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Analysis of Bone-implant Interfacial Stress during Disocclusion in Complete Implant-supported Prosthesis: A Finite Element Study

Gustavo Diniz Greco¹, Carolina Nemesio de Barros Pereira²,
Giovani Lana Peixoto de Miranda³, Guilherme Carvalho Silva³,
Cláudia Silami de Magalhães³ and Allyson Nogueira Moreira^{3*}

¹Department of Restorative Dentistry, Sistema Integrado de Ensino de Minas Gerais Ltda.,
Belo Horizonte, MG, Brazil.

²Private Practice, Belo Horizonte, MG, Brazil.

³Department of Restorative Dentistry, Faculdade de Odontologia, Universidade Federal de Minas Gerais, Pampulha, Belo Horizonte, MG, Brazil.

Authors' contributions

This work was carried out in collaboration between all authors. Author GDG designed the study, performed the study wrote the protocol and the first draft of the manuscript. Authors CNBP, GLPM and GCS managed the literature searches, analyses of the study and English translation. Authors CSM and ANM managed the literature searches, designed the study and final review. All authors read and approved the final manuscript.

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ABSTRACT

Aim: Little is known about the biomechanical behavior of disocclusion patterns in implant-supported prostheses. Thus, the aim of the present study was to analyze the stresses generated at bone-implant interface during different patterns of disocclusion in an implant-supported lower complete denture without free distal ends using the three-dimensional (3-D) finite element method.

*Corresponding author: E-mail: dangelogatil@terra.com.br;

Study Design: Finite element method.

Methods: A 3-D model of a complete denture supported by five inter-foraminal implants and two distal was developed (CAE software Abaqus). A canine guide disocclusion (CG) was simulated applying a nodal load of 15 N at an angle of 45° on the canine tooth prosthesis, while to a bilateral balanced occlusion (BBO) a similar load pattern was applied at four distinct points, bilaterally. Linear elastic static analysis was used to compare the magnitude of maximum and minimum principal stresses at bone-implant interface for each simulation.

Results: The disocclusion pattern generated during CG exhibited a greater stress concentration at the bone-implant interface of the distal implant on the working side. BBO showed a more homogeneous stress distribution pattern at the bone-implant interface of the two distal implants. Anterior implants showed lower stress concentration.

Conclusions: Bilateral balanced occlusion (BBO) resulted in a more favorable stress distribution in this complete implant-supported prosthesis model.

Keywords: Dental occlusion; dental implant; biomechanics; dental stress analysis.

1. INTRODUCTION

Prosthetic rehabilitation using dental implants has shown long-term predictability primarily in completely edentulous patients [1,2]. However, biological and mechanical failures can still occur. Understanding the biomechanical phenomena of the bone-implant-prosthesis system is essential for the maintenance and stability of the osseointegrated rehabilitation [2].

Due to the presence of anatomical jaw structures such as the mandibular canal, implant-supported complete-fixed prostheses with cantilevers have been used frequently and have been found to be reliable [1]. The placement of four to six implants in the inter-foraminal region allows complete mandibular rehabilitation by means of a complete fixed denture with distal cantilever extension, which may restore aesthetics, phonetics, and function of the stomatognathic system [1,3]. This prosthesis configuration has been shown to have long-term predictability in clinical evaluation [1].

Although prostheses with free ends on both sides are acceptable, the cantilever length should not be more than 1.5 times the distance between the most distal and the most medial implant. Increased cantilever length may compromise stress distribution in implant, bone, and prosthetic components [4,5]. When the free end is loaded, the implant closest to the load experiences compressive stress, while the adjacent implants experience tensile stress [5].

This extended length can result in unfavorable stress distribution even if more implants are used for support [6]. Thus, it is important to reduce or even eliminate the cantilever extension in implant-supported prostheses. In edentulous patients, if anatomy is favorable, implants should

be placed distal to the mental foramen. This allows the construction of prostheses with shorter cantilevers or even without them [6].

