UNESP - Universidade Estadual Paulista

“Júlio de Mesquita Filho”

Faculdade de Odontologia de Araraquara

Luís Carlos Leal Santana

Avaliação mecânica de diferentes configurações do conceito All-on-4 em mandíbulas atróficas: análise tridimensional por elementos finitos

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Orientador: Prof. Dr. Luis Geraldo Vaz
Coorientador: Prof. Dr. Fernando Pozzi Semeghini Guastaldi

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Luís Carlos Leal Santana

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Dedico este trabalho,

À **Deus**. Força infinita que rege as leis naturais de todo o Universo, as quais estão distantes da compreensão do ser humano. Este trabalho é apenas um pequeno grão de areia frente à tua grandeza.

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“A teoria sem a prática vira 'verbalismo', assim como a prática sem teoria, vira ativismo. No entanto, quando se une a prática com a teoria tem-se a práxis, a ação criadora e modificadora da realidade.”
Paulo Freire[*]

[*] Freire P. Educação como prática da liberdade. São Paulo: Paz e Terra, 1989.

Santana LCL. Avaliação mecânica de diferentes configurações do conceito All-on-4 em mandíbulas atróficas: análise tridimensional por elementos finitos [tese de doutorado]. Araraquara: Faculdade de Odontologia da UNESP; 2019.

RESUMO

A reposição de elementos dentários por meio da técnica All-on-4 permite a reabilitação de mandíbulas edêntulas mediante a instalação de uma prótese total fixa sobre quatro implantes dentários. As principais vantagens desta técnica estão associadas à inclinação distal, 30 ou 45 graus, dos implantes mais posteriores, dentre as quais destacam-se a redução do risco de injúrias ao nervo alveolar inferior, o maior contato entre o tecido ósseo e a superfície do implante, e a redução na extensão do cantilever protético. Sob a perspectiva da distribuição de esforços mecânicos, reduções na extensão do cantilever resultam em redução do braço de alavanca e melhor distribuição de tensões na barra protética e no tecido ósseo peri-implantar. Por outro lado, há de se considerar que o comportamento mecânico de próteses implantossuportadas também pode ser influenciado pelas características geométricas dos implantes dentários. Recentemente, a implementação da técnica All-on-4 com implantes dentários curtos foi considerada uma alternativa viável para a reabilitação de maxilas reabsorvidas. Porém, existem evidências limitadas quanto à distribuição de esforços mecânicos sobre o complexo prótese/implante/osso mediante o uso de configurações alternativas do conceito All-on-4 em mandíbulas atróficas. Assim, o objetivo do presente estudo foi avaliar o impacto de diferentes configurações do conceito All-on-4 sobre as tensões geradas em implantes, componentes protéticos e osso peri-implantar. Os modelos de mandíbula atrófica foram gerados em *software* apropriado (Rhinoceros 5.0 SR 12), no Centro de Tecnologia da Informação “Renato Archer”. Os arquivos de desenho assistido por computador (CAD) de componentes protéticos e implantes dentários (Implacil de Bortoli) foram importados ao Rhinoceros 5.0 SR 12 para a configuração dos modelos All-on-4. Assim, foram geradas diferentes configurações do conceito All-on-4 a partir de implantes dentários, de comprimento padrão (11 mm) ou curtos (≤ 8 mm), com conexão protética do tipo cone Morse ou hexágono externo. Os modelos foram submetidos a condição de carga oblíqua (θ = 75º) com 300 N, no sentido línguo-vestibular, na região posterior da barra protética. Os materiais dúcteis (implantes e componentes protéticos) foram submetidos a análise pelo critério de tensão de von Mises (σ_{vm}). As análises de tensões principais máxima (σ_{max}) e mínima (σ_{min}) foram utilizadas para avaliar os picos de tensão de tração e compressão do tecido ósseo peri-implantar, respectivamente. Os dados de tensões médias obtidas a partir do critério de σ_{vm} ($P\sigma_{vm}$) foram submetidos à análise estatística para a comparação múltipla (one-way ANOVA e teste pós-hoc de Tukey) ou de pares (teste t-Student) de médias independentes, considerando significância estatística o valor de $p < 0.01$. Os resultados do primeiro estudo obtidos com implantes do tipo cone Morse indicaram que a configuração All-on-4 com implantes distais curtos aumenta significativamente a $P\sigma_{vm}$ geradas na plataforma dos implantes ($p < 0.0001$; t-Student), entretanto, reduz as tensões de tração e compressão na crista óssea peri-implantar. No segundo estudo, os resultados obtidos com implantes do tipo hexágono externo indicaram que tanto o comprimento quanto a angulação do implante distal da configuração All-on-4 afetam significativamente a $P\sigma_{vm}$ geradas na plataforma de implantes e em componentes protéticos ($p < 0.0001$; one-way ANOVA e Tukey) e as σ_{max} e σ_{min} geradas na crista óssea peri-implantar. Em ambos os estudos, a resistência dos materiais dúcteis e não-dúcteis não ultrapassaram os valores limítrofes de resistência à tração ou compressão. Em conclusão, os resultados do presente estudo podem direcionar o uso racional de implantes de curtos, hexágono externo ou cone Morse, a partir de diferentes configurações do conceito All-on-4 em mandíbulas atróficas.

Palavras-chave: Implantação dentária. Estresse mecânico. Análise de elementos finitos. Prótese dentária fixada por implante.

Santana LCL. Mechanical evaluation of different configurations of the All-on-4 concept in atrophic jaws: three-dimensional finite element analysis [Tese de Doutorado]. Araraquara: Faculdade de Odontologia da UNESP; 2019.

ABSTRACT

The replacement of teeth through the All-on-4 technique allows the rehabilitation of edentulous jaws by installing a full-arch fixed prosthesis over four dental implants. The main advantage of this technique is associated with the distal inclination of the most posterior implants, 30- or 45-degrees angle, which entails lower risks of injuries to the inferior alveolar nerve, greater bone-to-implant contact, and reductions in the cantilever length. From the standpoint of mechanical stress distribution, reductions in the cantilever length results in reduced lever arm and better stress distribution in the prosthetic bar and the peri-implant bone tissue. On the other hand, it should be considered that the mechanical behavior of implant-supported prostheses may also be influenced by the geometric characteristics of dental implants. Recently, the All-on-4 technique performed with short dental implants was considered a viable alternative for the treatment of reabsorbed jaws. However, there is limited evidence regarding the mechanical performance of the prosthesis/implant/bone complex when alternative configurations of the All-on-4 concept are performed in atrophic mandibles. Therefore, the aim of the present study was to assess the impact of different configurations of the All-on-4 concept on the stresses generated at the level of implants, prosthetic components and peri-implant bone. The atrophic mandible models were generated at the Renato Archer Information Technology Center. The computer-aided design (CAD) files of the prosthetic components and dental implants (Implacil de Bortoli) were imported into the Rhinoceros 5.0 SR 12 in order to generate the All-on-4 models. Thereafter, different configurations of the All-on-4 concept were generated by using standard (11.0 mm) or short (≤ 8.0 mm) length dental implants with Morse taper or external hexagon connections. The models were submitted to oblique loading ($\theta = 75º$; 300 N), in the posterior region, and linguo-buccal direction, of the prosthetic bar. The ductile materials (implants and prosthetic components) were submitted to the von Mises stress criteria (σ_{vm}). The maximum (σ_{max}) and minimum (σ_{min}) principal stresses were used to evaluate the tensile and compressive stresses in the peri-implant bone region, respectively. The quantitative variables of the σ_{vm} ($P\sigma_{vm}$) were submitted to pairs (t-Student test) or multiple (one-way ANOVA and Tukey's post-hoc test) comparisons, considering statistically significant the p-value < 0.01. The results of the first study obtained with Morse taper implants indicated that the All-on-4 configuration designed with distal short implants significantly increases the $P\sigma_{vm}$ generated in the implants platform ($p < 0.0001$; t-Student) but, however, reduces the tensile and compressive stress peaks in the peri-implant bone crest. In the second study, the results obtained with external hexagon implants indicated that both distal implants length and angulation significantly affect the stresses generated at the level of the implants platform and prosthetic components ($p < 0.0001$; one-way ANOVA and Tukey) and the σ_{max} and σ_{min} generated in the peri-implant bone crest. In both studies, the stress values of ductile and non-ductile materials did not exceed the boundary values of tensile or compressive strength. In conclusion, the results of the present study may direct the rational use of short dental implants, with Morse taper or external hexagon connections, from different conigurations of the All-on-4 concept performed in atrophic jaws.

Keywords: Dental implantantation. Mechanical stress. Finite element analysis. **Dental prosthesis, implant-supported.**

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1 INTRODUÇÃO

As alterações dimensionais do rebordo ósseo ocorrem naturalmente após a extração de elementos dentários e tem como principal justificativa os processos de reabsorção e remodelação óssea causadas pela ausência do estímulo biomecânico, um dos principais reguladores do metabolismo ósseo, advindo da função mastigatória[1,2]. Posto que os processos de reabsorção e remodelação ocorrem de forma progressiva sobre a altura e a largura de arcos edêntulos[1], a atrofia óssea mandibular é uma característica comum àqueles pacientes que permanecem desdentados por longos períodos de tempo[3,4].

A reabilitação de mandíbulas atróficas com próteses totais implantossuportadas representa um desafio clínico axiomático, uma vez que as características anatômicas de mandíbulas severamente reabsorvidas restringem a seleção do número, comprimento, diâmetro, e/ou o posicionamento de implantes dentários[5]. Tais restrições implicam em alterações no desenho final da prótese dentária, podendo resultar em sobrextensão do cantilever distal e maiores tensões transmitidas aos componentes protéticos e tecido ósseo peri-implantar[6]. Do ponto de vista biomecânico, estudos anteriores sugeriram que a extensão do cantilever distal de próteses totais implantossuportadas não ultrapassasse 20 mm ou 1,5× a distância anteroposterior do implante mais anterior ao mais posterior posicionado no arco edêntulo[7,8]. Por outro lado, os resultados do estudo conduzido por Bevilacqua et al.[9] (2011) demonstraram que a inclinação e o comprimento de implantes distais associados a menor extensão do cantilever protético suscita a redução dos valores de tensão na barra protética e no tecido ósseo peri-implantar. De forma contraditória, à partir do conceito All-on-4™ (Nobel Biocare, AB, Göteborg, Sweden), Almeida et al.[10] (2015) demonstraram que a inclinação de implantes distais promoveu maiores tensões ósseas peri-implantares em maxilas atróficas.

O conceito All-on-4™ surgiu como uma opção de tratamento promissora para a reabilitação imediata de mandíbulas ou maxilas edêntulas[11]. A técnica All-on-4™ permite a reabilitação do arco edêntulo, mediante o uso de uma prótese total imediata parafusada sobre quatro implantes instalados na região anterior da mandíbula ou maxila, de modo que os implantes mais posteriores estejam inclinados, no sentido distal, a 30 ou 45 graus em relação ao plano oclusal[12,13]. As vantagens associadas à inclinação distal dos implantes mais posteriores foram explicadas sob os pontos de vista biológicos e biomecânicos. Do ponto de vista biológico, a inclinação do implante distal é fundamentada na possibilidade de maior ancoragem do implante ao tecido ósseo, permitindo que a reabilitação oral seja realizada sem a necessidade de procedimentos cirúrgicos para a lateralização do nervo alveolar inferior[12,14]. À luz do conhecimento sobre a biomecânica de próteses implantossuportadas, a inclinação de implantes distais permite reduções na extensão do cantilever protético e no braço de alavanca, resultando na melhor distribuição de tensões nos implantes e no tecido ósseo peri-implantar[6,7]. Não obstante, a geometria dos implantes dentários é um outro fator que deve ser levado em consideração em relação ao comportamento mecânico de próteses implantossuportadas.

Pellizzer et al.[15] (2018), destacaram a importância de se considerar o uso de implantes dentários cônicos nos casos em que as limitações anatômicas do sítio edêntulo impeçam a instalação de implantes cilíndricos de maior diâmetro. Embora o conceito All-on-4™ tenha sido introduzido com implantes com conexão protética do tipo hexágono externo, estudos pré-clínicos demonstraram os maiores valores de torque de inserção e estabilidade em implantes cônicos com conexão protética do tipo cone morse[16,17]. De fato, implantes com conexão interna cônica projetada sob o conceito *plataform switching* (quando o diâmetro do componente protético é menor em relação à plataforma de assentamento do implante) tem sido associados a menores valores de tensão óssea peri-implantar[18] e manutenção da crista óssea marginal ao redor de implantes[19]. Não obstante, estudos prévios também demonstraram que o comprimento de implantes dentários pode influenciar o comportamento mecânico de próteses implantossuportadas[10,20].

