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The influence of bone quality on the biomechanical behavior of full-arch implant-supported fixed prostheses

Leonardo Perez Faverani [a,b], Valentim Adelino Ricardo Barão [c,*], Gabriel Ramalho-Ferreira [a],
Juliana Aparecida Delben [d], Mayara Barbosa Ferreira [b],
Idelmo Rangel Garcia Júnior [a], Wirley Gonçalves Assunção [b]

[a] Department of Surgery and Integrated Clinic, Aracatuba Dental School, Univ Estadual Paulista (UNESP), José Bonifácio 1193, Araçatuba, São Paulo 16015–050, Brazil
[b] Department of Dental Materials and Prosthodontics, Araçatuba Dental School, Univ Estadual Paulista (UNESP), José Bonifácio 1193, Araçatuba, São Paulo 16015–050, Brazil
[c] Department of Prosthodontics and Periodontology, Piracicaba Dental School, University of Campinas (UNICAMP), Av Limeira, 901, Piracicaba, São Paulo, 13414–903, Brazil
[d] Department of Dental Materials and Prosthodontics, Araraquara Dental School, Univ Estadual Paulista (UNESP), Humaitá, 1680, Araraquara, São Paulo, 14801–903, Brazil

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ABSTRACT

We evaluated the influence of bone tissue type on stress distribution in full-arch implant-supported fixed prostheses using a three-dimensional finite element analysis. Stresses in cortical and trabecular bones were also investigated. Edentulous mandible models with four implants inserted into the interforaminal region were constructed from different bone types: type 1 — compact bone; type 2 — compact bone surrounding dense trabecular bone; type 3 — a thin layer of compact bone surrounding trabecular bone; and type 4 — low-quality trabecular bone. The mandible was restored with a full-arch implant-supported fixed prosthesis. A 100-N oblique load was applied to the left lower first molar of the prosthesis. The maximum (σmax) and minimum (σmin) principal stress values were determined. The σmax in the type 4 cortical bone was 22.56% higher than that in the type 1 bone. The σmin values in the cortical bone were similar among all the bone types. For the superstructure, increases of 9.04% in the σmax and 11.74% in the σmin in G4 (type 4 bone) compared with G1 (type 1 bone) were observed. For the implants, the highest stress values were located in G4, and the lowest values were observed in G1. In the trabecular bone, the highest stress was generated in G1 and G2. In conclusion, the more compact bones (types 1 and 2) are the most suitable for supporting full-arch implant-supported fixed prostheses, and poor bone quality may increase the risk of biological and mechanical failure.

1. Introduction

Rehabilitation with implant-supported prostheses is considered a feasible therapy for edentulous patients [1–4]. Currently, approximately 300,000 patients per year are treated with dental implants in the United States [5]. The insertion of four to six implants into the interforaminal area of the edentulous mandible provides great stability for implant-supported prostheses with a distal cantilever [6,7]. However, factors such as oral hygiene, the inter-arch relationship, treatment cost, patient acceptance, and masticatory function may influence treatment options [8–10].

In this sense, the bone availability and inter-arch space should be appropriate for the placement of implants in the mandibular anterior region [11]. The volume and quality of the alveolar ridge influence the biomechanical and esthetic results, the stability of the implant-supported prostheses, and the health of the surrounding tissues [12]. After tooth loss, the structure of the mandibular bone undergoes a constant process of physiological resorption, which causes the decline of the alveolar perimeter and the expansion of the trabecular bone, decreasing the bone density. These factors may influence treatment with dental implants [13,14].

The quality of bone tissue is classified into the following four categories based on the ratio of cortical to trabecular bone: type 1 — primarily compact bone; type 2 — compact bone surrounding dense trabecular bone; type 3 — a thin layer of compact bone surrounding trabecular bone; and type 4 — a thin layer of cortical bone surrounding low-density trabecular bone [15]. The quality of the bone architecture influences the transfer and distribution of physiological forces, which dictates the treatment prognosis [16,17]. Low-quality bone tissue, especially type 4, is associated with a high rate of implant treatment failure [18] due to a reduced cortical/trabecular tissue ratio and low adhesion force, which jeopardizes osseointegration [16–21].

A three-dimensional finite element analysis (3D-FEA) has previously been used to evaluate the performance of bone tissue with different quality patterns in implant-supported single crowns attached to implants of different lengths [22] and in multi-unit prostheses with prefabricated bars [14,23]. For low-quality bone tissue, an increase in implant length has been shown to reduce stress distribution [19,22].

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* Corresponding author at: Av Limeira, 901, Piracicaba, São Paulo, 13414–903, Brazil. Tel.: +55 19 2106 5719; fax: +55 19 2106 5218.
E-mail address: barao@fop.unicamp.br (V.A.R. Barão).

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Other studies [14,23] have demonstrated that bone types 3 and 4 generated the highest stress concentrations under axial and buccolingual loads. Type 4 cortical bone also exhibited high stress values under all loading conditions [14]. However, it has been suggested that bone quality is not the only factor that influences stress distribution because bone tissue helps to support implant-supported prostheses retained by prefabricated bars [14].

There are limited data concerning the factors that affect the biological performance of bone tissue and the stress patterns associated with different designs of implant-supported prostheses. Thus, the aim of this study was to evaluate the influence of different bone types (Types 1 to 4) on stress distribution in mandibular full-arch implant-supported prostheses using an FEA model based on computed tomography (CT) images. We hypothesized that the stress on the implant/superstructure assembly and on the peri-implant bone tissue would be significantly lower in bone types 1 and 2.

2. Materials and methods

This study was approved by the Human Research Ethics Committee of Aracatuba Dental School-UNESP, Brazil (process number: 2008–00939).

