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**ANÁLISE BIOMECÂNICA DO EFEITO DA ESPLINTAGEM E DA CONEXÃO  
PROTÉTICA EM IMPLANTES EXTRA-CURTOS**

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PROTÉTICA EM IMPLANTES EXTRA-CURTOS**

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*“O valor das coisas não está no tempo que elas duram, mas na intensidade com que acontecem. Por isso, existem momentos inesquecíveis, coisas inexplicáveis e pessoas incomparáveis.”*

Fernando Sabino

## RESUMO

O objetivo deste estudo foi avaliar a distribuição da tensão em implantes extra-curtos inseridos em mandíbula com atrofia óssea, utilizando-se diferentes tipos de conexão protética (Cone Morse – CM e Hexágono Externo – HE) associadas a duas técnicas de confecção das coroas protéticas (separadas ou esplintadas). Um segmento de mandíbula tridimensional foi construído com base em imagem de tomografia computadorizada. Foram modeladas quatro configurações de dois implantes extra-curtos na região de primeiro e segundo molares inferiores, variando-se as conexões e as coroas protéticas. Os modelos foram carregados com força mastigatória normal. Os valores de tensão principal máxima ( $\sigma^{\max}$ ), mínima ( $\sigma^{\min}$ ), cisalhamento ( $\tau$ ) e deformação máxima ( $\epsilon^{\max}$ ) foram analisados para o tecido ósseo e os valores da tensão equivalente de von Mises ( $\sigma^{vM}$ ) para as estruturas dos implantes, parafusos e pilares protéticos. As conexões CM apresentaram maiores picos de tensão frente às conexões HE para implantes, pilares protéticos, parafusos protéticos e tecido ósseo. A simulação da esplintagem das coroas, independente do tipo da conexão, apresentou menores picos de tensão quando comparado aos grupos com coroas separadas, tanto para implantes, quanto para pilares protéticos, parafusos protéticos e tecido ósseo. A conexão HE apresentou melhor comportamento biomecânico quando comparada à conexão CM, independente da realização de esplintagem das coroas protéticas. A esplintagem das coroas protéticas, em região posterior de mandíbula atrófica, parece permitir melhor distribuição das tensões para o sistema prótese/implante e tecido ósseo. O tipo de conexão exerceu influência no comportamento biomecânico do sistema prótese/implante, observando-se melhores resultados quando da associação da conexão HE com esplintagem das coroas.

**Palavra-Chaves:** Implantes Dentários; Biomecânica; Análise de elementos finitos; Implantes dentários extra-curtos;

## ABSTRACT

The aim of this study was to evaluate the stress distribution on extra-short implants in cases of mandibular bone atrophy, with the use of different implant-abutment connections (Morse Taper - MT and External Hexagon – EH), associated with two crown designs (single-unit or splinted). A three-dimensional segment of the mandible was constructed, based on a computed tomography image. Four configurations of two extra-short implants in the mandibular first and second molar region were modeled, with variations in the implant-abutment connections and crown designs. The models were loaded with normal masticatory force. The values of maximum ( $\sigma^{\max}$ ), minimum ( $\sigma^{\min}$ ) principal, shear stress ( $\tau$ ) and maximum strain ( $\epsilon^{\max}$ ) were analyzed for the bone tissue and the values of equivalent von Mises stress ( $\sigma^{vM}$ ) for the structures of the implants, prosthetic screws and abutments. The MT connections showed the highest peaks of stress when compared to EH connections for implants, prosthetic abutments, prosthetic screws and bone tissue. Splinted crowns, irrespective of the implant-abutment connection, showed lower peaks of stress when compared with the groups with single-unit crowns, both for implants and for abutments, prosthetic screws and bone tissue. The EH showed better biological behavior when compared with MT, irrespective of crown designs. Splinted crowns in the posterior region of the atrophied mandible appeared to allow better distribution of stresses to the prosthesis/implant system and bone tissue. The implant-abutment connection had an influence on the biomechanical behavior of the prosthesis/implant system, with better results being observed with the association of the EH connection with splinted crown.

**Key-words:** *Dental Implants; Biomechanics; Finite Element Analysis; Extra-short dental implants;*

## LISTA DE ABREVIATURAS E SIGLAS

MEF	Método de Elementos Finitos
$\sigma^{\max}$	Tensão principal máxima
$\sigma^{\min}$	Tensão principal mínima
T	Tensão de cisalhamento
$\epsilon^{\max}$	Deformação máxima
$\sigma^{\text{vM}}$	Tensão equivalente de von Mises
CM	Cone Morse
HE	Hexágono Externo
FE-UFJF	Faculdade de Engenharia da Universidade Federal de Juiz de Fora
HEE	Hexágono Externo Esplintado
HENE	Hexágono Externo Não Esplintado
CME	Cone Morse Esplintado
CMNE	Cone Morse Não Esplintado
1ºM	Primeiro Molar
2ºM	Segundo Molar

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## 1 INTRODUÇÃO

A utilização dos implantes dentários é considerada um procedimento terapêutico de sucesso estético-funcional para a reabilitação da ausência dentária em região posterior dos arcos maxilo-mandibulares (MARKOVIC et al., 2015; ZEMBIC et al., 2013). A ausência dentária associada a fatores sistêmicos e a longos períodos de edentulismo pode acarretar em reabsorções em altura e espessura do osso alveolar (ANITUA; PINAS; et al., 2014). A redução em altura pode ser considerada um fator de risco para o tratamento restaurador com implantes dentários, especialmente na região posterior de mandíbula e maxila, onde estão presentes estruturas anatômicas, como o nervo alveolar inferior e o seio maxilar (MISCH et al., 2006; ROSSI et al., 2010), as quais apresentam-se como regiões submetidas a maiores forças mastigatórias (KOC; DOGAN; BEK, 2010).

As soluções terapêuticas para reabilitação de rebordos reabsorvidos, principalmente na região posterior da mandíbula, limitam-se a procedimentos cirúrgicos complexos como enxerto de tecido ósseo (SONG; LEE; KIM, 2015), lateralização do nervo alveolar inferior (SUZUKI et al., 2012) e distração osteogênica (CHIAPASCO et al., 2004), ou como alternativa a instalação de implantes curtos (com 6 a 8 mm de comprimento) e/ou extra-curtos (menores do que 6 mm de comprimento) (AL-JOHANY et al., 2017; MENDONÇA et al., 2014).

No entanto, os procedimentos cirúrgicos com o objetivo de ganho ósseo, especialmente em altura, como enxertos de tecidos ósseos e a distração osteogênica apresentam altas taxas de reabsorção do osso enxertado e baixa previsibilidade, respectivamente (PERDIJK et al., 2011). Além do aumento da morbidade do procedimento, há maiores riscos de complicações pós-operatórias, alterações neuro-sensorias, como na técnica de lateralização do nervo alveolar inferior (LEE et al., 2014), e aumento do tempo terapêutico.

A opção de tratamento de mandíbulas posteriores atróficas com implantes curtos ou extra-curtos apresentou maior segurança após a evolução dos diversos tratamentos de superfície. Estudos que avaliaram o desempenho de implantes curtos demonstraram taxas de sobrevivência e sucesso comparáveis àqueles obtidos com implantes de comprimento convencional (<10mm) (ANITUA; ALKHRAIST; et al., 2014; MANGANO et al., 2016); ANNIBALI et al., 2012; MEZZOMO et al., 2014). Desta

foram, mais recentemente, a instalação de implantes dentários extra-curtos tem sido proposta em situações de altura óssea severamente reduzida (GULJE et al., 2014; THOMA et al., 2015).

Embora alguns estudos relatem taxas de sobrevivência favoráveis quando de reabilitações com implantes curtos (RAVIV; TURCOTTE; HAREL-RAVIV, 2010; THOMA et al., 2015), observa-se certa incerteza, na literatura, quanto ao seu comportamento biomecânico, com relação à região da osseointegração e nos componentes protéticos, pois as coroas protéticas apresentam-se mais longas, devido ao maior espaço entre os arcos maxilomandibulares (BLANES et al., 2007; LAN et al., 2012), com uma proporção coroa/implante considerada como desfavorável. Além disso, a menor área de contato osso/implante, devido ao comprimento reduzido do implante, sugerem um comportamento biomecânico de risco (JAYME et al., 2015; SANZ; NAERT, 2009), principalmente quando da reabilitação com implantes unitários (RENOUARD; NISAND, 2005). O aumento na concentração de tensões e o maior desafio biomecânico podem incorrer em reabsorções ósseas, pela sobrecarga oclusal, em falhas da osseointegração, ou soltura e/ou fratura de parafusos protéticos (ROSSI et al., 2010; TONIOLLO et al., 2016).