O uso de implantes dentários curtos (≤ 8,0 mm) tem sido considerado uma alternativa viável e segura, pois possibilita a reabilitação de mandíbulas atróficas sempre que há restrições para o uso de implantes de comprimento padrão (> 8 mm)[21,22]. O resultado de um estudo de revisão sistemática demonstrou, recentemente, que as taxas de sobrevivência de implantes curtos são similares àquelas observadas em implantes dentários de comprimento padrão (≥ 10,0 mm) instalados em sítios submetidos ao tratamento cirúrgico para aumento ósseo vertical[23]. Do ponto de vista biomecânico, Kheiralla e Younis[24] (2014) demonstraram por meio do método de elementos finitos a similaridade dos valores de tensão de von Mises encontrados em implantes de plataforma regular (ø 3,75 x 13 mm) e plataforma larga (ø 5,5 x 8 mm). Além disso, os resultados deste último estudo demonstraram poucas diferenças dos valores de tensão óssea peri-implantar entre os implantes de plataforma regular e plataforma larga. Ainda assim, longe de ser uma complicação frequente, há que se considerar a possibilidade de fratura óssea peri-implantar nos casos de reabilitação oral de mandíbulas atróficas com próteses instaladas sobre implantes de maior diâmetro[25-27].

Alguns estudos têm relatado o uso de implantes curtos para a reabilitação oral com próteses totais parafusadas sobre quatro implantes[28,29]. Maló et al.[28] (2015) considerou que a técnica All-on-4 realizada com implantes dentários curtos pode ser uma alternativa viável para a reabilitação protética de maxilas reabsorvidas. Em conformidade com Maló et al.[28] (2015), em um estudo de série de casos clínicos, Moura et al.[29] (2018) relataram a viabilidade do uso de próteses totais implantossuportadas por quatro implantes dentários curtos (6,0 mm) e conexão cônica em mandíbulas atróficas. Após 4 anos de acompanhamento, os autores deste estudo indicaram a ausência de complicações técnicas (afrouxamento ou fratura de parafusos) ou biológicas (peri-implantite). Sob o aspecto biomecânico, pouco se sabe a respeito das tensões ósseas peri-implantares geradas a partir de configurações alternativas do conceito All-on-4™ em mandíbulas atróficas. Os resultados do estudo conduzido por Özdemir Doğan et al.[20] (2014) demonstraram que a configuração All-on-4 projetada com implantes distais curtos (7,0 mm) promove a redução e o aumento das tensões de compressão e de von Mises no tecido ósseo peri-implantar e nos implantes, respectivamente, em comparação a configuração All-on-4 com implantes distais angulados a 30 graus em relação ao plano oclusal. Todavia, posto que o desenho experimental deste estudo considerou as tensões geradas nos implantes e no tecido ósseo peri-implantar, subsiste a escassez de dados em relação a influência de configurações alternativas do protocolo All-on-4 sobre as tensões geradas no complexo componente protético/implante/osso peri-implantar.

2 PROPOSIÇÃO

O presente estudo teve como objetivo geral a avaliação mecânica, por meio do método de elementos finitos, de diferentes configurações do conceito All-on-4 projetadas com implantes dentários de comprimento padrão (11,0 mm) ou curtos (≤ 8,0 mm) e conexão protética do tipo hexágono externo ou cone morse, em mandíbulas atróficas. Para isto, o presente trabalho foi subdividido em 2 estudos com objetivos específicos descritos a seguir:

2.1 Proposição Específica do Artigo 1

O objetivo do primeiro estudo foi avaliar as tensões de von Mises geradas ao nível dos implantes, além das tensões de tração e compressão geradas no tecido ósseo peri-implantar, a partir de configurações All-on-4 projetadas com implantes cone morse, sendo a principal variável a configuração do implante distal – 11,0 mm de comprimento e angulado a 30º em relação à crista óssea; ou 8,0 mm de comprimento e paralelo entre os demais implantes.

2.2 Proposição Específica do Artigo 2

O objetivo do segundo estudo foi avaliar o impacto do comprimento e da inclinação de implantes distais da configuração All-on-4, sobre as tensões de von Mises geradas em implantes e componentes protéticos, tensões de tração e compressão geradas no osso peri-implantar, além do deslocamento geral dos modelos projetados com implantes de conexão hexagonal externa, sendo a principal variável a configuração do implante distal - 11,0 mm de comprimento e angulado a 30º em relação à crista óssea; ou ≤ 11,0 mm de comprimento e paralelo entre os demais implantes.

3 PUBLICAÇÕES

3.1 Publicação 1*

Journal of Oral Rehabilitation

Short implants with platform switching design reduces the peri-implant bone stress in the "All-on-4" configuration - a finite element study

Journal:	*Journal of Oral Rehabilitation*
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Short implants with platform switching design reduces the peri-implant bone stress in the "All-on-4" configuration - a finite element study

Running head: All-on-4 design and distal short Implants

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Summary

Background: Short dental implants have been used for the rehabilitation of complete edentulous atrophic jaws. However, there remains a paucity of data on the biomechanical performance of the All-on-4 configuration performed with platform-switched distal short dental implants.

Objectives: This study determined wether the use of straight short or tilted standard distal implants would result in similar values of stress at the level of implants and peri-implant bone tissue.

Methods: Two models of human atrophic mandibles were constructed. The All-on-4 configurations consisted of tilted standard (θ = 30°; 11 mm-length, AO4T model) and straight short (θ = 0°; 8 mm-length, AO4S model) distal implants. A resultant force of 300 N was performed obliquely in the left side and posterior region of the prosthetic bar. The von Mises equivalent stress (σ_{vm}) and maximum and minimum principal stresses (σ_{max} and σ_{min}) were performed at level of the implants and surrounding bone, respectively.

Results: The AO4T configuration presented the highest values of tensile and compressive stress at the peri-implant bone crest around the platform region of the mesial (σ_{max} = 10.76 MPa/ σ_{min} = - 36.49 MPa) and distal (σ_{max} = 131.48 MPa/ σ_{min} = - 195.13 MPa) left implants. The AO4S configuration statistically increased the mean stresses in the platform of the implants ($p < 0.001$).

Conclusion: The "All-on-4" configuration performed with distal short implants with platform-switching design has potential to reduce the tensile and compressive stresses performed at the level of the peri-implant bone crest.

Keywords: Biomechanics, Implant-supported dental prosthesis, Platform switching, Dental implant-abutment design, Finite element analysis,

Introduction

The All-on-4™ (Nobel Biocare, AB, Göteborg, Sweden) concept has emerged as one of the most promising treatment option for the oral rehabilitation of completely edentulous patients. This concept is performed by using a full-arch fixed prosthesis connected to four dental implants (02 mesial straight and 02 distal tilted) placed in the anterior region of the jaw.[1] The reasons behind the use of distally tilted implants were explained from the biological and biomechanical

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perspectives. The biological rationale of distally tilting implants resides in the fact that this approach enables the achievement of higher implant anchorage into the bone tissue while the oral rehabilitation is performed with lesser risks to injure the inferior alveolar nerve.[2] Biomechanically, distally tilted implants allow reductions in the cantilever extensions,[3] which is associated with better stress distribution in the implants and surrounding bone.[4,5] Noteworthy, the geometry of dental implants is another factor that should be addressed in the biomechanics of implant-supported prosthesis.

The authors of a recent biomechanical study concluded that dental implants with tapered geometry should be considered whenever anatomical limitations precludes the use of wide-diameter cylindrical implants.[6] Although the All-on-4™ concept was introduced with platform-matched implants (i.e. external hex prosthetic connection), pre-clinical studies showed that morse taper implants with internal conical connection were associated with higher insertion torque and increased values of implant stability.[7,8] Indeed, implants with internal conical connection and platform switching design (i. e. standard diameter abutments connected to wide-diameter implants) have been associated with lower stress values in the peri-implant bone region[9] and significantly lower marginal bone loss.[10] Further, the biomechanical behavior of protocols with implant-supported prosthesis was found to be influenced by the number and length of dental implants.[5,11,12]

Short-length (≤ 8 mm) dental implants have been considered a viable alternative to procedures for bone augmentation.[13,14] In fact, the survival rates of shorter implants were found to be similar to that of standard-length (≥ 10 mm) implants.[15] In a finite element study, the All-on-4 configuration performed with distal short straight implants resulted in lower compressive stress transmitted to the supporting bone compared to distal long tilted implants.[12] Recently, our research group showed that an alternative configuration of the All-on-4™ concept performed with platform-matched implants of 6 mm-length markedly increased the tensile stress in the peri-implant bone crest when compared with the standard configuration of the All-on-4™ concept with distal tilted implants (unpublished data; under review). Despite that few studies have evaluated the biomechanical performance of the All-on-4™ concept and alternative protocols performed with four dental implants,[16-19] there is a lack of evidence regarding the biomechanics

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of the All-on-4 protocol designed with platform-switched short dental implants. Therefore, using the All-on-4 configuration, this three-dimensional finite element study sought to investigate the stresses generated by platform-switched tilted standard and straight short distal implants in atrophic mandibles.

Material and methods

3D models

Three-dimensional Class II atrophic mandible models were generated in accordance with the classification proposed by Luhr et al. (1996).[20] All models were generated at the Renato Archer Information Technology Center (CTI, Campinas, SP, Brazil) with an appropriate modelling software (Rhinoceros 5.0 SR12; McNeel North America, Seattle, WA, USA), as described elsewhere [21]. To better simulate the properties of resorbed mandibles, the cortical/trabecular bone ratio predicted for the models was 3:1.[22] The stereolithography (stl) files provided by the manufacturer (Implacil De Bortoli, São Paulo, Brazil) were used to generate computer-aided design (CAD) images of dental implants and prosthetic components. A prosthetic bar made of nickel-chromium (Ni-Cr) was generated with 6-mm height, 5-mm thickness and 13-mm cantilever extensions.[23] The dimensions of bone width (10 mm) and height (15 mm) and the distance between the bone ridge and the bottom surface of the prosthetic bar (4 mm) was maintained in all models.

Experimental design

This study used tapered implants with internal conical prosthetic connection and platform switching design. Initially, the thread geometry of the implants was simplified with the Rhinoceros 5.0 SR12 to reduce the impact of complex geometries in the finite element simulations. Afterwards, the implants were positioned into the atrophic mandible models accordingly with the All-on-4 configuration.[24] The distal implants were tilted at 30° angle or placed straight into the models. In order to facilitate the stress analysis, it was assumed that both mesial implants and prosthetic components were in the “mesial left” (ML) and “mesial right” (MR) areas, whereas the two distal implants and prosthetic components were in the “distal left” (DL) and “distal right” (DR) areas. The morse taper implants were placed 2 mm below the bone crest[25] and the inter-implant

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distance of 15 mm was maintained in all models.[26] Those implants with more than 10 mm in length were considered as "standard" dental implants, while those with 8 mm in length were considered as "short" ones.[27] The assembled implants and abutments are shown in Fig. 1. Straight and 30° angled abutments with 3.5 mm in height were connected to the straight placed and distally tilted implants, respectively. Two models were generated: **AO4T** - anterior straight standard and posterior tilted standard implants; and **AO4S** - anterior straight standard and posterior straight short implants (Fig. 2).

Meshing and loading conditions

A ten-noded quadratic tetrahedral mesh was generated on Ansys Workbench R18.2 (Ansys Inc., Canonsburg, PA, USA) software for ductile (implants and prosthetic components) and non-ductile materials (cortical and trabecular bone). The tetrahedral geometry of the elements was maintained as much as possible to ensure the highest quality of the meshed models. The materials were considered linear elastic, isotropic and homogeneous. The Young modulus and Poisson ratio were defined for each material (Table 1). The mesh was adjusted for all structures, and the manual refinement was performed in the interface regions (i.e bone/implant interface, implant/abutment interface, abutment/superstructure interface). The manual refinement is regarded as an essential procedure because it enables to adjust the mesh in critical regions of interest (i. e. the interface area), which ensures the accuracy of the analysis.[18] The cortical and trabecular bone surfaces were regarded as perfectly connected. The implants were considered "osseointegrated" by assuming a bonded connection between the implants and bone. The implant/abutment and abutment/prosthetic bar interfaces were considered frictionless, with a 0.3 frictional coefficient, to better simulate the contact between these structures. The dimensions of the elements ranged from 0.10 to 2.0 mm (Fig. 3A). The number of nodes/elements generated in the AO4T and AO4S models were 1.790.698/1.208.528 and 1.598.783/1.082.033, respectively. The models were subjected to movement constraints, which were applied in all directions (x-, y- and z-components) in each node located in the posterior border of the ramus and angle of the mandible. A resultant force of 300 N was unilaterally applied at 75°

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angle in the linguo-buccal direction over the left side and posterior region of the prosthetic bar (Fig. 3B).[12]

Finite element analysis

The stress analysis was determined at the side of load application through the software Ansys Workbench R18.2. The maximum (tensile) and minimum (compressive) principal stresses were used to identify the stress peaks in the cervical region of the peri-implant bone area.[28] The measurements of the stresses in the implants were performed by using the numerical values probed from the stress areas in the von Mises equivalent stress criteria.

Statistical analysis

The statistical analysis was performed using the numerical values (n = 50) from the von Mises equivalent stress criteria predicted at the level of the implants' platform. The data were tested for Gaussian distribution (Kolmogorov-Smirnov normality test) and homogeneity of variances (Levene's test). Thereof, the Student t test was used to determine significant differences among the stresses performed in each model. All statistical tests were performed in GraphPad Prism 7 (La Jolla, CA, USA). The level of significance was set at .01.

