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Análise tridimensional por elemento finito do comportamento biomecânico de próteses totais fixas implantossuportadas: efeito do tipo de conexão protética, cargas oclusais e número de implantes

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Orientador: Prof.Dr. Marcelo Ferraz Mesquita

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"A sabedoria do ser humano não é definida pelo quanto ele sabe, mas pelo quanto ele tem consciência de que não sabe."

Augusto Cury

Resumo

A proposta neste estudo foi analisar a distribuição de tensão pelo método de elementos finitos tridimensional em próteses totais fixas inferiores implantossuportadas e região óssea peri-implantar, utilizando-se dois tipos de conexão im

plante-*abutment* externa e interna, correlacionadas ao efeito de cargas axiais e número de implantes. Modelos virtuais foram elaborados simulando uma prótese total fixa implanto suportada mandibular, de acordo com o protocolo Branemark, tendo como fatores de estudo as conexões implant-*abutment* Cone Morse (CM) e Hexágono Externo (HE); quatro e cinco implantes; cargas axiais 100 N bilateral, 300 N bilateral e unilateral. As condições de análise foram: 1. Próteses fixas com conexão interna Cone Morse (CM) submetidas à seis condições experimentais constituindo os modelos M1, M2 e M3 com quatro implantes e cargas de 100 N e 300 N, respectivamente; os modelos M4, M5, e M6 com cinco implantes e cargas similares; 2. Próteses fixas com conexão externa Hex Externo (HE), submetidas às mesmas condições; 3. Comparação entre os dois sistemas de conexão. Os resultados de deformação óssea (µƐ), sob efeito de cargas axiais de 100 N, distribuíram-se homogeneamente nos grupos com CM e concentraram-se nos implantes distais nos grupos com HE. Sob efeito de cargas axiais de 300 N, a distribuição de tensão acompanhou a mesma tendência anterior, com aumento de deformação no osso (µƐ) e implantes (MPa) cerca de 1,5-2 vezes para os grupos com CM e 3 vezes para os grupos com HE. Dentro das condições do estudo concluiu-se que: 1. sob efeito de cargas axiais de 100 N o uso das duas conexões implante-*abutment* Cone Morse e Hexágono Externo é bem indicado; 2. sob efeito de cargas axiais de 300 N a conexão Cone Morse apresenta melhor indicação; 3. cinco implantes não representam benefício relevante em relação à quatro; 4**.** com o sistema de conexão Cone Morse, a solicitação mecânica distribui-se por todos os implantes e região óssea, com o sistema Hexágono Externo, concentra-se nos distais e região óssea circundante; 5. a distribuição de tensão na infraestrutura protética é similar com os dois sistemas de conexão, apresentando resistência mecânica satisfatória com a conexão Hexágono Externo e cargas axiais de 100 N e insuficiente para ambas as conexões sob cargas axiais de 300 N.

Palavras-Chave: Implantes dentais, próteses implantossuportadas, biomecânica.

Abstract

The purpose of this study was to analyze the stress and strain distribution by three-dimensional finite element method in implant supported fixed prostheses and peri-implantar bone region, using two types of implant-abutment connection internal and external, correlated to the effect of axial loadings and number of implants. Virtual models were developed by simulating a mandibular implant supported fixed prostheses, according to the Branemark protocol, with study factors: implant-abutment connection Morse taper (MT) and External hexagon (EH); four or five implants; bilateral axial loadings 100 N, bilateral and unilateral axial loadings 300 N.The analysis conditions were: 1. Fixed prostheses with internal connection Morse taper interface (MT) simulating six experimental conditions, making the models M1, M2 and M3 with four implants and loads of 100 N and 300 N, respectively; models M4, M5, M6 with five implants and similar conditions; 2. Fixed prostheses with external connection External hexagon interface (EH), submitted to same conditions; 3. Comparison between the two connection systems. The results of von Mises stress and bone strain, under effect of 100 N axial loadings, were distributed evenly for all implants for groups with MT, focused mainly on the distal implants for groups with EH. Under effect of 300 N axial loadings, the stress and strain distribution followed the same tendency, with values increased of 1.5-2 times for the MT group and 3 times for EH groups. Within the analysis conditions the study concluded that: 1. under effect of axial loadings of 100 N, the use of two implant-abutment connections MT and EH can be well indicated; 2. under effect of axial loadings of 300 N, the Morse taper connection provides a better indication; 3. Five implants do not represent relevant benefit over four; 4. with Morse taper connection system, the mechanical stress is distributed for all implants and bone area, with the External hexagon, focuses on the distal region and surrounding bone; 5. the stress distribution in prosthetic infrastructure is similar with the two connection systems and the mechanical strength is satisfactory for groups with prosthetic connection EH and 100 N axial loadings, and insufficient for both prosthetic connections under effect of 300 N axial loadings.

Keywords: Dental implants, implant-supported prostheses, biomechanics.

Sumário

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Introdução

A reabilitação através de implantes osseointegrados tem sido extensivamente indicada, há pelo menos três décadas, inicialmente dirigida aos pacientes totalmente edêntulos, ampliando sua indicação em próteses parciais e unitárias (Branemark, 1969; Branemark, 1977; Binon, 2000). Para que haja efetiva osseointegração do implante, torna-se imprescindível a adequada distribuição de cargas oclusais e adaptação passiva do complexo prótese-implante-osso (Branemark, 1977; Misch, 2006; Isidor, 2006), o que destaca a importância do estudo dos diversos fatores biomecânicos de influência.

Apesar dos altos índices de sucesso relatados, a ocorrência de falhas ainda pode ser observada, tanto em implantes de carga imediata, quanto mediata. Em relação ao protocolo de carga imediata a região anterior da mandíbula composta por osso altamente compacto, apresenta potencial para adequado suporte e estabilidade primária aos implantes. Em ambas as situações, os fatores de insucesso podem estar relacionados principalmente à aspectos biomecânicos, que ainda não se encontram completamente compreendidos, cujas conseqüências também permanecem inconclusivas pela literatura vigente (Korioth et al,1998; Duyck et al,2000; Sahin *et al.*, 2002; Misch,2006; Francetti *et al.*, 2008; Testori *et al.*, 2008). Dentre estes, há consenso de que a magnitude das forças oclusais, gera o aumento do padrão de tensão e deformação, podendo induzir à perda óssea marginal, conhecida como saucerização (Shen *et al.*, 2010) com influência direta aos componentes do complexo prótese-implante-osso (Mericske-Stern & Zarb, 1996; Mericske-Stern *et al.*, 2000; Sahin *et al.*, 2002; Misch, 2006; Isidor, 2006). As forças geradas podem ser externas (funcionais e parafuncionais), ou internas (pré-carga), além de outros fatores interferentes como número, disposição e configuração dos implantes (Korioth *et al.*, 1998; Duyck *et al.*, 2000), tipo e material da prótese, conexão protética, além da densidade óssea (Sahin *et al.*, 2002; Misch, 2006).

Considerando a quantidade e disposição de implantes, ainda não há consenso quanto à melhor configuração em próteses implanto-suportadas. Com este propósito, estudos *in vivo* e laboratoriais têm sido feitos visando não somente a redução do tempo de tratamento, como também a simplificação dos protocolos, através da redução do número de implantes e do risco cirúrgico (Skalak, 1983; Korioth *et al.*, 1998; Duyck *et al.*, 2000;Francetti *et al,*2008;Testori *et al,*2008). Esta abordagem pode ser viável e vantajosa, desde que não apresente prejuízo ao sistema (Davidoff, 1996), sendo para isto imprescindível a manutenção do polígono de sustentação, através do aumento de espaço inter-implantar (Skalak, 1983).

A esplintagem de coroas protéticas sobre múltiplos implantes tem sido recomendada por diversos estudos experimentais e *in vivo*, sugerindo melhor distribuição de cargas, desde que haja assentamento passivo, evitando assim micromovimentações, responsáveis por tensões desfavoráveis entre osso-implante (Davidoff, 1996; Yokoyama *et al.*, 2005; Misch, 2006). Vários autores acreditam que quanto maior o número de elementos esplintados, menor o nível de tensão *g*erado, frente às forças mastigatórias, otimizando o resultado final (Korioth *et al.*, 1998; Duyck *et al.*, 2000; Sahin *et al.*, 2002).

O tipo de conexão implante-*abutment* pode influenciar significativamente na função a longo prazo das próteses implantossuportadas (Norton, 1997; Norton, 2000; Chun *et al.*, 2006) uma vez que o mecanismo de transmissão de cargas no conjunto prótese-implante-osso depende diretamente das propriedades físicas e configuração geométrica espacial dos implantes (Kitagawa *et al.*, 2005; Simsek *et al.*, 2006; Van Staden *et al.*, 2006)Incidência de problemas biomecânicos, especialmente em restaurações unitárias tem sido relatada nos sistemas com hexágono externo, gerando fratura e perda da função dos parafusos (Schwarz, 2000; Binon, 2000; Jokstad *et al.*, 2003), o que também é considerado um mecanismo de alerta ou proteção, impedindo a provável ocorrência de sobrecarga oclusal e consequente falha do implante (Khraisat *et al.*, 2002). Por outro lado, outros estudos demonstram não haver diferenças entre as conexões implant-*abutment* sobre este aspecto (Piermatti *et al.*, 2006; Theoharidou *et al.*, 2008; Tsuge & Hagiwara, 2009). Estes inconvenientes conduziram ao desenvolvimento de outras opções, visando uma melhoria da retenção e estabilidade. Surgiram a partir daí, os sistemas de implantes com interface interna cônica, dentre os quais, o tipo Cone Morse (Schwarz, 2000; Binon, 2000; Jokstad *et al.*, 2003). Há evidências de maior resistência do sistema de interface cônica interna, quanto à fadiga e torque rotacional, em relação ao sistema de Hexágono Externo, para restaurações unitárias, sugerindo a redução de fraturas e perda de parafuso (Khraisat *et al.*, 2002; Sahin *et al.*, 2002; Cehreli *et al.*, 2004; Kitagawa *et al.*, 2005). Os métodos mais utilizados nos estudos de biomecânica na Odontologia, para avaliação do índice de tensão podem ser por meio de *strain-gauge* (Fernandes *et al.*, 2003; Assunção *et al.*, 2009), análise fotoelástica (Fernandes *et al.*, 2003; Assunção *et al.*, 2009) e análise por elemento finito (Sahin *et al.*, 2002). A análise fotoelástica proporciona adequada informação qualitativa da concentração de tensão em todos os aspectos considerados, com restrições quanto aos dados quantitativos e à análise tridimensional das estruturas. A avaliação por *strain-gauge* é o único método que permite medição *in vivo*, porém com limitações para adesão dos sensores como nos pontos de aplicação de carga, resultando em dados não coincidentes com os seus respectivos experimentos *in vitro* (Sahin *et al.*, 2002). Pelo método por Elementos Finitos, pode-se obter com maior precisão, uma avaliação qualitativa e quantitativa de estruturas mais complexas, além da previsão de possíveis falhas (Sahin *et al.*, 2002; Kitagawa *et al.*, 2005), considerando-se as limitações inerentes a um modelo matemático (Hansson, 2003).

Diante das controvérsias, a literatura ainda carece de evidências quanto ao número mais apropriado de implantes e o seu conseqüente efeito em nível da região peri-implantar e estruturas protéticas, frente às diversas possibilidades de solicitação mecânica, assim como, da possível influência dos diferentes sistemas de conexão protética em próteses múltiplas. Com a evidente influência da tensão e deformação na perda óssea marginal, é premente a necessidade de estudos para se investigar a biomecânica das próteses implantossuportadas, possibilitando a validação e condução dos protocolos clínicos. Neste contexto, a proposta do estudo foi avaliar a influência de cargas axiais, número de implantes e conexão implante-*abutment,* na distribuição de tensão e deformação sobre implantes osseointegrados, osso e estruturas protéticas, suportando a hipótese de relevante influência destes fatores.

Capítulo 1

Stress distribution of internal connection in mandibular prostheses under effect of loadings and number of implants: Three-dimensional finite element analysis

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ABSTRACT

Purpose: The purpose of this study was to analyze the stress and strain distribution in implant-supported fixed prostheses and peri-implantar bone area, under the effect of axial loadings and number of implants, using the internal implant-abutment connection. **Material and Methods**: Virtual models were prepared by three-dimensional finite element method, consisting of jaw, implants and prosthetic structures, simulating a mandibular implant-supported fixed prostheses. Six simulated experimental conditions were prepared by differentiating the number of implants (4 or 5) and axial loadings (bilateral 100 N, bilateral or unilateral 300 N) to investigate the strain in bone, and stress in implants and prosthetic structures. **Results:** The results of von Mises stress and bone strain, under effect of 100 N axial loadings, were distributed homogeneously for all implants, especially in the cervical region. Under effect of 300 N axial loadings (bilateral and unilateral), the stress and strain distribution followed the same tendency, with an increase of 1.5-2 times for bone and implants**.** Under effect of the 300 N unilateral the strain occurred in all implants, predominantly on the load side. **Conclusion:** The internal connection Morse taper interface can be well indicated for both loading conditions, and the mechanical demand is similar for all implants; five implants do not represent a benefit over four; the mechanical strength of the infrastructure is insufficient for both loading conditions, and its stress distribution presents a different pattern.

Key words: Dental implants, implant-supported prosthesis, finite element analysis, biomechanics, bone strain.

INTRODUCTION

The use of osseointegrated implants in completely edentulous patients is a well-established treatment modality that has evolved into a routine, predictable procedure with long-term documented success [1-6]. However, the success of treatment is highly dependent of an effective osseointegration of the implant, which is, in turn, closely associated with the adequate distribution of occlusal loading and passive adaptation of the complex bone-implant-prosthesis [2, 6, 7].

In the specific case of immediate and mediate loaded implants, although success rates have been high, the occurrence of undesirable loss and failures still seems inevitable. Late implant failures have been observed after prosthesis delivery and have been largely related to biomechanical complications. However, the mechanisms responsible have not been completely understood, and several biomechanical factors are still unknown [8]. There is a consensus that the magnitude of occlusal forces leads to an increased stress pattern that can lead to marginal bone loss usually termed saucerization [9].These generated forces can be either external (functional and parafunctional) or internal (preload). Other interfering factors are the number, arrangement and configuration of implants [6, 8, 10, 11] and type of prosthetic material, prosthetic connection, and bone density [6, 8].

Reducing the number of implants may be beneficial, since it does not compromise the mechanics' of the system [12] , maintaining the vital circle of support through increased inter-implant space [13]. However, no consensus has been reached in relation to the proper number of implants or the best configuration for an implant-supported prosthesis. Not surprisingly, a number of *in vivo* and laboratory studies have been carried out for this purpose [10, 11, 13]. According to Duyck et al, 2000, the best configuration was observed with six and five implants, in relation to four and three elements; the worst configuration was with three implants.

In relation to implant supported prosthesis with multiple implants, experimental and *in vivo* studies have also shown that splinting of prosthetic crowns provides adequate settlement and, hence, avoids micro-movements responsible for deleterious stress between bone and implants [6, 12, 14-17]. Despite generating a more uniform stress distribution, it is considered that splinting may not be significant for internally connected implants [17].

As for the implant-abutment connections, there are many different types available, mainly described as internal or external connection types. Nonetheless, the design of the interface between components has been shown to have a profound influence on the stability of screwed joints [5]. A new approach to implant design, where the implant and abutment are united through an internal conical interface without the use of a third connecting component, the abutment screw. has been developed aiming to improve retention and stability of the system [18]. With the morse taper interface [3, 19], it has been demonstrated that the conical portion of the interface was capable to absorbe vibrational and functional loads, acting as a buffer against load and micromovement.

In respect to single unit prosthesis, the internal connection systems have showed greater resistance to fatigue and rotational torque, suggesting the reduction of fractures and loosening of screws [8, 20-22]. The companies promoting conical abutment systems have recommended their use mainly for single tooth situations and cemented prostheses [5]. In a previous study Norton,1997 [18] showed that the internal conical joint was significantly more stable joint, when compared to an External hexagon or butt joint in resisting extreme bending moments.

The methods commonly used for biomechanical studies in Dentistry to assess the levels of stress can be by means of strain-gauge [23, 24] photoelastic [23, 24], or finite element analysis [8, 24]. Photoelastic analysis provides qualitative information of the appropriate stress concentration in all aspects considered, but yields limited quantitative data and three-dimensional representation. The evaluation by strain-gauge allows *in vivo* measurement, but with limitations such as the fixation of the sensors and the point of load application, resulting in data that does not coincide with their respective *in vitro* experiments [8, 24].

The finite element analysis was used for the first time in implant dentistry in 1976, and after this, it has been used extensively to predict the biomechanical performance of dental implants, prosthetic infrastructure, materials and the surrounding bone behavior [25]. By this method, a qualitative and quantitative evaluation of complex structures can be obtained with greater accuracy, and then, predict possible failures [8, 21] within the limitations inherent to a mathematical model [26]. Additionally, the achievement of an appropriate, effective mathematical model is crucial to elucidate physical phenomena, which requires the inclusion of comprehensive structural simulation.

The evidences regarding the many factors that influence the performance of multiple prostheses are still scarce, such as the best configuration and layout, implant-abutment connection, and its consequent effect on the peri-implant area and prosthetic structures under loading. Considering the significant influence of stress and strain in marginal bone loss, the purpose of this study was to evaluate the influence of axial loading and number of implants on stress distribution in mandibular implant-supported prostheses and peri-implantar bone, through the 3D finite element method, using the morse taper internal implant-abutment connection.

MATERIAL AND METHODS

1. Geometry Model

Three-dimensional virtual models representing an edentulous mandible with a fixed implant-supported prosthesis, according to the Branemark protocol, with four or five implants were obtained. The structures (mandible, implants, abutments, prosthetic infrastructure, and acrylic resin prosthesis) were modeled using specific software Rhinoceros 4.0 SR8 (McNeel North America, Seattle, WA, USA).

A virtual image of an adults' mandible, provided by a CT scan from the database of Three Dimensional Technologies Division, was used to perform the BioCAD protocol (Renato Archer Information Technology Center, Campinas, SP, Brazil). This protocol consisted of the demarcation of the major landmarks on the CT image, to obtain a more simplified edentulous mandible model, which was essential for later the generation and refinement of the mesh. The mandible was modeled with 2 mm uniform thickness of type II compact bone [27] and trabecular bone inside it.

Three-dimensional images of the implants (cylindrical implants of 3.75 x 13 mm with morse taper connection), abutments, and screws that served as the basis for modeling were provided by the manufacturer (Neodent, Curitiba, PR, Brazil). For the configuration with four implants, the location of each implant corresponded to regions of the first premolar and lower canine in each side; with five implants, one implant was added in the midline. The distance between the implant platforms was about 4 mm, and the distal ones were positioned 3 mm distal of mental foramen. The prosthetic infrastructure was made with a titanium bar with 4 mm circular cross-section, 50 mm interforaminal length, and 15mm length on each side in the cantilever region [28, 29] with 80 mm total length, space for washing and sanitizing of about 3 mm over the edge, and was modeled to obtain a rigid connection between implants and prosthesis. The resin prosthesis was modeled from average measurements from the laboratory.