Com o intuito de reduzir a concentração de tensões e melhorar a dissipação das forças mastigatórias, a literatura sugere o uso de implantes com conexões protéticas cônicas, as quais apresentam-se mais estáveis quando comparadas com as conexões protéticas do tipo hexagonal externa, a utilização de implantes com maior diâmetro e/ou a união das coroas (esplintagem) para aumentar a área de contato osso/implante (TSOUKNIDAS et al., 2015). Contudo, a união de implantes contíguos pode dificultar a higienização e provocar complicações biológicas como a peri-implantite (OGAWA et al., 2010).

Diversas metodologias já foram aplicadas buscando-se o entendimento do comportamento biomecânico das reabilitações com implantes curtos. Análises a base de testes destrutivos, como testes de fadiga por meio de ciclagem mecânica, ou a base de testes não destrutivos, como análises de extensiometria (SOTTO-MAIOR et al., 2012) ou MEF (FUH et al., 2013; KONG; PARK; CHOI, 2016). Assim, a utilização de uma metodologia, como o MEF, possibilita uma análise mais crítica da distribuição de tensões e deformações, prevendo sítios de concentrações e/ou dissipações de tensões, verificando-se a resistência a fratura e possibilitando melhor indicação para a utilização dos implantes extra-curtos com maior confiabilidade.

## 2 PROPOSIÇÃO

O presente estudo teve por objetivo avaliar o comportamento biomecânico de simulação de implantes extra-curtos inseridos em mandíbula com atrofia óssea, com diferentes tipos de conexão protética (Cone Morse e Hexágono Externo) associadas a duas técnicas de confecção das coroas protéticas (separadas ou esplintadas), quanto à distribuição das tensões de tração ( $\sigma^{\max}$ ), de compressão ( $\sigma^{\min}$ ) e de cisalhamento ( $\tau$ ), da deformação máxima ( $\epsilon^{\max}$ ) para o tecido ósseo e as tensões de von Mises ( $\sigma^{vM}$ ) nas estruturas do implante, do pilar protético e do parafuso protético.

### 3 MATERIAIS E MÉTODOS

#### 3.1 Delineamento experimental

Um segmento tridimensional da região posterior de uma mandíbula com atrofia óssea, parcialmente edêntula, foi construído virtualmente com base em imagens de tomografia computadorizada de feixe cônicos (Sistema de Imagem 3D Cone Beam i-CAT; Imaging Sciences International, Hatfield, EUA). O segmento ósseo foi constituído por osso medular envolto por osso cortical com a espessura de 2 mm (espessura média de osso cortical encontrada na região posterior de mandíbula) (MARKOVIC et al., 2015).

A partir de tal segmento ósseo, quatro montagens foram construídas simulando-se a presença de dois implantes extra-curtos na região de primeiro e segundo molares inferiores, variando-se as conexões protéticas (Cone Morse – CM e Hexágono Externo – HE). O desenho dos implantes foi desenvolvido a partir da geometria de produtos com conexão do tipo plataforma HE e CM de dimensões 4x5mm (SIN Sistema de Implantes, São Paulo, Brasil) e com espaçamento entre os centros de cada implante definido em 11mm para todos os grupos, de acordo com estudos presentes na literatura (YILMAZ et al., 2011).

Sobre os implantes dentários, foram reproduzidos os pilares protéticos (SIN Sistema de Implantes, São Paulo, Brasil), os parafusos protéticos (SIN Sistema de Implantes, São Paulo, Brasil) e duas coroas protéticas parafusadas a base de zircônia (separadas ou esplintadas), possuindo, ambas, a anatomia de um primeiro molar inferior. A proporção coroa/implante utilizada para os modelos foi de 2:1. Salienta-se que a relação ideal coroa-raiz recomendada é de 1:2, e no mínimo de 1:1 para um dente pilar (ANITUA; ALKHRAIST; et al., 2014).

Com o auxílio do programa Solidworks 2016 (3D tech-Solidworks, Waltham, EUA), os quatro modelos experimentais foram definidos através da combinação das plataformas de conexão e da união entre as coroas protéticas (Quadro 1 e Figura 1).

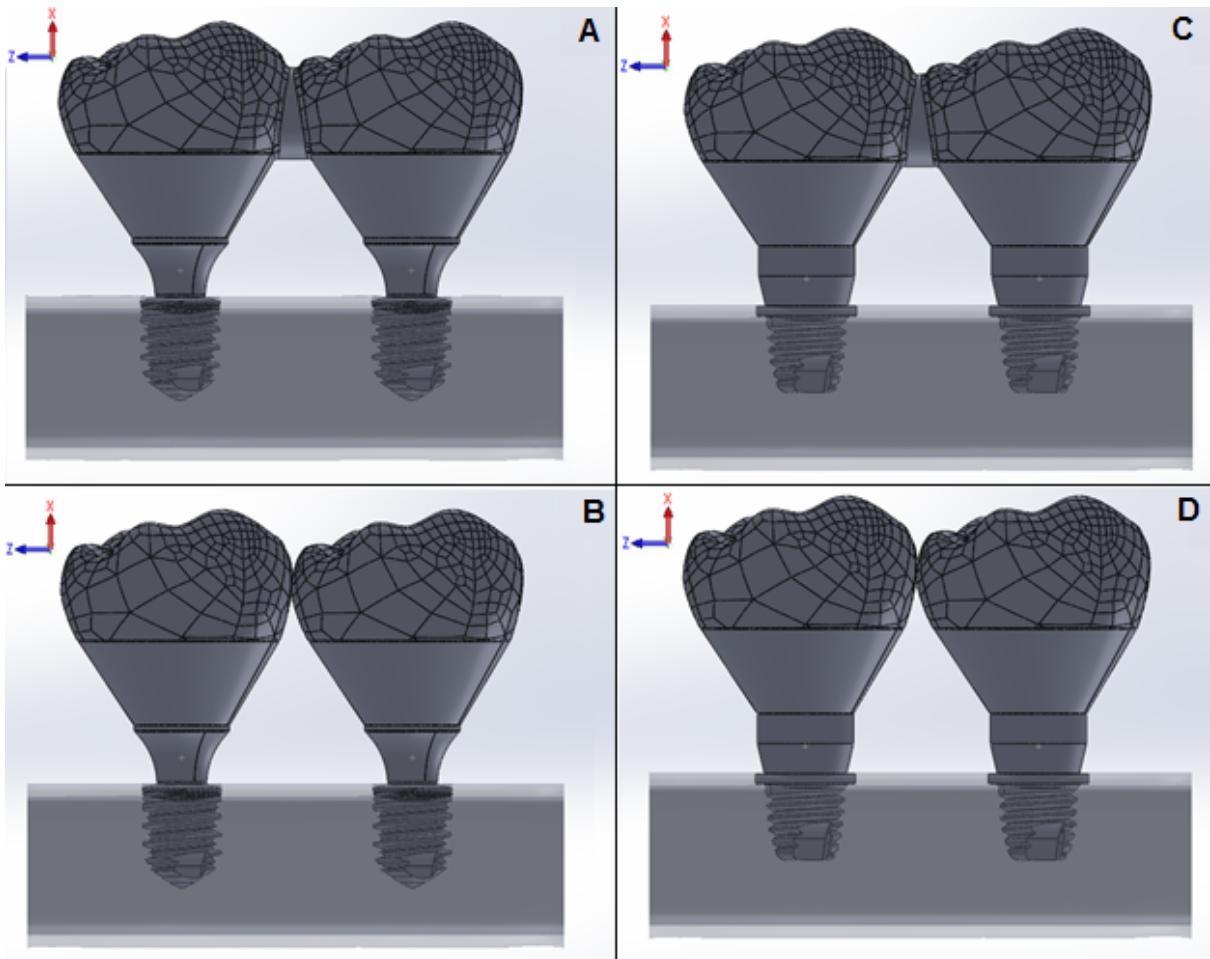
**Quadro 1 - Classificação e divisão dos grupos.**

<b>Grupo</b>	<b>Conexão Protética</b>	<b>Coroa Protética</b>
<b>HEE</b>	HE	Esplintadas
<b>CME</b>	CM	Esplintadas
<b>HES</b>	HE	Separadas
<b>CMS</b>	CM	Separadas

### 3.2 Análise por elementos finitos

Posteriormente à montagem dos grupos com auxílio do programa Solidworks 2016 (3D tech-Solidworks, Waltham, EUA), as montagens foram exportadas para programa de análise matemática dos elementos finitos (AnsysWorkbench versão 14.0 – Swanson Analysis Inc., Houston, EUA), onde uma análise biomecânica não-linear tridimensional para elementos finitos foi realizada.

As propriedades biomecânicas dos implantes, pilares protéticos, parafusos protéticos, coroas e o tecido ósseo foram representados por modelos isotrópicos, homogêneos e linearmente elásticos (Tabela 1) (FUH et al., 2013; İPLIKÇIOĞLU; AKÇA, 2002; KONG et al., 2016).