Results

Von Mises Equivalent Stress

The stress values observed in the implants were below the yield strength of titanium-based materials.[29] The maximum peak values of the von Mises equivalent stress were observed around the inner surface of the platform (in contact with the abutment) of the distal left implants in the AO4T (383.63 MPa) and AO4S (450.52 MPa) configurations (Fig. 4A). The pattern of stress distribution was notably different among the distal implants of the AO4T and AO4S models (Fig. 4B). Statistically, the alternative configuration of the All-on-4™ concept performed with distal short implants significantly increased the values of mean stress in the platform region of the mesial left (95%, $p < 0.0001$) and distal left (16%, $p < 0.0001$) implants when compared with the arragement performed in the AO4T model (Fig. 5).

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Principal Stress Assessments

The maximum and minimum stress peaks observed in the AO4T and AO4S models did not reach the physiological limits of bone resistance.[30,31] The values of compressive stress (minimum principal stress) in the peri-implant bone crest were remarkably higher than the tensile stress (maximum principal stress). The compressive stress distribution mainly occurred in the buccal and lingual aspects of the distal left peri-implant supporting bone. The AO4T model showed a larger area of compressive stress compared with the AO4S design (Fig. 6).

The arrangement of the distal implant notably influenced the principal stresses in the peri-implant crestal bone. The highest values of maximum and minimum principal stresses occurred in the distal left area of the peri-implant crestal bone in the AO4T model (Table 2). The modified configuration of the All-on-4™ concept designed with distal short dental implants substantially reduced the values of compression (minimum principal stress) in the mesial and distal left areas of the peri-implant bone crest in 78% and 44%, respectively.

Discussion

Although finite element studies have shown the biomechanical performance of full-arch prosthetic restorations supported by four dental implants,[18,28,32] the influence of alternative configurations of the All-on-4™ concept performed with platform switched short dental implants have not yet been addressed. Herein, finite element simulations were carried out in atrophic mandibles using different configurations of the All-on-4™ concept. More specifically, this study evaluated wether the use of straight short (θ = 0°; 8 mm-length) or tilted standard (θ = 30°; 11 mm-length) distal implants with internal conical connection and platform switching design would result in similar values of stress at the level of implants and peri-implant bone tissue.

To our knowledge, the predictions of technical failures in implant-supported prosthesis (i.e screw fracture and loosening) can not be measured by clinical parameters and may be regarded as clinically impracticable. Thereby, finite element simulations have been often used to better understand the biomechanical issues related to the oral rehabilitation performed with the All-on-4 configuration.[16-19] In spite of that, intrinsic limitations of the finite element method must be acknowledged. It is known that finite element simulations

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precludes the use of dynamic loads that naturally occurs during mastication. Besides, there is no consensus on the ideal proportion of bone-to-implant contact in the finite element models. In the present study, the implants were considered "osseointegrated" by assuming a bonded connection between the implants and bone. In addition, since that oblique forces better represents the clinical scenario of the occlusal loads,[33,34] a resultant force of 300 N (branched into the x-, y- and z-components) was performed obliquely (θ = 75°) in the buccolingual direction over the left side of the prosthetic bar.

In contrast to most finite element studies that assessed the biomechanics of the All-on-4 system,[12,16,17,19] the inter-implant distance and the cantilever length of the models AO4T and AO4S were maintained to facilitate the interpretation of the results. In fact, just few numerical simulations have provided detailed information about the parameters used in the All-on-4 configurations.[11,18] In regards of the cantilever extensions, earlier studies suggested that the cantilever length should not exceed 20 mm[35] or 1.5 times the anteroposterior distance of the most anterior and most posterior implants.[36] In this respect, the 13-mm cantilever length was considered averaged for the All-on-4 configurations simulated in this study.

Considering the biomechanical behavior of implant-supported prosthesis, previous finite element studies have found the highest values of stress in the neck and platform of the implants.[18,28,32] In this regard, the mean stresses in the platform region were determined by probing the numerical values from the von Mises stress areas, as described previously.[37] The student t test was carried out to evaluate significant differences on the mean stresses predicted for the platform region of the mesial and distal left implants of the AO4T and AO4S models. The results of the current study showed that the arrangement of the distal implant in the models AO4T and AO4S significantly influenced the stresses performed in the implants and peri-implant bone crest. The All-on-4 configuration performed with distal short dental implants significantly increased the mean stresses in the platform region of the mesial and distal left implants. Although AO4T and AO4S models presented the maximum and minimum stress peaks within the physiological limits of bone resistance,[30,31] the use of distal short dental implants markedly reduced the tensile and compressive stress peaks in the peri-implant bone crest. These results are in line with a previous study[12] that compared the

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All-on-4 protocol and alternative conigurations designed with distal short dental implants. However, it should be noted that the results of the latter study were obtained with cylindrical implants with external hex prosthetic connection. Moreover, the implants in the AO4T and AO4S models were placed 2 mm below the bone ridge as recommended by previous studies.[38,39]

In summary, the results of the present study disagrees with the recent findings of our group that evaluated the All-on-4 configuration performed with distal implants of 6-mm-length and external hex connection (unpublished data; under review). The divergence against the outcomes found in our latter study can be explained by the different biomechanical behavior of implants with platform matching and platform switching design.[9] Besides, the apical positioning of morse taper implants below the bone crest is associated with lower stress in the peri-implant bone region.[40] Further, the results of the present study may be seen as an encouragement towards the use of the All-on-4 configuration with distal short dental implants with platform switching design. Nevertheless, it should be borne in mind that this is an *in silico* analysis that does not encompass all the complexity of the oral rehabilitation with implant-supported prostheses. Our recommendations for future research includes the biomechanical aspects of the All-on-4 configuration performed with short implants and ending abutments and different materials. In addition, because severe bone atrophy precludes the mid-crest-positioning of dental implants,[41] the biomechanical behavior of dental implants placed with a palatal approach should addressed. Above all, long-term clinical trials are necessary to confirm the results obtained from this finite element analysis.

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Conclusion

Based on the results of the present study and within the limitations of an *in silico* analysis, it can be concluded that both AO4T and AO4S configurations has the potential to be used for implant-supported restorations.

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Figure Legends

Figure 1. Standard and short length morse taper implants assembled to the prosthetic abutments. Straight abutments consisted of a single piece abutment and abutment screw.

Figure 2. Frontal view of the All-on-4 configurations. (a) AO4T configuration with standard length implants. (b) AO4S configuration with short length distal implants.

Figure 3. Finite element mesh and loading conditions. (a) Upper view of the All-on-4 configuration (AO4T) and the detailed features of the tetrahedral mesh. (b) Oblique loading condition performed in the prosthetic bar.

Figure 4. Representative images of the von Mises stress patterns in the mesial and distal left implants of the models AO4T (upper images) and AO4S (lower images). (a) The color scale depicts different levels of stress in the neck of the implants. (b) Stress distribution in the distal aspect of the tilted-standard and straight-short distal implants.

Figure 5. Values of mean stress predicted for the implants of the AO4T and AO4S configurations.*** Signifficant diference between the mesial left implants ($p < 0.0001$); ††† Significant diference between thedistal left implants ($p < 0.0001$).

Figure 6. Representative images of the compressive stress patterns. The color scale depicts different levels of stress performed in the AO4T (left) and AO4S (right) configurations.

Tables

Table 1. Mechanical properties assigned for each structure in the finite element simulation.

Material	Structure	Young modulus (E), MPa	Poisson ratio (v)	Reference
	Cortical bone	13,700	0.30	[42]
	Trabecular bone	1,370	0.30	[43]
Titanium	Implants	110,000	0.33	[43]
Ti-6Al-4V alloy	Abutments and screws	110,000	0.33	[44]
Ni-Cr alloy	Prosthetic bar	210,000	0.28	[21]

MPa: Megapascal; Ti-6Al-4V: Titanium-6Aluminium-4Vanadium alloy; Ni-Cr: Nickel-chromium alloy.

Table 2. Maximum and minimum values (in MPa) of the tensile and compressive stresses found in the peri-implant bone crest in the distal left (DL) and mesial left (ML) areas in each model.

Maximum Principal Stress (σ_{max})				
Groups/Region	AO4T (DL)	AO4T (ML)	AO4S (DL)	AO4S (ML)
Max	131.480	10.763	40.189	6.903
Min	-1.538	-9.383	-5.907	-4.215
Minimum Principal Stress (σ_{min})				
Groups/Region	AO4T (DL)	AO4T (ML)	AO4S (DL)	AO4S (ML)
Max	6.914	2.436	6.167	1.598
Min	-195.130	-36.492	-86.699	-28.773

MPa: Megapascal; AO4T: anterior straight standard and posterior tilted standard implants; AO4S: anterior straight standard and posterior straight short implants.

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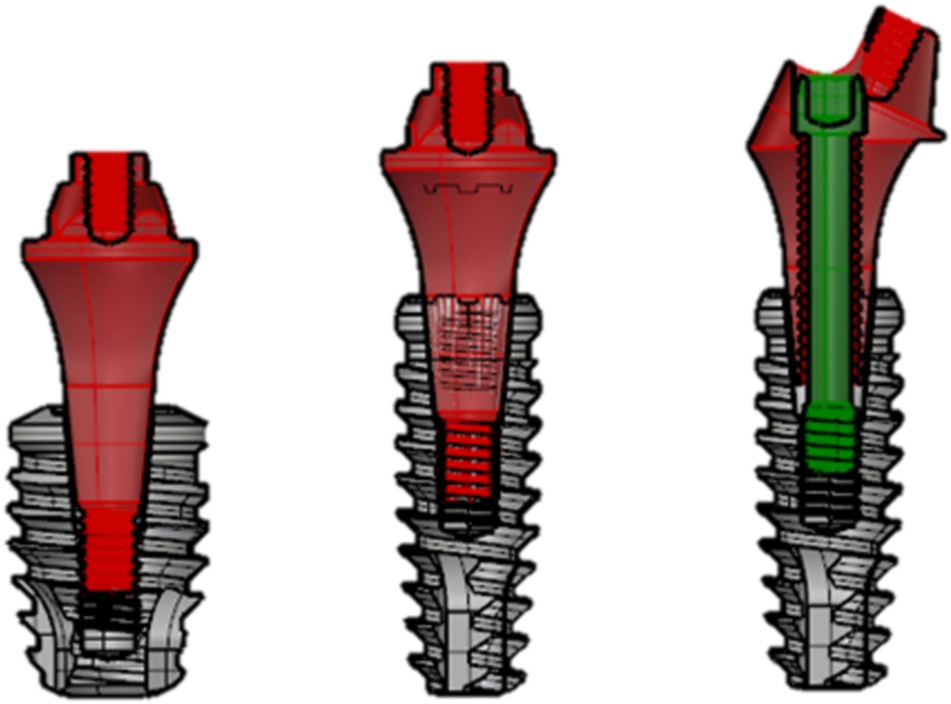

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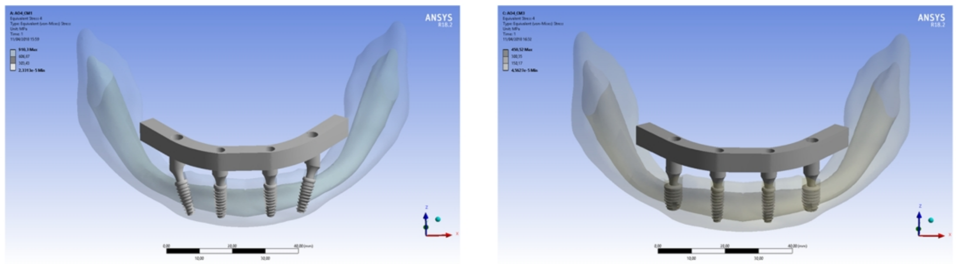

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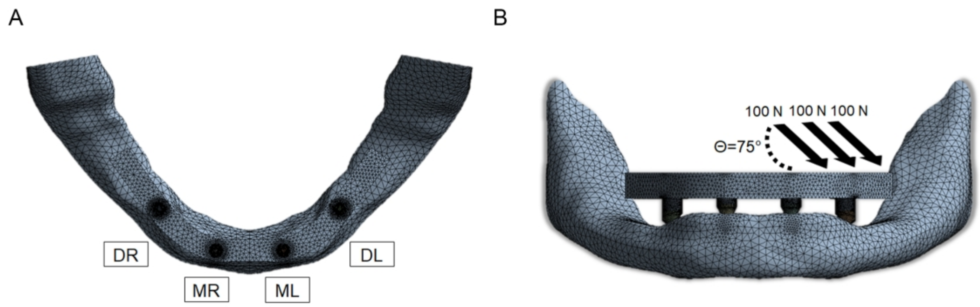

