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ALOISIO ORO SPAZZIN

“DESEMPENHO BIOMECÂNICO DE SISTEMAS DE BARRA PARA RETENÇÃO ADICIONAL DE SOBREDENTADURAS:

ANÁLISE DE ELEMENTOS FINITOS”

PIRACICABA

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UNIVERSIDADE ESTADUAL DE CAMPINAS
FACULDADE DE ODONTOLOGIA DE PIRACICABA

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Orientador: Prof. Dr. Lourenço Correr-Sobrinho

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e orientada pelo Prof. Dr. Lourenço Correr Sobrinho

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“A possibilidade de realizarmos um sonho é o que torna a vida interessante”

Paulo Coelho

RESUMO

Neste estudo foram avaliados os efeitos da amplificação do desajuste horizontal, material e formato da secção transversal da barra, e da reabsorção óssea peri-implantar na distribuição das tensões estáticas em um sistema de barra para retenção adicional de sobredentaduras utilizando o método dos elementos finitos. Para a análise computacional, foi criado um modelo tridimensional incluindo dois implantes de titânio e uma barra metálica colocada na região anterior de uma mandíbula severamente reabsorvida. Quatro diferentes ligas (ouro, prata-paládio, cobalto-cromo e titânio comercialmente puro) e três diferentes formatos da secção transversal (circular, ovóide e Hader) da barra foram avaliados. Uma região anterior de mandíbula simulando uma reabsorção óssea peri-implantar de 1,4 mm de altura foi também criada. Os modelos foram exportados para programas de simulação mecânica, em que deslocamentos foram aplicados simulando distorção da barra que sofreu contração durante os procedimentos laboratoriais. Quatro análises foram realizadas, separadamente, para reduzir a quantidade de modelos envolvidos: Capítulo 1 – i) diferentes desajustes horizontais (10, 50, 100, e 200 µm) utilizando liga de ouro como material da barra; ii) diferentes materiais da barra simulando 50 µm de desajuste horizontal (neste capítulo foi utilizada barra de secção transversal circular); Capítulo 2 – iii) diferentes secções transversais da barra simulando diferentes desajustes horizontais (10, 50 e 100 µm); iv) diferentes secções transversais da barra simulando 1,4 mm de reabsorção óssea peri-implantar e 50 µm de desajuste horizontal (neste capítulo foi utilizado liga de cobalto-cromo como material da barra). Os dados foram analisados por meio de figuras e dados numéricos gerados pelos programas. A amplificação do desajuste horizontal aumentou os níveis de tensões estáticas nas estruturas do sistema. Materiais mais rígidos e geometrias mais complexas da barra aumentaram os níveis de tensões estáticas no sistema de barra quando desajustes horizontais estão presentes. A reabsorção óssea simulada aumentou a deformação e a concentração de tensões no tecido ósseo peri-implantar quando desajustes horizontais estão presentes.

Palavras-chave: Biomecânica, Próteses e Implantes, Materiais Dentários.

ABSTRACT

In this study were evaluated the effects of horizontal misfit amplification, material and cross-section geometry of the bar, and peri-implant bone loss on the distribution of static stresses in an overdenture-retaining bar system using finite element analysis. For the computational analysis, a three-dimensional model was created including two titanium implants and a metallic bar placed in the anterior part of a severely resorbed jaw. Four different alloys (gold, silver–palladium, cobalt–chromium, and commercially pure titanium) and three different cross-section geometries (circular, ovoid and Hader) of the bar were evaluated. An anterior part of jaw simulating a peri-implant bone loss of 1.4 mm height was also created. The models were exported to mechanical simulation software, where horizontal displacements were applied simulating the settling of the bar that suffered shrinkage during laboratory procedures. Four analyses were carried out, separately, to reduce the quantity of involved models: Chapter 1 – (i) different horizontal misfits (10, 50, 100, and 200 µm) using gold alloy as bar material; (ii) different bar materials simulating 50-µm misfit horizontal (circular cross-section of the bar was used in this chapter); Chapter 2 – (iii) different cross-section geometries of the bar simulating different horizontal misfits (10, 50 and 100 µm); (iv) different cross-section geometries of the bar simulating 1.4-mm peri-implant bone loss and 50-µm horizontal misfit (cobalt-chromium alloy was used as bar material in this chapter). Data were analyzed using figures and numerical data generated by software. The amplification of the horizontal misfit increased the levels of static stress in the structures of the system. Stiffer materials and more complex geometries of the bar increased the levels of static stress on bar system when horizontal misfits are present. The bone loss simulated increased the strain and stress concentration in the peri-implant bone tissue.

Key-words: Biomechanics, Prostheses and Implants, Dental Materials.

SUMÁRIO

INTRODUÇÃO

Indivíduos desdentados totais com mandíbula severamente reabsorvida, geralmente têm problemas associados a utilização de próteses totais convencionais, devido à retenção e estabilidade deficientes, e consequente diminuição da eficiência mastigatória (Bergman & Carlsson, 1985; van Waas, 1990). Estes problemas podem ser solucionados utilizando sobredentaduras implantorretidas ou implantossuportadas (Andreiotelli *et al.*, 2010; Attard & Zarb, 2004). A literatura sugere vários benefícios das sobredentaduras mandibulares em comparação às próteses totais convencionais, os quais incluem aumento na retenção, adaptação, função, eficiência mastigatória e qualidade de vida (Fueki *et al.*, 2007).

De acordo com "*The glossary of prosthodontic terms*" uma *overdenture* (sobredentadura) é definida como "qualquer prótese dentária removível que recobre um ou mais dentes naturais, raízes de dentes naturais remanescentes, e/ou implantes dentários, e é parcialmente suportada por estes" (The glossary..., 2005). Sobredentaduras implantossuportadas são definidas como próteses que obtêm seu suporte inteiramente pelos implantes, enquanto, sobredentaduras implantorretidas têm seu suporte pelos tecidos intrabucais e implantes dentários (Andreiotelli *et al.*, 2010).

Sobredentaduras mandibulares podem ser retidas por 2 implantes utilizando diferentes sistemas de retenção. Os anéis de retenção (*O'rings)* permitem a prótese girar em várias direções (Kimoto *et al.*, 2009), e apresenta satisfação de tratamento ao indivíduo reabilitado (Burns *et al.*, 2011). Em algumas situações, a inclinação dos implantes inviabilizam a utilização deste sistema. Outra opção é utilizar conexões (*attachments*) resilientes para reter a prótese em uma barra rígida conectada aos implantes (Romero *et al.*, 2000). A maior diferença entre dentes e implantes osseointegrados é que implantes não possuem ligamento periodontal como na dentição natural (Richter, 1989). Deste modo, a literatura sugere o requerimento de adaptação passiva entre prótese e implantes, uma vez que estes não conseguem se adaptar a desajustes protéticos (Kan *et al.*, 1999).

As técnicas convencionais de laboratório – fundição em monobloco – não permitem a confecção de infraestruturas rígidas com níveis aceitáveis de adaptação, e distorções podem ser geradas em qualquer etapa do processo de fabricação (Romero *et al.*, 2000). A maioria das distorções ocorre devido à alteração volumétrica dos materiais utilizados, que incluem material para moldagem, gessos, ceras, revestimentos, fundição do metal e aplicação do revestimento estético (Assif *et al.*, 1996; Carr, 1991; Carr & Stewart, 1993; Gettleman & Ryge, 1970; Humphries *et al.*, 1990; Inturregui *et al.*, 1993; Linke *et al.*, 1985; Nakaoka *et al.*, 2011). Muitos autores recomendam métodos para melhorar a adaptação em próteses múltiplas, que incluem técnicas de impressão (Assif *et al.*, 1996; Carr, 1991; Lee *et al.*, 2008; Ma & Rubenstein, 2012), soldagem (Fornaini *et al.*, 2012; Parel, 1989; Tiossi *et al.*, 2012), eletro-erosão (Nakaoka *et al.*, 2011; Romero *et al.*, 2000; Sartori *et al.*, 2004), e sistemas CAD-CAM (Karl & Taylor, 2011; Karl *et al.*, 2012; Tan, 1995), no entanto, vários destes afirmam que ainda são necessários mais dados para definir o limite para que o assentamento da infraestrutura seja clinicamente aceitável, sugerindo que certo grau de desajuste é uma realidade clínica para próteses múltiplas.

Em estudo prévio de nosso grupo foi avaliado o efeito da amplificação do desajuste vertical na distribuição de tensões em um sistema de barra conectada a dois implantes osseointegrados para retenção adicional de sobredentaduras utilizando o método dos elementos finitos. O aumento do desajuste vertical proporcionou aumento considerável nos níveis de tensões na estrutura da barra, embora não tenha havido influência considerável no tecido ósseo peri-implantar (Spazzin *et al.,* 2011). Porém, os desajustes ocorrem tridimensionalmente (Jemt & Book, 1996), e pouco é conhecido a respeito do efeito do desajuste horizontal na distribuição das tensões estáticas em próteses múltiplas parafusadas.

Outro importante fator com limitada informação na literatura, é o efeito da rigidez da barra, que pode ser influenciada pelo material ou forma da sua secção transversal.

Várias ligas, além do titânio comercialmente puro, têm sido propostos para confeccionar infraestruturas protéticas. As primeiras infraestruturas implantossuportadas fabricadas em ouro começaram a ser usadas em reabilitações bucais nos anos 70 (Jemt *et al.*, 1999). Devido ao alto custo das ligas nobres, ligas alternativas começaram a ser pesquisadas (Bergendal & Palmqvist, 1995; Cox & Zarb, 1987; Hulterstrom & Nilsson, 1991). Um estudo avaliou a distribuição das tensões em próteses totais fixas com diferentes materiais da infraestrutura (Sertgoz, 1997). Porém, os autores não consideraram os desajustes que podem estar presentes em infraestruturas protéticas para próteses múltiplas sobre implantes. Quanto à forma da secção transversal da barra, várias possibilidades estão disponíveis, as quais podem ser circular, ovóide e barra Hader. Esta última consiste em uma barra rígida conectando dois ou mais pilares ou implantes, e tem sua secção transversal lembrando uma fechadura, possuindo uma barra retangular com parte superior circular criando uma área retentiva para a fêmea (clipe) colocada dentro da prótese removível (The glossary..., 2005).