**Figura 1 - Modelos experimentais – A) Cone Morse Esplintado (CME); B) Cone Morse Separado (CMS); C) Hexágono Externo Esplintado (HEE); D) Hexágono Externo Separado (HES);**

Para a análise foi gerada uma malha de elementos e nós em todos os modelos que foram submetidos a processo de refinamento e uma análise de convergência a 5% foi realizada para confirmar sua precisão e garantir a comparação dos resultados.

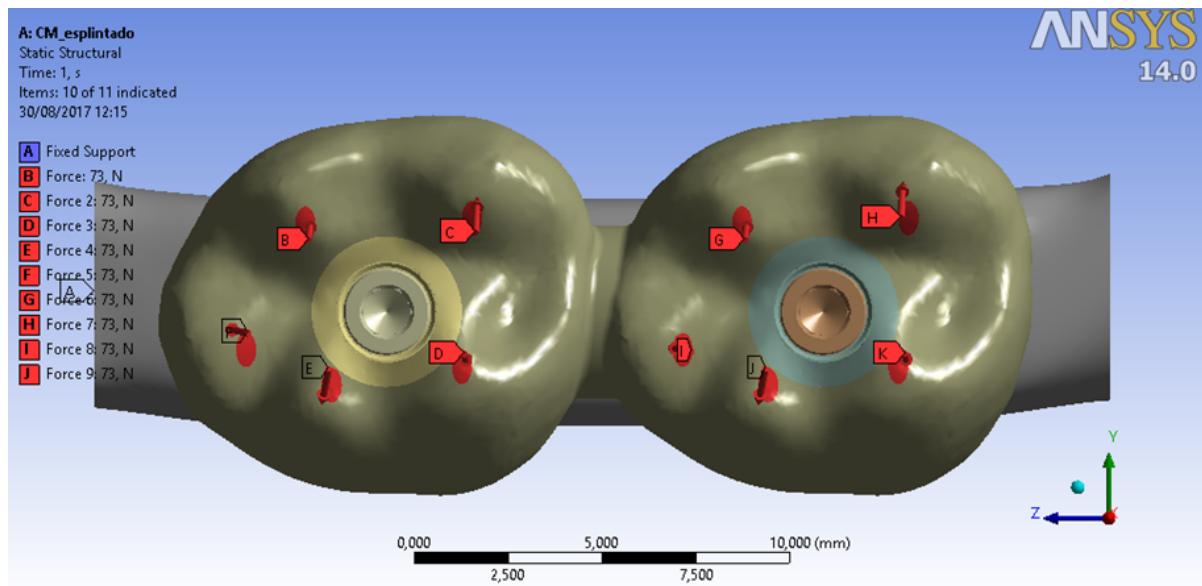
Após a análise de convergência, o valor do tamanho da malha foi definido em 0,2 mm. Os modelos apresentaram uma série de elementos cuja quantidade variou de 262.025 a 190.277 e um número de nós que variou de 449.535 a 327.912. As condições de contorno foram definidas mediante a fixação da distância nas superfícies externas mesial e distal do segmento ósseo em todas as direções dos eixos cartesianos (x, y e z). O carregamento dos modelos foi realizado nos pontos de contatos oclusais correspondentes a uma oclusão normal (Figura 2).

**Tabela 1** - Propriedades mecânicas das estruturas que compõem os modelos.

Estrutura	Módulo de Young (E – Gpa)	Coeficiente de Poisson ( $\delta$ )
<b>Titânio (Implante, parafuso e pilar protético)*</b>	100	0,35
<b>Zircônia (Coroa)†</b>	210	0,31
<b>Osso Medular*</b> ‡	1,85	0,30
<b>Osso Cortical*</b>	13,7	0,30

\*(IPLIKÇIOGLU; AKÇA, 2002) †(FUH et al., 2013) ‡(KONG et al., 2016)

Quando foi simulada a posição de intercuspidação entre os dentes, a relação de contato do dente antagonista ocorreu nas vertentes triturantes e deslizantes das cúspides dentárias dos arcos opostos. Para os molares inferiores (coroas), a relação de contato ocorreu nas vertentes deslizantes e triturantes das cúspides vestibulares e nas vertentes triturantes das cúspides linguais. O carregamento oclusal foi caracterizado por uma carga de 365N aplicada na direção da oclusão normal, perpendicular à cúspide da coroa e distribuída em cinco pontos de contato oclusal com área de 5 mm<sup>2</sup> para cada dente/corona (HATTORI et al., 2009; TONIOLLO et al., 2016) (Figura 2).

**Figura 2-** Carregamento dos modelos experimentais.

As regiões de contato não-linear foram definidas nas interfaces implante-tecido ósseo, implante-pilar protético e pilar protético-parafuso protético. A análise de contato

assegurou a transferência da força e da deformação entre as diferentes estruturas. Os coeficientes de atrito estabelecidos foram de 0,3 para as interfaces titânio-titânio e zircônia-zircônia (ALKAN; SERTGOZ; EKICI, 2004), de 0,65 para a interface titânio-osso cortical (YU et al., 2005) e de 0,77 para a interface titânio-osso medular (GRANT et al., 2007).

Os resultados avaliados para esta metodologia são o campo de  $\sigma^{\text{vM}}$  para o implante, pilar protético e parafuso protético e, o campo de  $\sigma^{\text{max}}$ ,  $\sigma^{\text{min}}$ ,  $\tau$  e  $\epsilon^{\text{max}}$  para o tecido ósseo foram obtidos para a comparação numérica e codificada por cor entre os grupos de todos os modelos.

Os valores de  $\sigma^{\text{vM}}$  são definidos como o início da deformação de materiais dúcteis (IPLIKÇIOĞLU; AKÇA, 2002), como os implantes metálicos. Assim, estes valores podem ser importantes para interpretar as tensões que ocorrem dentro do material dos implantes, pilares protéticos e parafusos de retenção. A falha pode ocorrer quando os valores de  $\sigma^{\text{vM}}$  excedem o limite de elasticidade do material do implante, pilar protético, parafuso protético considerado 550 Mpa.

As tensões principais oferecem a possibilidade de se distinguir em  $\sigma^{\text{max}}$  e  $\sigma^{\text{min}}$ . Os valores de  $\sigma^{\text{max}}$  (comumente tração) e os valores de  $\sigma^{\text{min}}$  (comumente compressão) são importantes para materiais friáveis, como o tecido ósseo. A falha pode ocorrer quando as  $\sigma^{\text{max}}$  ou de  $\sigma^{\text{min}}$  são iguais ou superiores à resistência de tração ou de compressão do osso, podendo ser detectada quando as  $\sigma^{\text{max}}$  excederem 100-130 MPa ou as  $\sigma^{\text{min}}$  excederem 170-190 Mpa (IPLIKÇIOĞLU; AKÇA, 2002).

## 4 ARTIGO

Artigo submatido ao periódico The International Journal of Oral & Maxillofacial Implants (Anexo B).

### **Biomechanical analysis of the effect of splinting and prosthetic connection on extra-short implants**

#### **Abstract**

The aim of this study was to evaluate the stress distribution on extra-short implants in cases of mandibular bone atrophy, with the use of different implant-abutment connections (Morse Taper - MT and External Hexagon – EH), associated with two crown designs (single-unit or splinted). A three-dimensional segment of the mandible was constructed, based on a computed tomography image. Four configurations of two extra-short implants in the mandibular first and second molar region were modeled, with variations in the implant-abutment connections and crown designs. The models were loaded with normal masticatory force. The values of maximum ( $\sigma^{\max}$ ), minimum ( $\sigma^{\min}$ ) principal, shear stress ( $\tau$ ) and maximum strain ( $\varepsilon^{\max}$ ) were analyzed for the bone tissue and the values of equivalent von Mises stress ( $\sigma^{VM}$ ) for the structures of the implants, prosthetic screws and abutments. The MT showed the highest peaks of stress compared to EH connections for implants, prosthetic abutments, prosthetic screws and bone tissue. Splinted crowns, irrespective of the implant-abutment connections, showed lower peaks of stress when compared with the groups with single-unit crowns, both for implants and for abutments, prosthetic screws and bone tissue. The EH showed better biological behavior when compared with MT, irrespective of crown designs. Splinted crowns in the posterior region of the atrophied mandible appeared to allow better distribution of stresses to the prosthesis/implant system and bone tissue. The implant-abutment connection had an influence on the biomechanical behavior of the prosthesis/implant system, with better results being observed with the association of the EH platform with splinted crown.

**Key-words:** Dental Implants; Biomechanics; Finite Element Analysis; Extra-short dental implants;

## Introduction

The use of dental implants is considered a successful esthetic and functional prosthetic therapy procedure for rehabilitating the absence of teeth (1, 2). The absence of teeth associated with systemic factors and long periods of edentulism may result in resorptions in the height and thickness of the alveolar bone (3). Reduction in height may be considered a risk factor for restorative treatment with dental implants, especially in the posterior region of the mandible and maxilla, where anatomic structures such as the inferior alveolar nerve and maxillary sinus are present (4, 5). These are regions submitted to the highest masticatory forces (6).