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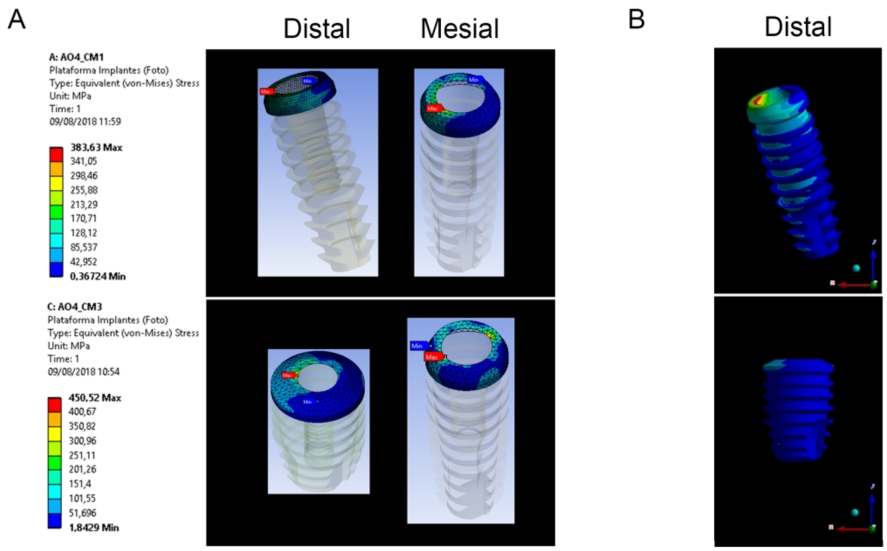

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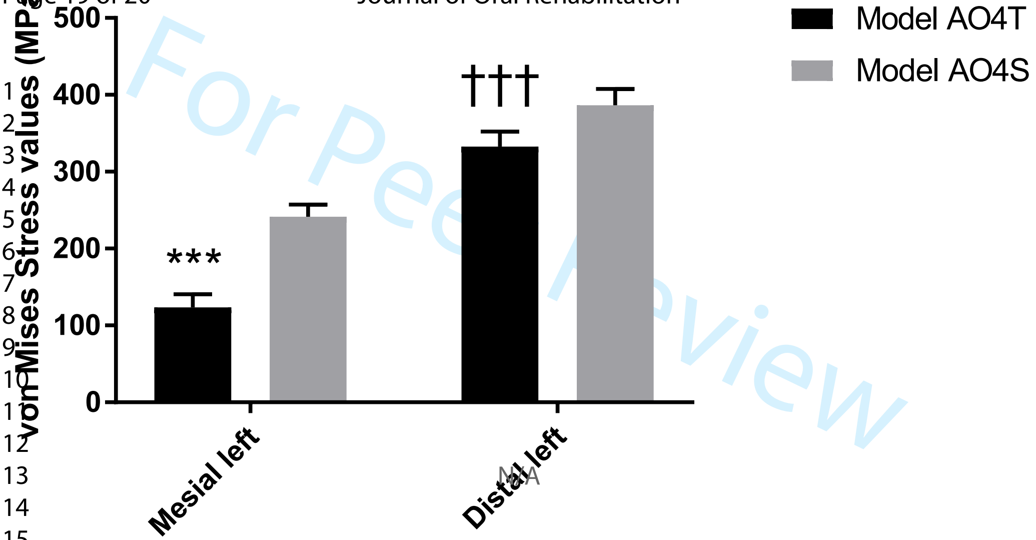

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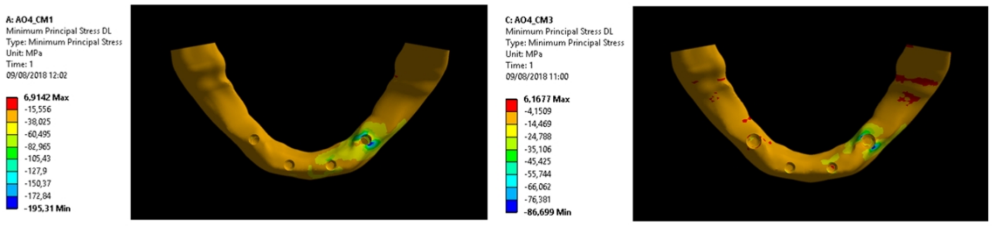

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3.2 Publicação 2*

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Title	Biomechanical behavior of different configurations of the All-on-4 concept in atrophic mandible models: A 3D finite element study with statistical analysis
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Abstract

This study performed finite element simulations using different configurations of the All-on-4 concept to evaluate wether the use of straight short (6 mm-length), straight standard (11 mm-length) or tilted standard (30° angled; 11 mm-length) posterior implants would result in similar stress levels in the prosthetic components, implants and surrounding bone. Different implant treatment alternatives were performed in atrophic mandible models. The All-on-4 configuration (H1 model) consisted of anterior straight standard and posterior tilted standard implants. Other configurations consisted of anterior straight standard and posterior straight short implants (H2 model) or anterior and posterior straight standard implants (H3 model). The dimensions of the prosthetic bar was maintained in all models. Three oblique forces of 100 N were simulated in the posterior region of the prosthetic bar. The values of mean stress were predicted for the ductile materials using the von Mises equivalent stress (σvm) criteria. The values of mean stress were submitted to the analysis of variance (ANOVA) and Tukey's post hoc tests ($\alpha = 0.01$). The stress peaks in the cervical region of the peri-implant bone area were measured by the maximum (σmax) and minimum (σmin) principal stresses. The H1 model (All-on-4) reduced the σmax and σmin in the posterior region of the peri-implant bone area. The H2 and H3 models significantly reduced the mean stresses in the bar screws, abutments and abutments screws ($p < 0.01$). The arrangement of the posterior implant in the All-on-4 configuration markedly influenced the mean stresses in the ductile materials and the σmax and σmin in the cervical peri-implant bone area.

Keywords	Dental implants; Mechanical stress; Finite element analysis; Short implants
Taxonomy	Materials Structure

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Figure 1 - Implant Dimensions.tif [Figure]

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Figure 3 - Mesh and Loading.tif [Figure]

Figure 4 - Mean Stress.tif [Figure]

Figure 5 - Principal Stress.tif [Figure]

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Data will be made available on request

Highlights

- Alternative All-on-4 designs increased the stresses in the prosthetic bar.
- Alternative All-on-4 configurations presented higher values of σ_{max} and σ_{min}.
- The standard All-on-4 design showed higher values of stress in the prosthetic screws.

Biomechanical behavior of different configurations of the All-on-4 concept in atrophic mandible models: A 3D finite element study with statistical analysis

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Abstract

This study performed finite element simulations using different configurations of the All-on-4 concept to evaluate wether the use of straight short (6 mm-length), straight standard (11 mm-length) or tilted standard (30° angled; 11 mm-length) posterior implants would result in similar stress levels in the prosthetic components, implants and surrounding bone. Different implant treatment alternatives were performed in atrophic mandible models. The All-on-4 configuration (H1 model) consisted of anterior straight standard and posterior tilted standard implants. Other configurations consisted of anterior straight standard and posterior straight short implants (H2 model) or anterior and posterior straight standard implants (H3 model). The dimensions of the prosthetic bar was maintained in all models. Three oblique forces of 100 N were simulated in the posterior region of the prosthetic bar. The values of mean stress were predicted for the ductile materials using the von Mises equivalent stress (σ_{vm}) criteria. The values of mean stress were submitted to the analysis of variance (ANOVA) and Tukey's post hoc tests (α = 0.01). The stress peaks in the cervical region of the peri-implant bone area were measured by the maximum (σ_{max}) and minimum (σ_{min}) principal stresses. The H1 model (All-on-4) reduced the σ_{max} and σ_{min} in the posterior region of the peri-implant bone area. The H2 and H3 models significantly reduced the mean stresses in the bar screws, abutments and abutments screws ($p < 0.01$). The arrangement of the posterior implant in the All-on-4 configuration markedly influenced the mean stresses in the ductile materials and the σ_{max} and σ_{min} in the cervical peri-implant bone area.

Keywords: Dental implants; Mechanical stress; Finite element analysis; Short implants

1. Introduction

The tooth loss is a common problem, not strict, but highly prevalent, in the elder population [1, 2]. In general, long-term edentulous patients exhibit excessive alveolar bone resorption, which sometimes restricts the placement of dental implants, especially in the posterior area of the mandible [3]. Noteworthy, such restrictions affects the final prosthesis design [4] and may result in long prosthetic cantilevers [5] which is associated with a higher amount of stress transmitted to the prosthetic bar, prosthetic screws, abutments and peri-implant bone [6].

The All-on-4™ (Nobel Biocare, AB, Göteborg, Sweden) protocol introduced by Maló et al. [7] enables the rehabilitation of severely resorbed jaws with complete fixed prosthesis connected to four dental implants. The rationale behind this concept is that by distally tilting the posterior implants at 30° or 45°, bone-to-implant contact can be improved, reductions in the cantilever length can be achieved, and the oral rehabilitation can be performed with a minimum risk to cause injury in the inferior alveolar nerve [8]. However, the presence of a minimum bone volume is of utmost important to perform the All-on-4™ treatment with dental implants of "sufficient" length (at least 10 mm) [7, 8]. Otherwise, complementary surgical procedures for vertical bone augmentation are priorly indicated [9, 10].

A trend to avoid, whenever possible, surgical procedures for bone augmentation, such as osteogenic distraction and interpositional bone grafts, is supported by the higher risks of clinical complications, and increased treatment time and costs these procedures entail for the patients [3, 9]. In this context, the use of shorter implants (≤ 8 mm) have been considered advantageous because it enables the rehabilitation of severely atrophic jaws whenever standard length implants (> 8 mm) cannot be placed without prior bone augmentation [10, 11]. Besides, the survival rates of short dental implants was found to be similar to that of the standard implants placed in vertically augmented bone [9].

The All-on-4™ concept performed with short dental implants may be considered a feasible alternative for complete rehabilitation of resorbed maxilla with fixed prosthesis [12]. However, despite the results of few studies that evaluated the biomechanics of different configurations of the All-on-4™ concept [13-15], there remains a paucity of data if the use of alternative All-on-4 configurations performed with short dental implants in atrophic mandibles would result in improved biomechanical performance in the prosthetic components, implants and the peri-implant bone.

Therefore, using three-dimensional finite element analysis, our group sought to evaluate the biomechanical aspects of different configurations of the All-on-4™ concept. More specifically, this study aim to test the null hypothesis that different configurations of the All-on-4™ concept would result in similar stress levels in the implants and prosthetic components.

2. Material and methods

2.1 Geometric reconstructions

Three-dimensional atrophic mandible models with 10 mm in width and 15 mm in height were generated in accordance with the classification proposed by Luhr et al.[16]. All models were generated at the Renato Archer Information Technology Center (CTI, Campinas, SP, Brazil) with an appropriate modelling software (Rhinoceros 5.0 SR12; McNeel North America, Seattle, WA, USA), as described elsewhere [17]. To better simulate the properties of resorbed mandibles, the cortical/trabecular bone ratio predicted for the models was 3:1 [18]. The stereolithography (stl) files provided by the manufacturer (Implacil De Bortoli, São Paulo, Brazil) were used to generate computer-aided design (CAD) images of dental implants, abutments, abutments screws and bar screws. The prosthetic bar made of nickel-chromium (Ni-Cr) was molded with 6 mm in height and 5 mm in thickness, in a horseshoe design, following the shape of the mandible, with a cantilever length of 13 mm on both sides [19]. The dimensions of bone width and height and the distance between the bone ridge and the bottom surface of the prosthetic bar was maintained in all models.

2.2 Implants system and experimental design

This study used dental implants and prosthetic components with external hexagon platform connection. Initially, the thread geometry of the implants was simplified in the Rhinoceros 5.0 SR12 platform to reduce the impact of difficult geometric features, which optimizes the computation efforts. Thereafter, the implants were placed into the atrophic mandible models according to the All-on-4 configuration [20]. The posterior implants were distally tilted at 30° angle, or placed vertically, into the models. In order to facilitate the stress analysis, it was assumed that both anterior implants and prosthetic components were in the “mesial left” (ML) and “mesial right” (MR) areas, whereas the two most posterior implants and prosthetic components were in the “distal left” (DL) and “distal right” (DR) areas. The implants were placed at the level of the bone crest [21], and the inter-implant distance of 15 mm was maintained in all models [22]. Those implants with more than 10 mm in length were considered as “standard” dental implants, while those with less than 8 mm in length were considered as “short” ones [23]. The dimensions of the implants are shown in Fig. 1. Straight and 30° angled abutments with 3 mm in height were connected to vertically placed and distally tilted implants, respectively. A total of three models were generated: **H1** (All-on-4) - anterior straight standard and posterior tilted standard implants; **H2** - anterior straight standard and posterior straight short implants; and **H3** - anterior and posterior straight standard implants (Fig. 2).

2.3 Meshing and loading conditions

A 10-noded tetrahedral mesh was generated on Ansys Workbench R18.2 (Ansys Inc., Canonsburg, PA, USA) software for ductile (implants and prosthetic components) and non-ductile materials (cortical and trabecular bone). The tetrahedral geometry of the elements was maintained as much as possible to ensure the highest quality of the meshed models. The materials were considered linear elastic, isotropic and homogeneous. The mechanical properties (Young modulus and Poisson ratio) was defined for each material (Table 1). The meshes were adjusted for all structures, and a manual refinement was performed in all regions of interest (i.e bone/implant interface, implant/abutment interface, abutment/superstructure interface). The manual refinement is regarded as an essential procedure because it enables to adjust the mesh in critical regions of interest, which ensures the accuracy of the analysis [15]. The surfaces of the cortical and trabecular bone were regarded as perfectly connected. The implants were considered “osseointegrated” by assuming a bonded connection between the implants and bone. The implant/abutment and abutment/prosthetic bar interfaces were considered frictionless, with a 0.3 frictional coefficient, to better simulate the contact between these structures. The dimensions of the elements were 0.10 to 2.0 mm. The number of nodes and elements in each model are shown in Table 2. All models were subjected to movement constraints, which were applied in all directions (x, y, z) in each node located in the posterior border of the ramus and angle of the mandible. Three static forces of 100 N were unilaterally applied at 75° angle in the linguo-buccal direction over the left side and posterior region of the prosthetic bar [24] (Fig. 3).