A literatura tem mostrado certa remodelação óssea em próteses sobre implantes. Estudos específicos mostraram perda óssea vertical de até 1,4 mm após 5 e 10 anos de avaliação clínica em diferentes sistemas de barras para sobredentaduras (Meijer *et al.*, 2004; Meijer *et al.*, 2009). Limitada informação está disponível na literatura a respeito do comportamento biomecânico de próteses com certo grau de perda óssea. Neste contexto, o trabalho avaliou o comportamento biomecânico, através do método dos elementos finitos, de sistemas de barra para retenção adicional de sobredentaduras, sob os efeitos do desajuste horizontal, material e geometria da barra, e reabsorção do tecido ósseo peri-implantar.

O presente trabalho é apresentado no formato alternativo de tese de acordo com as normas estabelecidas pela deliberação 002/06 da Comissão Central de Pós-Graduação da Universidade Estadual de Campinas. O artigo referente ao Capítulo 1 foi publicado no periódico *Journal of Prosthodontics: Implant, Esthetic, and Reconstructive Dentistry*. O artigo referente ao Capítulo 2 foi submetido ao periódico *Journal of Biomechanics*, e encontra-se nas normas de submissão.

CAPÍTULO 1*

Effects of Horizontal Misfit and Bar Framework Material on the Stress Distribution of an Overdenture-Retaining Bar System: A 3D Finite Element Analysis

Abstract

Purpose: To evaluate the influence of horizontal misfit change and bar framework material on the distribution of static stresses in an overdenture-retaining bar system using finite element (FE) analysis. **Materials and Methods:** A 3D FE model was created including two titanium implants and a bar framework placed in the anterior part of a severely resorbed jaw. The model set was exported to mechanical simulation software, where horizontal displacement (10, 50, 100, and 200 µm) was applied simulating the settling of the framework, which suffered shrinkage during laboratory procedures. Four bar materials (gold alloy, silver–palladium alloy, commercially pure titanium, and cobalt–chromium alloy) were also simulated in the analysis using 50 µm as the horizontal misfit. Data were qualitatively evaluated using von Mises stress, given by the software. **Results:** The misfit amplification presented a great increase in the stress levels in the inferior region of the bar, screw-retaining neck, cervical and medium third of the implant, and cortical bone tissue surrounding the implant. The higher stiffness of the bar presented a considerable increase in the stress levels in the bar framework only. **Conclusion:** The levels of static stresses seem to be closely linked with horizontal misfit, such that its amplification caused increased levels of stress in the structures of the overdenture-retaining bar system. On the other hand, the stiffness of the bar framework presented a lower effect on the static stress levels.

Keywords: Implant prosthesis; bar material; fit; stress; finite element analysis.

Introduction

Overdentures retained by two implants can be attached using different systems. O-ring attachments allow the prosthesis to rotate in all directions.[1] Sometimes, however, the inclination of the implants may preclude the use of these attachments. Another possibility is to use resilient attachments to attach the denture to a rigid bar assembly that interconnects with the osseointegrated implants.[2] When this system is chosen, a passive fit between the bar framework and the implants is required for a successful restoration.[3,4] The major difference to teeth is that osseointegrated implants do not have the resiliency of the periodontal membrane found in natural dentition.[5,6] Therefore, the implants are unable to fit to the misfits.

Potential distortion can be created at any step of the implant prosthesis fabrication process. The error is due primarily to the volumetric inconsistency and linear expansion of the fabrication materials used.[7–9] When there is a poor fit between structures, tensile, compressive, and bending forces may be introduced into an implant-retained restoration and may result in failure of the components.[4,10,11] In addition, a poor fitting framework may also transfer unwelcome stress to the bone/implant interface, which could induce a loss of osseointegration.[12,13] However, some studies have found that dental implants tolerate certain levels of misfit.[14,15] Today, it is difficult to determine these states due to the limitations of these studies and ethical principles involved in "*in vivo*" studies. Numerical analysis can help overcome the limitations of traditional experimental methods by offering accurate and reliable information about the biomechanical efficiency of multiple implant prostheses with regard to bar framework, implant, and bone response.[16]

A recent study[17] using finite element analysis (FEA) showed that the amplification of vertical misfits increased the concentration of static stress in the mechanical part of an overdenture-retaining bar system; however, this increase was not considerable in the periimplant bone tissue. Little is known about the influence of horizontal misfit in static stress distribution in implant prostheses.

Another important factor for which there is still limited data is the effect of the stiffness of the bar material. Several alloys and metals have been used to make prosthetic frameworks. The first implant-supported frameworks, fabricated of gold alloy, began to be used in oral rehabilitations in the early 1970s.[18] Nevertheless, the high cost of noble alloys led to a search for alternative alloys. A study evaluated the effect of four framework materials on the stress distribution in a six-implant-supported fixed denture and periimplant bone tissue.[16] However, the authors did not consider the misfits present in implant dentures.

The aim of this study was to evaluate, using 3D FEA, the influence of: (1) level of horizontal misfit (10, 50, 100, 200 μm); and (2) bar materials [type IV gold alloy (Au), silver–palladium alloy (Ag–Pd), commercially pure titanium (Ti), and cobalt–chromium alloy (Co–Cr)] with 50 μm of horizontal misfit on the distribution of static stresses in an overdenture-retaining bar system. The two hypotheses tested were that: (1) the amplification of the horizontal misfit increases the levels of static stresses in mechanical and biological parts of the system; and (2) the higher stiffness of the bar material increases the levels of static stresses in mechanical and biological parts of the system when a horizontal misfit is present.

Materials and methods

Geometric model

The 3D model was defined starting from clinical data taken from a common situation. The anterior part of a severely resorbed jaw and an overdenture-retaining bar system above two osseointegrated implants were modeled using a 3D parametric solid modeler (Rhinoceros 3.0 software; McNeel, Seattle, WA). The geometry of the modeled jaw portion was obtained starting from computed tomography data with type III bone.[8] Two 3.75-mm diameter × 10-mm length Ti implants (Nobel Biocare, Yorba Linda, CA), with external hexagon, were selected. A circular bar (2 mm diameter) and two UCLAs of an overdenture-retaining bar system were also modeled, with an 18.5-mm distance between the UCLA centers.

Finite element model

The finite element (FE) model was obtained by importing the solid model into mechanical simulation software (NEiNastran 9.0; Noran Engineering Inc., Westminster, CA) using the STEP (∗.stp) format. The corresponding elastic properties, such as Young's modulus and Poisson ratio, were determined from values obtained from the literature[17,19–23] (Table 1).

The following assumptions were made. All materials were presumed to be linear elastic, homogenous, and isotropic.[24] The implant thread and cancellous and cortical bone were removed because after several convergence tests, they were found to be irrelevant to the analysis and provided a relevant reduction in elements. Complete adhesion was considered between bone and implant and bar and implant provided by osseointegration and preload of the screw, respectively. Screw and implant were considered a single structure because this assumption was irrelevant for the purpose of the analysis. The model stability was carried out to obtain a reliable model, which was regarded as relevant to engineering and clinical aspects.

A 3D FE model was constructed using a tetrahedral element, with ten nodes. The volumes were redefined in the new environment and meshed, finally resulting in a model with 13,272 elements and 15,152 nodes. All nodes on the bone's external surface were constrained in all directions to allow application of the displacement condition and stresses to be created in the models.

Two FEAs were carried out separately. For horizontal misfit effect, four models were created with different levels of horizontal misfit (10, 50, 100, 200 μm) between bar and implant, using Au as the bar material: Au/10, Au/50, Au/100, and Au/200. For bar-material effect, four models were created using different bar materials (Au, Ti, Ag–Pd, Co–Cr) with 50 μm horizontal misfit between bar and implant: Au/50, AgPd/50, Ti/50, and CoCr/50.

The displacements were applied on the bar end to simulate the elimination of the horizontal misfit through tightening of the retaining screws. The misfits simulate a condition of linear distortion that could be created by contraction during the fabrication process, reducing the bar length (Fig 1). Model stability was again checked, and particular attention was paid to the refinement of the mesh at the bone/implant interface. The results of the FEA were represented by figures and color gradients of stresses and presented in terms of the von Mises stress values because a higher von Mises stress is a strong indication of a greater possibility of failure.

Results

Von Mises stresses that occurred in the bar framework, periimplant bone tissue, retaining screw, and implant for all models are presented in Figures 2 and 3. The maximum stress values found in these structures are presented in Tables 2 and 3. The cancellous bone presented inconsiderable changes in stress values under the various tested conditions.

Horizontal misfit effect

Figure 2 represents distribution of von Mises stresses within the overdenture-retaining bar system concerning the different levels of horizontal misfits using gold alloy as the bar material. Stresses were concentrated in the inferior region of the bar, in the whole diameter of the retaining-screw neck, along the cervical and middle third of the implant, and in the cortical bone tissue surrounding the implant. The misfit amplification presented a great increase in stress values in these structures (Table 2).

Bar material effect

Figure 3 represents the distribution of von Mises stresses within the overdenture-retaining bar system for the different bar materials with 50 μm horizontal misfit between bar and implant. Stresses were concentrated in the same areas as the horizontal misfit effect; however, the higher stiffness of the bar presented a considerable increase in the stress levels in the cortical bone tissue and bar framework, while the retaining screw and implant presented few changes in the stress values (Table 3).

Discussion

FEA is an established theoretical technique used in engineering problems. The role of bioengineering cannot be underestimated, and biomechanical principles have been verified in many studies.[25] The basic purpose of these studies is to extrapolate the findings relevant to the risk factors instead of experiencing them empirically in clinical applications.