The constructed models were exported in STEP format software for numerical analysis by finite elements.

2. Finite Element Analysis:

The numerical analysis by finite element method was performed using the ANSYS Workbench 12.0.1 program and included three steps: pre-processing, processing and post-processing.

Pre-processing: This includes the definition of material properties, mesh generation, boundary and loading conditions.

Material properties: The materials were considered to be isotropic, elastic, linear, and homogeneous, characterized by the modulus of elasticity (E) and Poisson's ratio, shown in Table 1.

Mesh Generation: The mesh was generated with tetrahedral elements with 10 nodes and manual control of refinement was performed with the aid of lines and surfaces made during the modeling stage, so that for the regions of greatest interest (peri-implant bone and components of the prosthesis). In such cases, the elements were made with smaller size, resulting in a higher density of nodes in the region (Figure2a, 2b-Apêndice, pg. 102). The number of elements and nodes in each structure is shown in Table 2.

Boundary and Loading Conditions: A multibody approach was performed defining the interaction between each structure by simple contact (juxtaposed) or glued. The glued contacts were attributed to: bone-implant interface that was assumed to be completely osseointegrated; implant-abutment-prosthetic screws interface; prosthetic infrastructure-acrylic resin prosthesis, and cortical-trabecular bone interface. The remaining interactions were due to single contacts or juxtaposed. The cut surfaces of the posterior mandible were fixed in all directions on space. **Loading Conditions**: Static loading was applied on the occlusal surfaces related to posterior teeth position. The positions were located in the occlusal rims and were assumed to be opposing a conventional complete denture with 100 N bilateral axial loading on each side and, in the same way, applied 300 N bilateral axial loading each side, and 300 N unilateral axial loading, assuming that the opposing arch would be a fixed implant-supported prosthesis [4] (Figure3- Apêndice, pg.102).

Processing: Six experimental conditions were subjected to analysis, according to axial loading (100 N, 300 N bilateral, 300 N unilateral) and number of implants (4 or 5), as follows: **M1** (4 implants, 100 N), **M2** (4 implants, 300 N bilaterally), **M3** (4 implants, 300 N unilaterally), **M4** (5 implants, 100 N), **M5** (5 implants, 300 N bilaterally), **M6** (5 implants, 300 N unilaterally).

Post-processing and analysis of results: The results of displacement, von Mises stress and strain degree obtained during processing were analyzed with graphical visualization for qualitative and quantitative comparisons among the six conditions. The areas of focus for this analysis were the peri-implant bone, implants, their abutments, infrastructure, and prosthetic screws for the verification of effects caused by the variables presented.

Table 1 Physical properties of bone and materials.

	Modulus of Elasticity (E)(GPa)	Poisson's ratio	References
Cortical bone	13.7	0.30	30, 31
Trabecular bone	1.37	0.30	30, 31
Implant,abutment,infrastruture. (Ti cp)	110	0.33	32
Acrylic resin	3.8	0.30	33

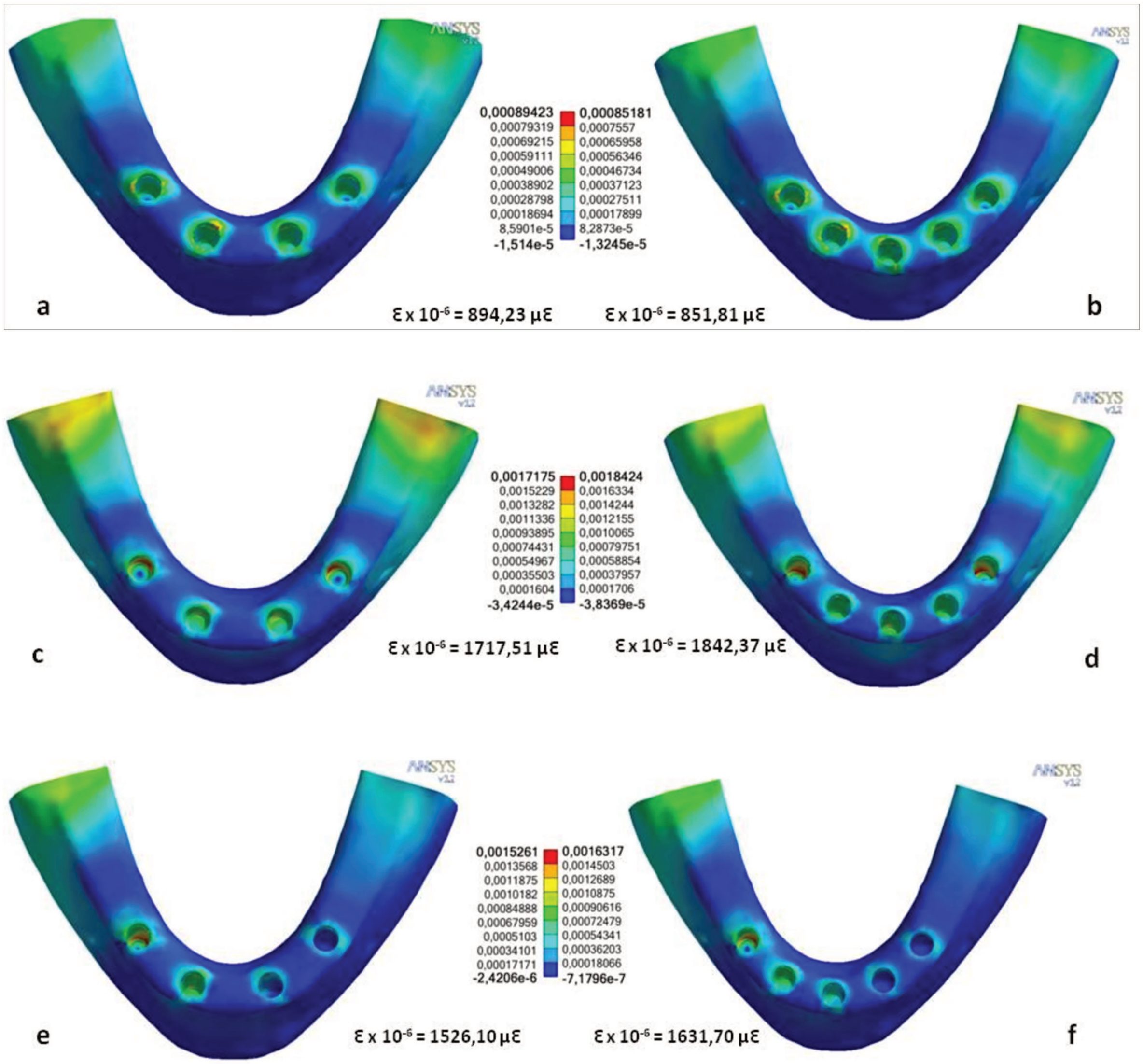
Table 2 Number of Elements and Nodes

Structures	Elements	**N**odes
Cortical bone (mandible)	14229	25221
Trabecular bone (mandible)	11210	18877
Implants	2145	3643
Abutments	1554	2715
Screws	521	971
Infrastructure	7572	13276

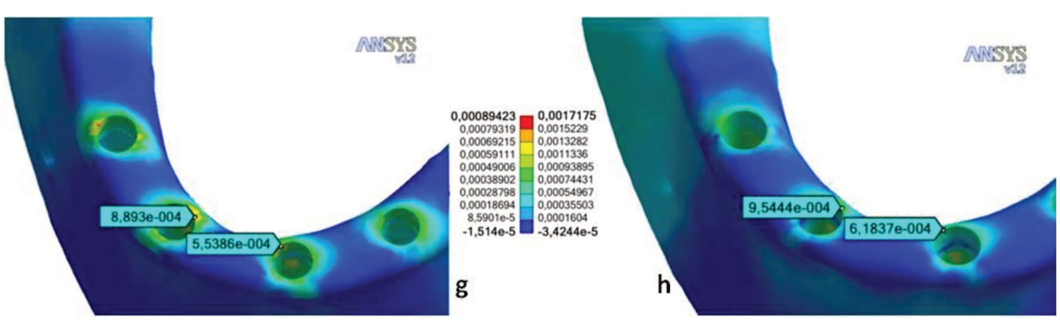
RESULTS

According to the results of this study, the peri-implant bone micro strain in both groups of morse taper connection under effect of bilateral 100 N axial loading was distributed evenly for all implants with higher concentration in the cervical cortical bone. The addition of one implant showed no significant difference if compared M1 and M4 (Figure 1a, 1b)**.** Under the effect of 300 N bilateral axial loading, the strain distribution was presented within all implants with higher levels in the distal ones (Figure 1c, 1d). Under the effect of unilateral 300 N axial loading, despite the strain distribution in all implants, it was observed predominance in the loaded unilateral side (Figure 1e, 1f). The addition of one implant showed no significant difference for 300 N bilateral (M5) and unilateral (M6) (Figure 1d, 1f).

Under the effect of 300 N axial loadings, bilateral and unilateral conditions, the values of bone strain almost doubled (1,5-2 times) in relation to 100 N axial loading, extending from the cortical to the trabecular bone (Figure 1g, 1h) for both four and five implant configurations.

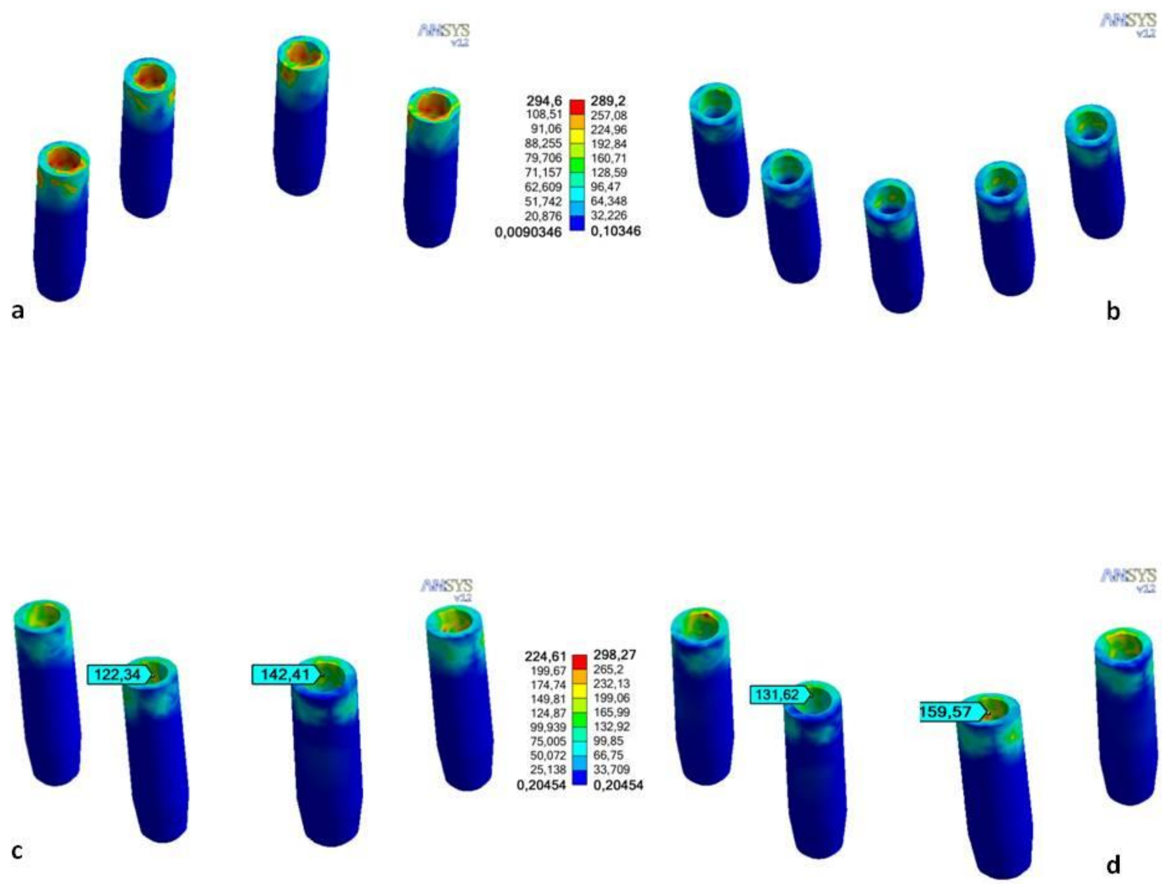


Figures 1a to 1f Bone strain (με) under 100 N axial loadings with 4 **(a)** and 5 **(b)** implants; under 300 N axial loading bilaterally with 4 **(c)** and 5 **(d)** implants and unilaterally with 4 **(e)** and 5 **(f)** implants.



Figures 1g, 1h- An average increase of bone strain from 100 N (g) to 300 N (h) axial loading

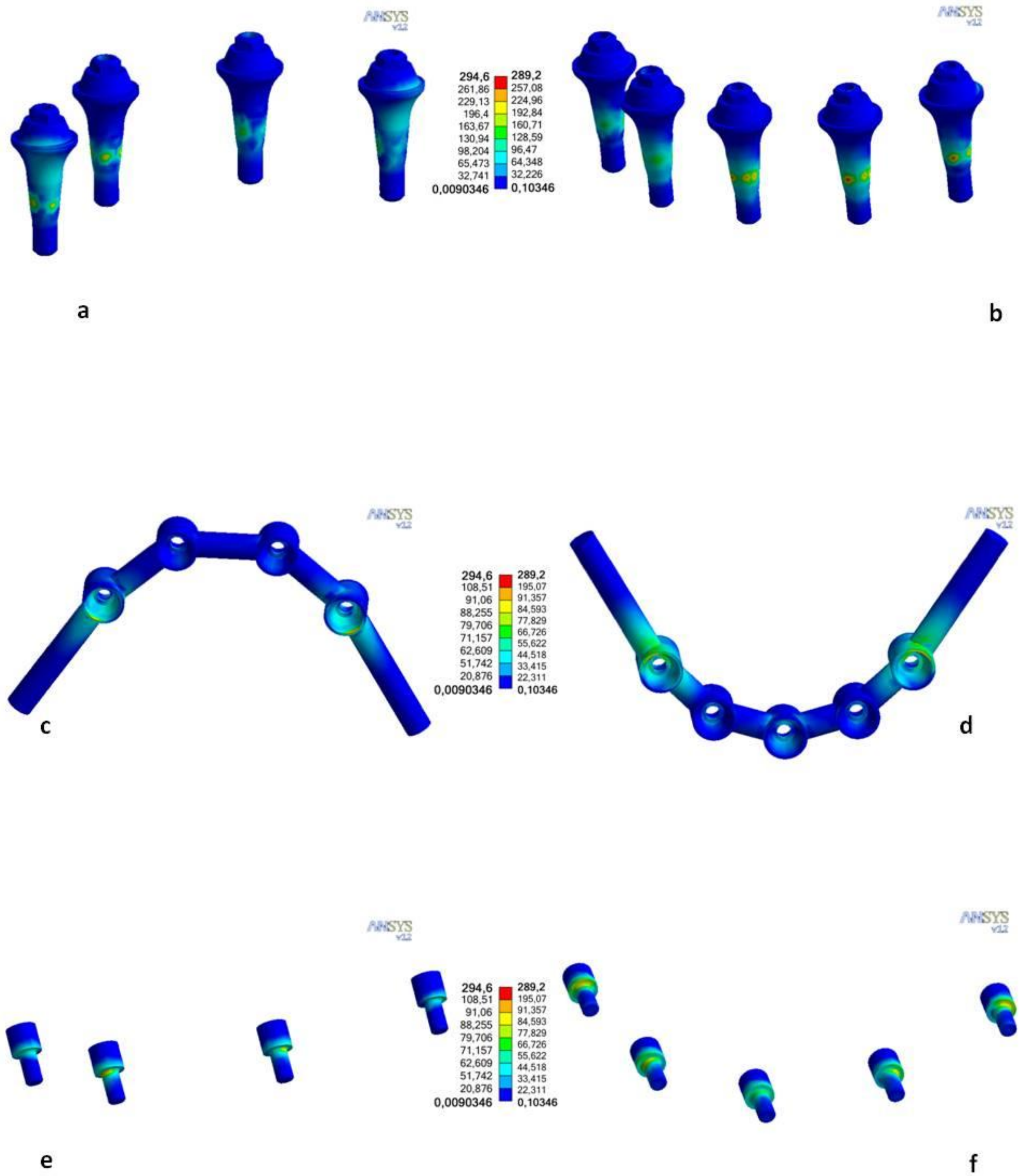
In relation to implants, under the effect of 100 N axial loading the von Mises stress showed, for the model with four implants (M1), a higher stress concentration distributed evenly for all implants (Figure 2a); for the model with five implants (M4) showed the same tendency of the previous group, but with better stress distribution. The addition of one implant, showed no significant difference (Figure 2b). Under the effect of 300 N axial loadings, the values of von Mises stress for implants increased an average 1,5-2 times in relation to 100 N axial loading (Figures 2c, 2d) for both implant configurations.