The geometry of the completely edentulous mandible of a 60-year-old man was reconstructed from cone-beam CT images (I-Cat Cone Beam Volumetric Tomography and Panoramic Dental Imaging System, Imaging Sciences International, Hatfield, PA, USA). The patient was informed about the procedure and signed an informed consent form. The mandibular section was imaged with 2-mm slices, and the patient was rehabilitated with a conventional complete denture. The denture was duplicated in self-polymerized acrylic resin mixed with barium sulfate in a 3:1 ratio to allow for the radiopacity of the denture during the CT scan. After the duplicated denture was adjusted, the CT scan was performed.

The CT assessment data were imported into the Simpleware 4.1 software package (Simpleware Ltd, Rennes Drive, Exeter, UK) for the construction of the 3D solid geometries of the edentulous mandible and denture. Based on the actual positions of the mandible and denture, the mucosal geometry was deduced, and the mucosa remained in contact with the inner surface of the denture [22]. In the edentulous mandible, both the cortical and trabecular bones were determined according to the CT data. The mucosa and the cortical bone were approximately 3.0 and 1.5 mm thick in the interforaminal area, respectively.

A 3D constitutive model of an edentulous mandible was obtained. Four different types of bone (types 1, 2, 3 and 4, with varying elastic moduli of the bone tissue) were used based on the bone quality classification system suggested by Lekholm and Zarb [15]. The model was rehabilitated with a fixed full-arch implant-supported prosthesis.

Four implants, 11.5 mm in length and 3.75 mm in diameter, were modeled using CAD software (SolidWorks 2010, Dassault Systèmes SolidWorks Corp., Concord, MA, USA) and were virtually inserted into each model. In all the models, the implants were placed in the center of the mandibular alveolar crest, 10 and 20 mm away from the midline on both sides of the mandible [24], as shown in Fig. 1.

The implants and prosthetic components were imported into the Simpleware software and were merged with the edentulous mandible and prosthesis in all the groups according to the level of bone quality (G1 — bone type 1; G2 — bone type 2; G3 — bone type 3; and G4 — bone type 4). Finally, a finite element mesh of the models was obtained using the Simpleware software. The mesh refinement was established based on a convergence analysis (5%) [25]. The models contained a total of 244,388 elements and 70,387 nodes, as shown in Fig. 2.

The meshed models were imported into finite element analysis software (Abaqus 6.10-EF1, Dassault Systèmes Simulia Corp., Providence, RI, USA) to evaluate the stress distribution. The mechanical properties (elastic modulus and Poisson coefficient) of the materials are presented in Table 1 [23,26–29].

Complete bonding between the bone tissue and implants was assumed to simulate osseointegration with no motion between the structures during loading [18,30–33]. To reproduce the clinical setting, a contact was applied between the implants and the superstructure [34]. The superstructure was glued to the acrylic resin prosthesis [35].

The models were supported by the masticatory muscles and temporomandibular joints. The forces generated by the masticatory elevator

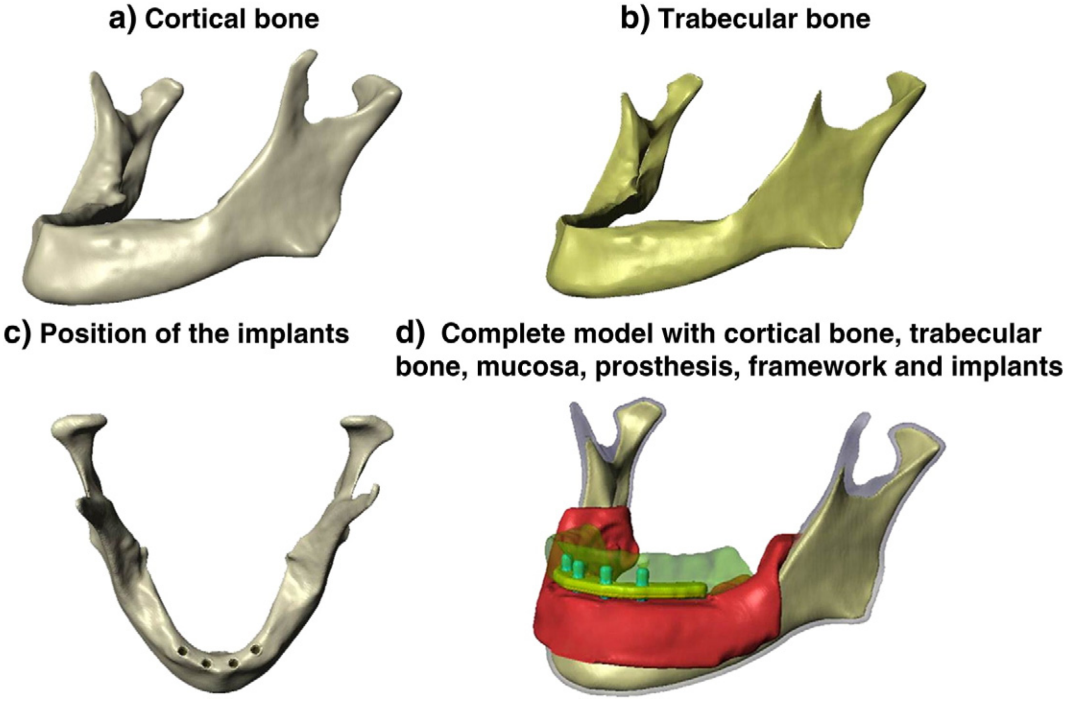

Fig. 1. Models representing a) cortical bone, b) trabecular bone and c) implants inserted into the interforaminal region. d) Complete model with cortical bone, trabecular bone, mucosa, prosthesis, framework and implants.