The occlusal pattern can be considered a critical factor for the longevity of any oral rehabilitation, including the implant-supported prostheses. The periodontal ligament of the natural dentition exhibits a fully different behavior from that observed in the implant-bone interface [4,7]. Thus, stresses generated in the bone-implant interface and in the prosthesis components differ from those observed in the natural dentition. If the occlusal forces exceed the capacity of the prosthesis system, oral rehabilitation may fail due to overloading or unfavorable load distribution [4,5,7-9]. Complete dentures may present canine guide disocclusion (CG) or bilateral balanced occlusion (BBO). Besides having different effects on occlusal balance and stability, they may influence the stress generated at the bone-implant interface. Thus, the pattern of disocclusion may influence the preservation of the osseointegration since occlusal overload on implants may increase the incidence of marginal bone loss [10].

Using the finite element method (FEM), many experimental and computational biomechanical studies have analyzed a variety of situations involving rehabilitation with dental implants [3,8,11-15]. This method has been widely used in implant dentistry biomechanics. An example is the evaluation of stress distribution at the implant-bone interface and between implants and prosthetic abutments under different conditions and varying size of implants and method of retention [13-15]. Therefore, it is considered a valuable method to assess stresses and displacements in structures such as implant-supported prostheses.

The aim of the present study was to compare the stress generated at the bone-implant interface in implant-supported complete mandibular prosthesis without free distal ends by simulating two patterns of disocclusion using the finite element method, in a linear three-dimensional simulation.

2. MATERIALS AND METHODS

The 3-D model was modified from a previous study [8], with the insertion of two distal short implants. The mesh of each component of the model was set separately and these meshes were subsequently joined to obtain the complete model. The interface between each component pair (bone-implant, implant-metallic infrastructure, and metallic infrastructure-artificial teeth) was generated using the CAE software (Abaqus, Dassault Systemes, Waltham, MA, USA). Each node in the contact surface of one component was constrained to move together with the adjacent node of the other component. This model contained 148,399 elements and 33,964 nodes. The mesh was tested and the areas of interest were refined until the response did not change significantly.

The model simulated a mandible with seven titanium implants, five of them installed between the mental foramina, with a distance of 4 mm between their platforms. These inter-foraminal implants were cylindrical and possessed a height and diameter of 13 and 3.75 mm respectively (Brånemark System Mk III, Nobel Biocare, Gothenburg, Sweden). Two posterior implants, located at the midpoint of the occlusal surface of the first molar, were cylindrical, and possessed a height and diameter of 5 and 5 mm (Titamax WS, Neodent, Curitiba, PR, Brazil). The height of the simulated prosthetic components was 3 mm and were composed of titanium (Multi-unit Abutment, Nobel Biocare, Gothenburg, Sweden). A distance of 3 mm was provided between the base of the prosthesis infrastructure and the bone surface (Fig. 1).

An implant-supported complete denture was designed with a nickel-chromium infrastructure (Wiron, BEGO, Bremen, Germany); the denture was 6 mm thick, 112 mm long, and a height of 4 mm. Over this structure, twelve acrylic resin teeth and acrylic gingival tissue were designed (Fig. 2). Implants 1 and 7 were short and most distally located. Implants 2 and 6 were situated close to the canine on the working and balancing sides respectively. Implants 3, 4, and 5 were

situated in the mental area between implants 2 and 6.

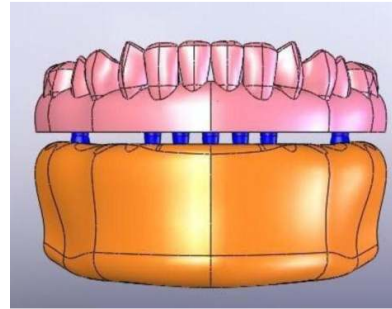


Fig. 1. Three-dimensional (3-D) CAD mandible model including implants, abutments, and the proposal prosthesis: complete metal-acrylic (hybrid) denture supported by 5 inter-foraminal and 2 distal dental implants