Figures 2a, 2b-von Mises stress (MPa) under 100 N axial loadings for 4 (a) and 5 (b) implants

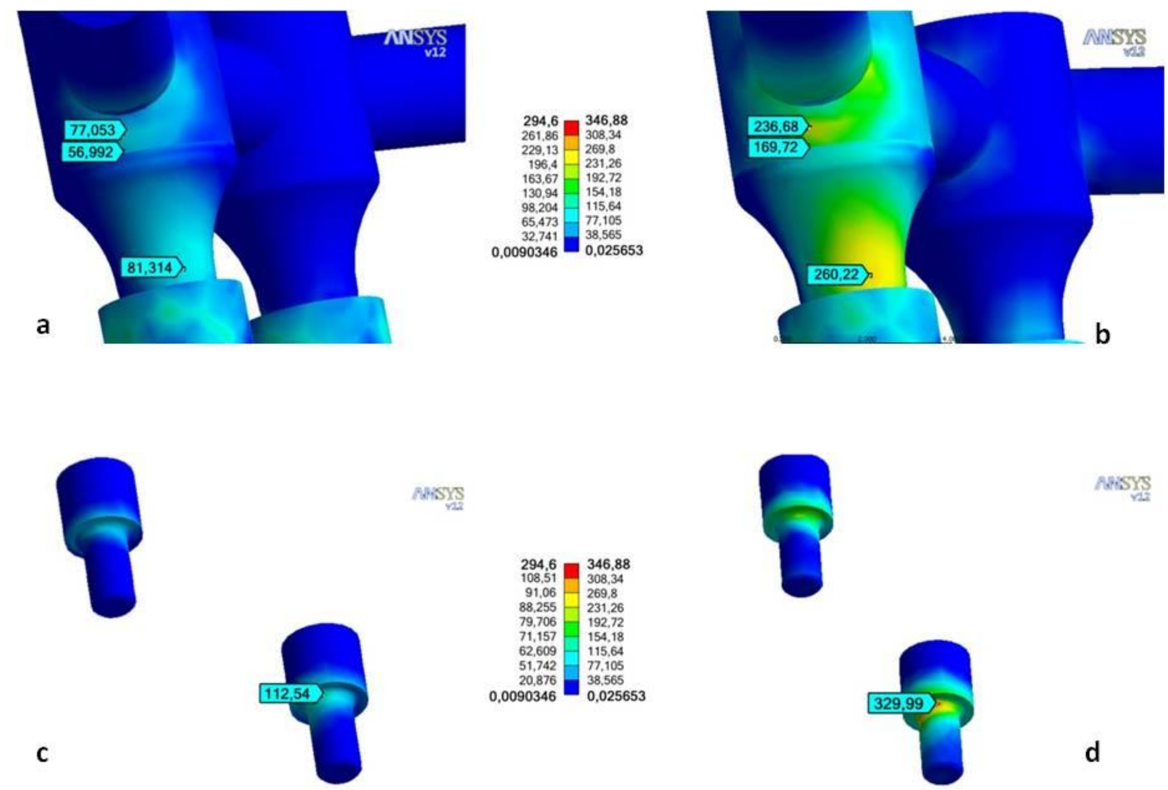
Figures 2c, 2d-An average increase of von Mises stress (MPa) from 100 N (c) to 300 N (d) axial loadings

In relation to prosthetic structures (abutments, infrastructures and screws) under the effect of 100 N axial loadings**,** the von Mises stress for abutments showed for the model with four implants (M1) the same tendency of the implants: stress evenly well distributed in all ones (Figure 3a); for the model with five implants (M4,) it showed behavior similar to the previous model (M1), but with a slightly higher tendency in the three median ones (Figure 3b). For the infrastructure, the von Mises stress for the model with four implants (M1) presented a higher concentration in the distal area extending to the cantilever region (Figure 3c); for the model with five implants (M4), the same tendency was observed but with an increase of stress in the central implant (Figure 3d). For the prosthetic screws the von Mises stress was distributed among all screws of the model with four implants (M1), with higher stress in the median ones (Figure 3e); for the model with five implants (M4) stress levels where higher in the distal ones, followed by intermediate ones and lower in the central implant (Figure 3f).



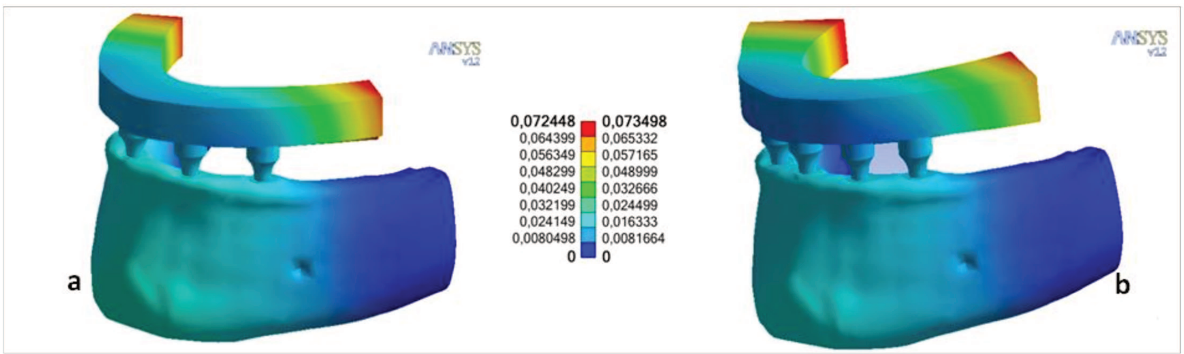
Figures 3a to 3f- von Mises stress (MPa) under 100 N axial loadings with for 4 and 5 implants for the abutments (a, b), infrastructure (c, d), prosthetic screws (e, f).

Under the effect of 300 N axial loadings, the values of von Mises stress for abutments, infrastructure, and screws showed an average increase of 3 times in relation to 100 N axial loading (Figure 4a-d), for both four or five implants models. The stress distribution followed the same tendency presented for 100 N axial loading. On both loading conditions, the von Mises stress values observed on the infrastructure were above the maximum strength resistance of cp titanium, especially in the cantilever area. For the prosthetic screws, the condition was less favorable for four implants (M1), under the effect of 300 N axial loading.



Figures 4a to 4d- An average increase of von Mises stress (MPa) from 100 N (a) to 300 N (b) axial loadings for the abutments and infrastructure and for the prosthetic screws (c, d).

The displacement for the mandible was significantly reduced, and the displacement of the prosthetic infrastructure showed approximately 50 percent higher, with variance of only 1% between four and five implants both with 100 N (Fig. 5a, 5b), and in the same way for the 300 N axial loadings.



Figures 5a, 5b- Displacement (mm) of the mandible and infrastructure with 4 (a) and 5(b) implants, 100 N axial loadings.

The tables below present values referring to a previous graphics analysis of strain and stress for bone, implants and prosthetic structures, with four and five implants, and the effect of axial loadings of 100 N and 300 N (Table 3, 4).

Table 3- Maximum Principal Elastic Strain for bone (μƐ)

Bone strain (μƐ)			
Number of implants		**4**	**5**
Axial loading	100N	889	749
	300N	954	866

* μƐ = Ɛ x10^{-6}

Table 4 - von Mises Stress (MPa) for implants, infrastructure, and screws

von Mises stress (MPa)							
		Implants		Infrastructure		Screws	
Number of implants		**4**	**5**	**4**	**5**	**4**	**5**
Axial loading	100N	122	123	77.05	73	112.54	97.56
	300N	131	200	236.68	216.98	329.99	311.57

Table 5- Displacement for mandible and prosthetic infrastructure (mm)

Displacement (mm)					
		Mandible		Prosthetic infrastructure	
Number of implants		**4**	**5**	**4**	**5**
Axial loading	100N	0.024	0.024	0.073	0.072
	300N	0.074	0.075	0.22	0.22

DISCUSSION

The establishment of parameters for evaluation and selection of appropriate treatment alternatives for implant-supported prostheses is essential, since the occlusal forces can affect oral implants and related structures. When these forces exceed the mechanical or biological load-bearing capacity of the osseointegrated oral implants or the prosthesis, either a mechanical failure or a failure in the osseointegration may occur. In such cases, the excessive load can be described as an overload [7]. Applying force to a bone structure generates stress, which deforms its structural arrangement, namely strain. Therefore, it is important to keep in mind that changes in bone mass, resorption or remodeling, are dependent on strains rather than stress *per se* [14].

As a general conversion rule, stress is related to strain as the resulting strain of a structure is equal to the applied stress divided by the modulus of elasticity of the material. Due to the minute variations observed, biomechanicians quantify such alterations in micro strain (με), a scale in which 10^6 με would equal a theoretical deformation of 100%, thus 1000 με equals to a deformation of 0,1%. For this reason, the micro strain unit (με) was used to analyze bone strain in this study.

According to Frosts' hypothesis [34, 35] on bone physiology, bone cells respond to local deformation produced by mechanical stress. This continuous process maintains the mechanical competence of the bone, which is also applied to the bone surrounding dental implants [7, 34, 35]. The bone is able to adapt a certain strain in a steady state. It is believed that a bone structure is in function within the strain range of approximately 100-1500 με. If the peak load on a bone results in strains within 1500-3000 με, a mild overload occurs, which can result in damage, which might be repaired with remodeling, with the formation of more bone by reshaping and strengthening the tissue. Therefore, loads within this range may result in an osseous adaptation. Nonetheless, repeated stress on the bone resulting in deformation greater than 3000 με could increase micro-damage, overcome the repair mechanism, and result in a fatigue failure. In this level, the values are already considered to be pathological, which can result in bone resorption. Values from 25,000 με would reach the limit, which could lead to sudden fracture. Conversely, if the strain in the bone, does not exceed 50-100 με, the level where optimal strains are not achieved, disuse of the bone occurs, and remodeling results in a net loss of bone, leading it to adapt to the new demand [8], [7], [34].

The axial loads used in this study were 100 N bilaterally and 300 N bilaterally and unilaterally. The 100 N axial loading simulates a conventional complete denture as the antagonist arch, which comprises most of the patients. The 300 N axial loading simulates an implant or tooth-supported prosthesis as antagonist. The third option, 300 N unilaterally simulated a common bite habit presented by patients [4]. In addition, there are many variations in maximal occlusal forces described in the literature, obviously due to different measuring methods and different location of measurements on the prosthesis.

According to the results of this study, under the effect of bilateral 100 N axial loading, the values of peri-implant bone strain where between 100-1500 με in both models of morse taper connection, which would be inserted into the normal strain pattern for bone tissue, [7, 34, 35] corresponding to bone function. Nonetheless, these bone structures presented high levels of stress. In such scenario, it is important to note that biomechanical stimulation would occur in all peri-implant areas. The model with five implants showed no significant difference if compared to the four implants model.

Some evidence observed in this study were confirmed with previous ones [16, 36, 37] that showed the prevalence of stress in the cervical portion of the peri-implant bone, which is in agreement with the marginal bone loss observed *in vivo* [7, 38] , especially during the first year of implants in function.

In relation to the implants and abutments, the addition of an implant showed no significant benefit to the biomechanics of these structures. Despite even stress distribution among all implants, the stress values presented were high, which could be justified by the basic principle of locking and friction of internal connection implant systems. The internal connection absorbs stress and minimize the effect of functional loads, reducing micromovements and providing improved strength and stability to the connection [5, 8, 18].Thus, it might be postulated that high forces could be absorbed by the conical interface and generate high stress within the connection interface, without detectable deleterious deformation of the metal components [5, 18].

In relation to prosthetic infrastructure, the stress distribution pattern, although extending to all pillars, is more concentrated in the distal ones, not being evenly distributed, which was described for the peri-implant bone, implants, and abutments. Thus, it can be suggested that the effect exerted by it has overcomed the effects of load-carrying mechanisms of the internal connection, extending to the prosthetic screws. Some studies confirm its important function of unifying the components, distribution of loads and reducing stress, compared to the separate structures [14-17]. Despite the obvious influence of the infrastructure at this level, the specific characteristics of internal connection were not neutralized, which can be confirmed by the maintenance of higher values of stress.

The cp titanium infrastructure presented stress values close to the yield strength of the metal, which is around 380-480 MPa [39], especially at the region of the distal implants and cantilever area, on both loading conditions. Other options of alloys may be considered such as Ti-6Al-4V or Co-Cr, materials with much higher resistance [39], which could be more favorable for the rehabilitation. However, Ti-6Al-4V alloys are used mainly for prefabricated components and machined parts and present more difficulty in welding, whereas cp Ti alloys has been commonly used in the laboratory for manufacturing and laser welding prosthetic infrastructure.

As the maximum displacement of the prosthetic infrastructure is minimal, and can be justified by stiffness of the connection, the difference between 4 and 5 implants can be disregarded and does not suggest any benefit by the addition of another implant in the central region.

As for the prosthetic screws, although there was stress on all screws, the highest stress concentration was presented in the intermediate ones in groups of 4 implants for both loading conditions, suggesting major efforts by the intermediate pillars in opposing at extrusion, consequently favoring the loosening of the 4 screws, especially with higher loading (300 N). Nevertheless, with 5 implants, the tendency to loosen would be primarily in the distal screws and lower than in the screws retaining a 4 implant-supported infrastructure, suggesting an influence of the number of implants over the biomechanical behavior of the prosthetic screws.

The results point to a large tendency for screw loosening, however, it is not possible to assure such phenomena, since the preload values of the screws were not evaluated in the present study. Clinical [40, 41] and laboratory studies [21] show a larger tendency toward loosening of screws retaining external connections single unit prostheses, suggesting a different tendency for multiple prostheses. The probable explanation is the effect of the different designs for single unit or multi unit prosthetic infrastructure, which can be inferred as primary factor responsible for the difference between the behavior of prosthetic screws.

With an increase of axial loads from 100 N to 300 N, the values of peri-implant bone strain focused mainly on the trabecular bone. The values did not increase at the same rate as the load: only 1,5 times, approximately. The strain values observed are within the 1500-3000 µƐ, representing an overload pattern, suggesting that such mechanical stimuli could lead to a bone regeneration process. A possible explanation is that the internal connection promotes better attachment between the rehabilitation components, thruits greater stiffness, higher absorption of stress and, hence, lower stress transference to the bone.

The greater stability and strength promoted by the internal connection, especially for single unit restorations [5, 18, 21, 22]. Inasmuch, such behavior could also be attributed to multi unit prostheses, where high levels of stress would also be absorbed by this system, that, without detectable deformation, would transfer undesirable forces to the bone-implant interface, which eventually could result in bone resorption or later failure of the rehabilitation. The results of this study partially confirm this hypothesis, by demonstrating higher stress absorption by the internal connection; however, it was not shown to have a deleterious effect on bone tissue, based on the values of strain imposed by Frost [34], since the effects observed would be considered as steady state and mild overload, both as a 100 N in 300 N axial loads, respectively.

Some clinical studies observed marginal bone integrity around functioning implants with the internal connections [42, 43]. Arvidson *et al*, 1992 [42] evaluated performance in a prospective study over 3 years for the treatment of edentulous jaw and observed that bone resorption was not shown as pronounced during the first year, compared to the subsequent 2 years. This occurrence could confirm the hypothesis that higher strain levels can induce bone remodeling [7, 35]. Arvidson *et al,* 1998 in subsequent monitoring for 5 years reaffirm the evaluation criteria and radiographic proper maintenance of marginal bone level, being considered as treatment success.

There are no long-term prospective and randomized clinical trials that evaluate the influence of controlled forces to the peri-implantar bone. In adition, scientific evidences regarding the effect of implant connection type and comparisons between different connections are still scarce [22], especially in multiple prostheses. Several aspects evaluated experimentally in laboratory simulations present many difficulties to be assessed *in vivo*. In addition, interpersonal variations may influence the degree of bone strength in individuals more likely or more resistant to fatigue or fracture episodes [7, 35]. For the quantification and qualification of these forces on the bone-implant interface, it is necessary to understand their behavior. *In vivo* forces on implants have been measured only at the abutment, with the proper insulation in the peri-implantar area still constituting a challenge. As the intraosseous strain has not been evaluated by biosensors, strain gradients that guide the process of bone remodeling are unknown. Thus, obtaining indisputable scientific evidence is until today, not possible [8].

The simulation of experimental method used in the present study, by three-dimensional finite element analysis, allows the assessment of stress, strain, and displacement of the structures in question, with measurement of stress distribution in the peri-implant region in several areas of choice. Clinically, this is difficult, if not impossible to be assessed, even by means laboratory experiments. Therefore, this method is considered to be a powerful analysis tool [21, 24]. However, being a mathematical model, the results should be interpreted with caution, given inherent limitations that still require clinical validation, despite strong correlations with *in vivo* studies have already been highlighted

[38]. The models used deviated in some respects from clinical situations, such as the fact that the bone was assumed to be linearly elastic. In fact, it is, to some extent, viscoelastic. It was also assumed to be isotropic, and in reality, it is anisotropic. And it was assumed to be homogeneous when it actually contains voids [26].

However, within the proposed analysis of alternatives on multiple prostheses and the possible behavioral differences among them, even the models with simplifications, provide valid results that can point to various tendencies and treatment options. Using this method, the accurate prediction of the stability and possible failure mechanisms may be useful in reducing the number of clinical trials [21]. Thus, absolute values become less relevant in relation to the larger goal, since the behavior trends are also outlined.

CONCLUSION

Within the analysis conditions, the present study concluded that the internal connection Morse Taper interface can be well indicated for both loading conditions, and the mechanical demand is similar for all implants; five implants do not represent a benefit over four; the mechanical strength of the infrastructure is insufficient for both loading conditions, and its stress distribution presents a different pattern.

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Capítulo 2

Evaluation by three-dimensional finite element of external implant-abutment connection in mandibular prostheses : Effect of loadings and number of implants.

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ABSTRACT

Purpose: To investigate stress and strain distribution in implant-supported fixed prostheses and bone peri-implantar bone area, under the effect of axial loadings and number of implants, using the external implant-abutment connection. **Materials and Methods**: Virtual models were prepared by three-dimensional Finite Element Method, consisting of mandible, implants and prosthetic structures, simulating a mandibular implant supported fixed prostheses. Six simulated experimental conditions were prepared by differentiating the number of implants (4 and 5) and axial loadings (bilateral 100 N, bilateral and unilateral 300 N) to investigate the strain in bone, and stress in implants and prosthetic structures. **Results**: The values of von Mises stress and bone strain, under effect of 100 N axial loadings, focused mainly in the cervical region, in some extent to the trabecular bone especially in the distal implants area. Under effect of 300 N axial loading bilaterally the stress and strain distribution followed the same anterior tendency, and there was a proportional increase of the stress, about 3 times. Under effect of 300 N axial loading unilaterally, the stress distribution occurred only on the load side. **Conclusions**: The external connection External hexagon interface can be well indicated under effect of 100 N axial loadings, and does not suggest a favorable treatment alternative under effect of 300 N axial loadings; the distal implants are more requested; five implants do not represent benefit over four in both loading conditions; the mechanical strength of the infrastructure is satisfactory under effect of 100 N axial loadings, and insufficient under effect of 300 N axial loadings, and its stress distribution presents a different pattern.

Keywords: Dental implants, implant-supported prostheses, finite element analysis, biomechanics, bone strain

INTRODUCTION

The rehabilitation by dental implants has been widely used for, at least three decades, initially aimed at totally edentulous patients, extending its indication to partial and unitary prosthesis [1-3]. Since the introduction of the osseointegration technique [1], the prosthetic solution for edentulous patients who cannot adapt to a mandibular complete denture is an implant-supported prostheses that has been an acceptable treatment alternative. However, to have effective osseointegration of the implant, it is essential to proper distribution of occlusal loading and passive adaptation of the complex bone-implant-prosthesis [2, 4, 5].

Despite the high success rates reported, the occurrence of faults yet seems inevitable, both in immediate and mediate load implants. The failure factors are mainly related to the biomechanical aspects, which are not yet fully understood, the consequences also remain inconclusive in the current literature [6]. Within the literature, there is a consensus that the magnitude of occlusal forces leads to increase stress pattern, sometimes leading to marginal bone loss, known as saucerization [7] with direct influence on the components of complex bone implant-prosthesis [4-6, 8, 9]. In all incidences of clinical loading, occlusal forces are first introduced to the prosthesis and then reach the bone-implant interface via the implant. So far, many researchers have focused on each of these steps of force transfer to gain insight into the biomechanical effect of several factors, such as number and distribution of supporting implants, implant-*abutment* connection, force and magnitude directions, prosthesis type, bone density and mechanical properties of the bone-implant interface [5, 6].

