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ScienceDirect

Procedia CIRP 65 (2017) 151 – 156

www.elsevier.com/locate/procedia

3rd CIRP Conference on BioManufacturing

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.

Peer-review under responsibility of the scientific committee of the 3rd CIRP Conference on BioManufacturing 2017

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

Peer-review under responsibility of the scientific committee of the 3rd CIRP Conference on BioManufacturing 2017
doi:10.1016/j.procir.2017.04.015

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].