The model used in this study implied several assumptions regarding the simulated structures. The structures in the model were all assumed to be homogeneous, isotropic, and linearly elastic. The proprieties of the materials modeled in this study, particularly the living tissues, however, are different. Due to the lack of precise information regarding the material properties of bone, cortical and cancellous bone were assumed to have these properties.[24] The other assumptions were implemented in the model after several procedures obtaining the model stability, which was regarded as relevant to engineering and clinical aspects.

The FEA showed great changes on the stress levels created in the overdenture-retaining bar system with respect to the different horizontal misfits. Although the horizontal misfits were tested only with Au alloy, it can be suggested that the other alloys demonstrate the same pattern of presenting greater values of stress according to the rise in horizontal misfit, but with higher values due to being stiffer than Au alloys. The misfit amplification induced a considerable increase in the concentration of static stresses in the bar, in the whole diameter of the retaining-screw neck, along the cervical and middle third of the implant, and in the cortical bone tissue surrounding the implant. These data are in agreement with the first hypothesis. A previous study[17] found that amplification of vertical misfit seems to have an influence on the stress distribution in the bar framework, while in periimplant bone tissue, the increase in stress levels was not considerable. These findings suggest that horizontal misfits may be more prejudicial to multi-unit prostheses than vertical misfits are.

Many studies have considered only the vertical misfit as the distortion of the piece.[4,13,15,17] The findings of the current study seem to suggest that horizontal misfits always should be evaluated in laboratory or clinical studies comparing framework fabrication techniques. Methodologies using digital or optical 3D readings can make the results of the research studies more reliable.[26]

Concerning the different bar materials, the Au alloys showed lower stress levels, principally in the bar framework. For other compounds of the system, such as the cortical bone and the retaining screw and implant, stress values were not considerably lower. The bar structure appeared to be more sensitive to the material stiffness, in agreement with recent literature.[17] However, these findings disagree with Natali et al's findings,[27] which suggested that lower framework resiliency could reduce stress levels transferred to the periimplant bone tissue.

The different materials were analyzed only with a horizontal misfit of 50 µm; higher horizontal misfits using materials with higher stiffness properties could induce more static stresses to the system. This misfit was chosen due to previous studies, such as the one conducted by Al-Fadda et al,[26] who verified the tridimensional accuracy of various methods for fabricating implant-prosthodontics frameworks with five implants and found an average of 49.2 µm of horizontal misfit (ranging from 21.4 to 134.8 µm) in conventional casting procedures. A previous study[28] evaluated the accuracy of three-unit implant frameworks and found an average of 48-µm horizontal misfit after casting. Many procedures, including soldering[28] and the use of a laser-scanned computer milled framework (Nobel Biocare),[26] among others, can reduce framework misfit. Thus, it seems prudent to optimize fit using a combination of the best available clinical and laboratory materials and methods when fabricating implant frameworks.[26] Clinically, the lowest horizontal misfit must be pursued, principally to decrease stress concentrations, since with the reduction of the horizontal misfit, the stress levels in the cortical periimplant bone tissue, bar framework, retaining screw, and implant of the overdenture-retaining bar system will be reduced, too.

In addition to acknowledging and supplementing studies using FEA to evaluate stress in bone tissue, it is essential to conduct more studies to show quantitative stress with respect to positive remodeling to the osseointegration. Other factors already under investigation, such as loading geared by a clip and configuration of the bar framework, may influence stress distribution in the bar-clip system. Another important factor needing attention is that laboratory studies comparing or evaluating techniques of framework fabrication should always consider the 3D misfit, evaluating vertical and, principally, horizontal misfits; however, the levels that actually cause biological response, such as resorption and remodeling of the bone, are not comprehensively known. Therefore, the stress data provided for FEA requires substantiation by clinical research.[29]

Conclusions

Within the limitations of this FEA, it was possible to conclude that:

1. The amplification of horizontal misfit increased the levels of static stress in the structures of the overdenture-retaining bar system.

2. The stiffness of the bar framework presented a lower effect in the static stress levels.

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Table 1 Materials properties

Material	Young's modulus (GPa)	Poisson's ratio (v)
Cortical bone[19]	13.7	0.3
Cancellous bone[19]	1.37	0.3
Titanium (implant)[21]	110	0.33
Titanium (screw)[20]	110	0.28
Type IV gold alloy[23]	80	0.33
Silver-palladium alloy[22]	95	0.33
Commercially pure titanium[20]	110	0.28
Cobalt-chromium alloy[22]	218	0.33

Table 2 Maximum stress (MPa) in the models testing horizontal misfit

Model	Structures of the model			
	Cortical bone	Bar	Retaining screw	Implant
Au/10	33	38	31	25
Au/50	165	195	155	127
Au/100	330	395	312	253
Au/200	660	810	629	330

Table 3 Maximum of stress (MPa) in the models testing bar material

Model	Structures of the model			
	Cortical bone	Bar	Retaining screw	Implant
Au/50	165	195	155	127
Ag-Pd/50	178	225	159	135
Ti/50	181	229	159	137
Co-Cr/50	188	253	161	141

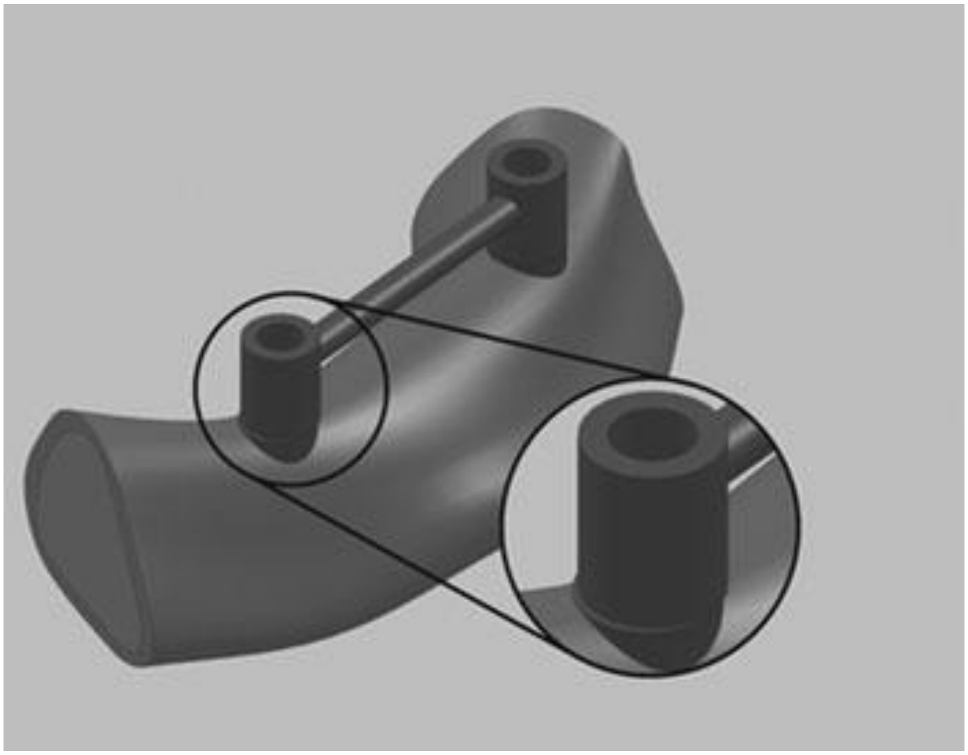

Figure 1 Design of the geometric model.

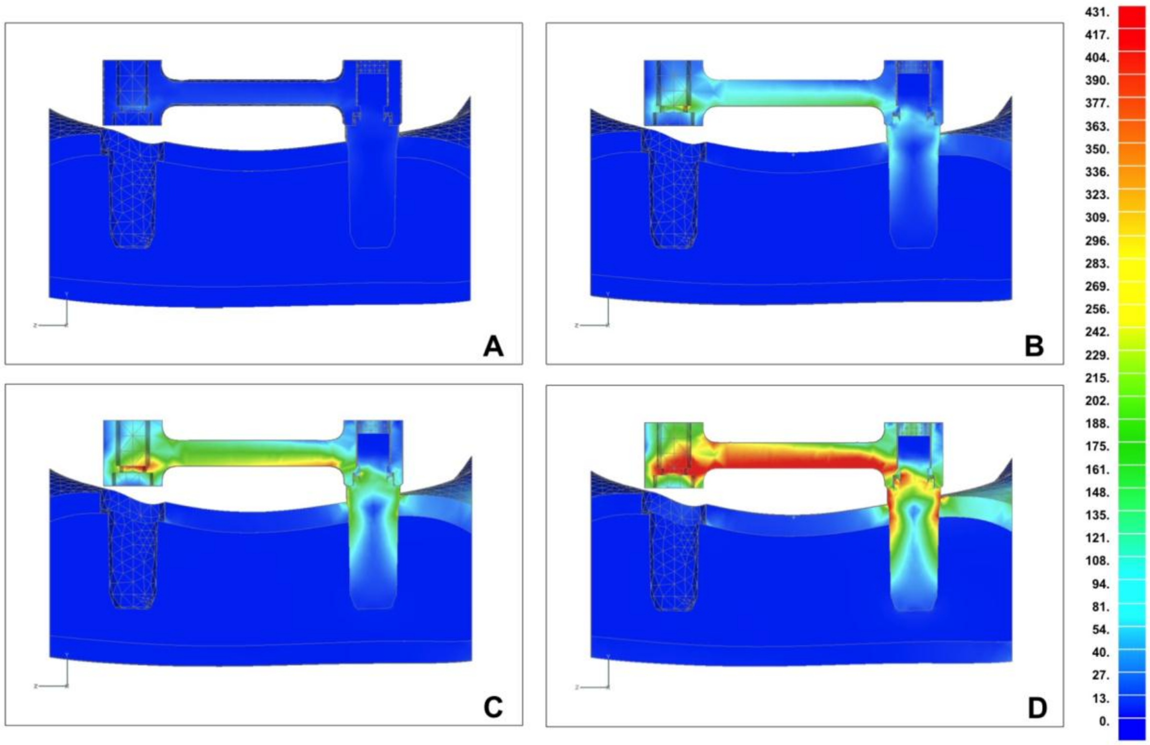

Figure 2 Von Mises stress (MPa) distribution in the models with different horizontal misfits for the gold bar framework: (A) 10 μm; (B) 50 μm; (C) 100 μm; and (D) 200 μm.