Therapeutic solutions for rehabilitation of resorbed ridges, particularly in the posterior region of the mandible are limited to complex surgical procedures, such as bone tissue grafting (7), lateralization of the inferior alveolar nerve (8), and osteogenic distraction (9), or alternatively, the insertion of short (6 to 8 mm in length) and/or extra-short implants (shorter than 6 mm in length) (10, 11).

However, the surgical procedures with the purpose of gaining bone, especially relative to height, with bone tissue grafts and osteogenic distraction present high rates of grafted bone resorption and low predictability, respectively (12). In addition to the increase in morbidity of the procedure, there are higher risks of post-operative complications, neuro-sensory changes such as occur with the inferior alveolar lateralization technique (13), and increase in time of therapy.

Studies that have evaluated the performance of short implants have demonstrated survival rates and success comparable with those obtained with implants of conventional length (14-17). Therefore, more recently, the insertion of extra-short dental implants has been proposed in situations of severely reduced bone height(18, 19).

Although some studies have reported favorable survival rates for rehabilitations with short implants (19, 20), a certain degree of uncertainty has been observed in the literature, with regard to their biomechanical behavior, region of osseointegration and prosthetic components, because the prosthetic crowns have been shown to be longer, due to the larger space between the maxillo-mandibular arches, with a crown-implant ratio considered unfavorable (21, 22). Furthermore, the smaller area of bone/implant contact due to the reduced length of the implant, suggested a biomechanical behavior or risk (23, 24), particularly in rehabilitation with single implants (25). Increase in the concentration of stresses and greater biomechanical challenge may result in bone

resorptions because of occlusal overload; failures in osseointegration, or loosening and/or fracture of the prosthetic screws (5, 26).

With the purpose of reducing the stress concentration and improve the dissipation of masticatory forces, the literature has suggested the use of implants with conical prosthetic connection, which have shown to be more stable when compared with the prosthetic connections of the external hexagon type, the use of larger diameter implants and/or the union of prosthetic crowns (splinting) to increase the bone/implant area of contact (27). However, the union of contiguous implants may make cleaning difficult and cause biological complications such as peri-implantitis (28).

There is still scarcity of data in the literature relative to understanding of the biomechanical behavior of extra-short implants. In view of the foregoing, and of the quest for more predictable procedures, the aim of this study was to evaluate the stress/strain distribution on the implant/prosthetic abutment/screw set and bone tissue of extra-short implants inserted in cases of mandibular bone atrophy, with the use of different types of implant-abutment connections (Morse Taper - MT and External Hexagon - EH), and associated with two crown designs (single-unit or splinted).

## **Materials and Methods**

### *Experimental Design*

A three-dimensional segment of the posterior mandible was created, based on a cone beam computed tomography image (3D Cone Beam i-CAT Image System; Imaging Sciences International). The bone model was composed of medullary bone enveloped by 2 mm thick cortical bone (mean cortical bone thickness found in the posterior region of the mandible (1).

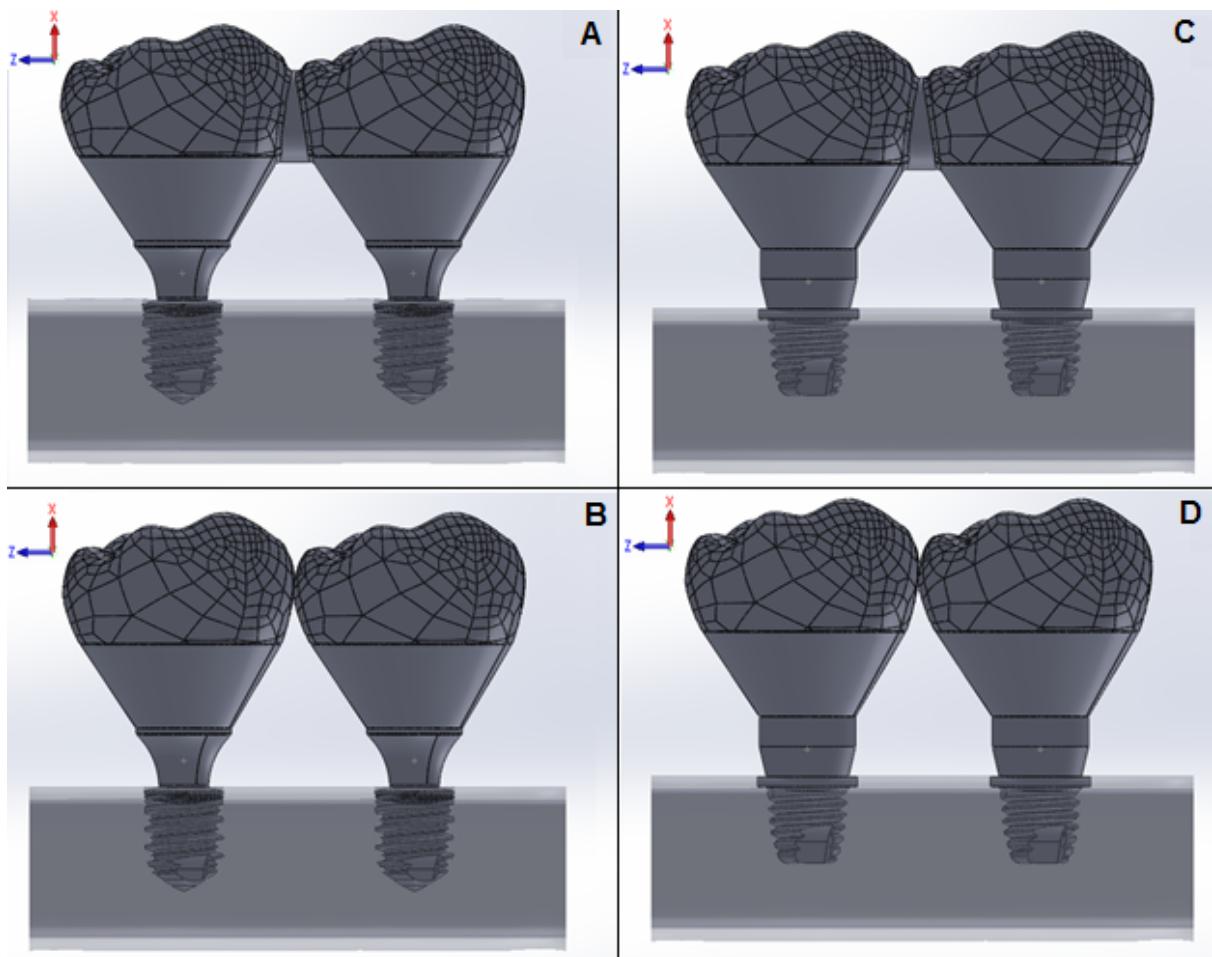
From this bone segment, four assemblies were constructed simulating the presence of two extra-short implants in the mandibular first and second molar region, with variation in the implant-abutment connections (MT and EH). The implant design was developed from the geometry of products with the EH and MT platforms measuring 4x5mm (SIN, São Paulo, Brazil), and with spacing between the centers of each implant defined at 11mm for all the groups (29).

On the dental implants, the abutments (SIN, São Paulo, Brazil); prosthetic screws (SIN, São Paulo, Brazil) and two screw-retained zirconium-based prosthetic crowns (single-unit or splinted), both with the anatomy of a mandibular first molar. The crown-implant ratio used for the models was 2:1.

With the aid of the Solidworks 2016 program (3D Tech-Solidworks, Waltham, USA), the four experimental models were defined by means of the combination of the implant-abutment connections and the crown designs (Figure 1).

#### *Finite Element Analysis*

The assemblies were exported to the finite element mathematical analysis program (AnsysWorkbench version 14.0 – Swanson Analysis Inc., Houston, USA), for non-linear biomechanical analysis. The biomechanical properties of the implants, abutments, prosthetic screws, crowns and bone tissue were represented by homogeneous, linearly elastic, isotropic models (Table 1) (30-32).



**Figure 1.** Experimental Models – A) Splinted Morse Taper (SMT); B) Single-unit Morse Taper (SUMT); C) Splinted External Hexagon (SEH); D) Single-unit External Hexagon (SUEH).

A mesh of elements and knots was generated in all the models, which were submitted to a process of refinement and analysis of convergence at 5%.