There is still no consensus on the best option in implant-supported prostheses. Reducing the number of implants may be feasible if it is an increase of inter-implant space [10]. On the other hand, higher forces were observed when three implants were used, with highest bending moments [9]. Overall, these clinical data suggest that the more the supporting implants, the safer the treatment may be [6].

The splinting of prosthetic crowns on multiple implants has been recommended by several experimental and *in vivo* studies, suggesting a better distribution of loads, provided that there is liability settlement, thus avoiding micro movements responsible for negative stress between bone-implants [5, 11-15]. Despite the controversy, many authors believe that the greater the number of elements splinted, the lower the stress level generated, optimizing the outcome [6, 9, 16].

The stress distribution mechanism in the bone-implant-prosthesis complex depends directly on the physical properties and geometric configuration of the implants [17]. The external connection interface external hexagon has been widely used initially in protocols and later on in partial and unitary prosthesis [3]. However, biomechanical problems, especially in single restorations, have been reported, causing fracture and loosening of screws [3, 18]. It is assumed that this type of connection acts as protective mechanism, preventing early failure of the implant and warning of the likely occurrence of occlusal overload [19]. Conversely, other studies have shown no differences between implant-abutment connections on this aspect [20-22].

Some of the main methods used in biomechanical studies in dentistry to assess the level of stress can be by means of strain-gauge [23, 24] photoelastic [23, 24] and finite element analysis. The photoelastic analysis provides qualitative information of the appropriate stress concentration in all aspects considered, but yields limited quantitative information [6, 24]. For *in vivo* or *in vitro* strain-gauge experimentation, however, this may not be provided due to several factors included in force transmission during load application by opposing teeth or by an apparatus. Placement of the gauges may have slight inaccuracies or the angulation of implants may not be as precise as in a theoretical model. Overall, the very nature of the physical experimental technique makes it inherently subject to random error [6].

By the method of finite elements, a qualitative and quantitative evaluation of more complex structures can be obtained with greater accuracy and then, it can predict possible failures [6, 17] within the limitations inherent in a mathematical model [25]. A correct qualification and quantification of forces on implants are very important to understand the biomechanics of implants. Biomechanical studies should, therefore, be designed not only for descriptive purposes, but also to offer reliable and accurate data that has clinical relevance. The literature still lacks information about the influence of many factors on multiple prostheses [6].

Hence, the purpose of this study was to evaluate the influence of axial loadings and number of implants on stress distribution, strain in mandibular implant-supported prostheses and peri-implantar bone by the finite element method in 3D, using the external implant-abutment connection, interface external hexagon.

MATERIAL AND METHODS

1. Geometry Model

Three-dimensional virtual models represent a mandible while fixed an implant-supported prosthesis according to the Branemark protocol with four or five implants. The structures (mandible, implants, abutments, prosthetic infrastructure and resin prosthesis) were modeled using a specific software Rhinoceros 4.0 SR8 (McNeel North America, Seattle, WA, USA).

From a mandible virtual image, an adult provided for CT scan from database of Three Dimensional Technologies Division, was used for the BioCAD protocol (Renato Archer Information Technology Center, Campinas, SP, Brazil).This protocol consisted of the demarcation of the major landmarks to obtain a more simplified edentulous mandible model, essential for the generation and refinement of the mesh later. The mandible was performed with uniform thickness of 2 mm compact bone type II [26], and trabecular bone inside it.

Three-dimensional images of the implants (cylindrical implants of 3.75 x 13 mm with External hexagon connection), abutments and screws that served as the basis for modeling were provided by the manufacturer (Neodent, Curitiba, PR, Brazil). For the configuration with four implants, the location of each one corresponding to regions of the first premolar and lower canine in each side; with five implants, adding one implant in the midline. The distance between the platforms is about 4 mm, and the distal ones positioned at the distal 3 mm of mental foramen. The prosthetic infrastructure was made with titanium bar with circular cross-section 4 mm, 50 mm length interforaminal region, 15mm on each side in the cantilever region [27, 28], with the 80 mm total length, space for washing about 3 mm over the edge, and with the function of rigid connection between implants and prosthesis. The resin prosthesis was modeled from average measures from the laboratory.

The constructed models were exported in STEP format software for numerical analysis by finite elements.

2. Finite Element Analysis:

The step of numerical analysis by finite element method was performed using the program ANSYS Workbench 12.0.1 and included in three steps : pre-processing, processing and pos-processing

Pre-processing: This includes the definitions of material properties, mesh generation, boundary conditions**,** and loading conditions.

Material properties: The materials considered were isotropic, elastic, linear and homogeneous, characterized by the modulus of elasticity (E) and Poisson's ratio, shown in Table 1.

Mesh Generation: The mesh was generated with tetrahedral elements with 10 nodes, and manual control of refinement with the aid of lines and surfaces made during the modeling stage, so that for the regions of greatest interest (peri-implant bone and components of implant-supported prostheses), the elements were made with smaller size, resulting in a higher density of nodes in the region (Fig.2c, 2d- Apêndice, pg 102). The number of elements and nodes in each structure is shown in Table 2.

Boundary conditions: A multibody approach was performed defining the interaction between each structure by simple contact (juxtaposed) or glued. The glued contacts were attributed to: bone-implant interface,that was assumed to be completely osseointegrated, implant/intermediate/prosthetic screws interface; prosthetic infrastructure/resin prosthesis, and cortical/trabecular bone interface. The remaining interactions were due to single contacts or juxtaposed. The cut surfaces of the posterior mandible were fixed in all directions of space. **Loading Conditions:** Static loading was applied on the occlusal surfaces related to posterior teeth positions (premolars and molars). The positions were located in the occlusal rims and were assumed to be opposing a conventional complete denture with 100 N bilateral axial loading each side and, in the same way, applied 300 N bilateral axial loading each side, and 300 N unilateral axial loading, assuming to be opposing a implant-supported prostheses [8].

Processing:

Six experimental conditions were subjected to the analysis, according to axial loading (100 N, 300 N bilateral, 300 N unilateral) and number of implants (4 or 5): M1 (4 implants, 100 N); M2 (4 implants, 300 N bilaterally); M3 (4 implants, 300 N unilaterally); M4 (5 implants, 100 N); M5 (5 implants,300 N bilaterally); M6 (5implants, 300 N unilaterally).

Post-processing and analysis of results:

The results of displacement, Von Mises stress and strain degree obtained during processing were analyzed by graphical visualization for qualitative and quantitative comparisons among the six conditions. The areas of focus for this analysis were the peri-implant bone, implants, their abutments, infrastructure, and prosthetic screws for the verification of the effects caused by variables presented and comparisons among groups.

Table 1-Physical properties of bone and materials.

	Modulus of Elasticity (E)(GPa)	Poisson's ratio	References
Cortical bone	13.7	0.30	[29, 30]
Trabecular bone	1.37	0.30	[29, 30]
Implant/infrastruct, abutment. (Ti cp)	110	0.33	[31]
Acrylic resin	3.8	0.30	[32]

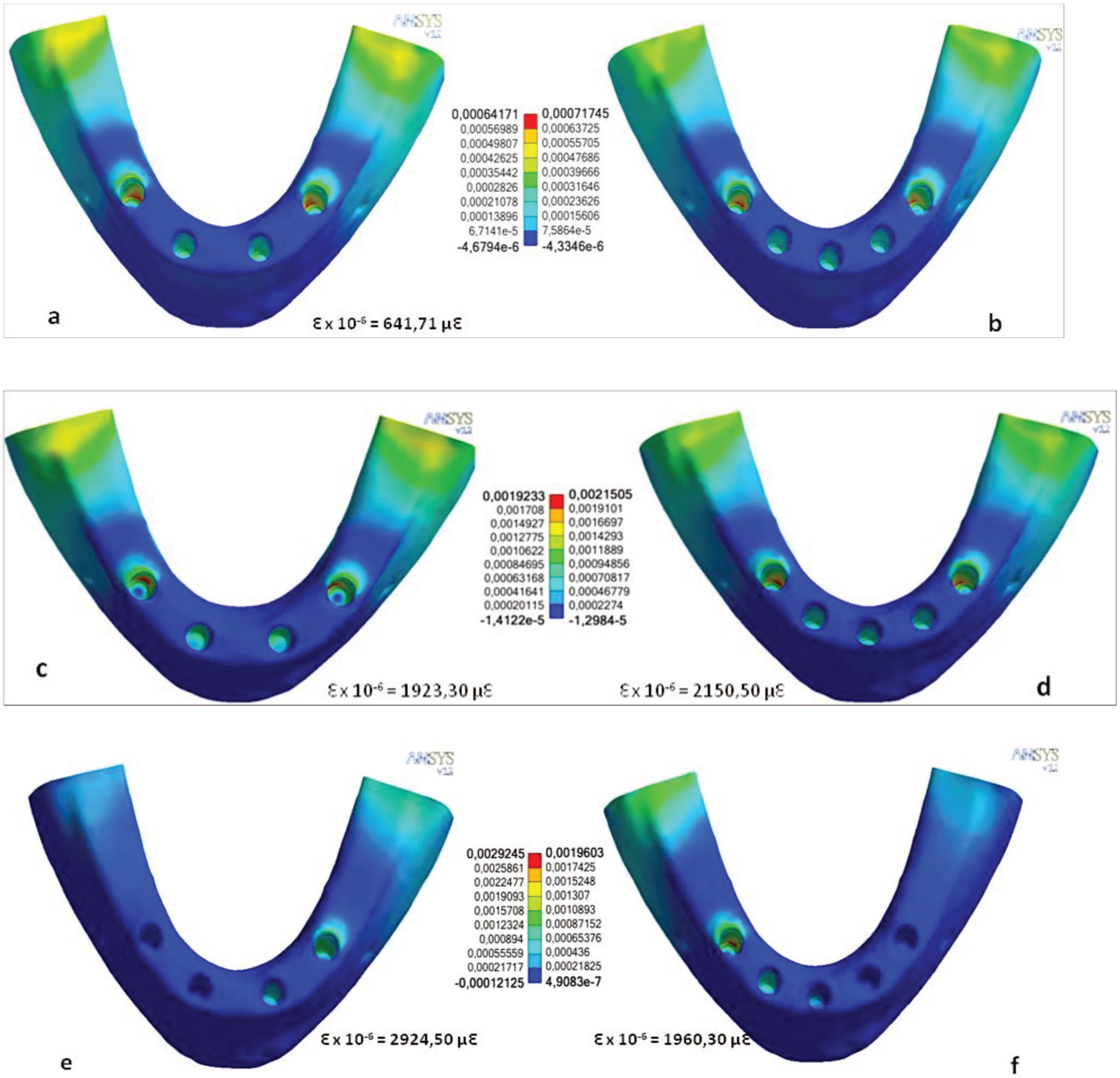
Table 2-Number of Elements and Nodes

Structures	Elements	**N**odes
Cortical bone (mandible)	14229	25221
Trabecular bone (mandible)	11210	18877
Implants	2145	3643
Abutments	1554	2715
Screws	521	971
Infrastructure	7572	13276

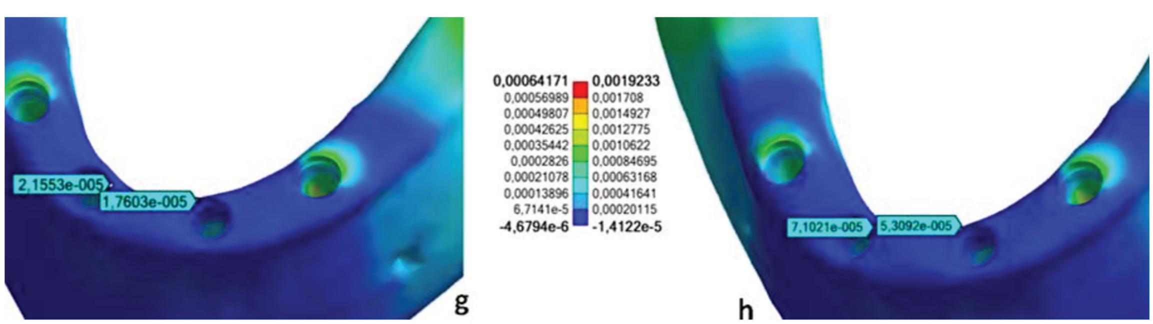
RESULTS

According to the results of this study, under the effect of 100 N axial loading bilaterally the peri-implant bone strain in both groups of external hexagon connection, focused on the distal implants, cervical cortical bone, extending also into the trabecular bone. The intermediate implants area getting practically unloaded. Model with five implants (M4) showed no significant difference as compared with four (M1) (Fig. 1a, 1b).

Under the effect of 300 N axial loading bilaterally, the peri-implant bone strain tripled compared to 100 N. In both models of external hexagon connection, focused on the distal implants, especially in the trabecular bone; the intermediate ones are practically unloaded (Fig. 1c, 1d). Under the effect of axial loadings of 300 N, unilaterally, in both groups of external hexagon connection, focused only on the loaded implants, while on the opposite side showed unloaded, both with four and with five implants (Fig. 1e, 1f). Models with five implants (M4) showed no significant difference as compared to four, for both loading conditions (Fig.1d, 1f).



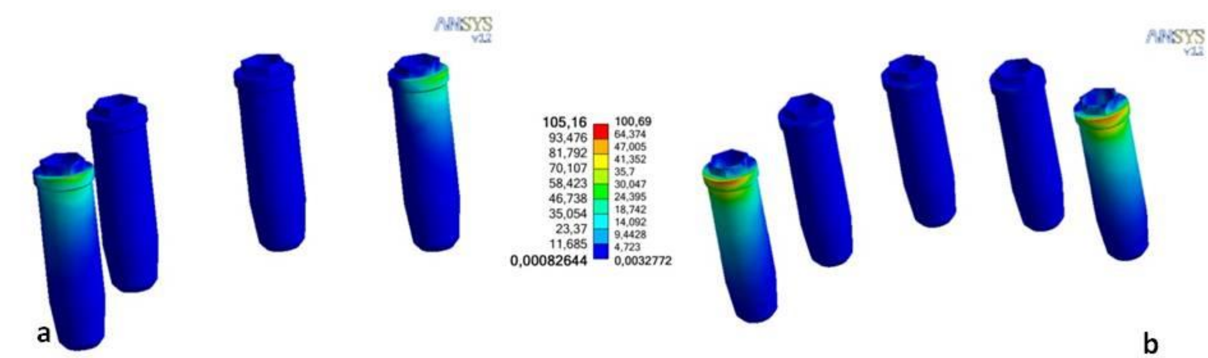
Figs. 1a to 1f -Bone strain (µƐ) under 100 N axial loadings with 4 **(a)** and 5 **(b)** implants ; under 300 N axial loading bilaterally with 4 **(c)** and 5 **(d)** implants and unilaterally with 4 **(e)** and 5 **(f)** implants

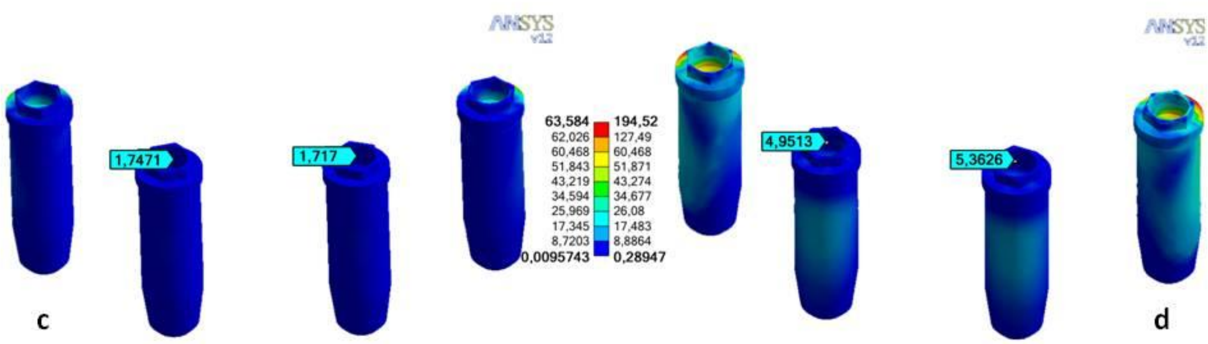


Figs. 1g, 1h- An average increase of bone strain from 100 N (g) to 300 N (h)axial loadings.

The values of the von Mises stress for implants, under the effect of 100 N axial loadings, presented for the model with four implants (M1), a higher stress concentration in the distal implants and the intermediate ones getting practically unloaded (Fig. 2a); for the model with five implants (M4), the same tendency of the previous group, but with significant increase of stress in the distal implants, about 40 percent and intermediate ones getting practically unloaded. The addition of one implant showed no significant difference (Fig. 2b).

Under the effect of 300 N axial loadings, the values of von Mises stress tripled in the same way of bone (Fig. 2c, 2d).

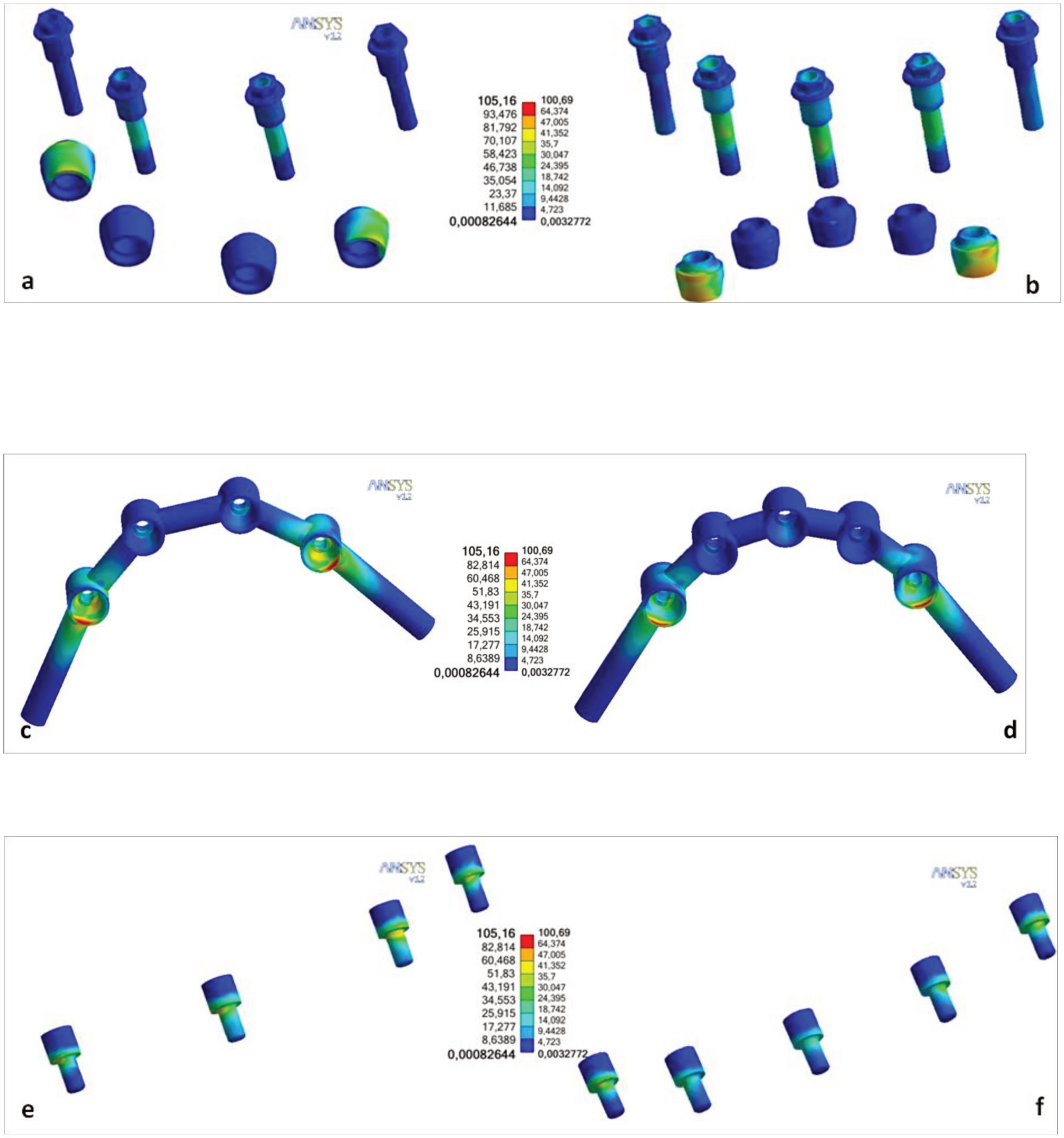




Figs. 2a, 2b- von Mises stress (MPa) under 100 N axial loadings for 4 **(a)** and 5 **(b)** implants.