2.4 Finite element stress analysis

The stress analysis was carried out at the side of load application through the software Ansys Workbench R18.2. The maximum (tensile) and minimum (compressive) principal stresses (σ_{max} and σ_{min}) were used to identify the stress peaks in the cervical region of the peri-implant bone area [25]. The measurements of the stresses in the implants and prosthetic components were performed by using the numerical values probed from the stress areas in the von Mises equivalent stress (σ_{vm}) criteria. The mean stress in the ductile structures and the average stress across the models were established as described elsewhere [26]. The general displacements of the models were also evaluated.

2.5 Statistical analysis

The statistical analysis were performed by using the numerical values from the σ_{vm} criteria obtained in each structure. The data were tested for Gaussian distribution (Kolmogorov-Smirnov normality test) and homogeneity of variances (Levene's test). Thereof, the one-way analysis of variance (one-way ANOVA) and tukey's post-hoc tests were used to determine significant differences among the structures of the models. All statistical tests were performed in GraphPad Prism 7 (La Jolla, CA, USA). The level of significance was set at .01.

3. Results

In general, the mean stresses observed in the prosthetic bar, bar screws, abutments, abutment screws and implants (Fig. 4) were within the limits of Ti-based materials resistance [27]. The relationship between the mean stress values and the average stress found across the models are shown in Table 3.

3.1 Implants, abutments and abutment screws

The lowest values of mean stress were observed in the platform of the implants in the H1 (150.93 MPa) and H3 (141.05 MPa) models, which were below the average (170.13 MPa). The mean stress in the platform of the implants in the H2 (218.40 MPa) model was 44.71% and 54.85% higher than those observed in the platform of the H1 and H3 models, respectively. The statistical analysis showed that the use of a tilted standard (H1 model) or straight standard (H3 model) posterior implants significantly reduced the mean stresses in the platform region when compared with the straight short posterior implant (H2 model) ($p<0.001$). The difference in the mean stresses between the H1 and H3 models was statistically significant ($p < 0.001$), but not remarkable.

The highest values of mean stress were noticed in the abutments of the H1 (349.38 MPa) and H2 (305.88 MPa) models, which were higher than the average value (304.91 MPa). The values of mean stress were 34% and 17% lower in the abutments of the H3 model in comparison to the H1 and H2 models, respectively. Likewise, the mean stress in the abutment screws in the H1 model (629.90 MPa) was 44% and 76% higher in comparison to the H2 (437.00 MPa) and H3 (357.31 MPa) models, respectively. The mean stresses in the abutment screws of the H2 and H3 models performed below the average values. The use of tilted standard posterior implant (H1 model) statistically increased the mean stresses in the abutments and abutment screws when compared with the straigth short (H2 model) or straigth standard (H3 model) implants positioning ($p<0.001$).

3.2 Prosthetic bar and bar screws

The highest values of mean stress in the prosthetic bar were found in the H2 (264.65 MPa) and H3 (259.99 MPa) models, which were above the average value (252.36 MPa). The H1 model statistically reduced in 13.8% and 11.8% the mean stress in the prosthetic bar compared to the H2 and H3 models ($p<0.001$), respectively. No statistically significant diferences were observed for the values of mean stress in the prosthetic bar for the H2 and H3 models ($p>0.01$).

The mean stress in the bar screws in the H1 model was 41.1% and 52.4% higher than those observed in the H2 and H3 models, respectively. The mean stresses in the bar screws of the H2 (311.20 MPa) and H3 (296.75 MPa) models performed below the average value (353.54 MPa). The statistical analysis showed that the mean stress in the bar screws was found to be significantly higher in the H1 model compared to the H2 and H3 models ($p<0.001$).

3.3 Bone

The arrangement of the posterior dental implant markedly influenced the principal stresses (σ_{max} and σ_{min}) in the cervical region of the peri-implant bone area in all models (Fig. 5). In the DL area, the All-on-4 configuration with tilted standard posterior implant (H1 model) reduced the σ_{max} peaks in the peri-implant bone area in 294.5% e 407.4% compared to the configuration with straigth short (H2 model) and straigth standard (H3 model) posterior implants, respectively. In the ML area, the values of σ_{max} were 88.4% and 161% lower in the H1 model in comparison with the H2 and H3 models, respectively. When compared to the H2 and H3 models, the H1 model reduced the σ_{min} peaks in 7.3% and 7.5% in the DL area, respectively. Conversely, in the ML area, the H1 model markedly increased the σ_{min} peaks in 102.9% (compared to the H2 model) and 41.5% (compared to the H3 model) (Table 4).

3.4 Models displacements

General displacements notably occurred in the buccal aspect of all models, which coincided with the direction of the load application. The magnitude of general displacements was similar among the models (H1: 0.23314 mm; H2: 0.23555 mm; and H3: 0.23426 mm). The largest distribution of such displacements occurred in the symphysis and in the left side of the prosthetic bar in the H1 and H2 models, respectively (Fig. 6).

4. Discussion

The prosthetic rehabilitation with dental implants is a highly predictable treatment [28], associated with the improvement of the speech and masticatory function [29]. However, the anatomical features of atrophic jaws often precludes the use of standard length ($\geq$ 10 mm) dental implants [30], which implies in surgical procedures for bone augmentation or the use of short dental implants [9]. Indeed, short dental implants have been used in one- or multiple-unit crown restorations [31], with success rates comparable to that of standard-length implants [32]. In a FEA study, similar values of σ_{vm} were observed in the peri-implant bone region of short- and standard-length dental implants [33]. However, when it comes to the oral rehabilitation of severely resorbed jaws, there is a paucity of data with respect to the optimal configuration with short dental implants to support complete fixed prosthesis. Recently, Maló et al. [12] performed the All-on-4™ treatment with dental implants of 7- to 8.5 mm-length and considered it a viable option to restore completely edentulous patients. In a case series study, Moura et al. [34] reported the use of four 6.0 mm-length dental implants to support complete fixed prosthesis in severely resorbed mandibles. After 4 years of follow-up, the authors reported no signs of biological or technical complications. Given that few studies considered the biomechanical behavior of alternative configurations of the All-on-4™ concept in resorbed mandibles [24, 26], this study evaluated the stress levels in the prosthetic components, implants and peri-implant bone area using different All-on-4 configurations in atrophic mandible models.

The present study considered the All-on-4 configuration proposed by Maló et al. [7] (H1 model) and alternative designs with straight short (H2 model) or straight standard (H3 model) posterior implants. The statistical analysis was carried out to test the hypothesis of no significant difference between the configurations in the stress levels generated in the prosthetic components (prosthetic bar, bar screws, abutments, abutment screws) and implants. The present results demonstrate that alternative designs of the All-on-4™ configuration significantly reduced the stresses in the bar screws, abutments and abutments screws when compared to the configuration with tilted standard posterior implants (H1 model). Moreover, the same alternative designs significantly increased the stress values in the prosthetic bar. Further, the mean stress in the platform region was influenced by the arrangement of the posterior implant. Therefore, the null hypothesis that different configurations of the All-on-4™ concept would result in similar stress levels in the prosthetic components and implants was rejected.

Three-dimensional finite element analysis (3D-FEA) is often used to elucidate the biomechanical issues related to the masticatory function with implant-supported prosthesis [35, 36]. This approach includes numerical simulations to predict the stress distribution and structural displacements induced by axial or non-axial loads in the prosthetic components, implants and surrounding bone [19, 26, 37]. One of the main advantage of this technique is the reliable representation of the complex structures of the jaw by using computed-tomography (CT) data and computer-assisted design softwares.

Additionally, the predictions of structural failures in implant-supported prosthesis may be considered as clinically impracticable. Notwithstanding, some restrictions are inherent to the numerical simulations. For instance, the 3D-FEA approach precludes the use of dynamic loads that naturally occur during mastication. Besides, as the percentage of bone-implant contact greatly varies across the histological studies on implants osseointegration [38, 39], there is no agreement to determine the ideal proportion of bone-implant contact in the finite element simulations. As in all other FEA studies, the bone-implant contact was considered to be 100%, whereas ductile and non-ductile materials were described as linear elastic, isotropic and homogeneous [19, 40].

To our knowledge, despite of the studies that evaluated the muscular activity of patients with implant-supported prostheses [41-43], little is known about the extent of occlusal forces in the All-on-4 restorations. In a clinical study, Duyck et al. [44] demonstrated that the magnitude of biting forces in patients with implant-supported prosthesis can range from 50 N to 400 N in the molar region. A biting force of 105 N (± 39 N) and 112 N (± 44 N) was found in the premolar and molar region of patients with implant-retained overdentures, respectively [45]. Further, using finite element approach, Demenko et al. [46] determined the ultimate oblique masticatory forces for implants of different length and diameter, by simulating a resulting occlusal load of 118.2 N at approximately 75° angle related to the occlusal plane. Considering that oblique forces better mimics the occlusal loads [47, 48], static forces of 100 N were simulated at 75° angle in the left side of the prosthetic bar with a resultant value of 300 N.

Although there is limited evidence regarding the biomechanical behavior of alternative All-on-4 configurations, the present study showed that the use of straight short and straight standard posterior implants significantly increased the mean stress in the prosthetic bar in comparison with the All-on-4 configuration with tilted standard posterior implants. Interestingly, both of the alternative All-on-4 configurations (H2 and H3 models) significantly reduced the mean stresses in the bar screws, abutments and abutments screws below the average values. These results are slightly in accordance with a recent study that showed the highest values of σ_{vm} in the prosthetic bar, bar screws and abutments, when the All-on-4 configuration was performed with straight standard posterior implants [6]. In this regard, such disparity can be explained by the differences between the methods used in the latter study and the current one. In the present study, the mean stresses in the ductile materials were determined by probing numerical values from the σ_{vm} stress areas, which were compared to the average stress values predicted for the models, as described previously [26]. Moreover, in order to avoid biased results related to additional variables in the All-on-4 configurations, the inter-implant distance and the cantilevers length were maintained in all models. Previous studies recommended that the cantilever length should not exceed 20 mm [49] or 1.5 times the anteroposterior distance of the most anterior and most posterior implants [50]. In this regard, the 13-mm cantilever length was considered averaged for the All-on-4 configurations simulated in this study. Notwithstanding, it should be noted that, in a clinical situation, the cantilever extensions of the H1 and H2 models are shorter when compared with the H3 configuration. Therefore, the magnitude of the stresses observed in the prosthetic components and implants in the All-on-4 configurations with tilted standard and straight short posterior implants may be slightly overestimated. In the level of the implants, the highest value of mean stress was noticed in the platform region of the posterior short dental implant. Besides, the All-on-4 configuration with straight standard posterior implants reduced the mean stress in the platform region in comparison with the configuration with tilted standard posterior implants. This is consistent with a previous study that evaluated the biomechanical behavior of the All-on-4 configuration and alternative designs [24]. In that study, the highest value of σ_{vm} was observed in the straight short posterior implant in an alternative All-on-4 configuration. Moreover, Ozan et al. [6] demonstrated that the stress values were higher in the All-on-4 configuration performed with straight standard rather than tilted standard posterior implants. Taken together, these results may help to avoid/reduce the technical problems (such as prosthetic fracture or screw loosening) related to the oral rehabilitations using the All-on-4 concept [51].

Although peri-implantitis is the major cause for peri-implant alveolar bone loss [52, 53], the hypothesis that bone microdamage and subsequent peri-implant bone resorption can be triggered by excessive occlusal loads should not be ruled out, even in the absence of microrganisms [54]. In this respect, it is of utmost importance to understand how the arrangement of the implants in the All-on-4 configuration could affect the stresses generated in the peri-implant bone region. In the present study, the tensile and compressive stress peaks in the cervical peri-implant bone region were reported according to the σ_{max} and σ_{min} criteria, respectively.The use of tilted standard posterior implants markedly reduced the σ_{max} in both anterior and posterior peri-implant bone area. The All-on-4 configurations with straight short or straight standard posterior implants slightly increased the σ_{min} in the peri-implant bone crest. These results are in accordance with other FEA studies that showed lower stress values in the peri-implant bone region when the All-on-4 configuration was performed with tilted standard posterior implants [6]. The current study showed that the use of tilted standard posterior implants markedly increased the σ_{min} in the anterior peri-implant bone crest, which might be related to the largest area of bone displacement observed in the symphisis region of the H1 model.

In summary, all models presented the maximum and minimum stress peaks within the physiological limits of bone resistance [55, 56]. The results of the present study may be seen as a guide for the rational use of alternative configurations of the All-on-4™ concept in atrophic mandibles. However, one should keep in mind that this is an in silico study which does not encompass all clinical features of the oral rehabilitation with implant-supported prosthesis. More studies focused on the biomechanical aspects of the full-arch implant-supported prosthesis should address some of the following questions: 1) how do All-on-4 configurations with end abutments perform compared to distal cantilevers? 2) how do distally angled implants with short cantilevers extension perform compared to straight implants with longer cantilevers? 3) which materials would result in better stress distribution and clinical performance? Because bone atrophy might restrict the mid-crest-positioning of dental implants [57], the biomechanics of All-on-4 configurations performed with dental implants placed with a palatal approach should addressed. In addition, long-term prospective clinical trials are suggested to confirm the results of these numerical simulations.