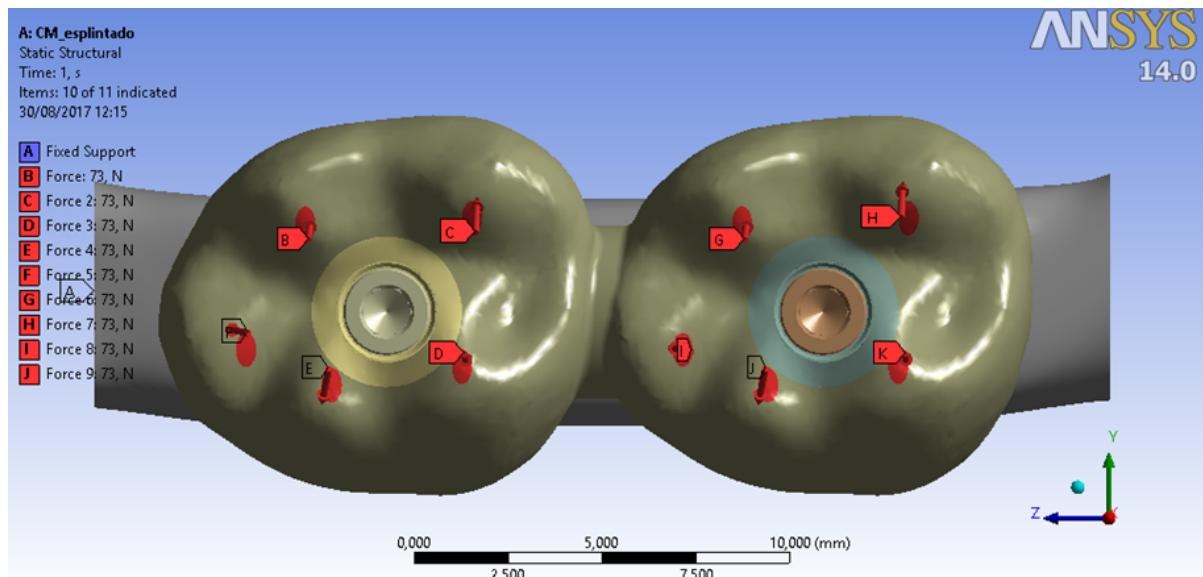
After the analysis of convergence, the value of the mesh size was defined at 0.2 mm. The models had a series of elements, the quantity of which varied from 262.025 to 190.277, and a number of knots that varied from 449.535 to 327.912. The contour conditions were defined by means of fixing the distance of the external mesial and distal surfaces of the bone segment in all the directions of the Cartesian axes (x, y and z).

Structure	Young's Modulus (E - Gpa)	Poisson Coefficient ( $\delta$ )
<b>Titanium (Implant, prosthetic screw and abutment)*</b>	100	0.35
<b>Zirconium (Crown)<sup>#</sup></b>	210	0.31
<b>Medullary Bone*<sup>&amp;</sup></b>	1.85	0.30
<b>Cortical Bone*</b>	13.7	0.30

\*[28] <sup>#</sup>[29] <sup>&</sup>[30]

**Table 1.** Mechanical Properties of the Structures that Compose the Models.

The models were loaded on the points of occlusal contacts corresponding to a normal occlusion with an occlusal load of 365N applied in the direction of normal occlusion, perpendicular to the zirconia crown and distributed on five points with an area of 5 mm<sup>2</sup> for each tooth/zirconia crown (26, 33) (Figure 2).



**Figure 2.** Loading of Experimental Models.

The regions of non-linear contact were defined at the following interfaces: implant/bone tissue; implant/abutment; and abutment/prosthetic screw. The frictional coefficients established were 0.3 for the titanium/titanium and zirconia/zirconia interfaces (34), 0.65 for the titanium-cortical bone interface (35) and 0.77 for titanium-medullary bone interface (36).

The results evaluated for this methodology were the von Mises stress ( $\sigma^{\text{vM}}$ ) field for the implant, abutment and prosthetic screw, and the maximum principal stress ( $\sigma^{\text{max}}$ ), minimum principal stress ( $\sigma^{\text{min}}$ ), shear stress ( $\tau$ ) and maximum strain ( $\epsilon^{\text{max}}$ ) fields for the bone tissue were obtained for numerical comparison and color coded among the groups of all the models.

## Results

The maximum  $\sigma^{\text{vM}}$  values for all the groups may be observed for the implants, abutments and prosthetic screws (Figure 3, Figure 4). The highest  $\sigma^{\text{max}}$ ,  $\sigma^{\text{min}}$ ,  $\tau$  and  $\epsilon^{\text{max}}$  for cortical and medullary bone for all the groups (Figure 5, Figure 6, Figure 7).

### *Implant*

The  $\sigma^{\text{vM}}$  values on the implants of the non-splinting groups showed higher concentration on the distal surfaces in both implants. However, on the implants of the groups with splinted crowns, a higher concentration of stresses was observed on the distal surface to that of splinted surface (Figure 4).

Single-unit implants showed the highest peaks of stress, and for the groups with morse taper platform, there was an increase in  $\sigma^{\text{vM}}$  of 42.58% for the 1st molar, and 9.09% for the 2nd molar. For the external hexagonal connection, the increase was 10.14% for the 1st molar, and 42.77% for the 2nd molar. When the results of splinted implant-abutment connections were compared, the lowest peak stress values were found on the external hexagon: 3.82% for the 1st molar, and 44.28% for the 2nd molar, compared with the peak stress values of the morse taper; for the single-unit implants, the difference in stresses was 38.55% for the 1st molar, and 42.77% for the 2nd molar (Figure 3).

### *Abutment*

The abutments of the EH connection showed higher concentration of  $\sigma^{\text{vM}}$  close to the contact edge of the prosthetic abutment with the prosthetic crown cylinder, in both the SEH and SUEH. However, the abutments of the MT connection showed a higher concentration of  $\sigma^{\text{vM}}$  on the contact edge of the abutment with the implant, in both Group SMT and Group SUMT (Figure 4).

In Group SUEH, the highest  $\sigma^{\text{vM}}$  values for the abutment were 210.54 MPa for the 1st molar and 449.81 MPa for the 2nd molar; and in the Group SEH, the highest values for the abutment were 182.69 MPa for the 1st molar and 351.94 MPa for the 2nd molar (Figure 3).

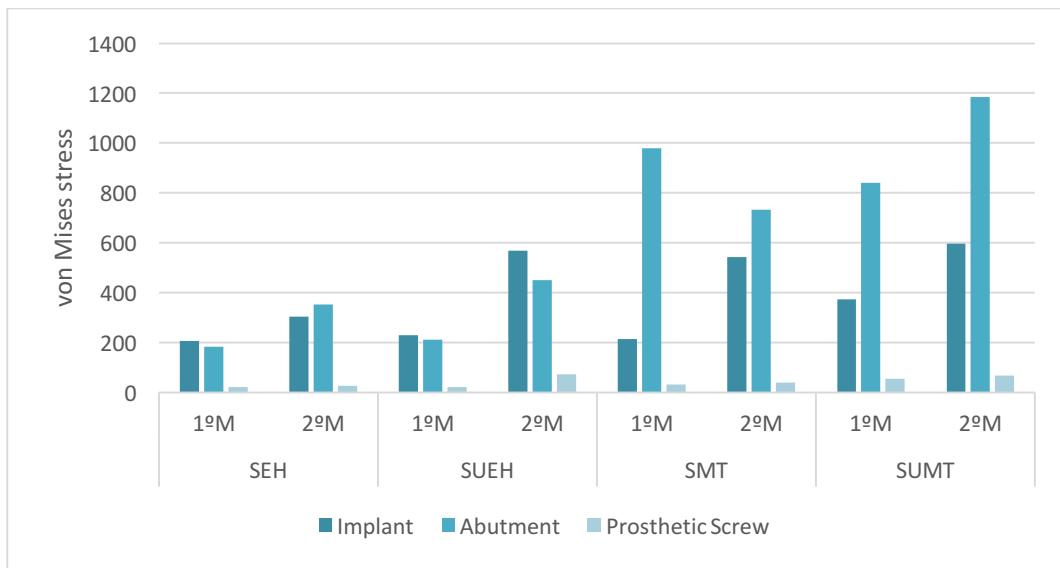
Group SUMT showed an increase of 61.70% of the  $\sigma^{\text{vM}}$  values for the 2nd molar when compared with Group SMT, while for the 1st molar, the SMT presented an increase of 16.43% in the  $\sigma^{\text{vM}}$  values when compared with the Group SUMT (Figure 3).