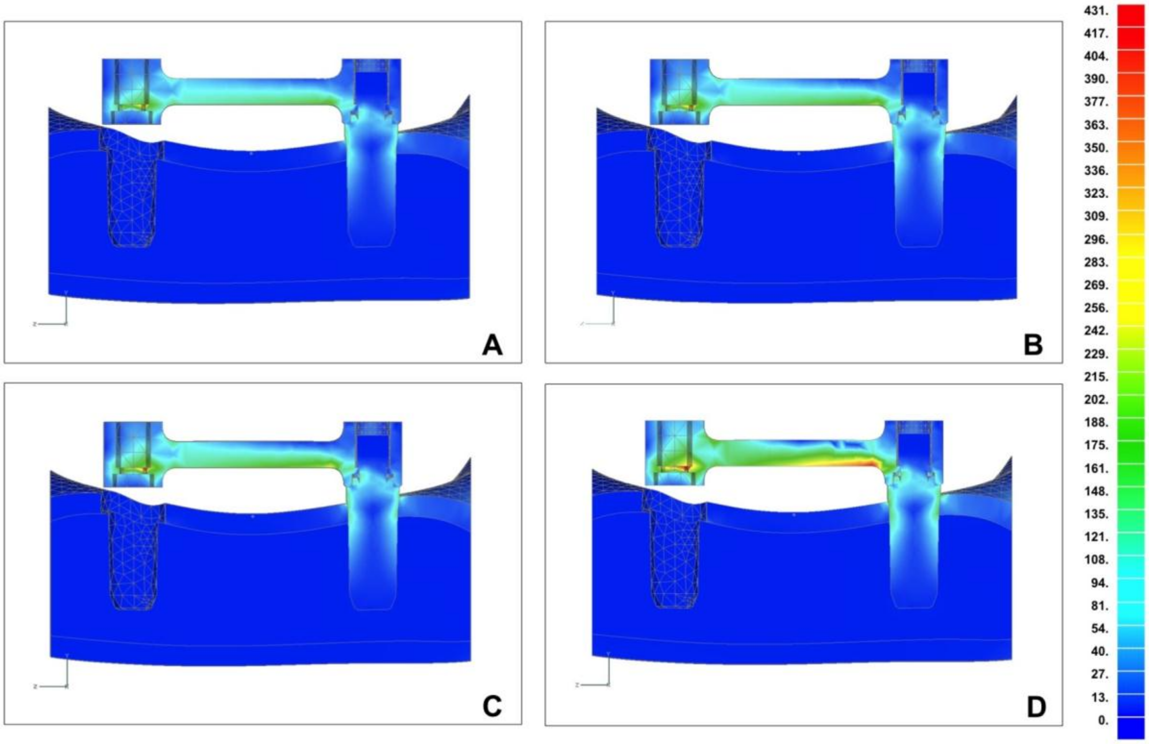

Figure 3 Von Mises stress (MPa) distribution in the models with different bar framework materials for 50 μm of misfit: (A) gold alloy; (B) silver–palladium alloy; (C) commercially pure titanium; and (D) cobalt–chromium alloy.

CAPÍTULO 2

Effect of bar cross-section geometry on stress distribution in overdenture-retaining system simulating horizontal misfit and bone loss

Abstract

This study evaluated the influence of cross-section geometry of the bar framework on the distribution of static stresses in an overdenture-retaining bar system simulating horizontal misfit and bone loss. Three-dimensional FE models were created including two titanium implants and three cross-section geometries (circular, ovoid or Hader) of bar framework placed in the anterior part of a severely resorbed jaw. One model with 1.4-mm vertical loss of the peri-implant tissue was also created. The models set were exported to mechanical simulation software, where horizontal displacement (10, 50 or 100 μm) was applied simulating the settling of the framework, which suffered shrinkage during the laboratory procedures. The bar material used for the bar framework was a cobalt–chromium alloy. For evaluation of bone loss effect, only the 50-μm horizontal misfit was simulated. Data were qualitatively and quantitatively evaluated using von Mises stress for the mechanical part and maximum principal stress and μ-strain for peri-implant bone tissue given by the software. Stresses were concentrated along the bar and in the joint between the bar and cylinder. In the peri-implant bone tissue, the μ-strain was higher in the cervical third. Higher stress levels and μ-strain were found for the models using the Hader bar. The bone loss simulated presented considerable increase on maximum principal stresses and μ-strain in the peri-implant bone tissue. In addition, for the amplification of the horizontal misfit, the higher complexity of the bar cross-section geometry and bone loss increases the levels of static stresses in the peri-implant bone tissue.

Keywords: Implant prosthesis, bar, fit, bone loss, stress, finite element analysis.

Introduction

Edentulous patients with severely resorbed mandible often experience problems with conventional dentures, such as insufficient stability and retention, together with a decrease in chewing ability (Bergman and Carlsson, 1985; van Waas, 1990). These problems can be solved with the use of implant-retained or implant-supported overdentures (Andreiotelli et al., 2010; Attard and Zarb, 2004). Overdenture in the mandible presents the following benefits in comparison to complete denture treatment: better chewing ability, better fit and retention, improved function, and improved quality of life (Fueki et al., 2007).

Mandibular implant overdenture retained to independent balls attachments (O-rings) allow the prosthesis to rotate in all directions (Kimoto et al., 2009), although they provide patient satisfaction for the treatment (Burns et al., 2011). Sometimes, however, the inclination of the implants may preclude the use of these attachments. Another possibility is to use resilient attachments to affix the denture to a rigid bar assembly that interconnects with the osseointegrated implants (Romero et al., 2000). When this system is chosen, a passive fit between the bar framework and the implants is required for successful restoration (al-Turki et al., 2002; Zarb and Symington, 1983). The major difference to teeth is that osseointegrated implants do not have the resiliency of the periodontal membrane found in natural dentition (Richter, 1989). Therefore, the implants are unable to fit to the misfits (Spazzin et al., 2011b).

Potential distortion can be created at any step of the implant prosthesis fabrication process. The error is due primarily to the volumetric and linear dimensional changes of the fabrication materials used (Assif et al., 1996; Carr and Stewart, 1993; Rubenstein and Ma, 1999). Several techniques have been developed to correct inaccuracies of fit resulting from the fabrication process (Karl et al., 2012; Sartori et al., 2004; Silva et al., 2008); however, implant prosthesis misfits are a clinical reality, as even these procedures are unable to completely eliminate the misfits (Sahin and Cehreli, 2001).

A previous study using finite element analysis (FEA) showed that the amplification of vertical misfits increased the concentration of static stress in the mechanical part of an overdenture-retaining bar system, although this increase was not considerable in the peri-implant bone tissue (Spazzin et al., 2011a). Another study evaluating the influence of horizontal misfit in static stress distribution in overdenture-retaining bar system showed considerable increase of the stress levels in mechanical and biological parts of the system (Spazzin et al., 2011b). The researchers suggested that horizontal misfits could do more damage for the peri-implant bone tissue in multi-unit implant prostheses.

Several cross-section geometry of the bar are available, including circular, ovoid and Hader. The latter is an eponym of technician Helmut Hader for a rigid bar connecting two or more abutments; when viewed in cross-section, it resembles a keyhole, consisting of a rectangular bar with a rounded superior (occlusal) ridge that creates a retentive undercut for the female clip within the removable prosthesis (2005). The bar material has presented an effect on stress levels, where stiffer material increases the stress in the system where misfit are found. Therefore, the different cross-section geometry of the bar could also influence stress distribution (Spazzin et al., 2011b).

Another factor with limited information concerns occurrence of stress distribution in overdenture bars after bone loss. Studies have shown a bone loss of 1.4 mm after 5- and 10-year evaluation (Meijer et al., 2004; Meijer et al., 2009). In this context, it is important to know the cross-section geometry of the bar to present better mechanical behavior when bone loss and misfit are found. Therefore, the aim of this study was to evaluate, using 3D FEA, the influence of: (1) cross-section geometry of the bar (circular, ovoid, or Hader) simulating three different horizontal misfits (10, 50 or 100 μm); and (2) cross section of the bar (circular, ovoid, or Hader) and marginal bone loss (0 or 1.4 mm) simulating 50-μm horizontal misfit on the distribution of static stresses in an overdenture-retaining bar system. The hypothesis tested was that the circular cross-section would present lower levels of static stresses in mechanical and biological parts when misfits and bone loss are found.

Materials and Methods

Geometric Model

Three-dimensional solid models reproducing anterior part of a resorbed mandible (without and 1.4-mm bone loss) and different overdenture-retaining bar systems (circular, ovoid, or Hader; Figure 1) above two osseointegrated implants (4.0 mm diameter × 10 mm length) were built using 3-D modelling software (SolidWorks 2010; SolidWorks Corp., Concord, MA, USA). The bar dimensions were the following: circular bar presented 15 mm of diameter; ovoid bar presented 20 mm of height and 15 mm of diameter in your superior part; and Hader bar presented 25 mm of height, 15 mm of diameter in your superior part, and 10 mm of width in your inferior part.

Finite element model

FE models were obtained by importing the solid model into mechanical simulation software (ANSYS Workbench 11; Ansys Inc., Canonsburg, PA, USA.). All materials used in the models were considered to be isotropic, homogeneous and linearly elastic. The elastic properties used (Table 1) were taken from literature (Abu-Hammad et al., 2000; Craig, 1989; Korioth and Johann, 1999; Sakaguchi and Borgersen, 1993).