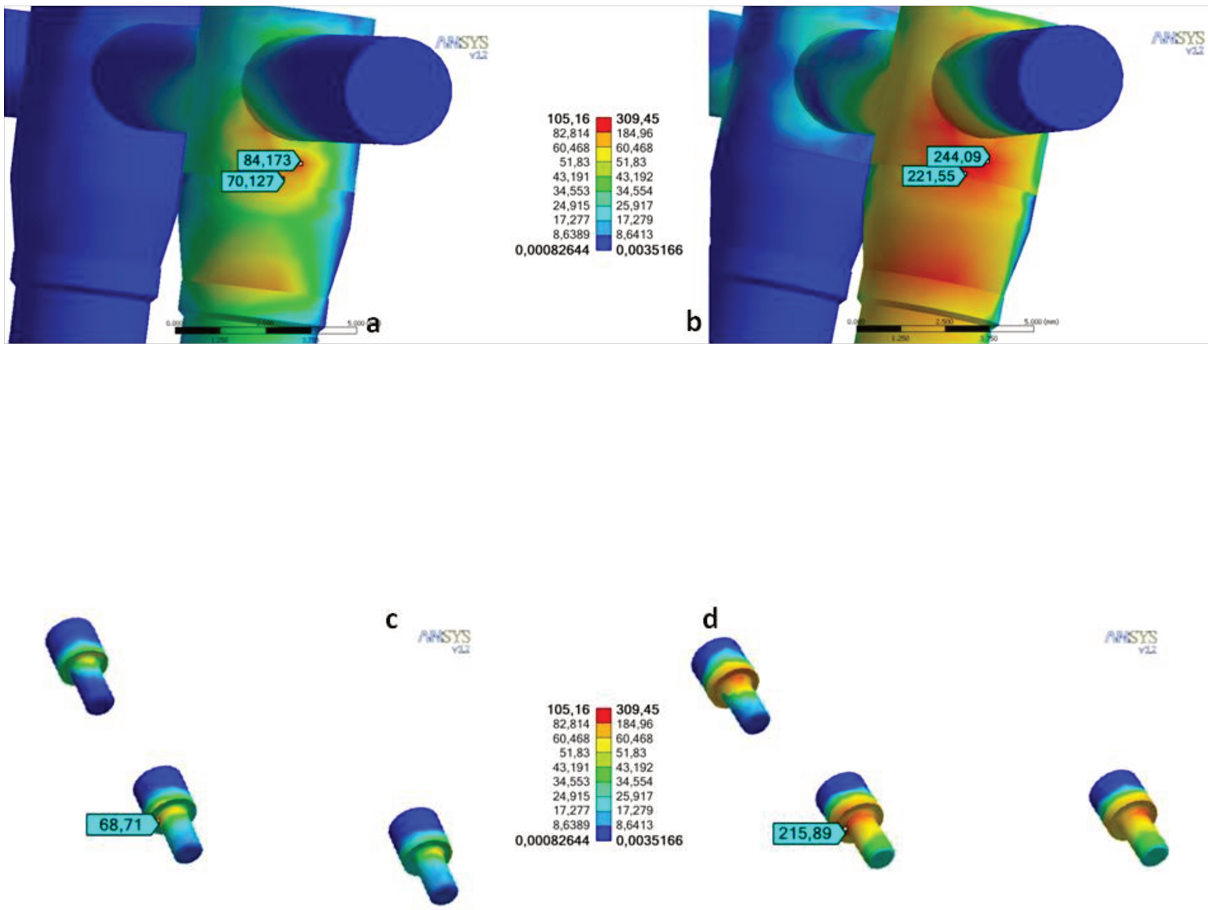
Figs.2c, 2d- An average increase of von Mises stress (MPa) from 100 N (c) to 300 N (d)axial loadings.

In relation to prosthetic structures (abutments, infrastructures and screws), under the effect of 100 N axial loadings, the von Mises stress for abutments showed for the model with four implants (M1), same tendency of the implants: the two distal ones showed higher stress concentration area toward the distal cantilevers, and the two intermediate ones remained practically without stress around their perimeter. On the other hand, their screws showed opposite tendency: higher levels of stress in the two intermediate and the two distal ones remained practically unloaded (Fig. 3a). In the model with five implants (M4), the abutments showed behavior similar to the previous model (M1), but with higher stress concentration, as well as their mounting screws, which though similar tendency, also present stress in the distal mounting screws (Fig. 3b). For the prosthetic infrastructure, the von Mises stress showed for the model with 4 implants (M1) a higher concentration in the distal ones extending to the cantilever region (Fig. 3c); for the model with 5 implants (M4), the same tendency was observed but with an increase of stress in the central implant (Fig. 3d). For the prosthetic screws, the von Mises stress showed for the model with four implants (M1) stress at all, but higher in the median ones compared to distal ones (Fig. 3e); for the model with five implants (M4) stress is also at all, higher levels in the distal ones, followed by intermediate ones and lower level in the central one (Fig. 3f).



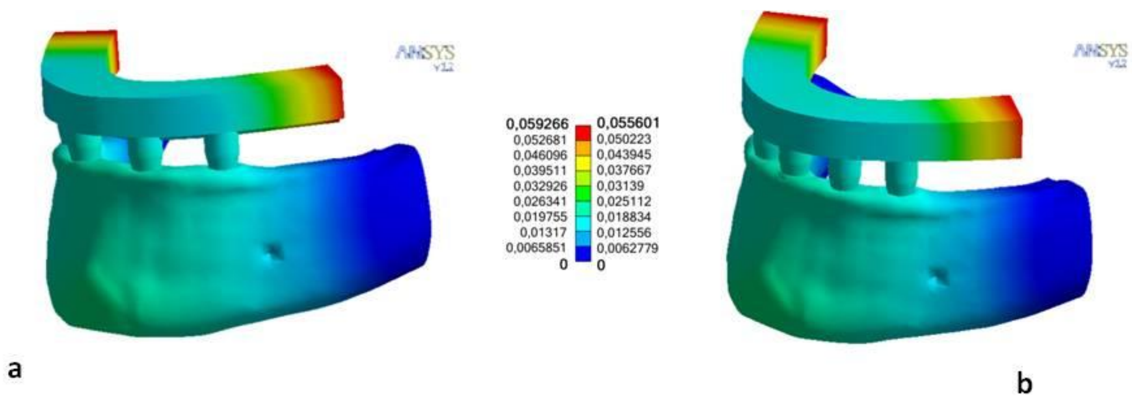
Figs. 3a to 3f- von Mises stress (MPa) under 100 N axial loadings with for 4 and 5 implants for the abutments (a, b), infrastructure (c, d), prosthetic screws (e, f).

In the same way of bone and implants, under the effect of 300N axial loading, the von Mises stress for abutments, infrastructure and screws also increased proportionaly (3 times) (Fig. 4).



Figs. 4a to 4d- An average increase of von Mises stress (MPa) from 100 N to 300 N axial loadings for the abutments and infrastructure (a, b), and for the prosthetic screws (c, d).

The displacement of the mandible showed minimal. The displacement of the prosthetic infrastructure showed approximately 50 percent higher than displacement mandibular, with variance of only 5 percent between the group with four and the group with five implants with 100 N (Figs. 5a, 5b) and 300 N axial loadings.



Figs.5a, 5b- Displacement(mm): Mandible and infrastructure with 4 (a) and 5(b) implants,100 N axial loadings

The tables below present values referring to a previous graphics analysis of strain stress, and displacement for bone, implants and prosthetic structures, with four and five implants, and the effect of axial loadings of 100 N and 300 N (Table 3, 4).

Table 3 - Maximum Principal Elastic Strain for bone (με)

Bone strain (με)		
Axial loadings	Number of Implants	
	4	**5**
100 N bilateral	215	198
300 N bilateral	710	642

* $\mu\varepsilon = \varepsilon \times 10^{-6}$

Table 4 - von Mises Stress (MPa) for implants, infrastructure, and screws

von Mises stress (MPa)							
Number of implants		Implants		Infrastructure		Screws	
		4	**5**	**4**	**5**	**4**	**5**
Axial loading	100N	1.74	1.70	84.17	66.17	68.71	63.39
	300N	4.95	5.18	2.44.09	202.04	215.89	201.17

Table 5- Displacement for mandible and prosthetic infrastructure (mm)

Displacement (mm)					
		Mandible		Prosthetic infrastructure	
Number of implants		**4**	**5**	**4**	**5**
Axial loading	100N	0.026	0.025	0.059	0.056
	300N	0.059	0.056	0.17	0.16

DISCUSSION

There are several factors that affect force magnitudes in peri-implant bone. The application of functional forces induces stresses and strains within the implant-prosthesis complex and affects the bone remodeling process around implants. Applying force to a bone (*stress)* deforms its structural arrangement (*strain*) and changes in bone mass are dependent on strains and not stresses *per se* [12]. Yet, the physiologic tolerance thresholds of human jawbones are not completely known and some implant failures may be related to unfavorable stress magnitudes [6].

According to Frost hypothesis [33, 34] about of bone physiology, bones cells respond to a local deformation produced by mechanical stress. The continuous process maintains the mechanical competence of the bone, which also applies to bone surrounding oral implants [4, 33, 34]. The bone adapts to a certain strain in a steady state. It is believed that a bone is in function within the strain range of approximately 100-1500 µƐ. If the peak load on a bone results in strains of 1500-3000 µƐ a mild overload occurs, which can result in mechanical fatigue damage, but it is repaired by remodeling, forming more bone by reshaping and strengthening. Therefore, loading influences on the bone in this interval may even result in an osseous adaptation. Repeated stress on the bone resulting in deformations greater than 3000 µƐ could increase the micro-damage, overwhelm the repair mechanism and result in a fatigue failure. In this level the values are already considered pathological, which can result in bone resorption. Values from 25,000 µƐ would reach the limit, which can lead to sudden fracture. Conversely, if the strain in the bone, does not exceed 50-100 µƐ, the level where optimal strains are not achieved, disuse of the bone occurs, and remodeling results in a net loss of bone, leading it to adapt to the new demand [33], [6], [4].

These values serve as reference for assessment of negative and positive effects of mechanical loads to bone. It can be considered as negative, both below 100 µƐ and above 3000 µƐ, by disuse or overload, respectively. As positive, between 100-1500 micro strain (µƐ), steady state and function of bone and between 1500-3000 µƐ, considering the occurrence of bone regeneration as a biological response [4]. Because of increased stress-strain induce marginal bone loss, termed as saucerization, this analysis is essential [7].

The axial loads used in this study were 100 N bilaterally and 300 N bilaterally and unilaterally. The 100 N axial loading simulates a complete denture as antagonist, that comprises the most of the patients. The 300 N axial loading simulates an implant or tooth-supported prostheses as antagonist. The third option, 300 N unilaterally, is a common bite habit. There are many variations in maximal occlusal forces mentioned in literature, obviously due to different measuring methods and different location of measurements on the prostheses [8].

According to the results of this study, under the effect of 100 N axial loading bilaterally, the values obtained between 100-1500 µƐ of peri-implant bone strain, in both models of external hexagon connection would be inserted in the normal pattern [4, 33, 34] corresponding to bone function. The models with five implants showed no benefit as compared to models with four.

These findings are corroborated for other FEA studies of osseointegrated implants in relation to stress distribution area, demonstrating that when maximum stress concentration is located in the cortical bone, it is in the contact area with the implant [14, 35, 36]; when it is in the trabecular bone, it occurs around the apex of the implant. In the cortical bone, stress dissipation is restricted to the immediate area surrounding the implant; in the trabecular bone, a fairly broader distant stress distribution occurs [37].

In relation to the implants, the occurrence of higher stress concentration in the distal ones for both groups, may suggest that the role of the intermediate ones is only for stabilizing, because they were practically unloaded. The abutments (minipilar) showed behavior similar to the implants, while its screws showed the opposite tendency: higher stress concentration in the intermediate elements and the distal ones practically unloaded. The addition of one implant showed no significant benefit.

The mechanisms of stress distribution can change with the type of prosthetic connection. On the external connection, the torque applied during tightening of the screw causes a degree of internal stress, responsible for fixation between the implant and abutment, and then the maintenance of preload is essential. The most probable cause of failure in clinical situations is the effect of the settlement that emerges from the micro movements at the implant-abutment connection, which may lead to the loss or fracture of the screw [6, 19, 38]. For single implant-supported prostheses cemented, surely the first goal is to obtain adequate retention, stability and strength to make the anti-rotational effect, because they are exposed to situations of greater risk due to load application [3]. In these situations, the system of internal connection has confirmed a superior performance [17, 25, 38, 39]. But in the multiple implants, the condition modifies: these requirements are already provided. Considering the basic principle of external connection systems, loss or premature fracture of the screw can serve as a possible protective mechanism, preventing occlusal overload on the bone-implant interface [19].

The prosthetic infrastructure suggests an influence on stress distribution. Some studies confirm its role as a unifying element, load distribution and stress reduction, compared to the separate structures [12-15]. Considering the material infrastructure of cp titanium, the mechanical strength is indicated under effect of 100 N axial loading with external hexagon as for four and five implants (M1 and M4) and no recommended under effect of 300 N axial loading, closing to the yield strength of 380-480 MPa alloy [40], especially at the intersection with the cantilever. Then, it could be considered the option for alloys with higher mechanical strength as Ti-6Al-4V, or Co-Cr [40].

As for the prosthetic screws, the highest stress concentration presented in the intermediate ones in groups of four implants with 100 N and 300 N, suggesting major effort of the intermediate pillars in opposing at extrusion, consequently favoring the loosening of the four screws in this situation. Already with five implants, the tendency of loosening of screws would be primarily in the distal ones and lower than with four implants, suggesting an influence of the number of implants. However, it is not possible to assert this tendency, since the preload values were not evaluated.

Clinical [41, 42] and laboratory studies [17] suggest a larger tendency of loosening screws for external connections related to single prostheses, whose tendency is completely different from multiple prostheses, since there are no other interfering factors [41]. On the other hand, previous studies for single restorations [20, 21] showed no expressive effect of the connection in this regard.

Another significant aspect is the similarity in behavior of both screws: screws of the prostheses and of the abutments in relation to stress distribution, suggesting a similar tendency to oppose the extrusion. It can be observed in both loading conditions.

With increasing axial loading from 100 N to 300 N, there was proportional increase of the stress with external hexagon connection, for all elements analyzed, such as: bone, implants, abutments, infrastructure and screws. This occurrence evidences the external connection behavior, which, with greater flexibility, allows greater release and transfers the stress field for the bone and the other components of the prosthesis, thus confirming the linear behavior of the model. The strain values in bone, focused mainly in apical trabecular bone, can be inserted between 1500-3000 µƐ. Although this values represents an average overload pattern, leading of bone regeneration, imminent risk of overload for the distal implants is much higher than that observed for the 100 N loadings beyond the presence of the cantilever and the others implants getting practically unloaded.

The bone physiology hypothesis is supported by studies in animals and humans through bone apposition most frequently between the strain levels from 3000 to 6700 µƐ, and above from this value, the process is replaced by resorption [4].

By the finite element method in 3D precise loading over predetermined points on the occlusal surface of a prosthesis can be accomplished, allowing the simulation of stress, strain and displacement of the structures in question, getting the evaluation of multiple conditions simultaneously [6]. However, since this is a mathematical model, the results should be interpreted with caution, given the inherent limitations that still require clinical validation, despite strong correlations with *in vivo* studies have already highlighted [43]. The models used deviated in some aspects from clinical situations, such as in the fact that the bone was assumed to be linearly elastic; and, in fact, it is to some extent viscoelastic. It was assumed to be isotropic; in reality, it is anisotropic. It was assumed to be homogeneous; in reality, it always contains voids [25]. However, the proposed analysis of alternatives on multiple prosthesis and the possible behavior differences between them, the models even with simplifications, provide valid results that can point various tendencies and treatment options. The accurate prediction of the stability and possible failure mechanisms in using this method may be useful to reduce the amount of clinical trials [17]. Thus, the absolute values become less relevant in relation to the larger goal, since the behavior tendencies are also outlined.

CONCLUSION

Within the analysis conditions, the present study concluded that: The external connection external hexagon interface can be well indicated under the effect of 100 N axial loadings, and does not suggest a favorable treatment alternative under the effect of 300 N axial loadings; the distal implants are more requested in both loading conditions, mainly under the effect of 300 N axial loadings, suggesting a risk of overload; five implants do not represent benefit over four in both loading conditions; the mechanical strength of the infrastructure is satisfactory under the effect of 100 N axial loadings, and insufficient under the effect of 300 N axial loadings, and its stress distribution presents a different pattern.

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Capítulo 3

Comparison between the effects of internal and external connections on the bone strain of mandibular fixed prostheses: A three-dimensional finite element analysis.