5. Conclusion

The hypothesis that different configurations of the All-on-4 concept would result in similar stress values in the prosthetic components and implants was rejected, since that at least one of the alternative configuration statistically resulted in higher mean stress in the prosthetic bar and implants. Moreover, the arrangement of the posterior implant in the All-on-4 configuration markedly influenced the mean stresses in the ductile materials and the σ_{max} and σ_{min} in the cervical region of the peri-implant bone area.

Declarations of interest

None.

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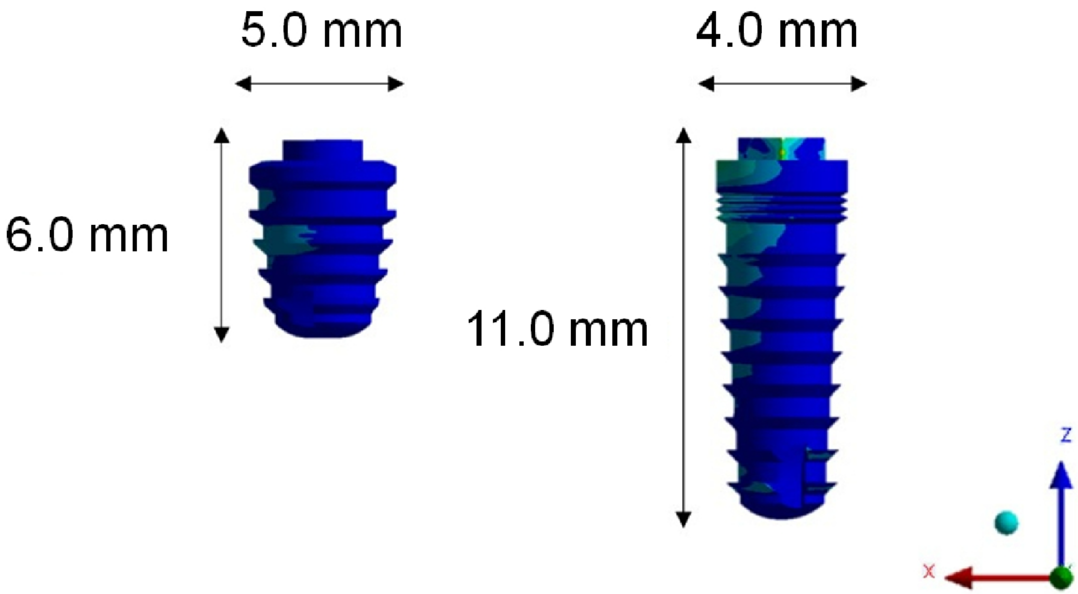
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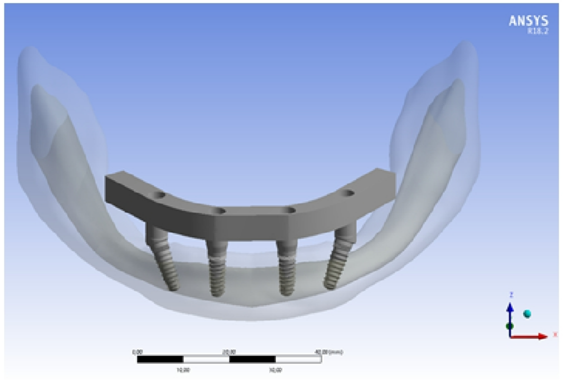
4.0 mm
6.0 mm
11.0 mm
Z
X

H1



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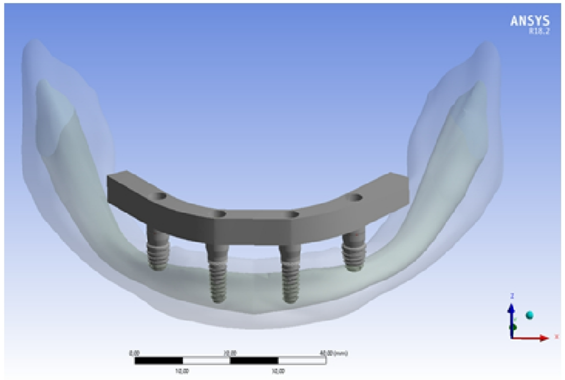

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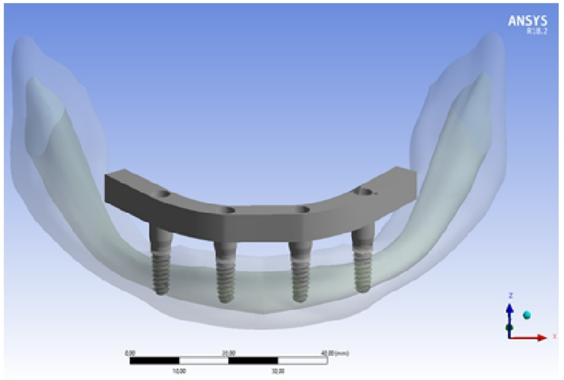

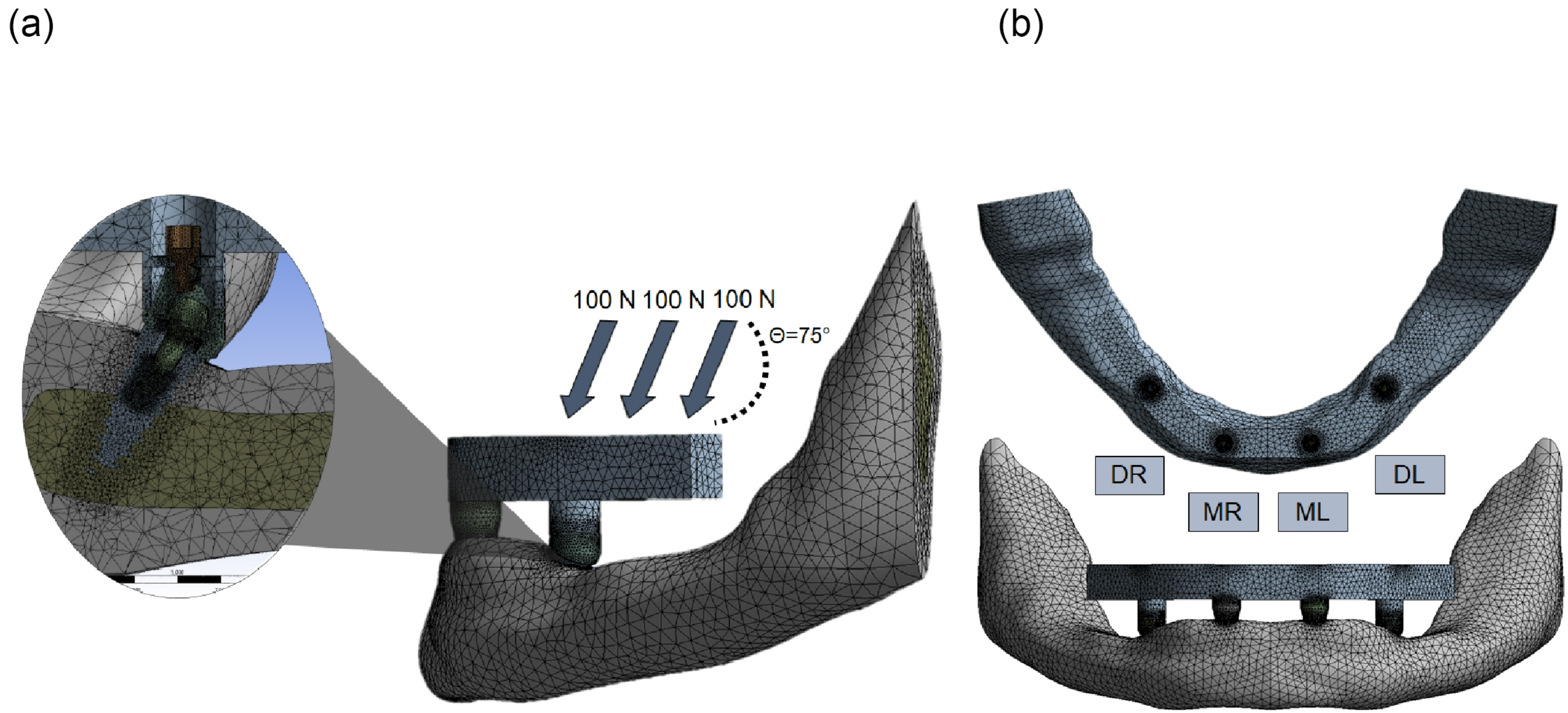

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(b)
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MR
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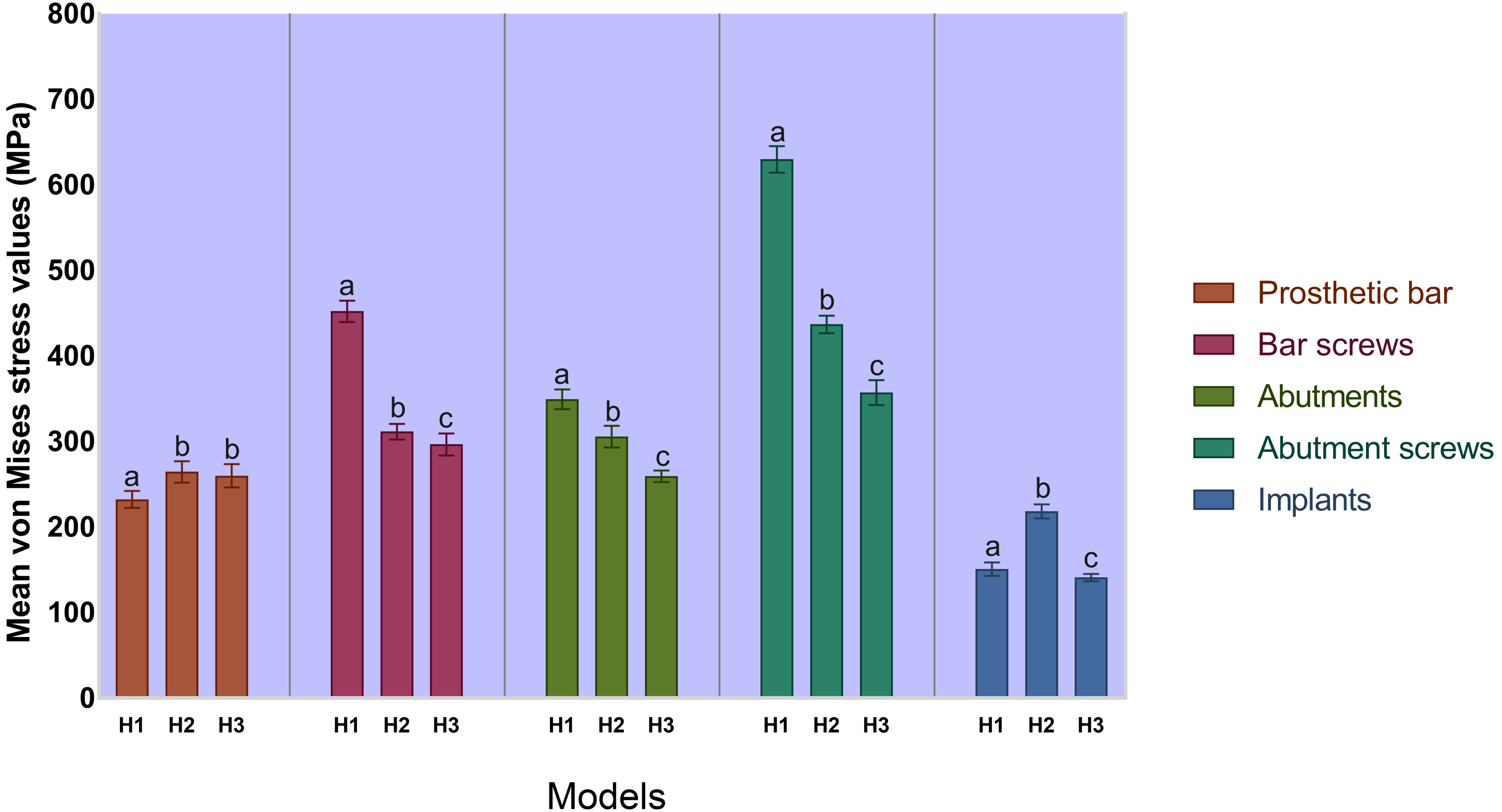