Two FEAs were carried out separately. In the first analysis, nine models were created with three bar cross-section geometries—circular (C), ovoid (O), or Hader (H)—and three levels of horizontal misfit (10, 50, or 100 µm): C10, O10, H10, C50, O50, H50, C100, O100 and H100. For the second analysis, three more models were created with three bar cross-section geometries—circular (C), ovoid (O), or Hader (H)—and 1.4 mm bone loss (bl) with 50-µm horizontal misfit: C50-bl, O50-bl and H50-bl. The models C50, O50 and H50 were used as control (without bone loss).

The displacements were applied on the bar end to simulate the elimination of the horizontal misfit through tightening of the retaining screws. The misfits simulate a condition of linear distortion that could be created by contraction during the fabrication process, reducing the bar length (Figure 2). The elements used were tetrahedral with 10 nodes. The total of elements generated in the FE models range from 368,366 to 434,597; and the total de nodes ranged from 596,904 to 698,045.

Model stability was carried out to obtain reliable models, which were regarded as relevant to engineering and clinical aspects. Particular attention was paid to the refinement of the mesh at the bone-implant interface. The implant thread was removed because convergence tests found it was not relevant to the analysis and provided a relevant reduction in elements.

Finite element analysis

The results of the FEA were represented by figures and color gradients. Von Mises stresses were used to evaluate the stress distribution in the bar framework and retaining-screw, because a higher von Mises stress is a strong indication of a greater possibility of failure. Maximum principal stress and μ-strain were used to evaluate the peri-implant bone tissue, the maximum principal stress was chosen because the failure of a brittle material occurs when the maximum principal stress exceeds the maximum stress recorded in a simple laboratory test (Iremonger, 1982).

Results

Von Mises stresses that occurred in the mechanical part for the models are presented in the Figures 3 and 5. Stresses were concentrated along the bar and in the join between bar and cylinder. Elastic micro strain distribution in the peri-implant bone tissue for the models is presented in the Figures 4 and 6. In the peri-implant bone tissue, the μ-strain was concentrated in the third cervical around of the implant. Maximum von Mises, for the bar framework and retaining screw, and maximum principal stress values for cortical and cancellous bone are presented in Tables 2 and 3.

Cross-section geometry and horizontal misfit effect

Figure 3 represents distribution of von Mises stresses in the mechanical part and the Figure 4 represents distribution of μ-strain in the peri-implant bone tissue concerning the cross section geometry of bar framework simulating three horizontal misfits. Overall, higher stress levels (Figure 3, Table 2) and μ-strain (Figure 4) were found for the models using Hader bar and this increase in the stress levels was more evident when 100- and 50-μm horizontal misfit were simulated.

Cross-section geometry and bone loss effect

Figure 5 represents distribution of von Mises stresses in the mechanical part and the Figure 6 represents distribution of μ-strain in the peri-implant bone tissue concerning the cross-section geometry of bar and bone loss simulating 50-μm horizontal misfits. The bone loss simulated presented considerable increase on maximum principal stresses (Table 3) and μ-strain (Figure 6) in the peri-implant bone tissue for the three cross-section geometry of the bar. However, the lower stress values were found for circular cross-section.

Discussion

FEA is an established theoretical technique used in engineering problems. The role of bioengineering cannot be underestimated, and biomechanical principles have been verified (Hannam, 2011). The model used in this study implied several assumptions regarding the simulated structures. The structures in the model were all assumed to be homogeneous, isotropic, and linearly elastic. However, the proprieties of the materials modeled in this study, particularly the living tissues, however, are different (Akagawa et al., 2003; Faegh and Muftu, 2010; Szabo and Thurner, 2012). Due to the lack of precise information regarding the properties of the bone, it was assumed to have these properties. Other assumptions were implemented in the model after several procedures obtaining the model stability, which was regarded as relevant to engineering and clinical aspects.

The computational analysis showed that, overall, the Hader bar presents higher stress levels the whole system compared with the other cross-section geometries of the bar. This increase on the stresses was more evident when higher misfits are found. The Hader bar presented an increase of around of 18% and 40% at maximum principal stress and 18% and 38% at μ-strain in the peri-implant tissue compared to ovoid and circular bar, respectively (Table 2). These findings can be associated to bar design, with a circular cross-section of the bar allows higher strain during the misfit closing, in agreement with the hypothesis suggested for Natali et al. (2006) that using a bar with low stiffness could reduce the stress levels in the peri-implant bone tissue.

When simulating the 1.4-mm vertical bone loss (Meijer et al., 2004; Meijer et al., 2009), the stresses in the mechanical part were not affected. However, in the current study, the maximum principal stress and μ-strain increased to 60% and 385%, respectively, in the peri-implant bone tissue for the three cross-section of the bar when the bone loss was simulated. These results show the bone loss does not decrease the stresses created by misfits, so it increased the stress levels and μ-strain. This bone loss value was used based on previous clinical study (Meijer et al., 2009). The authors evaluate three-implant system, IMZ (two-stage cylinder type), the Branemark (two-stage screw type), and the ITI-implant system (one-stage screw type), in implant-retained overdentures using two implants placed in the interforaminal region, connected with a bar. They presented bone loss values for up to 1.4 mm after 10 years. However, no clinical and radiographic relevant changes had developed between the implant systems, and the patients were still very satisfied with their implant-retained mandibular overdenture (Meijer et al., 2009). The bone loss was analyzed only with 50-μm horizontal misfit to decrease the model numbers, although higher horizontal misfits using this bone loss could induce more static stresses in the peri-implant tissue. This horizontal misfit was chosen due the previous studies present mean values of horizontal misfit around of 50 μm (Al-Fadda et al., 2007; Kano et al., 2004; Zervas et al., 1999).

Clinically, in addition to the lowest horizontal misfit to be pursued (Spazzin et al., 2011b), a improve biomechanical behavior could be obtained using bars with design of lower complexity, even as the circular bar decreased the stress concentration and μ-strain in the peri-implant bone tissue, and especially when bone loss is present, confirming the study hypothesis. In the current study, only static stresses were evaluated simulating the tightening of the retaining screw. The stress created by clip loading and angular misfits could increase these static stresses in the bar system. However, the levels that actually cause biological response—such as resorption and remodelling of the bone—are not comprehensively known. In addition, to acknowledge and supplement studies using FEA to evaluate stress in bone tissue, it is essential to conduct more studies to show quantitative stress with respect to positive remodeling to the osseointegration.

Conclusion

Within the limitations of the adopted methodology, it is possible to conclude that: (i) overall, the Hader bar showed higher level of static stress in the structures of the overdenture-retaining bar system and (ii) this increase in the stress concentration was more evident when higher misfits were simulated; (iii) the bone loss increased the stresses and strain in the peri-implant bone tissue; (iv) circular cross-section of the bar presented lower stress concentration when horizontal misfit and bone loss are found.

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Table 1. Materials properties adopted in the study

Material	Young's Modulus (GPa)	Poisson's Ratio	Reference
Cortical bone	13.7	0.3	(Abu-Hammad et al., 2000)
Cancellous bone	1.37	0.3	(Abu-Hammad et al., 2000)
Titanium (implant)	110	0.33	(Korioth and Johann, 1999)
Titanium (screw)	110	0.28	(Sakaguchi and Borgersen, 1993)
Cobalt–chromium (bar)	218	0.33	(Craig, 1989)

Table 2. Maximum von Mises stress (MPa) values found in the bar framework and retaining screw, and maximum principal stress (MPa) values found in the peri-implant tissue when different misfits and bar cross-sections were evaluated.

Model	Bar Framework	Retaining-screw	Cortical Bone	Cancellous Bone
C10	1.95	0.07	0.06	0.003
O10	1.86	0.09	0.08	0.0003
H10	2.20	0.12	0.09	0.004
C50	9.21	0.37	0.32	0.015
O50	10.9	0.45	0.38	0.018
H50	10.0	0.58	0.44	0.021
C100	17.5	0.74	0.64	0.031
O100	17.5	0.89	0.76	0.037
H100	24.5	1.19	0.89	0.043

Table 3. Maximum Von Mises stress (MPa) values found in the bar framework and retaining screw, and maximum principal stress (MPa) values found in the peri-implant tissue when the bone loss and different bar cross-sections were evaluated.

Model	Bar Framework	Retaining-screw	Cortical Bone	Cancellous Bone
C50	9.21	0.37	0.32	0.015
O50	10.9	0.45	0.38	0.018
H50	10.0	0.58	0.44	0.021
C50-bl	9.12	0.37	0.51	0.120
O50-bl	10.8	0.45	0.60	0.141
H50-bl	9.92	0.59	0.70	0.165

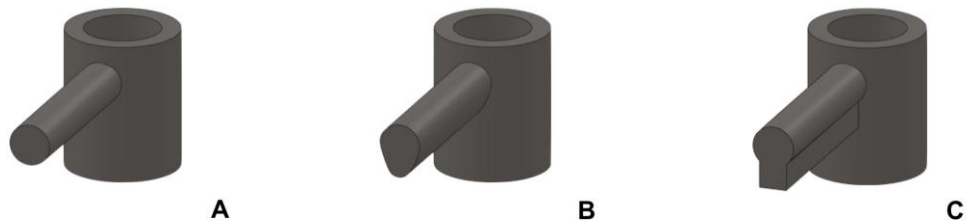

Figure 1. Design of the different cross-section geometry of the bar: (A) circular; (B) ovoid; and (C) Hader.