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ABSTRACT

Purpose: The purpose of this study was to use the three-dimensional finite element method to analyze influence of axial loadings and implant-abutment connectionns on stress and strain distribution in the peri-implantar bone of implant-supported fixed prostheses with four implants. **Material and Methods**: The prepared virtual models consisted of: jawbones, implants and prosthetic structures, which simulated a implant-supported fixed prosthesis with four implants. Four experimental conditions were prepared by differentiating the implant-abutment connections, such as Morse Taper (MT), and External Hexagon (EH); and bilateral axial loadings (100 N and 300 N). **Results:** Under the effect of 100 N axial loadings, the values of strain in the peri-implant bone for the MT group were distributed homogeneously for all implants, especially in the cervical region; for the EH group, the strain focused on the distal implants and extended also into the trabecular bone with the intermediate implants practically unloaded. The von Mises stress values for the implants showed a similar stress distribution to the one observed in bone for both connection systems. Under effect of 300 N axial loadings, the distribution of stress followed the same tendency as it had under effect of 100 N, although an increase of stress for the EH group was greater (3 times) than for the MT group (1,5-2 times). **Conclusion:** The two systems of implant-abutment connections can be satisfactorily used under the effect of 100 N axial loading. However, the biomechanical demand that arises from the use of external connections occurred on the distal implants, and by use of internal connection distributed evenly across all implants. With an increase in the mechanical demand (300 N axial loading), the indication of the internal implant-abutment connection represents a better treatment alternative, as it showed even stress distribution and similar bone stimulation. The mechanical strength of the infrastructure of the cp titanium alloy was satisfactory with an external connection under the effect of 100 N, and was insufficient with an internal connection for both loading conditions.

Key words: Dental implants, implant-abutment connection, finite element analysis, biomechanics, bone strain.

INTRODUCTION

One of the most important advances in Dentistry has been the successful replacement of lost natural teeth with osseointegrated implants. Its use in completely edentulous patients is a well-established treatment modality that has evolved into a routine, predictable procedure with documented long-term success [1-6]. The osseointegrated implants have a similar role to that of natural teeth, because they are continuously exposed to dynamic and static loadings. However, the implants occlusal loads are transmitted directly to the surrounding bone, which is different from natural teeth with healthy periodontium [7]. The success of the treatment is highly dependent on an effective osseointegration of the implant, which is, closely associated with the adequate distribution of occlusal loading and the passive adaptation of the bone-implant-prosthesis complex [2,6,8].

Multiple factors have been found to influence the predictability and longevity of loading protocols for completely edentulous arches. They include several oral conditions, such as periodontal status, occlusion, function-parafunction, loading procedures [9], the number and configuration of implants [6,10-12], type of prosthetic material, and prosthetic connection [6,12]. Although success rates have been high for immediate as well as for mediate loaded implants, the occurrence of undesirable loss and failures still seems unavoidable, and has been largely related to biomechanical complications. However, the mechanisms responsible for the loss are still not completely understood, and several biomechanical factors remain unknown [12]. There is a consensus that the magnitude of occlusal forces leads to an increased stress pattern that can lead to marginal bone loss [13]. Nonetheless, there currently exist no long-term prospective and randomized clinical trials that have evaluated the influence of controlled forces on the bone peri-implantar.

Moreover, the type of implant-abutment connection and the shape and geometry of the implant fixture can greatly influence stress concentrations around the implants and bone. The influence of connection became higher by changing the clinical situation from immediately placed to osseointegrated [14,15]. Currently, there are many different implant-abutment connections available. To date, most of the long-term clinical data on performance reported in the literature refer to external hexagonals, on account of their extensive use. Regarding the biomechanical problems, most of the reported cases have occurred in single restorations, thus leading to fractures and loosening screws [3,16]. On the other hand, some studies have shown no differences between implant-abutment connections regarding this aspect [17-19]. To overcome some of the inherent design limitations of external hexagonal connections, a wide range of alternative connections have been developed with the intent to improve retention and stability, such as internal connections, among which, is the morse taper interface [3,16].

Regarding the differences between implant-abutment connections, each one has its advantages and disadvantages. The external hexagon system is suitable for the two-stage method, for anti-rotation mechanisms and for good retrievability and compatibility among different systems. Possible disadvantages of the external hexagon are micromovements because of the size of the hexagon, a higher center of rotation that leads to lower resistance for rotational and lateral movements and a microgap leading to bone resorption. However, the weak-link to the fixture of the external hexagon configuration is often applied as a fail-safe mechanism for over-loading situations. Taper joint connections, with a conical seal or a morse taper, have advantages of better sealing capabilities in closing the microgap and consequently better stability of the joint [20].

However, the evidence regarding and comparisons between different connections are still scarce [21]. Most of the studies that emphasize this aspect refer only to single prostheses.

In multiple implants conditions, the splinting of prosthetic crowns has shown reliable settlement, avoiding the micro-movements responsible for negative stress between bone-implants [6,22-26]. Therefore, it can present a favorable option if there is a passive adaptation.

Reducing the number of implants has been a decisive trend in implant dentistry in order to support a prosthetic reconstruction for simplified clinical protocols with no harm to the rehabilitation system [22]. Nowadays, an implant-supported fixed prosthesis with four implants is considered a reliable treatment alternative for edentulous patients who have limitations in their bone anatomy, bone quality and quantity, as well as limited financial resources [27]. The reduction of the number of implants implicates selecting strategic positions to achieve a favorable occlusal force distribution, which increases the inter-implant space essential for this compensation [27,28]**.** Clinical studies also demonstrated that four implants, when optimally spread, can be sufficient to ensure long-term success of full-arch prosthesis [29].

Some of the methods used in biomechanical studies in Dentistry to assess the values of stress can be by means of strain-gauge [30,31] photoelastic [30,31], and finite element analysis [12,31].

The FEA is a numerical method of analysis for stress and strain in structures of any given geometry. The structure is discretized into the so called finite elements connected through nodes. The type, arrangement and total number of elements affect the accuracy of the results. This method has become one of the most successful engineering computational methods and most useful analysis tool, and it is showing capability and versatility in its application in Dentistry [32].

Many factors that can lead to mechanical stress are still unknown. Their discovery could explain the stress influence on multiple prostheses and their consequent effect on the peri-implant bone. Given the significant importance of predictable treatment outcomes through more efficient methods, the purpose of this study was to evaluate the influence of internal and external implant-abutment connections and different axial loadings on peri-implantar bone and implants of fixed prosthesis with four implants by employing a stress distribution analysis.

MATERIAL AND METHODS

1. Geometry Model

Three-dimensional digital models representing an edentulous mandible with an implant-supported prostheses according to the Branemark protocol with 4 implants were obtained. The structures (mandible, implants, abutments, prosthetic infrastructure, and acrylic resin prosthesis) were modeled using specific software Rhinoceros 4.0 SR8 (McNeel North America, Seattle, WA, USA).

From a mandible image, a CT scan of an adult, provided by the database of Three Dimensional Technologies Division, was used to perform the BioCAD protocol (Renato Archer Information Technology Center, Campinas, SP, Brazil).This protocol consisted of the demarcation of the major landmarks to obtain a more simplified edentulous mandible model, essential for the generation and later refinement of the mesh. The mandible was modeled with uniform 2 mm thickness of type II compact bone [33] and trabecular bone. Three-dimensional images of the implants (cylindrical implants of 3.75 x 13 mm with morse taper and external hexagon connection), abutments, and screws that served as the basis for modeling were provided by the manufacturer (Neodent, Curitiba, PR, Brazil). For the configuration with 4 implants, the location of each one corresponded to regions of the first premolar and lower canine in each side; the distance between the implant`s platforms was about 4 mm, and the distal ones positioned at 3 mm distal to the mentual foramen. The prosthetic infrastructure was made with a titanium bar with 4 mm circular cross section 50 mm length within the interforaminal region, and 15mm length on each side in the cantilever region [34,35] with 80 mm total length, and about 3 mm space for washing over the edge, and was modeled to obtain a rigid connection between implants and prosthesis. The resin prosthesis was modeled from average measures from the laboratory. The constructed models were exported in STEP format software for numerical analysis by finite elements.

2. Finite Element Analysis:

The step of numerical analysis by finite element method was performed using the program ANSYS Workbench 12.0.1 and included three steps: pre-processing, processing and post-processing.

Pre-processing: This includes the definitions of material properties, mesh generation, boundary conditions, and loading conditions.

Material properties: The materials were considered to be isotropic, elastic, linear, and homogeneous, characterized by the modulus of elasticity (E) and Poisson's ratio, shown in Table 1.

Mesh Generation: The mesh was generated with tetrahedral elements with 10 nodes, and manual control of refinement with the aid of lines and surfaces was made during the modeling stage, so that the regions of greatest interest (peri-implant bone and components of implant-supported prostheses), the elements were made with smaller size, resulting in a higher density of nodes in the region (Fig. 2a,2c- Apêndice, pg 102). The number of elements and nodes in each structure is shown in Table 2.

Boundary conditions: A multibody approach was performed defining the interaction between each structure by simple contact (juxtaposed) or glued. The glued contacts were attributed to bone-implant interface, that was assumed to be completely osseointegrated, implant-intermediate-prosthetic screws interface; prosthetic infrastructure-acrylic resin prosthesis, and cortical-trabecular bone interface. The remaining interactions were due to single contacts or juxtaposed. The cut surfaces of the posterior mandible were fixed in all directions on space. **Loading Conditions:** Static loading was applied on the occlusal surfaces related to posterior teeth positions. The positions were located in the occlusal rims and were assumed to be opposing a conventional complete denture with 100 N bilateral axial loading on each side and, in the same way, applied 300 N bilateral axial loading each side, assuming to be opposing a implant-supported fixed prostheses [4].

Processing: Four experimental conditions were simulated, according to axial loading (100 N, 300 N bilateral,) and implant-abutment connection as: Morse taper (MT) and External hexagon (EH) The models are named as follows **M1** (MT, 100 N), **M2** (MT, 300 N),**M3** (EH100 N), **M4** (EH, 300 N).

Post-processing and analysis of results: The results of von Mises stress and strain degree obtained during processing were analyzed by graphical visualization for qualitative and quantitative comparison among the four conditions. The areas of focus for this analysis were the implants and peri-implant bone for the verification of effects caused by variables presented and comparisons among groups.

Table 1 Physical properties of bone and materials.

	Modulus of Elasticity (E)(GPa)	Poisson's ratio	References
Cortical bone	13.7	0.30	[36,37]
Trabecular bone	1.37	0.30	[36,37]
Implant-.Abutment Infrastructure (Ti cp)	110	0.33	[38]
Acrylic resin	3.8	0.30	[39]

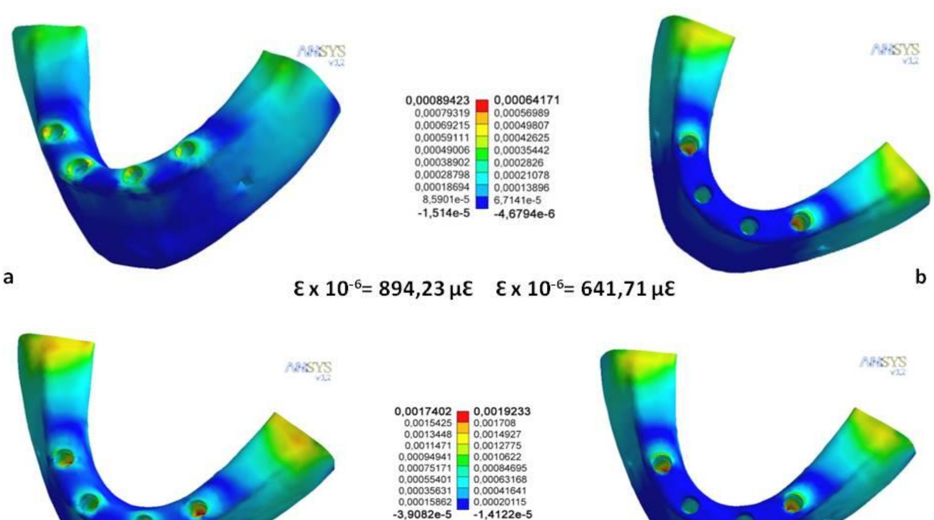
Table 2 Number of Elements and Nodes

Structures	Elements	**N**odes
Cortical bone (mandible)	14229	25221
Trabecular bone (mandible)	11210	18877
Implants	2145	3643
Abutments	1554	2715
Screws	521	971
Infrastructure	7572	13276

RESULTS

According to the results of this study, the peri-implant bone strain in MT group under the effect of 100 N axial bilateral loading were distributed evenly for all implants with higher concentration in the cervical cortical bone (Fig 1a). On the other hand, for group of External hexagon connection (EH), the strain focused only on the distal implants, cervical cortical bone, extending also into the trabecular bone. The intermediate implants area getting practically unloaded (Fig 1b).

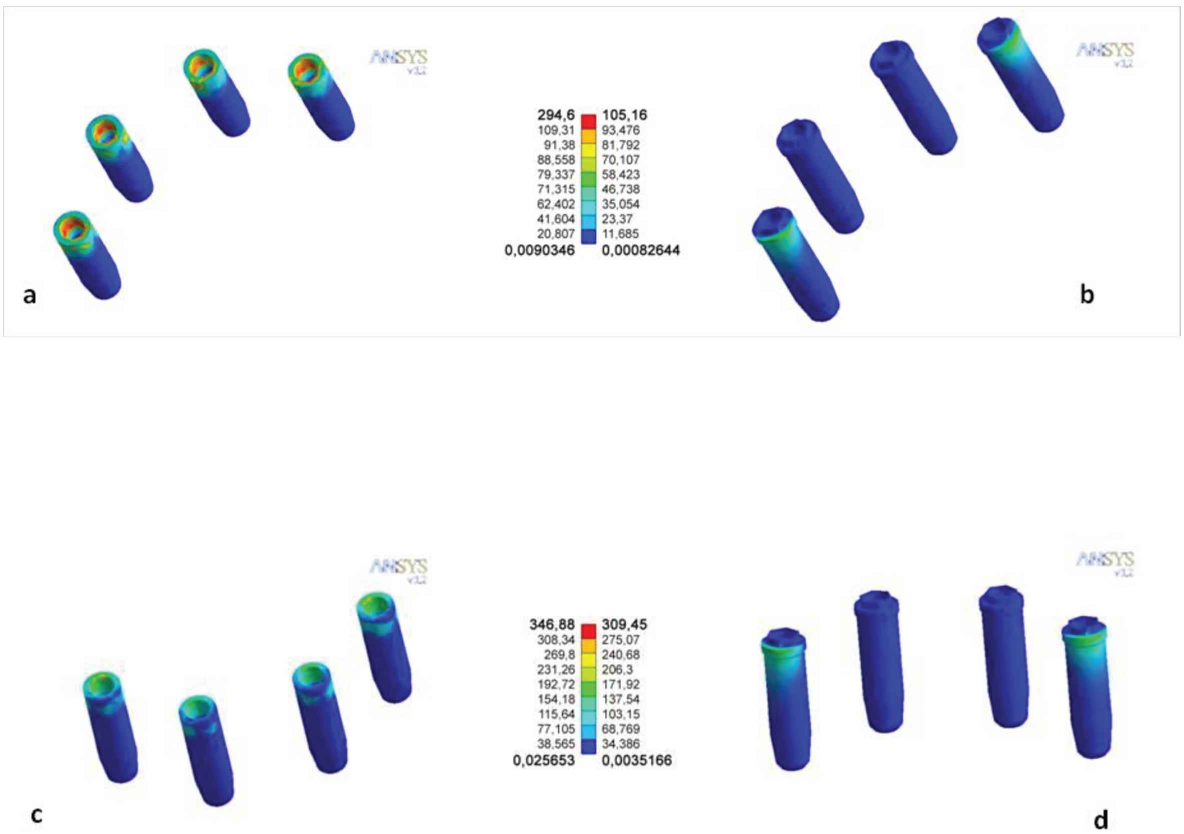
Under the effect of 300 N axial loadings for MT group, presented the same distribution tendency when loaded with 100 N, with strain distributed by all implants, although with higher levels in the distal ones the values almost doubled (1,5-2 times) in relation to 100 N axial loadings, and extending to the trabecular bone (Fig 1c). Under the effect of 300 N axial loadings for group of external hexagon connection, strain focused on the distal implants, especially in the trabecular bone; the intermediate ones getting practically unloaded. The values of bone strain tripled compared to 100 N axial loadings (Fig. 1d).



Figs. 1a to 1d -Bone strain (μƐ) under 100 N axial loadings with MT (a) and EH (b); under 300 N axial loadings with MT (c) and EH (d)

In relation to implants, under the effect of 100 N axial loadings the von Mises stress showed for group with morse taper connection a higher stress concentration evenly distributed for all implants (Fig. 2a). For the group with external hexagon connection, the values of the von Mises stress for implants presented a higher stress concentration in the distal implants with the intermediate ones practically unloaded (Fig. 2b).

Under the effect of 300 N axial loadings, for group with morse taper connection the values of von Mises stress increased an average 1,5- 2 times in relation to 100 N axial loadings (Fig. 2c); for group with external hexagon connection the values of von Mises stress tripled in the same way of bone (Fig. 2d).



Figs 2a-2d von Mises stress (MPa) under 100 N axial loadings with MT (a) and EH connections (b); under 300 N axial loadings with MT (c) and EH (d).

The tables below present values referring to a previous graphics analysis of strain for bone, von Mises stress for implants with morse taper and external hexagon connections, under effect of axial loadings of 100 N and 300 N (Tables 3, 4,).

Table 3- Maximum Principal Elastic Strain for bone [με].

	Bone strain [με]	
Axial loadings	Implant-abutment connection	
	Morse taper	**External hexagon**
100 N bilateral	889	215
300 N bilateral	954	710

* $\mu\varepsilon = \varepsilon \times 10^{-6}$

Table 4- von Mises Stress [MPa] for implants.

	von Mises Stress [MPa]	
Axial loadings	Implant-abutment connection	
	Morse taper	**External hexagon**
100 N	122	1.74
300 N	131	4.95

DISCUSSION

Loads on bones cause bone strains that generate signals detected by cells, which then generate responses. The genetically determined threshold for initiating cell responses to these signals helps to control modeling and remodeling of bone tissue, according to the Frost hypothesis [8,40,41]. The bone adapts to a certain strain in a steady state. It is believed that a bone is in function within the strain range of approximately 100-1500 µƐ. If the peak load on a bone results in strains of 1500-3000 µƐ, a mild overload occurs, which can result in mechanical damage repaired by cells with remodeling, forming more bone by reshaping and strengthening the tissue. Repeated stress on the bone resulting in deformations greater than 3000 µƐ could increase micro-damage, overcome the repair mechanism, and result in fatigue related failure. At this level, the strain values are already considered pathological, which can result in bone resorption. Values within 25,000 µƐ would reach the bone´s biological limit, which could lead to sudden fracture. Conversely, if the strain in the bone, does not exceed 50-100 µƐ, whereby the level of optimal strains is not achieved, disuse of the bone occurs and remodeling results in a net loss of bone, as the cells adapt the bone to the smaller demand [8, 12, 40]. For this reason, this study used the strain parameter to analyze bone behavior.