### *Prosthetic Screw*

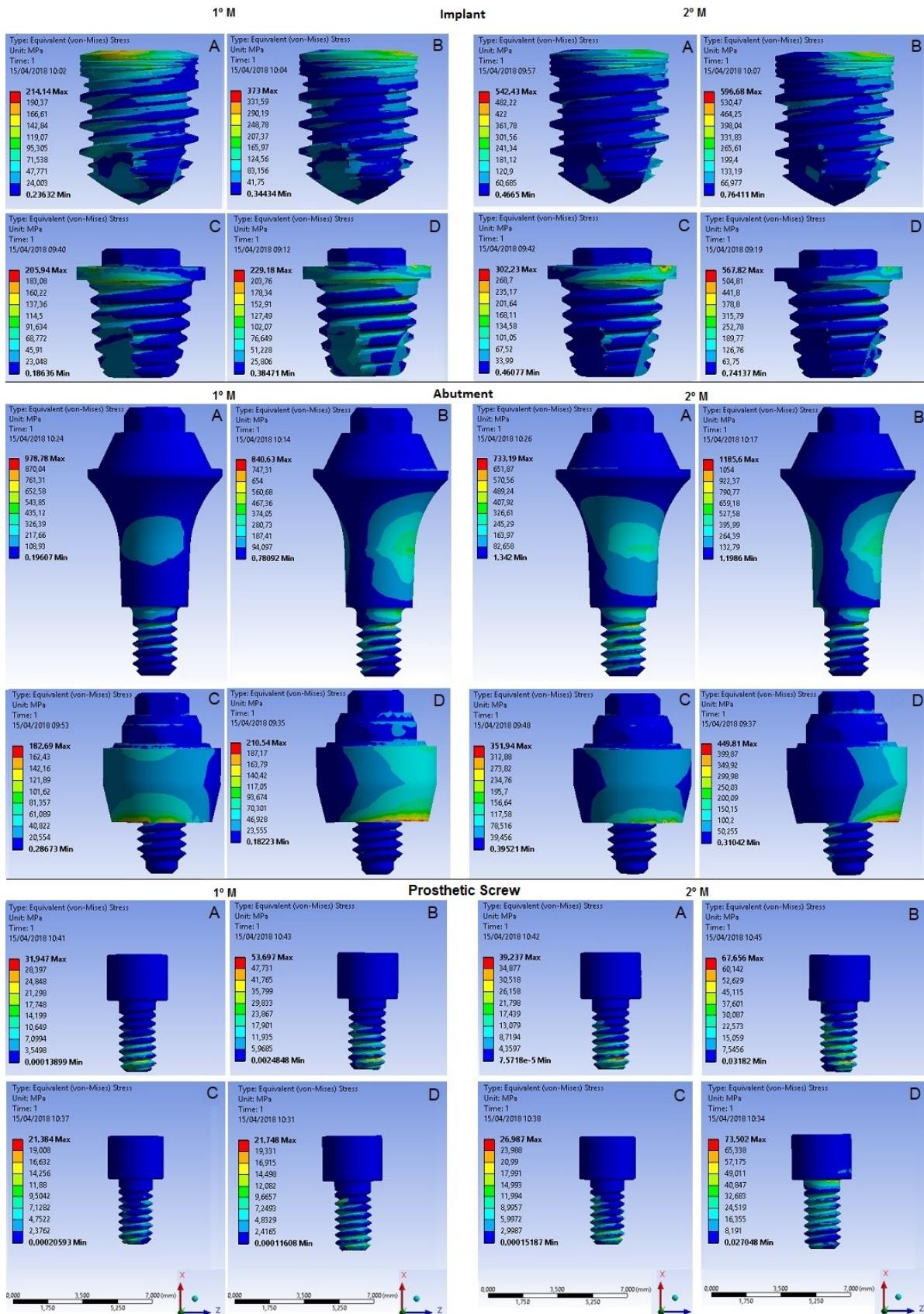
The distribution of  $\sigma^{\text{vM}}$  on the prosthetic screw of the groups with the splinted crowns showed higher concentration of stresses on the last threads, however, the groups in which the prosthetic crowns were not splinted, the distribution of  $\sigma^{\text{vM}}$  was observed on the threads in the center of the prosthetic screw threads. Thus, Groups SEH and SMT showed a distribution of  $\sigma^{\text{vM}}$  in one and the same region for the prosthetic screw of the 1st and 2nd molars (Figure 4).

The EH connection showed the highest  $\sigma^{\text{vM}}$  values when the crowns were not splinted (Table 2), for both the 1st molar (21.74 MPa for Group SUEH and 21.38 MP for the Group SEH); and for the 2nd molar (73.50 Mpa for Group SUEH and 26.98 MPa for Group SEH) (Figure 3).

Similarly, the MT connection showed the highest  $\sigma^{\text{vM}}$  values when the crowns were not splinted, for both the 1st molar (53.69 MPa for Group SUMT and 31.94 MP for the Group SMT); and for the 2nd molar (67.65 Mpa for Group SUMT and 39.23 MPa for Group SMT) (Figure 3).



**Figure 3.** Maximum values of  $\sigma^{\text{vM}}$  for the implants, abutments and prosthetic screws.



**Figure 4.** Distribution of  $\sigma^{\text{VM}}$  for implants, abutments and prosthetic screws of groups – A) SMT; B) SUMT; C) SEH; D) SUEH.

### *Cortical Bone Tissue*

The distribution of  $\sigma^{\max}$  and  $\sigma^{\min}$  on cortical bone tissue showed a higher  $\sigma^{\min}$  concentration in the region surrounding the implant in Group SUMT (Figure 5).

The MT connection showed the highest  $\sigma^{\max}$  and  $\sigma^{\min}$  values: 136.96 Mpa for Group SMT and 266.11 Mpa for Group SUMT (Figure 5). Therefore, the best form of distribution of these stresses for the cortical bone tissue was shown in the groups with the EH prosthetic connection (Figure 6). However, according to the distribution of the colors, the authors could affirm that the Group SUMT showed a higher concentration of  $\sigma^{\max}$  in the region of contact between the cortical bone tissue and implants (Figure 7).

The cortical bone tissue showed the highest  $\tau$  values for Groups SUMT and SCM (123.32 Mpa and 110.35 Mpa, respectively), being 49.92% (55.09 MPa) and 135.58% (46.84 MPa) higher than those of Groups SUEH and SEH, respectively (Figure 5).

The  $\varepsilon^{\max}$  was shown to be slightly higher for the groups with the MT platform (0.0090 Mpa and 0.0092 Mpa for Groups SUMT and SMT, respectively) when compared with the Groups SUEH and SEH (0.0074 Mpa and 0.0072 Mpa, respectively) (Figure 5).

### *Medullary Bone Tissue*

The distribution of  $\sigma^{\max}$  and  $\sigma^{\min}$  in medullary bone tissue presented a higher concentration in the region of contact with the implants in Group SUMT (Figure 5). However, Group SEH showed better distribution of  $\sigma^{\max}$  and  $\sigma^{\min}$  for the region of medullary bone tissue in contact with the implants inserted (Figure 6).

However, the distribution of  $\sigma^{\min}$  on medullary bone tissue showed a higher concentration in the distal region of splinting of the implants both in Groups SEH (Figure 6) and SMT (Figure 7).

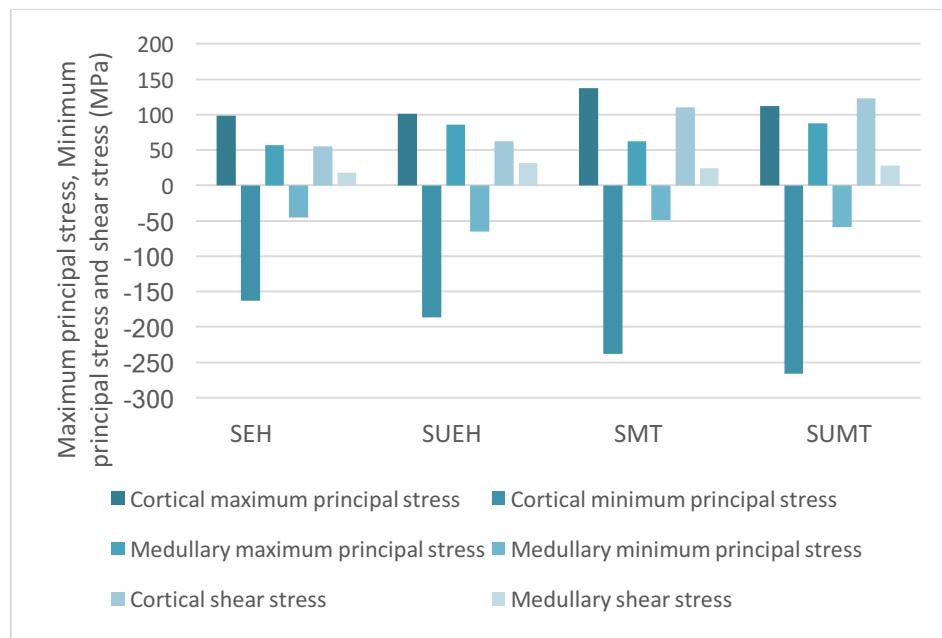
Group SUMT showed a higher concentration of  $\sigma^{\max}$  in the distal region to the contact interface of medullary bone tissue and cervical region of the implant (Figure 5), however, when the crowns were splinted, a better distribution of  $\sigma^{\max}$  e  $\sigma^{\min}$  was observed for the region around the implants inserted (Figure 6).

The highest  $\sigma^{\max}$  and  $\sigma^{\min}$  values (87.41 Mpa and 65.19 Mpa, respectively) were observed in Group SUMT and SUEH, respectively (Figure 5). The  $\sigma^{\min}$  showed a similar distribution for the medullary bone tissue with both MT and EH connections, so

that the groups with splinted crowns showed a better distribution of  $\sigma^{\min}$  (Figure 6, Figure 7).