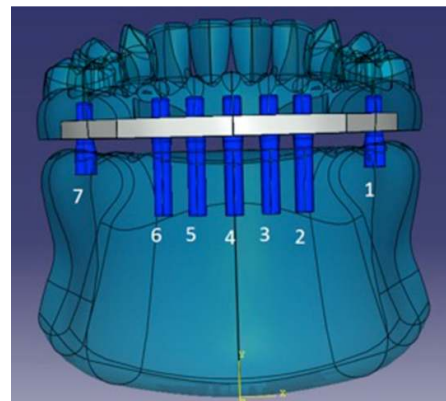


Fig. 2. Transparent frontal view of the 3-D CAD model of mandible and prosthesis. Note the numbered implants inserted into bone, and the abutments linking the implants into metal (nickel-chromium) prosthetic infrastructure

Poisson's ratio and elastic modulus of different materials used in the model were in accordance with the literature (Table 1) [3,4,816,17].

Canine guide (CG) disocclusion pattern was simulated by applying a nodal load of 15 N at an angle of 45° to the incisal third of canine near implant 2 in the working side. In the bilateral balanced occlusion (BBO), the points were distributed among the following: 5N at an angle of 45° in the same region of the canine guide simulation, 5N at 45° in the mesio-buccal and disto-buccal external ridges of the first molar on the working side, and 5N at 45° in the mesio-buccal and disto-buccal internal ridges of the first

molar on the non-working side (Fig 3). As the stress distribution in the artificial teeth was not relevant for the analysis, no special precaution was taken regarding the local stress concentration at the point of load application.

Table 1. The Poisson's ratio and elasticity modulus of different materials used in the model were determined according to the literature

Material	Young's modulus (MPa)	Poisson's ratio
Cortical bone	13700	0.3
Trabecular bone	1370	0.3
Titanium	110000	0.35
Acrylic resin	2700	0.35
Nickel-chromium	188000	0.28

The results were based on a linear elastic static analysis and were used to compare the magnitude of the principal stresses for each simulation.

3. RESULTS

The results of the stress distribution analysis at the bone-implant interface during CG disocclusion are shown in Figs. 3, 4, 5, and 6. During CG, areas of high tensile stress concentration were detected in the mesial region at bone-implant interface of implant 1, and compressive stresses were visualized at bone-implant interfaces of the distal regions of implants 1 and 2. Tensile and compressive stress patterns of implants 1 and 2 (canine area on the working side) differed, with compressive stresses greater than the tensile stresses. In implant 7 on the non-working side, the maximum and minimum stresses were lower and proportional.

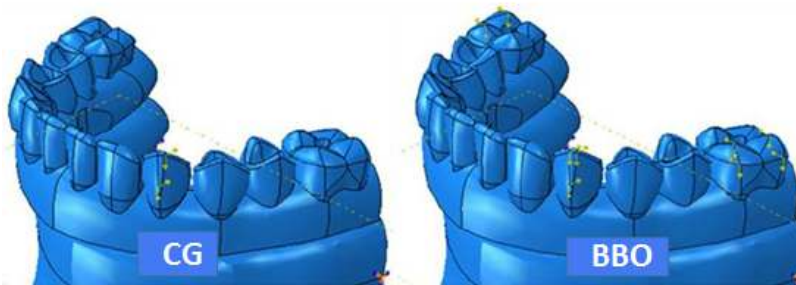


Fig. 3. 3-D CAD models simulating canine guide (CG): A nodal load of 15 N at an angle of 45° to the canine near implant 2. Simulation of bilateral balanced occlusion (BBO): the points were distributed among the canine on the working side, in the region of the canine guide (CG) simulation, in the external portion of the mesio-buccal and distal vestibule of the first molar on the working side, and in the internal aspects of the mesio-buccal portion of the atrium and the distal portion of the first molar on the non-working side.