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300
200
100
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b
b
a
b
c
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H1
H2
H3
H1
H2
H3
H1
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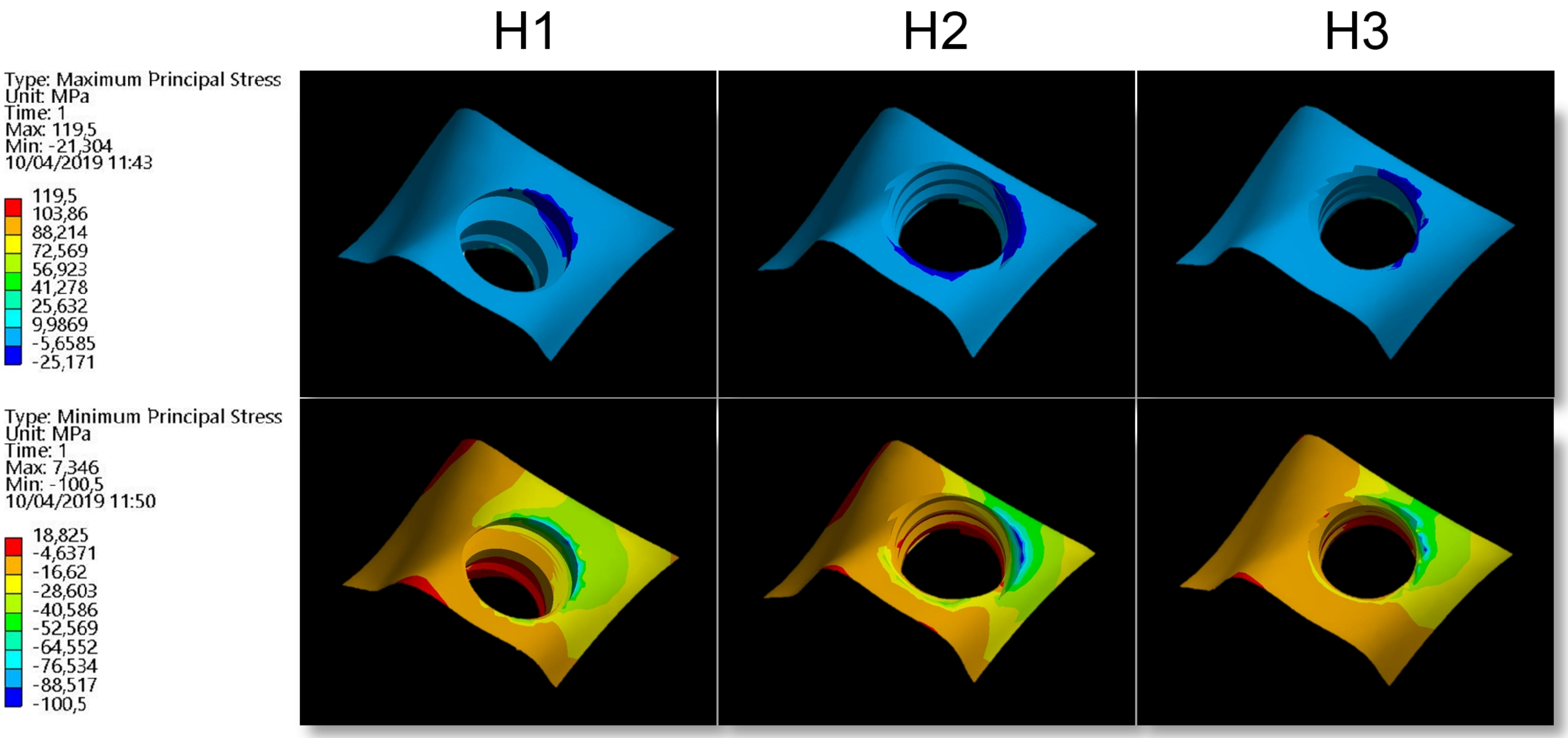
Models
Prosthetic bar
Bar screws
Abutments
Abutment screws
Implants


H1
H2
H3
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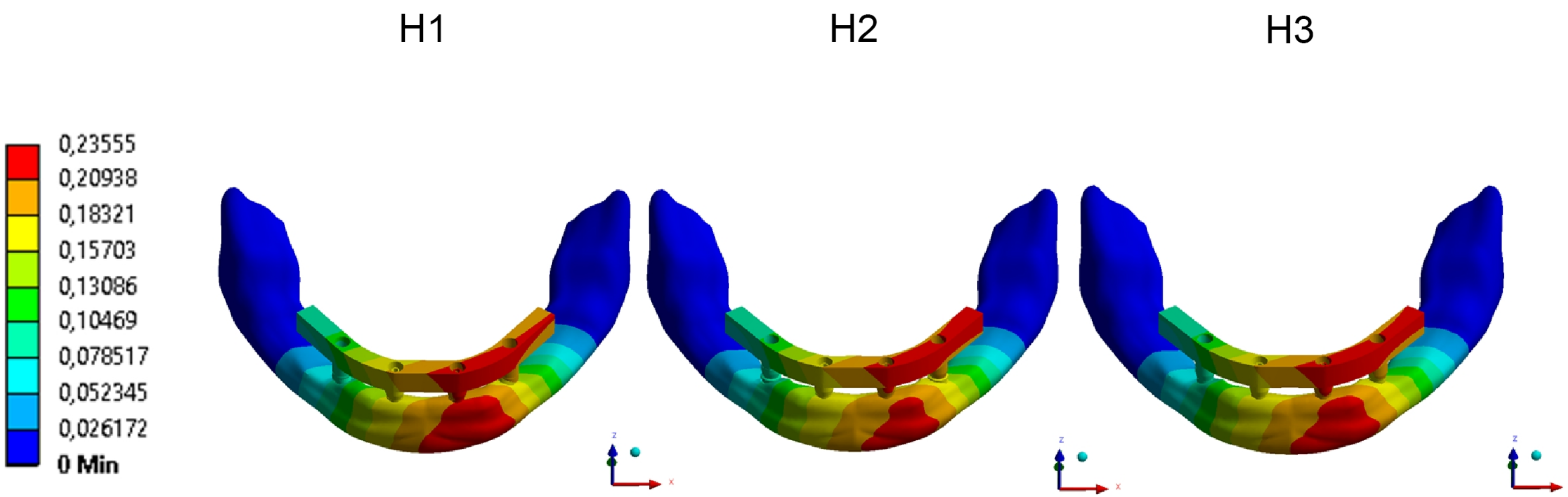
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Figure captions

Figure 1: Dimensions of standard- and short-length dental implants used in the All-on-4 configurations. The red, blue and green arrows indicate X, Y and Z axis.

Figure 2: Frontal view of the models H1, H2 and H3 illustrating the differencies among the All-on-4 configurations.

Figure 3: Meshing and loading conditions. (a) Lateral view of the detailed tetrahedral mesh generated in the All-on-4 configuration (H1 model). (b) Resultant load of 300 N obliquely applied in the prosthetic bar. ML - mesial left, MR - mesial right, DL - distal left, and DR - distal right.

Figure 4: Mean stress predicted for the ductile materials in each model. Different letters represents the statistical differences (p-value < 0.0001) between the structures of the models.

Figure 6: Magnitude of general displacements (in milimeters) after load application.

List of tables

Table 1

Mechanical properties of the materials assign in FEA.

Material	Structure	Young modulus (E), MPa	Poisson ratio (v)	Reference
	Cortical bone	13,700	0.30	35
	Trabecular bone	1,370	0.30	53
Titanium	Implants	110,000	0.33	53
Ti-6Al-4V alloy	Abutments and screws	110,000	0.33	54
Ni-Cr alloy	Prosthetic bar	210,000	0.28	14

Table 2

Number of elements and nodes in each model. **H1** - anterior straight-standard and posterior tilted-standard implants (All-on-4); **H2** - anterior straight-standard and posterior straight-short implants; **H3** - anterior and posterior straight-standard implants.

Groups	Elements	Nodes
H1	1,502,864	2,208,019
H2	1,281,872	1,883,953
H3	1,428,858	2,101,420

Table 3

The stress values (in MPa) predicted for each structure compared to the average stress values established across the models. The positive (+) and negative (-) signs indicates that the predicted values were above and below the average, respectively.

	Models			
Structure	H1	H2	H3	**Average stress (MPa)**
Prosthetic bar	-232.46	+264.65	+259.99	252.36
Bar screws	+452.25	-311.62	-296.75	353.54
Abutments	+349.38	+305.88	-259.49	304.91
Abutment screws	+629.90	+437.00	-357.31	474.33
Implants	-150.93	+218.42	-141.05	170.13

Table 4

The maximum (max) and minimum (min) peak values (in MPa) obtained for tensile (σ_{max}) and compressive (σ_{min}) stress in the cortical bone around the distal left (DL) and mesial left (ML) implants in each model.

Maximum Principal Stress (σ_{max})						
Groups/ Region	H1 (DL)	H1 (ML)	H2 (DL)	H2 (ML)	H3 (DL)	H3 (ML)
Max	23.551	3.826	92.932	7.211	119.500	9.987
Min	-25.171	-5.712	-22.136	-6.737	-21.304	-7.451
Minimum Principal Stress (σ_{min})						
Groups/ Region	H1 (DL)	H1 (ML)	H2 (DL)	H2 (ML)	H3 (DL)	H3 (ML)
Max	5.417	-0.226	18.825	0.2919	7.346	0.000
Min	-93.477	-21.378	-100.320	-10.534	-100.5	-15.099

Conflict of interest

Luis Carlos Leal Santana, Fernando Pozzi Semeghini Guastaldi, Henrique Takashi Idogava, Pedro Yoshito Noritomi, Camila Cristina De Foggi and Luis Geraldo Vaz, authors of the manuscript "Biomechanical behavior of different configurations of the All-on-4 concept in atrophic mandible models: A 3D finite element study with statistical analysis", declare no conflicts of interest.

4 CONCLUSÃO

Em suma, as conclusões do presente estudo foram:

1. Considerando-se a ausência de métodos clínicos capazes de avaliar o risco de fraturas protéticas e sobrecargas do tecido ósseo peri-implantar, a análise por elementos finitos representa um método viável para prever as regiões mais suscetíveis aos esforços mecânicos.

2. Posto que os valores de tensão de tração e compressão gerados na crista óssea peri-implantar diferem quanto ao tipo de conexão protética (hexágono externo ou cone Morse), há que se considerar incoerente a comparação entre os resultados obtidos no primeiro e no segundo estudo, em vista que a diferença quanto ao posicionamento dos implantes em relação à crista óssea exerce influência sobre os esforços mecânicos observados por meio do método de elementos finitos.

3. Em relação aos implantes com conexão protética do tipo cone Morse, a configuração All-on-4 projetada com implantes distais curtos (AO4S) associa-se ao menor risco de sobrecarga do tecido ósseo peri-implantar. Por outro lado, a configuração All-on-4 projetada com implantes distais angulados (AO4T) está associada ao menor risco de dano no módulo da crista dos implantes mesial e distal.

4. Em relação aos implantes com conexão protética do tipo hexágono externo, a configuração All-on-4 projetada com implantes distais de comprimento padrão e angulados a 30º (modelo H1) está associada ao maior risco de fratura de componentes protéticos, e ao menor risco de sobrecarga do tecido ósseo peri-implantar. Não obstante, a configuração All-on-4 com implantes paralelos, de comprimento curto (modelo H2) ou padrão (modelo H3), está associada ao menor risco de falhas técnicas e ao maior risco de sobrecarga do tecido ósseo peri-implantar.

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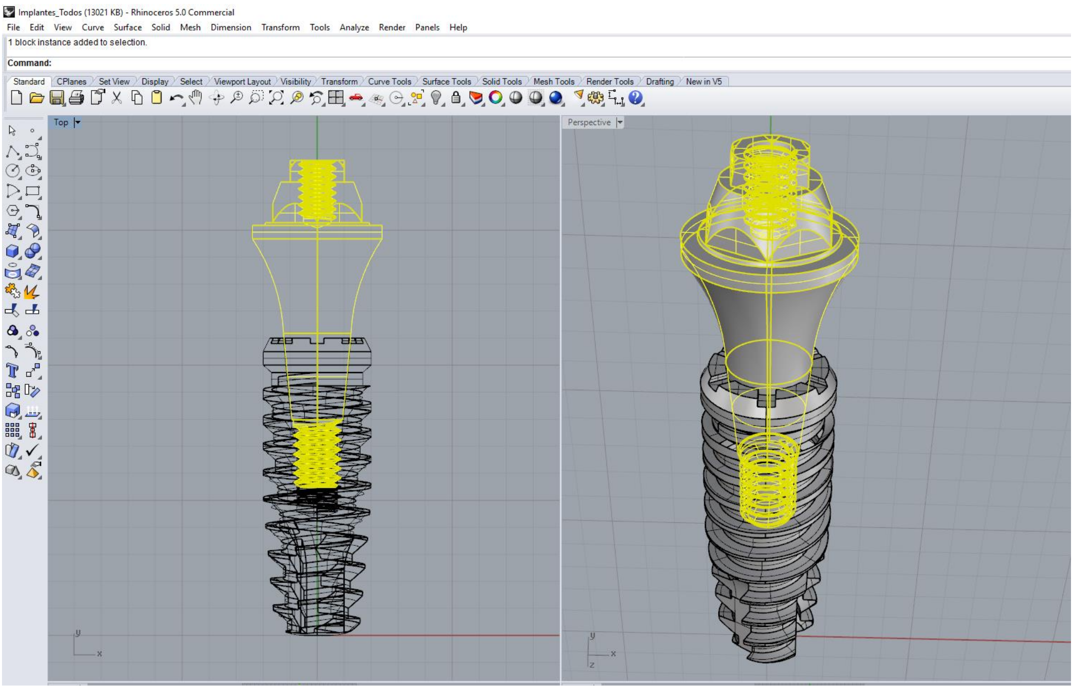
APÊNDICE A – MATERIAL E MÉTODOS

Modelos Tridimensionais

Modelos de mandíbula atrófica, com 10,0 mm de espessura e 15,0 mm de altura, foram gerados em um programa de modelagem tridimensional (Rhinocerus 5.0 SR 12; McNeel North America, Seattle, WA, EUA) a partir de dados disponíveis no Centro de Tecnologia da Informação Renato Archer. Para a simulação apropriada das características anatômicas de mandíbulas atróficas, a relação entre volume ósseo cortical e trabecular prevista para os modelos foi de 3:1. Arquivos de estereolitografia (stl) fornecidos pelo fabricante (Implacil De Bortoli, São Paulo, Brasil) foram utilizados para gerar arquivos de desenho assistido por computador (CAD) de implantes dentários, pilares e parafusos protéticos (Figura 1). Os arquivos CAD foram inseridos no programa de modelagem, e uma barra protética, com 6,0 mm de altura e 5,0 mm de espessura, foi confeccionada seguindo o formato do arco mandibular, com o cantilever distal medindo 13,0 mm de comprimento em ambos os lados do hemi-arco. As dimensões do volume ósseo e a distância entre a crista óssea e a superfície inferior da barra protética foram mantidas em todos os modelos.