It is difficult to quantify clinically the magnitude and direction of occurring occlusal forces, hence clinical achieves concerning these aspects are not available. The occlusal forces may exceed the mechanical or biological load-bearing capacity of the osseointegrated oral implants or the prosthesis, causing either a mechanical failure or a failure in the osseointegration. If this happens, the load can be classified as an overload [8].

The mechanical stress on bone result in strain, often expressed in micro-strain (µƐ), a scale in which 10^6 µƐ would equal a theoretical deformation of 100% , thus 1000 µƐ equals to a deformation of 0,1 % [42].

The axial loads used in this study were 100 N bilaterally and 300 N bilaterally. The 100 N axial loading simulates a complete denture as an antagonist arch that comprises the most patients. The 300 N axial loading simulates an implant or tooth-supported prostheses as the antagonist. There are many variations in maximal occlusal forces mentioned in the literature, obviously due to different measuring methods and different location of measurements on the prostheses [4].

In a previous study, one was able to prove that the performance difference between four and five implants was irrelevant. These findings are in accordance with those of Ogawa *et al* [27], which showed no significant difference between four and five supporting implants. Their study showed that biomechanical situation significantly altered only when they lowered the number of implants to three. This aspect suggests that not only the number but also the distribution of the implants plays an important role, appearing to have an interactive effect on implant loading.

The *All on four* concept, which uses two tilted distal implants and two anterior axial ones, has been recommended by some authors who believe that it creates an improvement in the biomechanical situation. The rationale of tilting is related to surgical and prosthetic advantages, such as the placement of longer implants in a dense, bony structure, which enhances their primary stability. In addition, a long cantilever can be avoided, thus improving load distribution and possibly increasing the anterior-posterior spread, independent of the shape of the mandibular body [29,43]. However, studies using finite element analysis performed on single [44] and multiple implants [45] showed that tilting implants may increase the stress on the surrounding bone, which may also be subjected to bending. Furthermore, in clinical conditions, care must be paid to the preparation of tilted implant sites because of the closeness of the mentual nerve. Another critical step is the placement of the angulation abutments for posterior placed implants. Therefore, it could be difficult to say whether the advantages of using tilted implants and angulated abutments can overcome the technical difficulties of the procedure as compared to using four axial implants [29].

On the other hand, Duyck *et al* [11] observed that the best configuration occurred with five to six implants in relation to three to four implants, and the worst configuration was evidenced for three implants.

Despite the proved differences between internal and external connections, the present study inserted, the values of peri-implant bone strain under the effect of 100 N bilateral axial loading between 100-1500 με in both connection systems, corresponding to bone function in normal patterns [8,40,41]. The external hexagon group extends also to the trabecular bone, although the morse taper group represents much higher level of stress. For the latter loading condition, both systems of connections can be used with good performance.

The prevalence of stress in the cervical portion of the peri-implant bone that occurred in both systems of connections, corroborates with previous studies *in vitro* [25,45,46] and *in vivo* [8,47], demonstrating marginal bone loss, especially during the first year of the implants in function. The lower values of mandibular displacement can be considered relevant, since the interforaminal region preserves its area of innervations.

Under the effect of 300 N bilateral axial loading, the peri-implant bone strain extending to the trabecular bone showed an increase in values between 1500-3000 με for both connection systems. In this condition of loading, the morse taper system suggests the better performance by providing more equivalent stress distribution within all implants and peri-implant bone, resulting in even bone stimulation, despite its absolute values remaining higher. On the other hand, the external hexagon system suggests the imminent risk of overload on the distal implants beyond the presence of the cantilever and the others implants becoming practically unloaded.

There exist no long-term prospective and randomized clinical trials that have evaluated the influence of controlled forces on the peri-implantar bone. Duyck *et al*, 2001[48] conducted a study to investigate bone response, and they installed the implants bicortically in rabbit tibiae and then applied static and dynamic loads. They confirmed that excessive loads can indeed trigger bone resorption through the induction of micro-damage in the bone. Despite those bone defects, bone islands were present in the contact region between the bone and the implant surface. This resulted in no significantly lower bone-to-implant contact around the dynamically loaded implants in comparison with the statically loaded implants.

In respect to stress distribution on the external hexagon groups, the prevalence of stress occurred in the distal implants surrounding the bone, suggesting that the function of the intermediate implants may be only for stabilizing the prosthesis; for the morse taper groups, the stress distribution occurred evenly among all implants surrounding the bone. Considering the loads´s transmission mechanism, the effects promoted in the bone were different. By increasing the axial loadings from 100 N to 300 N, a proportional increase of the stress (3 times) was observed for the external hexagon groups; on the other hand, for the morse taper groups, the stress did not increase at the same rate: only 1,5 times, approximately.

The external connection´s basic principle evidences the greater flexibility, release and transfer of the stress field for the bone. These aspects justify the proportional increase of the stress and the lower tendency of stress distribution across all the implants, focusing mainly on the distal implants related to the cantilever area. The most probable cause of failure in clinical situations is the effect of the settlement that emerges from the micro-movements at the implant-abutment connection, which may lead to the loss or fracture of the prosthetic screw [12,21,49].

The prevalence of stress that this study observed mainly on the distal implants closest to the point of load application, is in agreement with the findings of Ogawa *et al*, 2010 [27], which suggested that the distal implants still have a greater risk for mechanical overload, despite the biomechanical advantage of the distal implant.

For the internal connection system, better attachment is achieved by its greater stiffness, absorbing a higher rate of the stress, and resulting in lower stress transference to the bone, promoting a widely spread stress distribution for all implants by the prosthetic infrastructure. The hypothesis advocated is that high levels of stress can also be absorbed by this system, without detectable deformation, and transferring undesirable forces to the bone-implant interface, can result in resorption or later failure [21].

However, this study did not confirm a deleterious effect on bone tissue, for both connection systems, according to the values of strain imposed by Frost [40], since the effects have been considered as steady state and mild overload, as a 100 N or 300 N axial load was applied, respectively. But for the internal connection morse taper interface, these results can confirm the higher stress absorption, given the higher values of stress, and can be confirmed by previous study, that suggested that implants with internal connections showed widely spread force distribution compared with external hexagon implants [20].

The results of this study confirmed the influence of the type of connection in relation to the stress distribution pattern, as a load transmission mechanism. The models were assumed to have a glued bone to implant interface that was considered 100% osseointegrated, which corroborated with the findings of Pessoa *et al,* 2010, which suggested that the influence of connection becomes higher by changing the clinical situation from immediately placed to osseointegrated, mainly when the bone reaches levels close to the implant.

However, the evidence regarding the comparisons between different connections is still scarce [21], especially in multiple prostheses.

The finite element method in 3D allows the simulation of stress, strain, and displacement on the structures in question. However, being a mathematical model, the results should be interpreted with caution. The principal difficulty in simulating the mechanical behavior of dental implants is the modeling of the living human bone tissue and its response to applied mechanical forces. In general some simplifications are made in existing analysis as an assumption of homogeneous, linear, elastic material behavior for the jawbone, which is characterised by a single Young`s modulus and Poisson`s ratio. Despite of this, the method has been used extensively to predict the biomechanical performance of various dental implant designs as well as the effect of clinical factors on the success of implantation. An in-depth understanding of stress profiles encountered by the implant and more importantly in the surrounding jawbone can be gained through the use of FEA. This increase in knowledge of stress distributions and magnitudes within the implant and surrounding jawbone will aid the optimization of the implant design and insertion technique. It is of great importance that the clinician gains an understanding of the methodology, applications and limitations of FEA in implant dentistry and become more confident to interpret results of FEA studies and interpret these results to clinical situations [32] .

It remains necessary to perform studies to assess the behavior of prosthetic structures with different prosthetic connections, as well as to assess variations of the metal alloy used for casting the infrastructure, so that the effect of the implant connection system is evidenced to all the structures present in an implant supported rehabilitation.

CONCLUSION

Within the analysis conditions, the present study concluded that: The two systems of implant-abutment connection can be well indicated under effect of 100 N axial loading; the biomechanical demand resulting from the use of an external implant-abutment connection occurred on the distal implants; on the other hand, using an internal implant-abutment connection distributed evenly across all implants; under the effect of 300 N axial loading the internal connection represents a better treatment alternative, by evenly distributing stress and its corresponding bone stimulation, and with the external connection there is an imminent risk of overload for the distal implants.

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Considerações Gerais

O estabelecimento de parâmetros para avaliação e seleção de adequadas alternativas de tratamento para as próteses implantossuportadas é imprescindível, uma vez que as forças oclusais podem afetar os implantes orais e estruturas relacionadas. Quando excedem a capacidade de adaptação mecânica e biológica dos implantes osseointegrados ou da prótese, podem gerar falhas na osseointegração ou mecânicas, neste caso classificadas como sobrecarga (Isidor, 2006). As forças aplicadas em nível ósseo (*stress*) promovem deformação (*strain*) em seu arranjo estrutural e as alterações no osso dependerão diretamente deste processo (Bonnet *et al.*, 2009).

De acordo com a Hipótese de Frost (Frost, 1992; Frost, 2004) sobre a fisiologia óssea, as células respondem à deformação local provocada pelas cargas mecânicas. Este processo contínuo mantém a competência mecânica do osso, o que também se aplica aos ossos que circundam os implantes orais (Frost, 1992; Frost, 2004; Isidor, 2006). O osso se adapta até determinada deformação permanecendo estável, considerando-se que esteja em função com valores de aproximadamente 100-1500 µƐ. A partir de maior aumento de cargas, resultando em deformação de 1500-3000 µƐ, haverá uma média sobrecarga, que conduz à fadiga mecânica, induzindo ao processo de regeneração ou aposição óssea. Por outro lado, os valores acima de 3000 µƐ já seriam considerados patológicos, podendo sobrepor-se ao mecanismo de reparo ósseo, provocando danos por fadiga que podem resultar em reabsorção. Já a partir de 25000 µƐ atingiriam o limite, podendo levar à fratura repentina. De modo oposto, quando o grau de deformação alcançado não ultrapassa 100 µƐ, o processo de regeneração é substituído também por perda óssea, conduzindo o osso a se adaptar à nova demanda (Frost, 1992; Frost, 2004; Isidor, 2006).

Em relação ao carregamento oclusal selecionado, as cargas axiais de 100 N simulam a condição de pacientes com prótese total como antagonista, representando a maioria de pacientes com este tipo de reabilitação. O carregamento oclusal com cargas axiais de 300 N bilaterais simulam a condição de pacientes com próteses fixas implanto ou dento suportadas como antagonistas; quanto às cargas axiais de 300 N unilaterais, simulam a condição de um grupo significativo de pacientes que tem a mastigação unilateral como hábito . Há uma grande variabilidade quanto às forças de mordida mencionadas na literatura devido aos diferentes métodos e localização das medições (Mericske-Stern & Zarb, 1996).

O carregamento oblíquo foi testado com os referidos modelos, não sendo, no entanto, obtido um resultado condizente com os já alcançados com carregamento axial para este tipo de prótese. Provavelmente o fato de se tratar de prótese complexa compreendendo toda a mandíbula e com região de fixação posterior bilateral, pode ser o motivo de não se conseguir uma efetiva simulação do que seria o deslocamento lateral e oblíquo da mandíbula.

Sob efeito de cargas axiais de 100 N, simulando antagonista com prótese total convencional, tanto para o sistema de conexão Cone Morse como Hexágono Externo, os valores de deformação no osso periimplantar estariam inseridos no padrão de estabilidade, com valores de 100-1500 $\mu\varepsilon$ (Frost, 1992; Frost, 2004). Apesar da diferença na distribuição e nos valores de tensão entre as conexões, o acréscimo de mais um implante não foi relevante para ambos, dentro das condições analisadas.

Algumas evidências observadas neste estudo correspondem à de prévios estudos *in vitro* (Yokoyama *et al.*, 2005; Natali *et al.*, 2008; Bonnet *et al.*, 2009), que demonstraram a predominância de tensão na porção cervical do osso periimplantar, e *in vivo* (Barbier *et al.*, 1998; Isidor, 2006), que demonstraram a perda óssea marginal sobretudo durante o primeiro ano dos implantes em função.

Os resultados deste estudo confirmam os diferentes mecanismos de transmissão de cargas para as conexões protéticas interna (Cone Morse) e externa (Hex. Externo), promovendo comportamentos totalmente distintos tanto em relação à distribuição de tensão, quanto ao mecanismo de transmissão de cargas no conjunto prótese-implante-osso, além da diferença de efeitos para as próteses múltiplas.

Quanto à distribuição de tensão, nos grupos de conexão tipo Cone Morse, tanto com quatro como com cinco implantes, observa-se tensão em todos, além de região óssea peri-implantar. Já em relação aos grupos de conexão Hexágono Externo, tanto com quatro como com cinco implantes, a prevalência de tensão ocorre nos distais e região óssea circundante.

A função dos medianos sugere ser somente para estabilização, apresentando-se praticamente sem solicitação mecânica. O acréscimo de um implante não parece ter sido relevante para ambos os sistemas. Quanto ao mecanismo de transmissão de cargas, observa-se através do aumento das cargas axiais de 100 N para 300 N, que para o sistema de conexão interna Cone Morse, apesar da absorção de elevado valor de tensão, não houve transferência de igual teor ao osso (cerca de 1,5 vezes); já para o sistema de conexão externa Hexágono Externo, os valores aumentaram proporcionalmente ao aumento de cargas (cerca de 3 vezes).

Para o sistema de conexão interna, a provável justificativa para o padrão de distribuição de tensão é o seu princípio básico de travamento e fricção, que com maior rigidez e fixação, distribui melhor a carga por todos os implantes através da infraestrutura protética. O mecanismo de transmissão de cargas desproporcional ao aumento de solicitação mecânica pode estar relacionado ao seu maior teor de absorção e da ação das cargas funcionais (Sahin *et al.*, 2002), o que se comprova pelos valores absolutos bem superiores. Através destas características, o sistema promove maior resistência e estabilidade (Norton, 1997; Norton, 2000; Kitagawa *et al.*, 2005).

De modo oposto se comporta o sistema de conexão externa, que por sua maior flexibilidade permite maior liberação e transferência do campo de tensão ao osso, o que justifica o mecanismo de transmissão de cargas proporcional ao aumento de solicitação mecânica e a menor tendência de distribuição de tensão por todos os implantes, predominando principalmente nos distais ligados à área de cantilever, região de maior solicitação mecânica. Um dos prováveis fatores de falha com este sistema pode ser o efeito de assentamento decorrente dos micromovimentos na conexão implante-

abutment, podendo levar à perda ou fratura do parafuso (Khraisat *et al.*, 2002; Sahin *et al.*, 2002). Desta forma, a manutenção da pré-carga sugere ser essencial.

Sob efeito de cargas axiais de 300 N, simulando antagonista com próteses fixas, os maiores níveis de deformação predominam em região mais apical de osso trabecular, para os dois sistemas de conexão. O padrão de distribuição de tensão para os implantes e intermediários permanece igual ao observado com cargas de 100 N. Apesar das diferenças, em ambos os sistemas, os valores de deformação aumentados, passam a se inserir na categoria entre 1500-3000 µƐ, correspondendo a uma sobrecarga média que já induz ao processo de regeneração óssea, que no entanto ainda não promoveriam efeitos deletérios ao tecido ósseo. Baseando-se nestas evidências os resultados se inserem na categoria de bioestimulação óssea normal.

Com o aumento do carregamento oclusal, a melhor indicação seria com o sistema de conexão interna Cone Morse. Apesar dos valores de deformação para os dois sistemas estarem inseridos em um padrão de sobrecarga média, os valores absolutos do Cone Morse evidenciam melhor comportamento com aumento de solicitação mecânica, por terem, no máximo, duplicado, além da distribuição equivalente de tensão por todos os implantes. Mesmo com pequena diferença entre os valores numéricos de quatro e cinco implantes, a configuração com cinco implantes sugere melhor desempenho dos parafusos de fixação e também da linearidade de tensão distribuída, o que não pode ser afirmado por não terem sido avaliados os valores de pré-carga. Transpondo os resultados a uma situação clínica, esta preferência somente se justificaria se houvesse uma capacidade de resposta do paciente condizente à estimulação óssea.

A infraestrutura protética, através da esplintagem e distribuição de cargas dos elementos envolvidos assegura a obtenção de retenção, estabilidade e resistência em próteses múltiplas (Binon, 2000; Yokoyama *et al.*, 2005) diferindo substancialmente das próteses unitárias expostas às situações de maior risco frente à aplicação de cargas (Binon, 2000). O padrão de distribuição de tensões na infraestrutura protética, ao contrário do observado para o osso, implantes e intermediários se iguala nos dois sistemas de conexão protética, caracterizando a sua influência, o que se estende também aos parafusos de fixação. No entanto, as características específicas de cada conexão não foram neutralizadas e sim minimizadas, o que pode ser confirmado pelos valores absolutos de tensão dos grupos de conexão Cone Morse bem superiores aos obtidos pelos grupos de conexão Hex Externo, que neste aspecto apresentou maior resistência. Para os grupos de conexão Cone Morse, considerando o material da infraestrutura em titânio cp, a resistência se aproxima do seu limite 380-480 MPa (Wang & Fenton, 1996), sobretudo na intersecção com o cantilever em ambas as condições de carregamento oclusal. Já para os grupos de conexão Hexágono Externo, apenas com cargas de 300 N a resistência da infraestrutura seria insatisfatória. Nestas circunstâncias, pode-se considerar a utilização de ligas de resistência superior como Ti-6Al-4V ou Co-Cr (Wang & Fenton, 1996).

Quanto aos parafusos de fixação da prótese, a maior concentração de tensão nos implantes medianos dos grupos com quatro implantes para os dois sistemas de conexão protética, sugere maior esforço dos pilares anteriores se opondo à extrusão, favorecendo o afrouxamento dos quatro parafusos primeiramente. Já com cinco implantes, a tendência de afrouxamento seria primeiramente nos distais e menor do que com quatro. Nos grupos com conexão Cone Morse, apesar de valores absolutos de tensão bem superiores (cerca de 30-40%) o que sugere maior tendência ao afrouxamento, não é possível afirmar a influência da conexão, uma vez que não foram avaliados os valores de pré-carga. A situação apresenta similar tendência com aumento de cargas para 300 N.

A hipótese de que as cargas funcionais induzem a tensão e deformação, no complexo implante-prótese-osso e também interferem no processo de remodelação óssea é também defendida por outros autores (Isidor, 2006). A teoria da fisiologia óssea é corroborada por estudos em animais e humanos, através de aposição óssea com mais freqüência entre níveis de deformação de 3000 a 6700 µƐ e a partir deste valor, o processo é substituído por reabsorção (Arvidson *et al.*, 1992; Isidor, 2006).

