
Figure 1. Finite element methodology: The use of simulation methods such as FEM has been used in the analysis of complex problems, for which it is difficult to obtain an analytical solution. The figure depicts the analysis.

3.6. Rapid prototyping

First prototypes of the patient model and barriers (1.0 mm and 1.5 mm of thickness) were fabricated with ABS-M30 by Stratasys, (Acrylonitrile butadiene styrene). A FDM machine, Stratasys Fortus 400mc (Stratasys, Minnesota, USA) with a nozzle of 0.12 mm (T10) for the barriers and 0.25 mm (T16) for the jaws model was used. FDM deposits fused polymeric material layer by layer with appropriate levels of accuracy of +/- 0.127 mm per mm according to the manufacturer. AM parameters of 100% infill, 0.12-0.4 mm of layer height, 30 mm/s of speed has been determined. Also, material flow was set at 70%. A prototype with PLA was produced using 75% of flow, 0.2 mm of layer height and 30 mm/s of speed in a Rostock Max Delta (SeemeCNC, Indiana, USA).

4. Results and Discussion

4.1. Fabrication of the custom barriers with FDM.

Barriers were successfully designed and fabricated with ABS-M30 and PLA by material extrusion additive manufacturing process. Figure 2 shows the PLA barrier. The porosity of the material was given by the material flow through the nozzle at 75%. The thickness of the barrier was 1 mm.
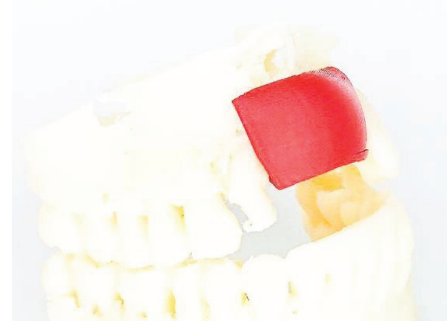

Figure 2. 3D printed barrier

4.2. Finite Element Method

Figure 3 shows the thermal distribution after 120 seconds. The barrier keeps a good isolation for the filler material inside of the barrier. It is of relative importance to retain a constant temperature inside of the filler material and the regenerated bone because this variation could affect an incomplete bone healing or changes in its density.
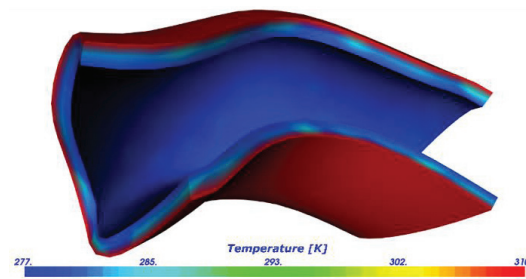

Figure 3. Transient thermal distribution (t=120 seconds) in the barrier.

Figure 4 shows the von Mises stress distributed along the barrier due to the thermal variation. Acute changes differences can cause a thermal expansion of the barrier and, consequently a thermomechanical stress. The mechanical behavior of an implant in the maxilla area can affect the bone reconstruction. The adaptive response of the surrounding bone occurs under the effect of stress. Implant features as the case of the barrier can cause excessive high, or low stresses can contribute to pathologic bone resorption or bone atrophy [22].
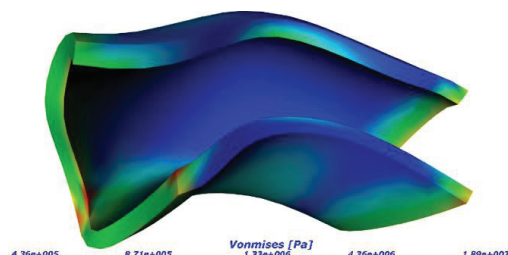