Figura 1 - Configuração de desenho assistido por computador referente ao implante com conexão protética do tipo cone morse e plataforma *switching*

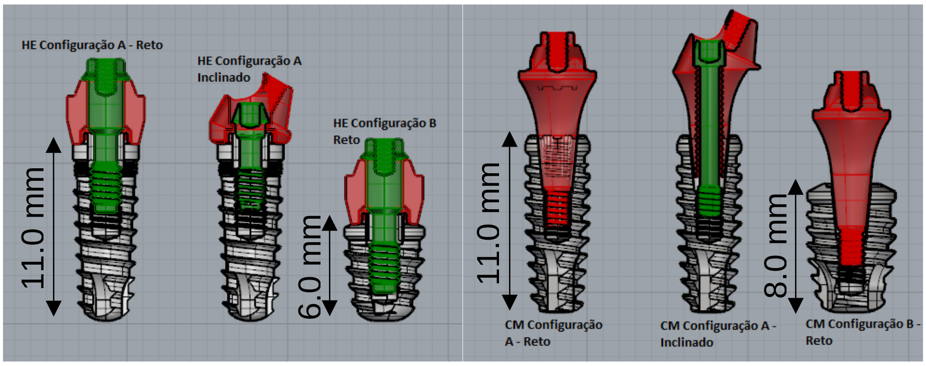


Autor: Núcleo de Tecnologias Tridimensionais (NT3D).
Fonte: Banco de Imagens do *Centro de Tecnologia da Informação Renato Archer*. 2019.

Sistema de Implantes e Desenho Experimental

O presente estudo utilizou componentes protéticos adequados a implantes com conexão do tipo hexágono externo ou cone morse. A geometria da rosca dos implantes foi simplificada no programa de modelagem para reduzir o impacto de geometrias complicadas sobre os esforços computacionais. Posteriormente, os implantes foram posicionados nos modelos de mandíbula atrófica de acordo com o conceito All-on-4™ (Nobel Biocare, AB, Göteborg, Sweden). Os implantes mais posteriores foram posicionados verticalmente, ou inclinados distalmente a 30° em relação à superfície da barra protética. Para facilitar a análise das tensões ósseas peri-implantares, assumiu-se que os implantes mais anteriores encontravam-se nas áreas “mesial esquerda” (ML) e “mesial direita” (MR), enquanto que os implantes mais posteriores localizavam-se nas áreas “distal esquerda” (DL) e “distal direita” (DR). Os implantes com conexão hexagonal externa e cone morse foram posicionados ao nível e 2,0 mm abaixo da crista óssea, respectivamente. Os implantes com 11,0 mm de comprimento foram considerados implantes dentários “padrão”, enquanto que aqueles com menos de 8,0 mm de comprimento foram considerados “curtos” (Figura 2). Pilares retos e angulados a 30°, com cinta de 3,0 mm de altura, foram conectados aos implantes posteriores verticais e angulados, respectivamente. Diferentes modelos da configuração All-on-4 foram gerados com implantes do tipo hexágono externo e cone morse (Figura 3).

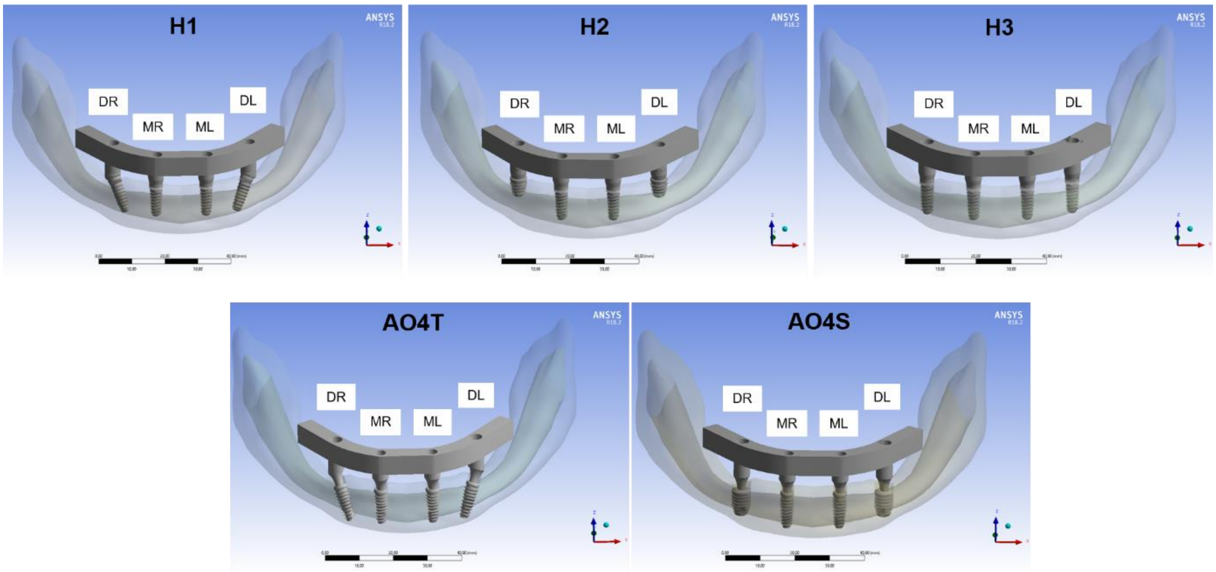
Figura 2 - Pilares protéticos retos acoplados aos implantes de comprimento padrão (11,0 mm) ou curtos (≤ 8,0 mm). Pilares protéticos angulados foram acoplados apenas aos implantes de comprimento padrão. Note que, diferente das configurações do tipo hexágono externo, o pilar protético cone morse reto é desprovido de parafuso passante



Autor: Luís Carlos Leal Santana.

Fonte: Adaptado do Banco de Imagens do *Centro de Tecnologia da Informação Renato Archer*. 2019.

Figura 3 - Configurações dos modelos All-on-4 com implantes com conexão cone morse ou hexágono externo.



Autor: Luís Carlos Leal Santana.

Fonte: Adaptado do Banco de Imagens do *Centro de Tecnologia da Informação Renato Archer*. 2019.

Geração da Malha e Condições de Carregamento

Uma malha tetraédrica de 10 nódulos foi gerada em programa de computador (Ansys Workbench R18.2, Ansys Inc., Canonsburg, PA, EUA) para os materiais dúcteis (implantes e componentes protéticos) e não dúcteis (osso cortical e trabecular). A geometria tetraédrica dos elementos foi mantida o máximo possível para garantir a alta qualidade de malha dos modelos. Os materiais foram considerados elásticos lineares, isotrópicos e homogêneos. As propriedades mecânicas (módulo de elasticidade e coeficiente de Poisson) foram definidas para cada material (Tabela 1). As malhas foram ajustadas para todas as estruturas, e um refinamento manual foi realizado em regiões de interesse (interface osso/implante; interface implante/pilar; e interface pilar/barra protética). O refinamento manual é considerado um procedimento essencial, pois permite o ajuste da malha em regiões críticas, passíveis de falhas matemáticas, o que garante a precisão da análise. As superfícies do osso cortical e trabecular foram consideradas perfeitamente conectadas. Como em outros estudos que utilizaram o método de elementos finitos, os implantes foram considerados 100% “osseointegrados”. Foi considerado o um coeficiente de atrito 0,3, entre as interfaces implante/abutment e pilar/barra protética. A dimensão mínima e máxima dos elementos foi 0,10 e 2,0 mm, respectivamente. Todos os modelos foram submetidos a restrições de movimento, as quais foram aplicadas em todas as direções (x, y, z) em cada nó localizado na borda posterior do ramo e ângulo mandibular. Três forças estáticas de 100 N foram aplicadas unilateralmente em ângulo de 75° na direção lingual-bucal no lado esquerdo e região posterior da barra protética (Figura 4).

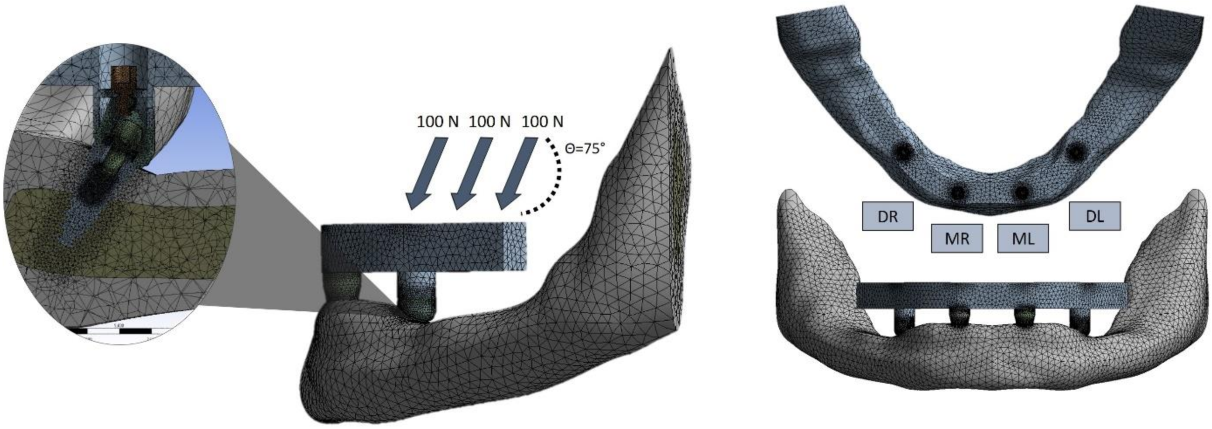
Tabela 1 - Propriedades mecânicas dos materiais dúcteis e não dúcteis

Material	**Estrutura**	**Módulo de Elasticidade (E), GPa**	**Coeficiente Poisson (v)**
	Osso cortical	13,70	0,30
	Osso trabecular	1,37	0,30
Titânio	Implantes	110,000	0,33
Liga Ti-6Al-4V	Pilares e parafusos protéticos	110,000	0,33
Liga Ni-Cr	Barra protética	210,000	0,28

Autor: Luís Carlos Leal Santana.

Fonte: Elaboração própria.

Figura 4 - Representação ilustrativa da malha após o refinamento manual em regiões críticas de interesse e condição de carregamento



Autor: Luís Carlos Leal Santana.

Fonte: Adaptado do Banco de Imagens do *Centro de Tecnologia da Informação Renato Archer*. 2019.

Análise de Tensões por Elementos Finitos

A análise de tensão foi realizada na região de aplicação de cargas através do software Ansys Workbench R18.2. As tensões principais máxima (σ_{max}) e mínima (σ_{min}) foram os parâmetros utilizados para identificar os picos de tensão na região da crista óssea peri-implantar. A análise de tensões equivalentes de von Mises (σ_{vm}) foi o critério utilizado para a análise de tensões em implantes e componentes protéticos. Em seguida, foi obtido o valor médio das tensões por meio da sondagem de valores numéricos nas áreas de concentração de tensão. A tensão média de cada estrutura dúctil foi comparada com sua respectiva tensão média geral dos modelos. O presente estudo também avaliou os deslocamentos gerais dos modelos H1, H2 e H3.

Análise Estatística

A análise estatística foi realizada utilizando-se os valores numéricos de σ_{vm} obtidos para cada estrutura. Os dados foram testados quanto a distribuição gaussiana (teste de normalidade de Kolmogorov-Smirnov) e homogeneidade de variâncias (teste de Levene). Em seguida, a análise de variância (one-way ANOVA) e o teste post-hoc de Tukey foram utilizados para determinar diferenças significativas entre as estruturas dos modelos. Todos os testes estatísticos foram realizados no Prism 7 (GraphPad, La Jolla, CA, EUA), considerando o nível de significância estatística o valor de $p < 0,01$.

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Araraquara, 10 de Setembro de 2019.

LUÍS CARLOS LEAL SANTANA