Medullary bone tissue showed higher  $\tau$  value for Group SUEH (31.23 MPa), being 13.43% higher than the value of Group SUMT (27.53 MPa) (Figure 5).

The  $\epsilon^{\max}$  was similar for the Groups SEH (0.027 MPa) and Group SUEH (0.042 MPa), and for the MT Groups, however, lower  $\mu_s$  values were observed for the Groups with splinting of crowns (Figure 5).



**Figure 5.** Maximum values of  $\sigma^{\max}$ ,  $\sigma^{\min}$  and  $\tau$  in cortical and medullary bone.

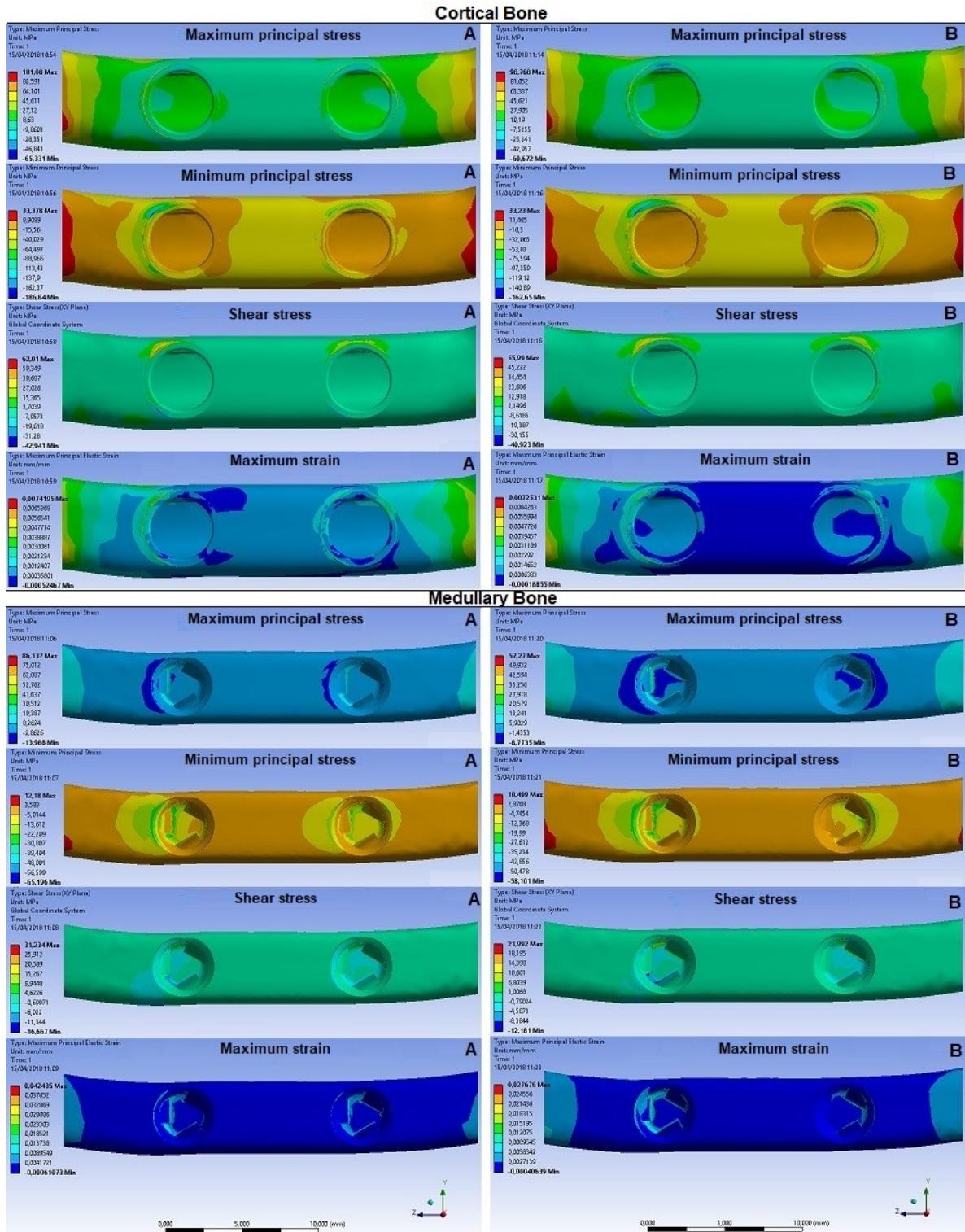


Figure 6. Distribution of  $\sigma^{\max}$ ,  $\sigma^{\min}$ ,  $\tau$  e  $\epsilon^{\max}$  in cortical and medullary bone – A) SUEH; B) SEH.

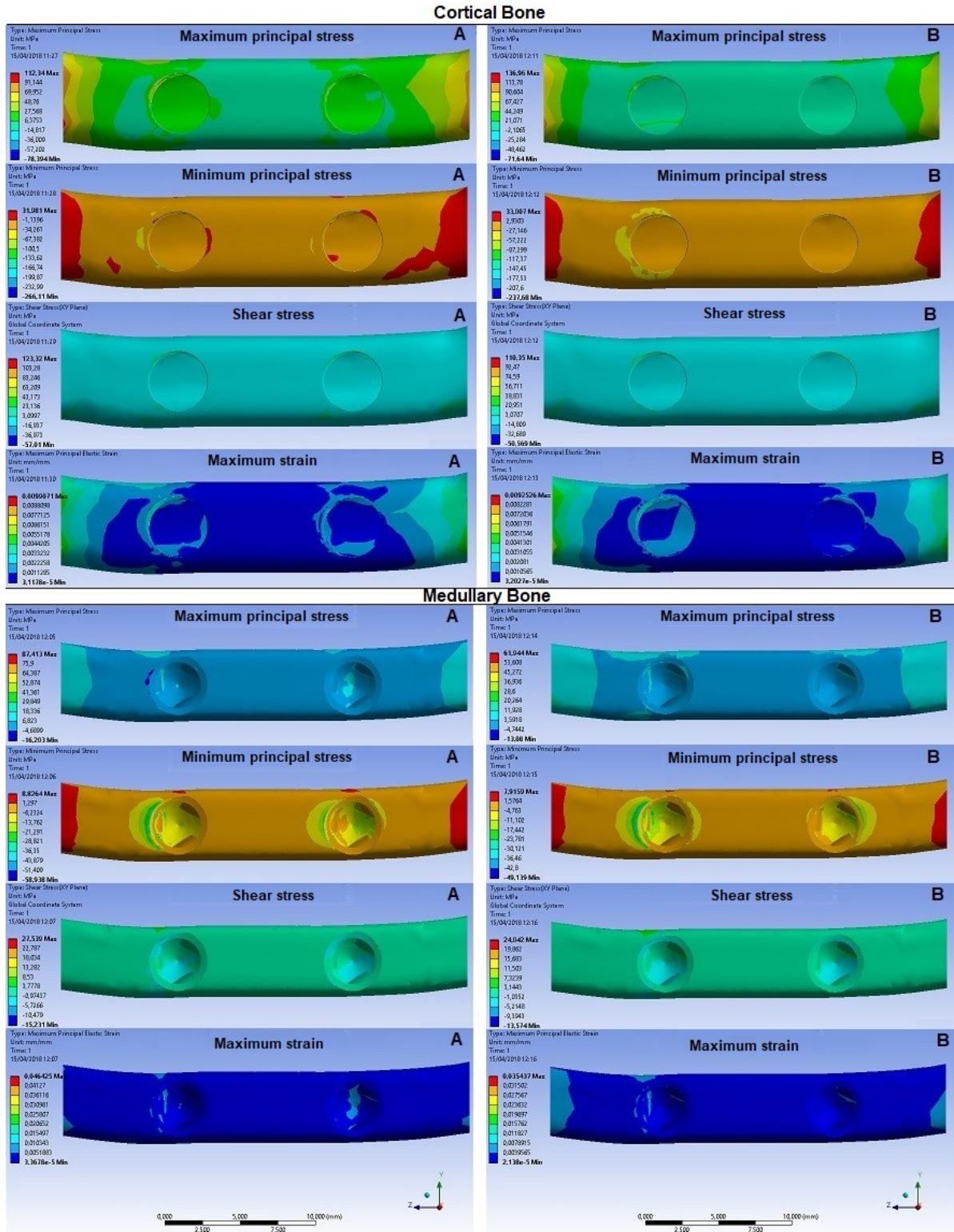


Figure 7. Distribution of  $\sigma^{\max}$ ,  $\sigma^{\min}$ ,  $\tau$  and  $\epsilon^{\max}$  in cortical and medullary bone – A) SUMT; B) SMT.

## Discussion

The results of the present study demonstrated that splinting of prosthetic crowns favored the biomechanical behavior, and the MT connections showed higher peak stresses compared with the EH connections for implants, abutments, prosthetic screws and bone tissues.