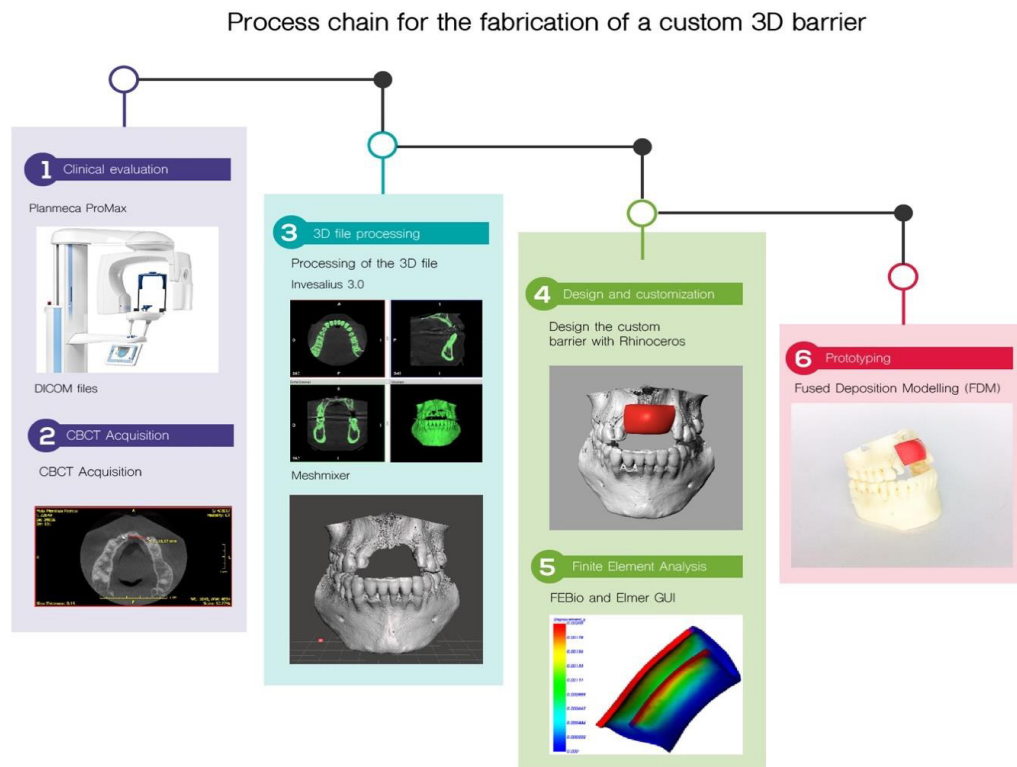*Figure 4. Von Mises stress produced by the thermal loads in the barrier.*

Process chain for the fabrication of a custom 3D barrier

Figure 5. Process chain for custom 3D barriers

4.3. Process chain for custom 3D barriers

A biodegradable and personalized 3D barrier for guided bone regeneration was successfully obtained by this additive manufacturing process (FDM) for GBR (Fig 5). The clinical evaluation with Promax 3D® CBCT device to obtain CBCT took 12s for scanning and 15 minutes for processing and analyzing. The process of cleaning, fixing and repairing the 3D model with Invesalius and other software had a duration of 40 minutes. The production of the 3D custom barrier took the following times a) Design - 45 min b) FEM – 2 minutes c) rapid prototyping of the 3D custom barrier with AM – 8 minutes and patient model 3 hours. So, this chain process for custom 3D barriers can be finished 4 hours approximately. Iterations on design and rapid prototyping of the barrier can produce delays no more of 2 hours. The obtained structure has well defined shapes and dimensions that can be implemented in other bone defects.

Conclusions

The proposed process chain for the production of a barrier for GBR showed the next results: a) a reproducible way to make GBR customizable for the implant needs of bone tissue, b) the barrier presents minors variations in its mechanical stress distribution due to the temperature changes. Stress concentrations appear only in small areas of the lateral borders (Fig. 4); then this design can be considered as optimal. c) and a process chain that can be used with different materials that offer degradation times of 8-10 months.

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