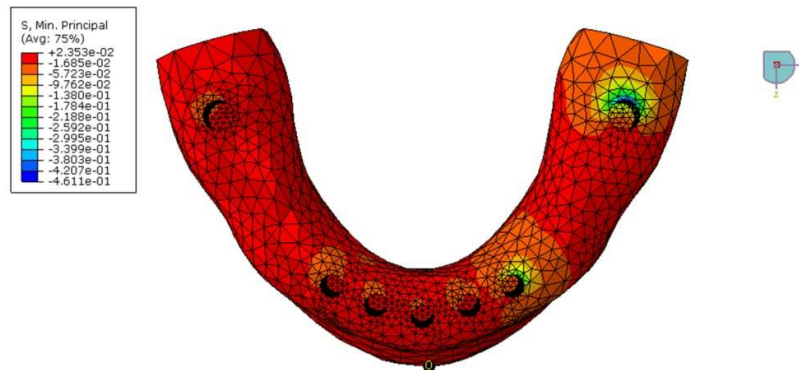


Fig. 4. Occlusal view of the 3-D mesh. CG stresses on the bone surface: Maximum principal stresses. Note the highest stress (tensile) in the mesial aspect of periimplant bone around implant number 1 and 2.

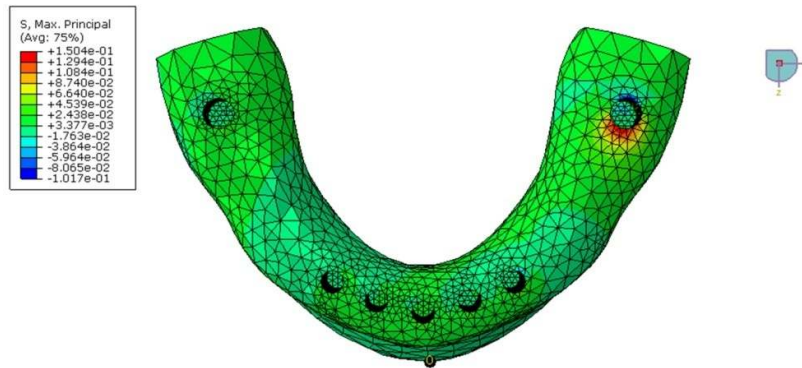


Fig. 5. Occlusal view of the 3-D mesh. CG stresses on the bone surface: minimum principal stresses. Note the highest stress (compressive) in the distal aspect of periimplant bone around implants number 1

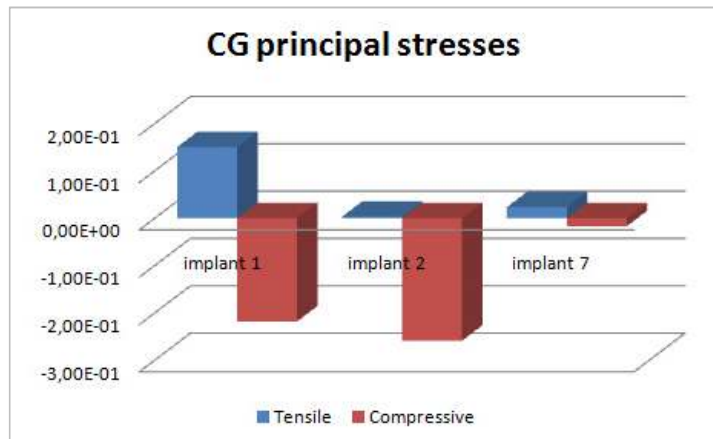


Fig. 6. Graphic distribution of maximum and minimum principal stresses in the bone-implant interface at implants 1, 2 and 7 in CG. These data confirm higher compression stresses around implant 1 and greater tensile stress at implants 2 and 7

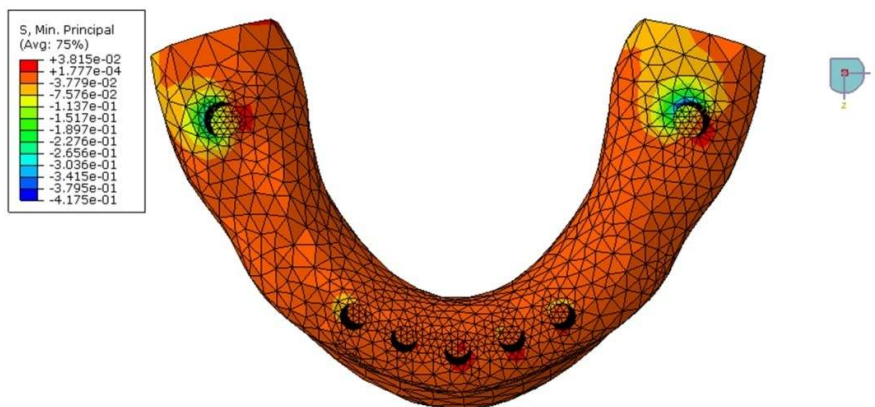


Fig. 7. Occlusal view of the 3-D mesh. BBO stresses on the bone surface: Maximum principal stresses. Note the highest stress (tensile) in the buccal aspect of periimplant bone around implant number 1 and in the lingual aspect around implant number 7