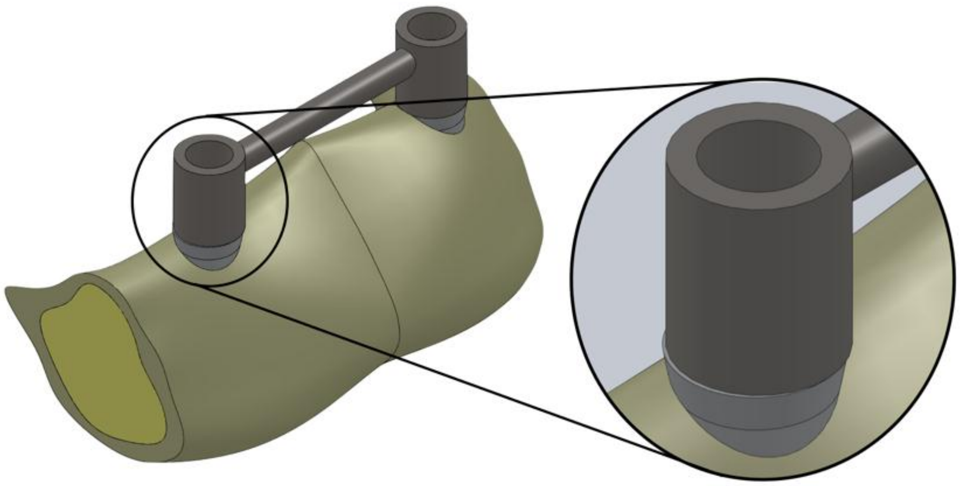

Figure 2. Design of the geometric model and misfit simulated.

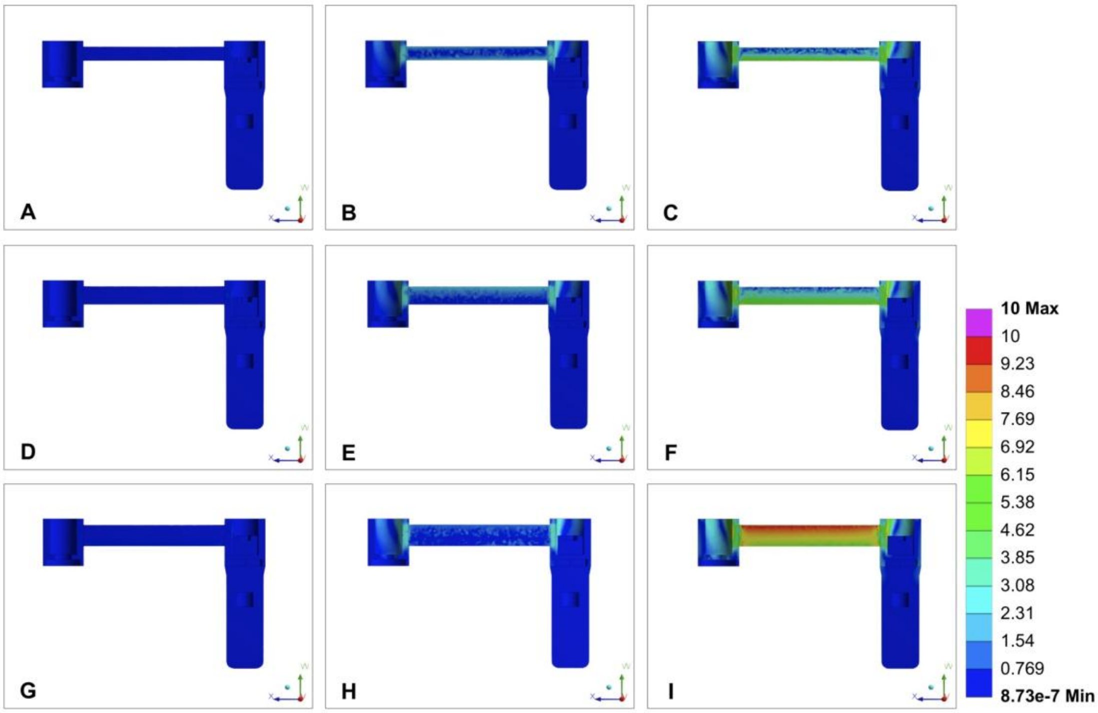

Figure 3. Von Mises stress (MPa) distribution in the mechanical part for the bar cross-section geometries simulating horizontal misfits: (A) 10 µm, (B) 50 µm, and (C) 100 µm using circular bar; (D) 10 µm, (E) 50 µm, and (F) 100 µm using ovoid bar; and (G) 10 µm, (H) 50 µm, and (I) 100 µm using Hader bar.

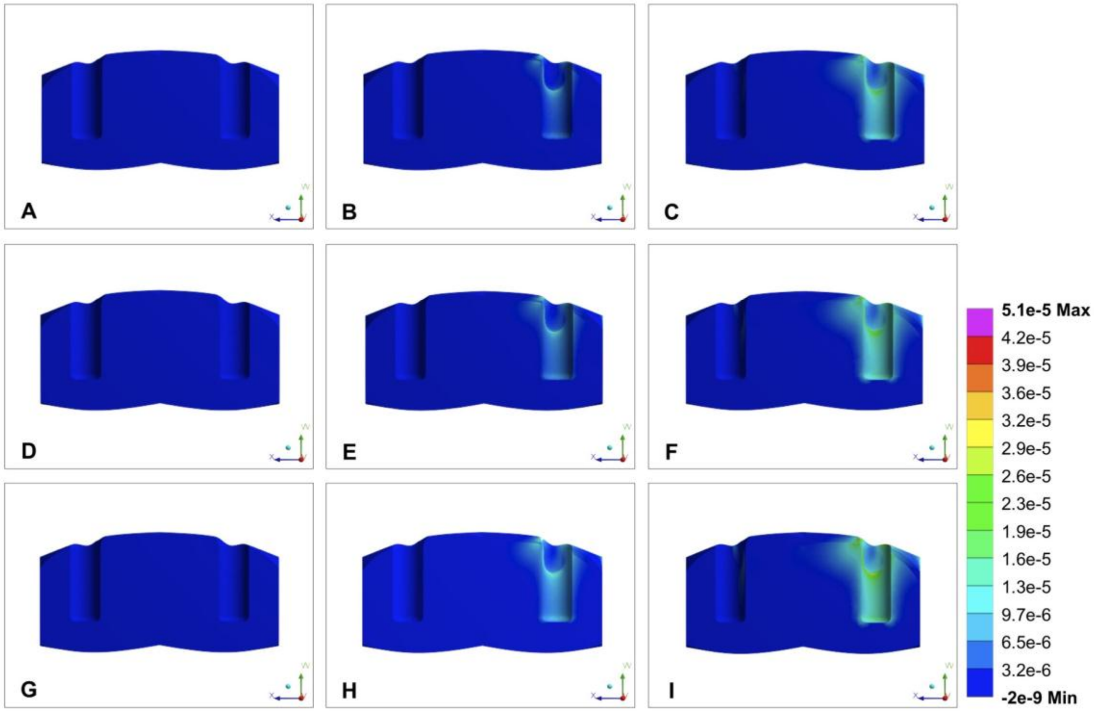

Figure 4. Maximum principal elastic strain (mm/mm) distribution in the peri-implant bone tissue for the bar cross-section geometries simulating horizontal misfits: (A) 10 µm, (B) 50 µm, and (C) 100 µm using circular bar; (D) 10 µm, (E) 50 µm, and (F) 100 µm using ovoid bar; and (G) 10 µm, (H) 50 µm, and (I) 100 µm using Hader bar.

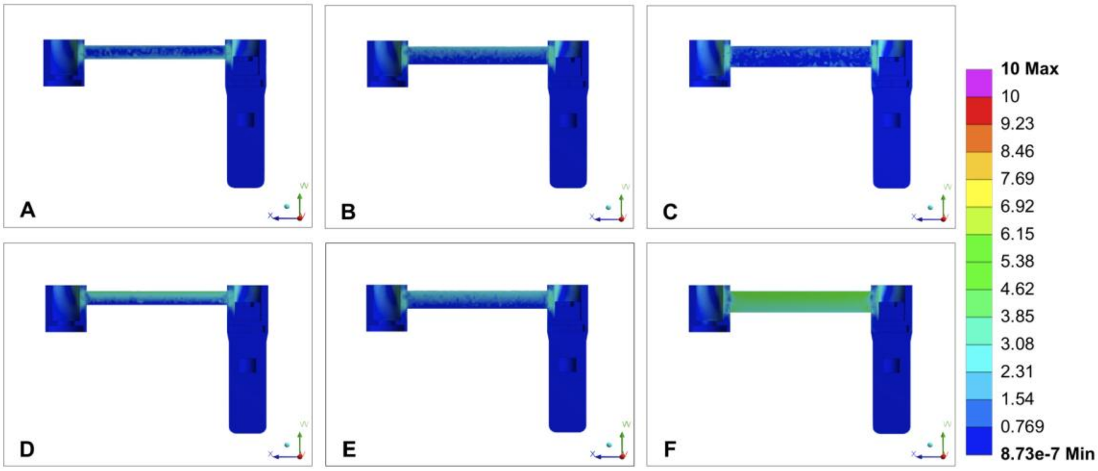

Figure 5. Von Mises stress (MPa) distribution in the mechanical part for bar cross-section geometries simulating different levels of bone loss and 50 μm misfit: (A) circular bar, (B) ovoid bar, and (C) Hader bar without bone loss; (D) circular bar, (E) ovoid bar, and (F) Hader bar simulating 1.4-mm bone loss.