Estudos experimentais em animais e clínicos apontam para uma significante influência das forças oclusais na interação osso-implante-prótese, porém o mecanismo que elucida a relação entre estes fatores é pouco conhecido. Barbier *et al*, 1998 demonstraram forte correlação entre a distribuição de tensão no tecido ósseo periimplantar e o fenômeno de remodelação óssea no modelo animal comparativo (Barbier *et al.*, 1998). Porém, as evidências ainda são escassas quanto a estudos clínicos randomizados e prospectivos, que avaliem a influência de forças controladas ao osso periimplantar, seus fatores de interferência e suas conseqüências. Aliando-se ao fato de que diferenças interpessoais podem influenciar no grau de resistência óssea, com indivíduos mais propensos e outros mais resistentes aos episódios de fadiga ou em situações extremas, fratura (Frost, 2004; Isidor, 2006).

Não existem estudos prospectivos de longa duração para avaliar o sucesso a longo prazo, assim como acompanhamento de problemas comparativos entre as diferentes conexões, (Khraisat *et al.*, 2002; Theoharidou *et al.*, 2008), sobretudo em próteses múltiplas.Também é importante considerar, que vários aspectos avaliados experimentalmente, apresentam uma série de dificuldades para avaliação clínica e comparação de seus resultados na íntegra, além das variações interpessoais. Para a quantificação e qualificação destas forças na interface osso-implante é necessário que se compreenda o seu comportamento. As forças *in vivo* sobre os implantes são medidas em região de *abutment*; sendo que seu adequado isolamento na região periimplantar ainda constitui um desafio. Como a deformação intra-óssea não tem sido avaliada através de biosensores, os gradientes de deformação que guiam o processo de remodelação óssea são desconhecidos. Desta maneira, a obtenção de uma prova científica incontestável ainda não foi concretizada (Sahin *et al.*, 2002).

Apesar do método de Elementos Finitos em 3D apresentar importante recurso para análise de tensão, deformação e deslocamento, clinicamente difíceis de se obter, através de outros experimentos, os seus resultados devem ser interpretados com cautela (Sahin *et al.*, 2002, Assunção *et al.*, 2009). Por ser um modelo matemático, as suas limitações inerentes devem ser consideradas. Mesmo através das fortes correlações com estudos *in vivo* já evidenciadas (Barbier *et al.*, 1998) ainda é preciso a validação clínica.

Estes modelos desviam em alguns aspectos, da situação clínica, como o fato do osso ser considerado linearmente elástico; na realidade, é viscoelástico, ser considerado isotrópico; na realidade é anisotrópico, e ser considerado homogêneo; na realidade ele pode conter vácuos em sua extensão (Hansson, 2003).

Porém, dentro da proposta de se analisarem as diferenças de comportamento entre conexões e quantidade de fixações em próteses múltiplas, os modelos, mesmo com simplificações, propiciam resultados relevantes, que podem apontar diversas tendências e opções de tratamento. A precisa previsão da estabilidade e os possíveis mecanismos de falha usando este método podem ser úteis como método complementar aos experimentos clínicos (Sahin *et al.*, 2002; Kitagawa *et al.*, 2005). Assim, os valores absolutos passam a ser menos relevantes em relação ao objetivo maior, pois as tendências de comportamento serão igualmente delineadas.

Como propostas para trabalhos futuros é importante a análise da infraestrutura metálica com ligas de Co-Cr pelo método de Elementos Finitos; a análise comparativa dos resultados através de outras metodologias experimentais e a avaliação da possibilidade de estudos *in vivo*.

Conclusão

Este estudo analisou a distribuição de tensão em próteses fixas mandibulares implantossuportadas e região óssea peri-implantar, utilizando-se dois tipos de conexão implante-*abutment* externa e interna, correlacionadas ao efeito de cargas axiais de 100 N (antagonista prótese total) e 300N (antagonista próteses fixas) e número de implantes (quatro e cinco). Considerando as limitações relativas às simplificações dos modelos, concluiu-se que:

Sob efeito de cargas axiais de 100N bilateral:

1. Não há superioridade de um sistema de conexão implante-*abutment* em relação ao outro, sendo que os dois podem ser bem indicados.
2. Cinco implantes não representam benefício em relação ao uso de quatro para os dois sistemas de conexão implante-*abutment* na condição avaliada.
3. A resistência mecânica da infra-estrutura protética com o titânio cp pode ser considerada satisfatória somente para o sistema de conexão implante-*abutment* Hexágono Externo.
4. Com o sistema de conexão implante-*abutment* Cone Morse, a solicitação mecânica distribui-se por todos os implantes e região óssea, com o sistema Hexágono Externo, concentra-se nos implantes distais e região óssea circundante.

Sob efeito de cargas axiais de 300 N bilaterais e unilaterais:

1. Com o aumento de solicitação mecânica, o sistema Cone Morse apresenta indicação mais apropriada, pela melhor distribuição das cargas, considerando-se que o paciente corresponda à estimulação óssea.
2. A resistência mecânica da infra-estrutura protética aproxima-se do limite de escoamento com o titânio cp, para ambos os sistemas de conexão, nas condições de análise.

Sob efeito de cargas axiais de 100 e 300 N:

1. A distribuição de tensão na infraestrutura protética é similar, não demonstrando influência dos dois sistemas de conexão implante-*abutment.*

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Apêndice

Descrição da Metodologia Ilustrada

1. Modelo Geométrico

Os modelos digitais foram confeccionados representando uma mandíbula edêntula, com a instalação de próteses fixas implantossuportadas de acordo com o protocolo Branemark, com variações do número de implantes (quatro e cinco), e do tipo de conexão implant-*abutment*, interface Cone Morse ou interface Hexágono Externo. As estruturas (mandíbula, implantes, intermediários, infraestrutura protética, prótese de resina) foram modeladas através do software específico Rhinoceros 4.0 SR8 (McNeel North America, Seatle,WA, USA).

A partir da imagem de uma mandíbula obtida por tomografia proveniente da base de dados da Divisão de Tecnologias Tridimensionais, Centro de Tecnologia da Informação Renato Archer (DT3D, CTI, Campinas,SP), foi construído o modelo de uma mandíbula edêntula, com aplicação do protocolo BioCAD (CTI, Campinas,SP). Este protocolo consiste da demarcação dos principais marcos anatômicos para se obter um modelo com simplificações, o que é considerado essencial para a posterior geração de malha e refinamento manual da mesma. A mandíbula foi confeccionada com espessura uniforme de 2 mm de osso cortical tipo II (Leklom,1985), contornando o osso trabecular **(Fig. 1a)**

As imagens tridimensionais dos implantes, intermediários e parafusos (protéticos e dos intermediários) foram cedidas pelo fabricante (Neodent, Curitiba, PR, Brasil) e serviram de base para a modelagem das estruturas propriamente ditas, sendo**:**

1) Implantes cilíndricos 3,75 x 13mm, com conexões interface interna Cone Morse ou externa Hexágono Externo; **2**) Intermediários tipo minipilar cônico; **3)** Parafusos protéticos e dos intermediários **(Fig 1b,1c).**

4) Infraestrutura composta por barra de secção circular de titânio, com secção circular de 4 mm, 50 mm de comprimento na região interforaminal e 15 mm de cada lado na área de cantilever, somando-se um comprimento total de 80 mm. O espaço considerado para higienização foi de 3 mm. A prótese de resina foi então modelada a partir da infraestrutura protética **(Fig. 1d, 1e).** A infraestrutura protética e a prótese de resina adaptada sobre a mesma foram modeladas, de acordo com medidas médias utilizadas em laboratórios de produção, com base na literatura de referência nos capítulos (Gallucci et al, 2009; Teixeira et al, 2010).

Após a construção, os modelos foram exportados em formato STEP para análise numérica computacional por Elementos Finitos.

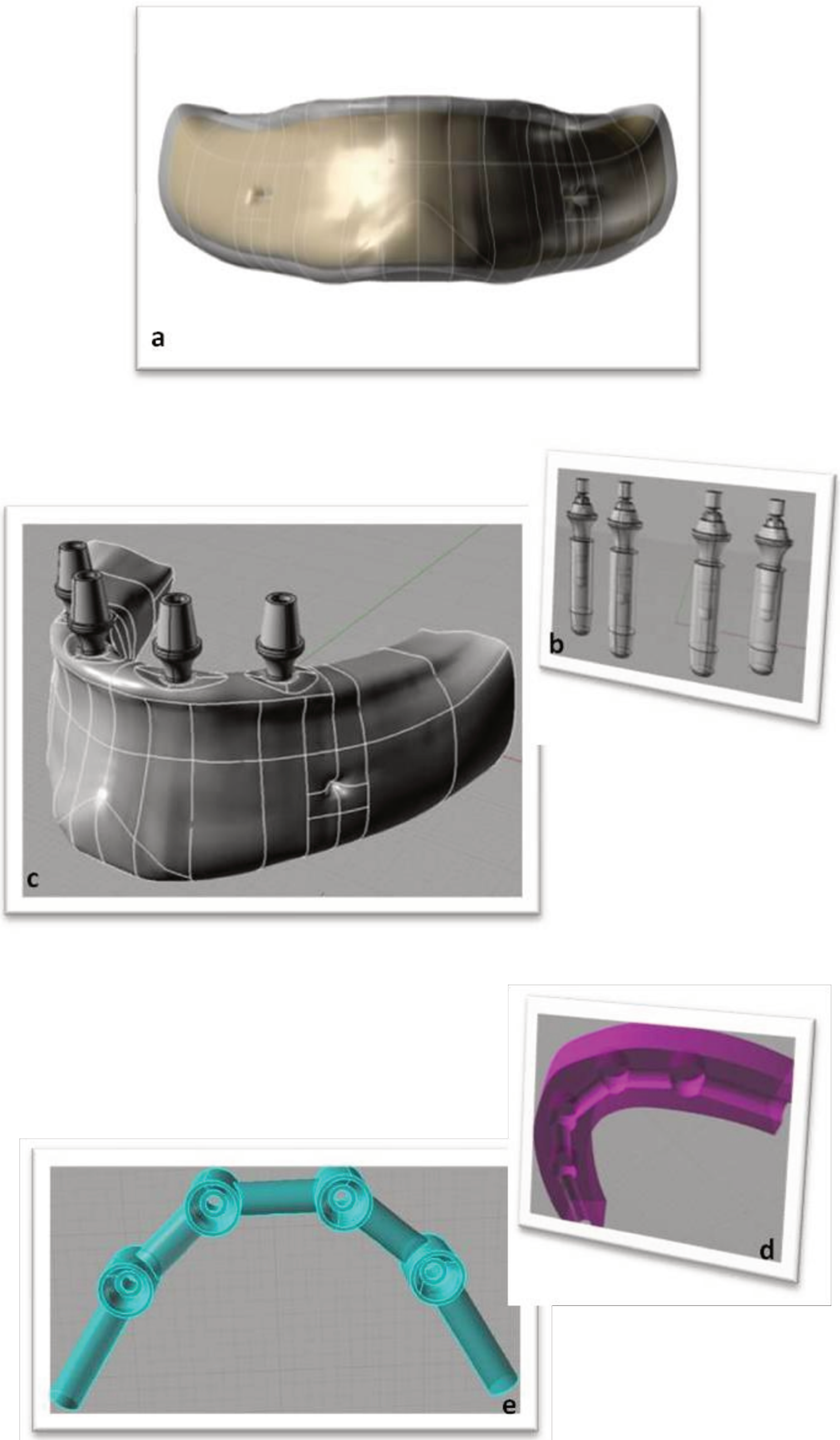

Fig.**1a - 1e Modelo Geométrico: a)** Mandíbula; **b)** Implantes-Intermediários-Parafusos; **c)** Mandíbula-Implantes-Intermediários; **d)** prótese de resina; **e)** infraestrutura metálica

2. Análise por Elemento Finito

A análise numérica pelo método de Elementos Finitos foi realizada utilizando o programa ANSYS Workbench 12.0.1 e inclui três etapas :

2.1 Pré- processamento; 2.2. Processamento; 2.3 Pós-processamento

2.1 **PRÉ-PROCESSAMENTO**

Inclui a etapa de definição das propriedades dos materiais, geração de malha, condições de contorno e condições de carga.

2.1.1. PROPRIEDADES DOS MATERIAIS: Os materiais foram considerados isotrópicos, elásticos, lineares e homogêneos, caracterizados pelos seus módulos de elasticidade (E) e coeficientes de Poisson, descritos na **Tabela 1** (pgs. 12, 40, 66).

2.1.2. GERAÇÃO DE MALHA : A malha foi gerada com elementos tetraédricos contendo 10 nós **e** controle manual da malha com refinamento nas regiões de interesse específico e realizado com auxílio das linhas e superfícies geradas na etapa de modelagem. Os elementos nas regiões de refinamento foram de pequeno tamanho resultando em região de alta densidade de nós **(Fig. 2a, 2b, 2c, 2d).** Os números de nós e elementos em cada estrutura são descritos na Tabela 2 (pgs. 12, 40, 66).

2.1.3. CONDIÇÕES DE CONTORNO:

Foi realizada uma abordagem multicorpos utilizada para estruturas complexas, com definição da interação entre cada estrutura sendo assim atribuídos contatos colados ou justapostos. Entende-se por justapostos aqueles contatos que se interagem sem fricção. Atribuiu-se contatos colados a: a). interface osso-implante, simulando osseointegração total; b). interface osso cortical-osso trabecular; c). união infraestrutura metálica-prótese; d)interfaces implante-intermediário e intermediário-parafuso protético (no local correspondente às roscas), simulando parcialmente o efeito de pré-carga, através do fenômeno de travamento das roscas. Atribuiu-se contatos justapostos às demais interfaces.A fixação do modelo ocorreu através da restrição dos deslocamentos, em todas as direções do espaço, das superfícies de corte posteriores da mandíbula **(Fig.3)**

CONDIÇÕES DE CARREGAMENTO: Cargas oclusais estáticas foram aplicadas em toda superfície oclusal relativa aos dentes posteriores. As condições foram 100 N axial bilateralmente, simulando uma arcada antagonista com prótese total convencional; 300 N axial bilateralmente, simulando antagonista com próteses implantossuportadas fixas; 300 N unilateralmente, simulando hábito de mordida unilateral **(Fig.3).**

2.2. **PROCESSAMENTO**

As condições experimentais já estabelecidas (pré-processamento) foram submetidas à análise propriamente dita, sob efeito dos seguintes fatores de estudo: número de implantes, cargas axiais e conexões protéticas, sendo 6 condições experimentais, a saber :

M1 (4 implantes, 100 N), **M2** (4 implantes, 300 N bilateral), **M3** (4 implantes, 300 N unilateral); **M4** (5 implantes, 100 N), **M5** (5 implantes, 300 N bilateral), **M6** (5 implantes, 300 N unilateral).

2.3 **PÓS-PROCESSAMENTO**

Os resultados da análise foram avaliados através da visualização gráfica dos campos de deslocamento, tensão de von Mises e deformação, obtidos na etapa de Processamento, que permitiram comparações entre dados qualitativos e quantitativos. As áreas de interesse para análise foram: região óssea peri-implantar, implantes, *abutments,* infraestrutura protética e parafusos.

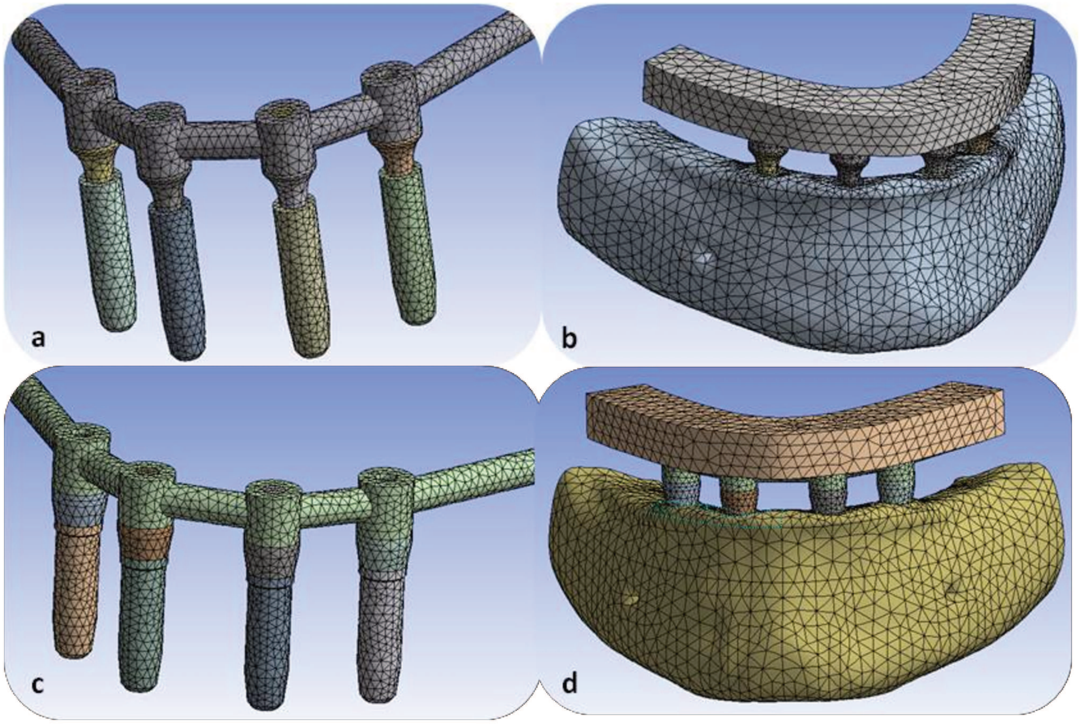

Fig 2a-d Geração da malha, elementos tetraédricos com 10 nós:
a, b) Implantes com conexão implante-*abutment* Cone Morse;
c, d) Implantes com conexão implante-*abutment* Hexágono Externo.

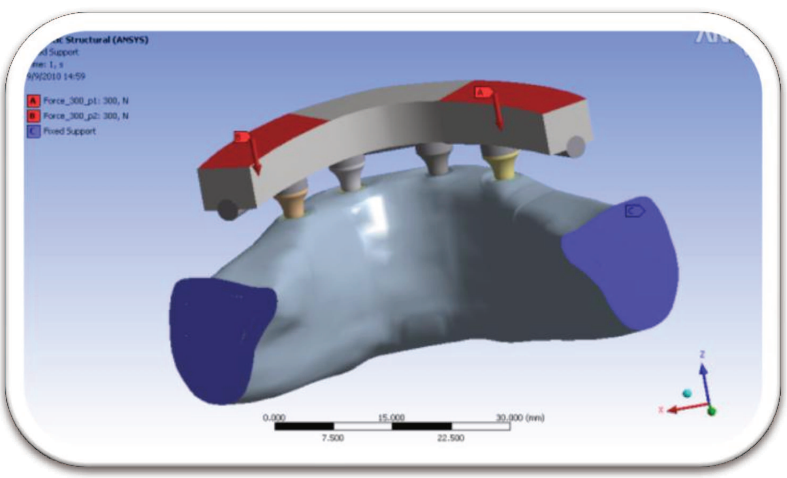

Fig.3- Condições de contorno, fixação e carregamento do modelo