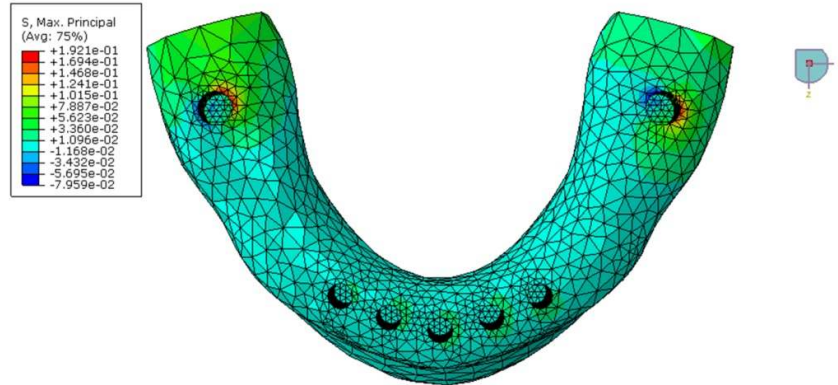


Fig. 8. Occlusal view of the 3-D mesh. BBO stresses on the bone surface: minimum principal stresses. Note the highest stress (compressive) in the lingual aspect of periimplant bone around implant number 1 and in the buccal aspect around implant number 7

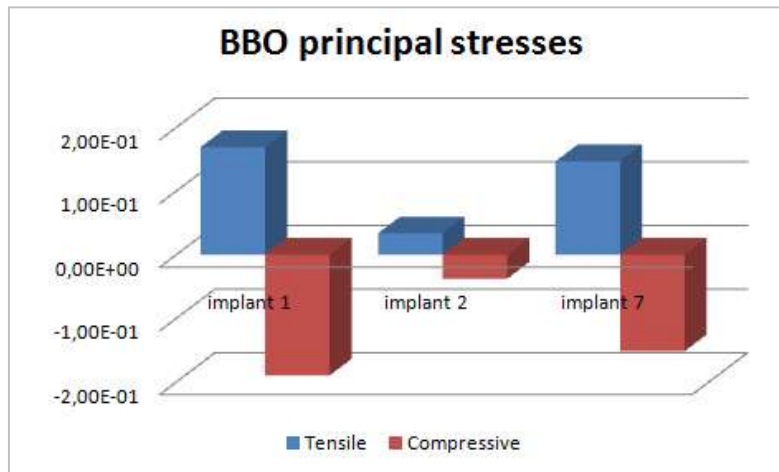


Fig. 9. Graphic distribution of maximum and minimum principal stresses in the bone-implant interface at implants 1, 2 and 7 in BBO. These data confirm that both implant 1 and 7 generate tensile and compression stresses, minimizing the bone loss around these implants and decreasing the stresses around implant 2.

The results of stress distribution analysis during BBO are shown in Figs. 7, 8, and 9. During BBO, stress concentration occurred in distal implants in a bucco-lingual direction. Tensile stresses were observed in a direction opposite to that of the force vector, in the buccal and disto-lingual regions of implants 1 and 7 respectively. Compressive stresses were observed at the bone-implant interface in the same direction of the force vector, in the lingual and buccal regions of implants 1 and 7 respectively.

Fig. 10 shows the distribution of maximum and minimum principal stresses at the bone-implant interface of implant 2 corresponding to the canine area on the working side. During BBO,

the tensile and compressive stresses were similar and lower. During CG, compressive stresses were greater than the tensile stresses. Both patterns of disocclusion showed low levels of tensile stresses in the surrounding areas.