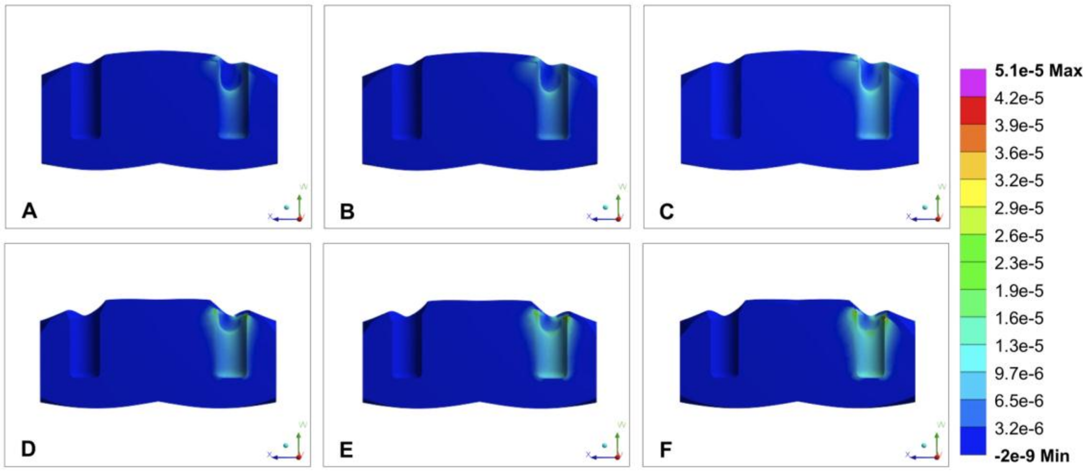

Figure 6. Maximum principal elastic strain (mm/mm) distribution in the peri-implant bone tissue for the bar cross-section geometries simulating different levels of bone loss and 50 µm misfit: (A) circular bar, (B) ovoid bar, and (C) Hader bar without bone loss; (D) circular bar, (E) ovoid bar, and (F) Hader bar simulating 1.4-mm bone loss.

CONSIDERAÇÕES GERAIS

O modelo básico utilizado no presente estudo necessitou de várias simplificações nas estruturas simuladas. Todos os componentes do modelo foram considerados homogêneos, isotrópicos e linearmente elásticos. No entanto, as propriedades de alguns dos materiais modelados são diferentes, particularmente o tecido ósseo (Akagawa *et al.*, 2003; Faegh & Muftu, 2010; Szabo & Thurner, 2012). Estas propriedades foram assumidas devido à complexidade e falta de informações precisas sobre as propriedades do tecido ósseo peri-implantar. As demais simplificações foram implementadas após diversos procedimentos para obtenção da estabilidade do modelo, o qual foi considerado relevante sobre os aspectos clínicos e de engenharia.

A análise computacional mostrou grandes alterações nos níveis de tensões criadas no sistema de barra associadas, principalmente, a amplificação do desajuste horizontal, confirmando a primeira hipótese do Capítulo 1. Spazzin *et al.* (2011) relataram que a amplificação do desajuste vertical tem influência somente na concentração de tensões na parte mecânica deste sistema de barra, enquanto que no tecido ósseo peri-implantar este aumento não foi considerável. Estes achados sugerem que desajustes horizontais podem ser mais prejudiciais às próteses múltiplas que desajuste verticais. Inúmeros estudos têm considerado apenas o desajuste vertical para avaliar a distorção da peça protética (Abduo & Swain, 2012; Abduo *et al.*, 2012; al-Turki *et al.*, 2002; Carr *et al.*, 1996; Farina *et al.*, 2012; Katsoulis *et al.*, 2012; Nakaoka *et al.*, 2011; Sartori *et al.*, 2004; Spazzin *et al.*, 2009; Spazzin *et al.*, 2010). Os resultados obtidos tanto no Capítulo 1 quanto no Capítulo 2 sugerem que desajustes horizontais devem ser sempre avaliados em estudos clínicos e laboratoriais quando o objetivo for comparar técnicas para obter passividade de prótese múltiplas sobre implantes. Metodologias utilizando leituras ópticas ou digitais tridimensionais podem informações mais precisas.

Em relação aos materiais da barra, a liga de Au mostrou níveis mais baixos de tensão, principalmente, na própria estrutura da barra. Para os outros componentes do sistema, tais como o osso cortical, o parafuso de retenção, e o implante, os valores de tensão foram menores, porém, de menor significância em relação a amplificação do desajuste horizontal. A estrutura da barra parece ser a parte mais sensível à rigidez do material e este achado está de acordo com os resultados de Abreu *et al.* (2010). O efeito da amplificação do desajuste foi avaliado no Capítulo 1 apenas utilizando liga de Au, como material da barra. Materiais mais rígidos poderiam aumentar os níveis de tensões para desajustes maiores, e assim, o efeito da rigidez da barra poderia ser mais evidente.

Esta hipótese pode ser suportada pelo Capítulo 2, onde uma maior complexidade no formato da barra aumentou consideravelmente os valores de tensão, e este aumento foi mais evidente para desajustes maiores. De modo geral, a barra Hader apresentou níveis mais elevados de tensões em todo o sistema em comparação as outras geometrias da barra. No tecido ósseo peri-implantar, a barra Hader apresentou aumento cerca de 18% e 40% na tensão máxima principal em comparação à barra ovóide e circular, respectivamente. Esses achados podem ser também associados a rigidez da barra, uma vez que a secção transversal circular permite maior deformação durante o fechamento do desajuste. Confirmando a hipótese de Natali *et al.* (2006), que maior resiliência da barra apresentaria menor concentração de tensões no tecido ósseo peri-implantar quando desajustes horizontais estivessem presentes.

Quando simulada a perda óssea vertical, a tensão máxima de von Mises na parte mecânica do sistema não foi alterada consideravelmente. No entanto, a tensão máxima principal e a microdeformação aumentou cerca de 60% e 385%, respectivamente, no tecido ósseo peri-implantar quanto a reabsorção óssea foi simulada, independente da geometria da barra. Estes resultados mostram que a reabsorção do tecido ósseo peri-implantar não diminui as tensões criadas pelos desajustes, o que ocorre é o inverso. Este valor de reabsorção óssea foi utilizado com base em um recente estudo. Os autores avaliaram três sistemas de implantes, IMZ, Branemark e ITI, em sobredentaduras implantorretidas utilizando dois implantes e uma barra colocados na região anterior de uma mandíbula, e relataram perda óssea de até 1,4 mm após 10 anos de acompanhamento clínico (Meijer *et al.*, 2004; Meijer *et al.*, 2009). Os materiais da barra e a reabsorção óssea foram analisados simulando somente 50 µm de desajuste horizontal para diminuir significativamente o número de modelos na análise, embora desajustes maiores poderiam amplificar os resultados obtidos. Este valor de desajuste foi escolhido devido a vários estudos apresentarem média de desajuste horizontal próximo a este valor (Al-Fadda *et al.*, 2007; Kano *et al.*, 2004; Zervas *et al.*, 1999).

Clinicamente, menor desajuste horizontal deve ser almejado. Além disso, a associação de barras resistentes, porém de geometrias e materiais que não a tornem demasiadamente rígida deveriam ser preferidas, principalmente se reabsorção no tecido ósseo peri-implantar for evidenciada. Estudos adicionais, em relação ao carregamento proporcionado pelo clipe do sistema de retenção da sobredentadura, podem trazer resultados mais fidedignos ao que acontece clinicamente. Estudos que analisam o comportamento biomecânico de prótese sobre implantes utilizando o método dos elementos finitos são importantes, porém é essencial conduzir estudos para quantificar valores de tensão que proporcionem remodelação óssea positiva ou negativa a osseointegração. Além disso, os dados de tensão advindos da análise de elementos finitos requerem comprovação por estudos clínicos e laboratoriais.

CONCLUSÃO

Dentro das limitações da metodologia aplicada, as seguintes conclusões podem ser obtidas:

1. A amplificação do desajuste horizontal aumentou os níveis de tensões estáticas nas estruturas do sistema de barra para retenção adicional de sobredentaduras;

2. O aumento da rigidez da barra, proporcionado pelo material ou pela geometria da secção transversal, aumentou os níveis de tensões estáticas no sistema quando desajustes horizontais estavam presentes.

3. A reabsorção óssea simulada aumentou a deformação e os níveis de tensões estáticas no tecido ósseo peri-implantar quando desajustes horizontais estavam presentes.

4. A barra com secção transversal circular proporcionou a menor concentração de tensões quando desajustes horizontais e reabsorção óssea estavam presentes.

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APÊNDICE

METODOLOGIA ILUSTRADA

1. MODELO GEOMÉTRICO

O modelo tridimensional básico para a análise foi definido a partir de uma situação comum clinicamente. Foram modelados uma região anterior de mandíbula e um sistema de barra colocados sobre dois implantes dentários (Figura 1). No Capítulo 1 foi utilizado o programa Rhinoceros 3.0 software (McNeel, Seattle, WA, EUA), e no Capítulo 2 o programa SolidWorks 2010 (SolidWorks Corp., Concord, MA, EUA).

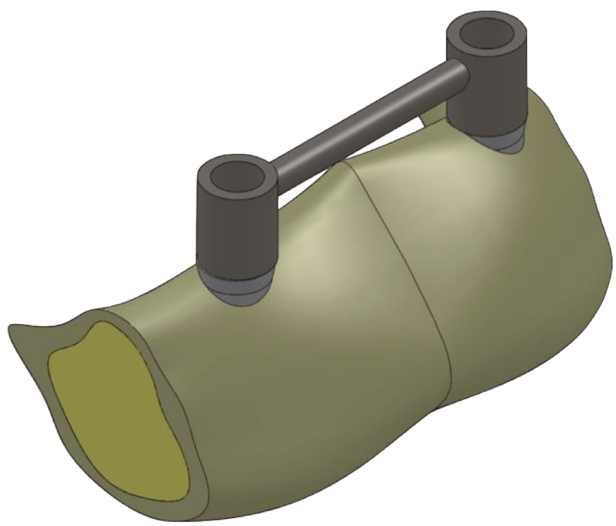

Figura 1 – Modelo tridimensional.

A geometria da porção mandibular foi obtida a partir de uma tomografia computadorizada com osso tipo III (Lekholm & Zarb, 1985) (Figura 2A). No capítulo 2 foi modelado também uma condição de reabsorção óssea vertical de 1,4 mm (Meijer *et al.*, 2009) (Figura 2B).