Regardless the patterns of disocclusion, stresses were lower in the anterior implants (Figs. 3, 4, 5, and 6).

4. DISCUSSION

Occlusion is a key factor that determines the success of any dental prostheses, specially the implant-supported ones, because in such situations, functional and parafunctional loads

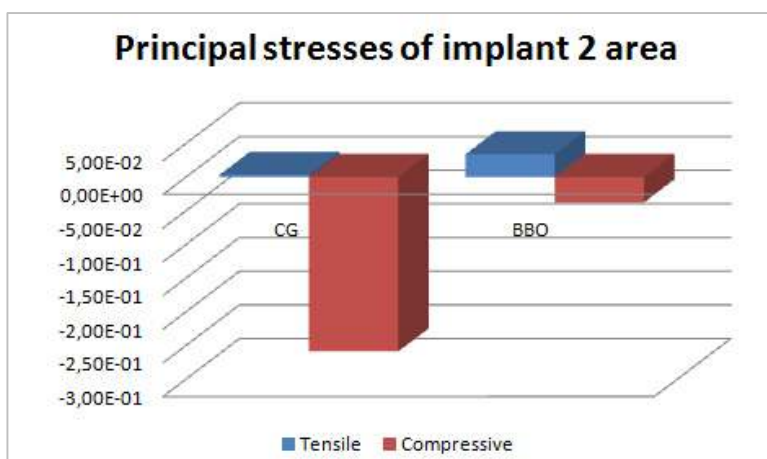


Fig. 10. Maximum and minimum stresses in the region of the implant 2 in bone-implant interface. It is observed a counterbalanced stresses in the BBO pattern and a higher concentration of stresses in the CG pattern.

will not be dissipated by the periodontal ligament, as occurs in natural teeth [4,7]. Functional loads generate stresses, and these will be transferred through all materials that compose a implant-supported prosthesis, from the veneering material to the peri-implant bone. The type and amount of stresses reaching each component of the implant-bone-prosthesis complex are critical for the clinical longevity of an oral rehabilitation [5,14,16]. Biomechanical stress may result on biological or prosthetic complications in a dental implant-prosthesis complex [16]. These complications include implant crestal bone loss [10], early implant failure, fracture of the prosthesis, abutment or prosthetic screw loosening, and problems with overdenture attachments [16]. An engineering approach to resolve biomechanical problems involves determining the nature of complications and then designing an approach to eliminate their underlying causes. Treatment planning should incorporate methods to reduce stress and minimize its initial and long-term effects. The treatment plan is altered when forces are greater or bone is less dense than usual to minimize the negative impact of stress on the implant, bone, and restoration. The goal is to decrease the amount of force, or increase the implant-bone surface area, to decrease the chance of implant-restoration complications [5,16]. One factor that may contribute to the control of undesirable stresses is the disocclusion pattern of the prosthesis.

The concepts and philosophies underlying disocclusion patterns were developed during the initial phase of the last century when Christensen

[17-22] advocated the use of BBO for rehabilitation with removable dentures for achieving greater stability and masticatory efficiency. Using the concepts of mutually protected occlusion, Nagao [23] in 1919 recommended CG for natural dentition and fixed prostheses [24-26]. Nowadays, still there is no unanimous consensus on the primary choice of disocclusion pattern for complete fixed dentures, since both concepts have been supported mainly by simple clinical observation and personal experience [27]. A comprehensive literature review found no difference in masticatory efficiency or patient satisfaction in conventional complete dentures adjusted either with CG or BBO [27]. However, for a complete implant-supported prosthesis with a distal free end, CG disocclusion has been shown to be more favorable, as it involves generation of lower stresses in the peri-implant interface when compared with BBO [8]. When considering disocclusion patterns in complete implant-supported prostheses without cantilevers, no data is available.