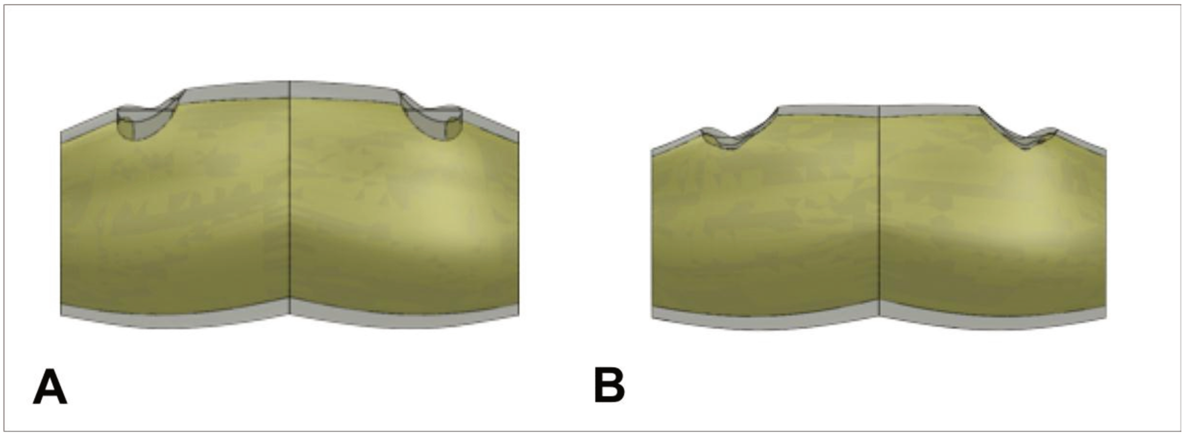

Figura 2 – Estrutura óssea modelada: (A) osso padrão sem reabsorção; (B) osso com 1,4 mm de reabsorção óssea vertical.

Para o estudo foram também modelados implantes dentários com hexágono externo (Figura 3B) e parafusos de retenção da barra (Figura 3A). A rosca destes componentes foram removidas após testes de convergência que mostraram ser irrelevantes para a análise e reduziram consideravelmente o número de elementos. Três barras com diferentes secções transversais foram também criadas para a análise (Figura 4).

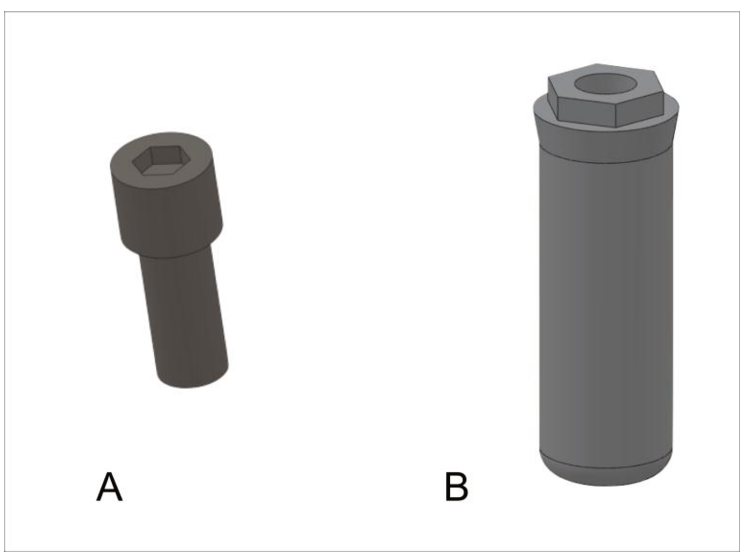

Figura 3 – Parafuso de retenção da barra (A) e implante dentário (B) modelados.

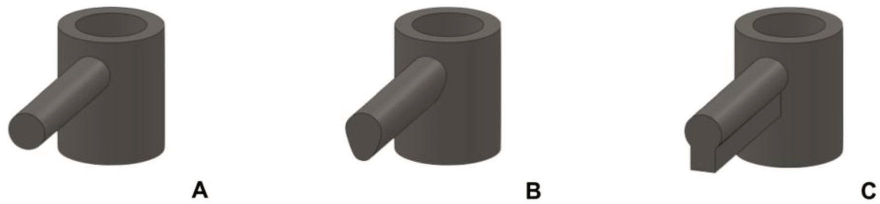

Figura 4 – Formas da secção transversal da barra: circular (A), ovóide (B), e Hader (C).

2. MODELO DE ELEMENTOS FINITOS

O modelo de elementos finitos foi obtido importando o modelo geométrico (sólido) para programas de simulação mecânica. No Capítulo 1 foi utilizado o programa NEiNastran 9.0 (Noran Engineering Inc.,Westminster, CA, EUA), e no Capítulo 2 o ANSYS Workbench 11 (Ansys Inc., Canonsburg, PA, EUA).

As propriedades elásticas dos componentes do sistema foram determinados a partir de valores obtidos na literatura (Tabela 1, Capítulo 1 e 2). O modelo malha com elementos finitos foram criados utilizando um elemento tetraédrico com dez nós (Figura 5).

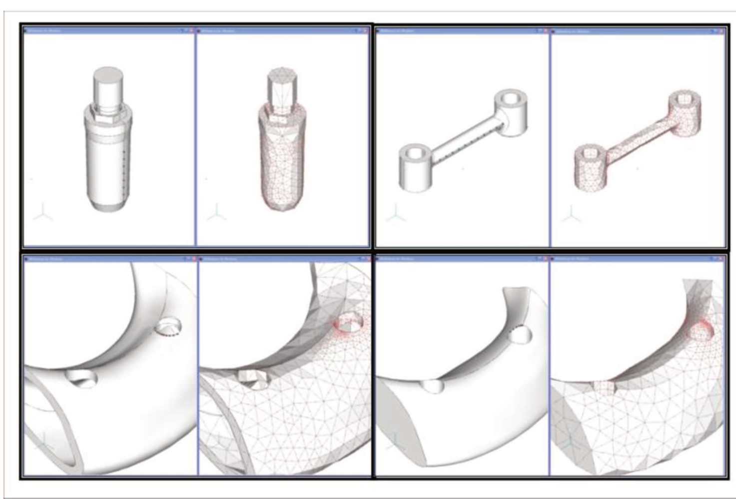

Figura 5 – Malha do modelo criado com elementos finitos.

Todos os nós na superfície externa do osso foram restritos em todas as direções, para permitir a aplicação da condição de deslocamento e tensões serem criadas nos modelos (Figura 6).

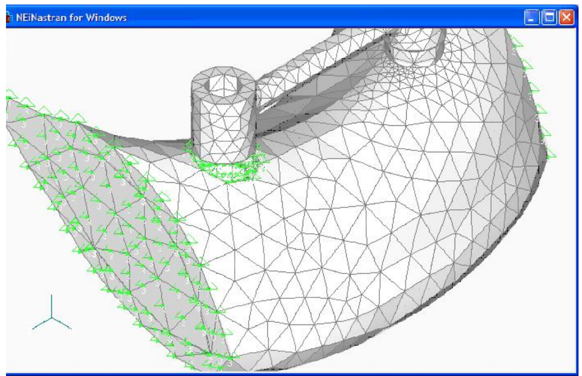

Figura 6 – Restrições de movimentos aplicadas no modelo

Os deslocamentos foram aplicados em uma das extremidades da barra para simular a eliminação do desajuste horizontal proporcionado pelo aperto dos parafusos de retenção. Os deslocamentos horizontais simulam uma condição de distorção linear ocorrida pela contração da estrutura durante o processo de fabricação, reduzindo o comprimento da barra (Figura 7). A estabilidade do modelo foi novamente verificada, e atenção especial foi dada ao refinamento da malha na interface osso e implante .

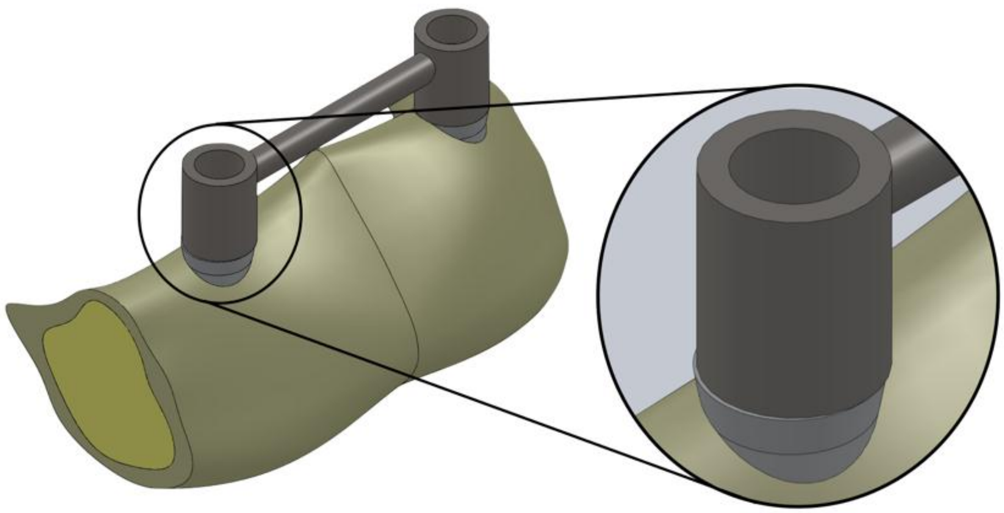

Figura 7 – Vista amplificada do desajuste horizontal simulado.

3. DELINEAMENTO E ANÁLISE

Quatro análises foram realizadas, separadamente, para reduzir a quantidade de modelos envolvidos: Capítulo 1 – i) diferentes desajustes horizontais (10, 50, 100, e 200 µm) utilizando liga de ouro como material da barra; ii) diferentes materiais da barra simulando 50 µm de desajuste horizontal (neste capítulo foi utilizada barra de secção transversal circular); Capítulo 2 – iii) diferentes secções transversais da barra simulando diferentes desajustes horizontais (10, 50 e 100 µm); iv) diferentes secções transversais da barra simulando 1.4 mm de reabsorção óssea peri-implantar e 50 µm de desajuste horizontal (neste capítulo foi utilizado cobalto-cromo como material da barra). Os dados foram analisados por meio de figuras e dados numéricos dados pelos *softwares*.

Anexo 1

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