A complete implant-supported prosthesis, without free distal ends, should be the first choice of treatment for fully edentulous patients. Force magnifiers, such as cantilevers, offset loads, and monumental forces to the implant body dramatically increase the force applied to a prosthesis, and reduce bone strength which should be considered for a consistent approach to implant reconstruction [5,28]. The greater the length of the cantilever, the greater the surface deformation of the bone around the distal implant [5,29]. So keep the length of the cantilever arm to

a minimum [5,6,28,30,31] or elimination in the prescription to the dental technician in implant-supported prostheses should be addressed when possible [31]. However, the height of the posterior mandibular bone after tooth loss, and the anatomical position of the inferior alveolar nerve may compromise or even impair conventional implant placement. With the advent of short implants, that have been proved to be successful mainly when they are splinted to other implants [32,33], the cantilever can be eliminated in some cases. On the other hand, implant length does affect the overall surface area through geometry [34]. Longer implants has been suggested to provide greater stability under lateral loads as same as teeth with longer roots represent a better biomechanical system to resist [34], although the aforementioned anatomical conditions often impair the placement of long implants in the mandibular posterior region of fully edentulous patients. Anyway, it can be addressed that, whenever possible, short or long implants may be placed in the posterior areas to avoid cantilevers.

In the present study, a non-cantilevered complete implant-supported prosthesis with short implants placed in the posterior mandibular region, representing a viable form of oral rehabilitation, was designed and analyzed using the 3-D finite element method. Numerical modeling of peri-implant structures for biomechanical studies presents the advantage of being non-invasive, and also allows identification and calculation of stresses, strains and displacements at bone-implant interface [3,4,7,8,11-15]. In the present simulation, the principal maximum and minimum stresses were analyzed. The Von Mises stresses were not analyzed, since they are suitable only for ductile materials such as metal. The selected method has proved to be adequate for bone analysis because it allows visualization of areas experiencing compressive and/or tensile stresses, and evaluation of a possible bone remodeling behavior. Identification of the nature of the stresses, tensile or compressive, is essential in biomechanical analysis, since different stresses result on distinct actions on bone. Interfacial stresses to an implant should be compressive in nature due to bone's ability to better resist under compressive stresses; consequently tensile stresses are more deleterious [35].

In the current analysis, CG showed concentration of compressive stresses at the implant-bone

interface of the distal region of implants 1 and 2. Remarkable tensile stresses were also observed in the implant 1 region. Lower the tensile stress at the bone-implant interface, better would be the treatment prognosis since these stresses at high intensity can promote bone resorption [10,35], putting the prosthetic rehabilitation at biomechanical risk. During the BBO simulation, stress concentration was observed in the bucco-lingual direction. Implants 1 and 7 showed areas of tensile stress concentration in the opposite direction of loading and areas of compressive stress in same direction of loading. Although the compressive and tensile stress values during BBO were greater than that during CG, they were similar, better distributed, and alternated between the working and non-working sides. This could result in balanced bone remodeling. Bone remodeling refers to the sequential and combined action of osteoblasts and osteoclasts, which remove and replace old bone with new tissue [35]. Balanced mechanical remodeling occurs in a situation wherein bone is resorbed and deposited simultaneously. The adaptation of bone to an applied load corresponds to the physiologic strain, which allows the bone to gain density and strength [35]. This phenomenon occurs after the balance of forces has been re-established [16,35]. Both patterns of disocclusion exhibited low tensile stresses at the bone-implant interfaces in the anterior implants, which was expected, since these areas are subjected to lower masticatory functional forces. Also, the presence of distal implants contributed to a more equilibrated stress distribution, regardless the disocclusion pattern, preserving the anterior implants. Since there are no clinical studies comparing both patterns of disocclusion in implant-supported complete prostheses, the results of the present study could not be linked to a clinical reality. Nevertheless, the present findings may suggest the BBO as a better disocclusion scheme considering the biomechanical aspect of the present prosthesis design. Obviously, besides the biomechanical factor, other aspects such as laboratorial technical ability and clinical experience should be considered when choosing between considering the disocclusion patterns.

5. CONCLUSION

Within the limitations of this study, it can be concluded that the bilateral balanced occlusion (BBO) pattern was more favorable biomechanically as it involved generation of lower compressive stresses in the anterior

implants and exhibited a more homogenous tensile and compressive stress distribution at the bone-implant interface.

CONSENT

It is not applicable.

ETHICAL APPROVAL

It is not applicable.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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