Furthermore, simulation of splinted crowns, irrespective of the type of implant-abutment connection (MT or EH) in both groups showed lower peaks of stress when compared with the groups with single-unit crowns, both for implants and for abutments, prosthetic screws and bone tissue, as was observed in the study of Toniollo et al. (2017), in which the MT connection also presented lower stress values for the surrounding bone tissue when the prosthetic crowns were splinted.

The magnitude and distribution of  $\sigma^{\max}$  and  $\sigma^{\min}$  were evaluated under occlusal load, simulating the occlusal contacts, thus a decomposition of forces with three dimensional components occurred, which differed from other previous studies that exclusively evaluated the components of axial forces (37-39).

The  $\sigma^{\max}$ , commonly known as tensile stress, was concentrated at the interface of bone/implant contact in a more uniform manner in the splinted groups; the  $\sigma^{\min}$ , commonly known as compressive stress, showed higher concentration in the interproximal region of the implants in the groups with single-unit crowns (not splinted). The oblique loads of the condition of loading the models generated stresses around the implants, and in agreement with the results of this study of Yilmaz, Seidt (29), the present study also observed higher stress values for the single-unit crowns. Moreover, these showed higher stress values, in both the group with MT and EH connections.

The distribution of  $\epsilon^{\max}$  on bone tissue observed was better for the splinted groups, particularly in Group SEH. These results were in agreement with the study of Wang, Leu (40), in which the authors verified that the stresses were generated with horizontal instead of vertical loads, with this result being attributed to the distribution of stresses achieved by the rigidity of the prosthetic crown splinting (40).

The stress patterns indicated a more uniform load distribution for the groups with splinted crowns in this study. Huang et al. (2005) reported that splinted crowns could help with stress distribution when implants of different diameters were used. Oblique loads generated greater deformations, particularly around the single-unit crowns. Splinting of the prosthetic crowns of implants reduced the lateral forces, improved the stress distribution and minimized the deformation of implants (42, 43).

Moreover, the result of the present study could be influenced by the unfavorable crown-implant ratio.

In the study of Merz et al. (2000), by means of the FEM, the authors evaluated the stresses caused by lateral loads on implants of the MT and EH, and observed that the conical interface distributed the stresses more uniformly, when compared with the external hexagon interface. However, the study of Sotto-Maior et al. (2015), evaluated the influence of the crown-implant ratio in MT and EH short implants, and the authors observed that the conical implants with a crown-implant ratio of 2:1 of the MT connection showed higher stress values, the same as that observed in the present study. Furthermore, the authors concluded that the crown-implant ratio influenced the stress distribution only under oblique loading. In contrast, some clinical studies have shown different results. In the study of Blanes et al. (2009), the authors observed no influence of the crown-implant ratio on the loss of the peri-implant bone crest. Moreover, in another study, Blanes et al. (21), observed that rehabilitations with single implants did not present increasing loss of bone crest or implant failure when the survival of splinted crowns was evaluated.

In the study of Hansson (46), using FEM, the authors observed that the implants with external hexagon connections, showed peak shear stress at the interface between the bone and implant localized in the marginal bone crest. However, better stress distribution was observed on the surrounding tissues for implants with external hexagon connections, and that the peak shear stress was shown to be more apical, which could reduce marginal bone resorption. Therefore, the prosthetic connection represented the most fragile point of rehabilitations with dental implants, because they must present resistance to the masticatory forces, and resistance to the penetration of bacteria into the abutment-implant interface.

Analysis of the extra-short implants of this study allowed verification of the highest stress values in the groups with MT prosthetic platforms, for both Group SMT and Group SUMT. A possible explanation for these higher peak stresses would be the different functional behaviors of the platforms analyzed, because the connection of the morse taper type, the major portion of the occlusal load is absorbed at its conical interface, preventing de-stabilization of the prosthetic component. This would allow greater stability for retaining the position of the prosthetic component by axial forces, differently from the external hexagon connection that determines the position of the clip, but there is no stabilization of the prosthetic component by the clip, to enable the

lateral load to be absorbed, particularly by the prosthetic screw (47, 48). However, reduction in the diameter of the abutment could cause higher stress concentrations between the interface of the abutment and the cervical portion of the implant, particularly when associated with the increase in crown-implant ratio, as was observed in the present study. As observed in another study, the concentration of stress  $\sigma^{vM}$  occurred in the areas of contact between the abutment and implant, and between the abutment and prosthetic screw (49).

However, the macrogeometrical difference between the MT and EH connections is a peculiarity that must be taken into consideration - the way it interferes in the stress distribution - and could generate stress concentrations in the cervical region, as observed in the implants with MT prosthetic connections in the present study, thus influencing the biomechanical behavior of the different prosthetic platforms (50).

The use of the three dimensional model of the posterior portion of the mandible for computed simulation by means of the FEM, showed benefits for evaluating the biomechanical behavior of rehabilitations with extra-short implants, thus contributing to predicting the biomechanical behavior of this therapeutic option in the rehabilitation of patients (51), particularly relative to the peri-implant bone responses during rehabilitative treatment, as observed in the study of Yoda et al. (52). In this study, the use of the finite element model allowed analysis of the internal stress distribution of the structures evaluated, providing important data which, when analyzed together with the numerical values of the stresses ( $\sigma^{Max}$ ,  $\sigma^{Min}$  and  $\sigma^{vM}$ ) and associated with the fracture strength values of mechanical trials, could allow better evaluation of the biomechanical behavior of the rehabilitations with extra-short implants in mandibular ridges with bone atrophy (53).

The results of the present study suggested that there was advantage to splinting the prosthetic crowns when performing rehabilitations with extra-short implants, especially in the posterior regions of atrophic mandibles (54), however, the implant-abutment connection appeared to have an influence on the biomechanical behavior. Considering that the present study had limitations in its capacity for dynamic occlusion or multiple bone layers, clinical and mechanical studies that evaluate the biomechanical behavior of extra-short implants in the posterior regions of maxilla are necessary for validating the findings presented (55). The number of *in silico*, *in vitro* and *in vivo* studies of rehabilitations with extra-short implants with single-unit or

splinted crowns and the type of implant-abutment connection used, are still limited (56). Therefore, new *in vitro* and *in vivo* trials with extra-short implants are necessary for better guidance relative to the selection of implant-abutment connections of implants, particularly in the posterior region of the maxillae.

## Conclusion

Within the limitations of this study, it could be affirmed that:

- The EH connection showed better biological behavior when compared with the MT, irrespective of performing crown splinting.
- Crown splinting in the posterior region of the atrophied mandible appeared to allow better distribution of stresses to the abutment-implant system and bone tissue.
- The implant-abutment connection had an influence on the biomechanical behavior of the abutment-implant system, with better results being observed with the association of the EH platform with splinted crown.

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## 5 CONSIDERAÇÕES FINAIS

As reabilitações com implantes extra-curtos em região posterior de mandíbula atrófica tratam-se de assunto recente, sendo pouco estudado e discutido na literatura. Desta forma, considerando que o presente estudo apresenta limitações em sua capacidade de oclusão dinâmica ou múltiplas camadas de osso, novos estudos clínicos e mecânicos são necessários para avaliar o comportamento biomecânico de implantes extra-curtos, para validar os achados do presente estudo, e melhor orientação da seleção das conexões protéticas dos implantes, principalmente na região posterior da mandíbula.

Os resultados sugerem que há vantagem na esplintagem das coroas protéticas quando da realização de reabilitações com implantes extra-curtos, especialmente em região posterior de mandíbula atrófica. Entretanto o tipo de conexão pareceu influenciar no comportamento biomecânico.

Quando simulada a esplintagem das coroas, independente do tipo da conexão (CM ou HE), ambos os grupos apresentaram menores picos de tensões quando comparados aos grupos com coroas separadas, tanto para implantes, quanto para pilares protéticos, parafusos protéticos e tecido ósseo. O mesmo foi observado no estudo de Toniollo et al. (2017), em que as conexões CM também apresentaram menores valores de tensão para o tecido ósseo circundante quando realizada a esplintagem das coroas sobre implantes de diferentes comprimentos.

Além disso, os resultados do presente estudo demonstram que as conexões CM apresentaram maiores picos de tensões frente às conexões HE para implantes, pilares protéticos, parafusos protéticos e tecido ósseo. O estudo de Sotto-Maior et al. (2015) avaliou a influência da proporção coroa/implante em implantes curtos CM e HE e os autores observaram que os implantes cônicos com proporção coroa/implante 2:1 de conexão CM apresentaram valores de tensão mais elevados. Tal proporção influenciou a distribuição de tensões sob carga oblíqua, apenas.

A conexão protética representa o ponto mais frágil das reabilitações com implantes dentários. A esplintagem das coroas, em região posterior de mandíbula atrófica, parece permitir melhor distribuição das tensões para o sistema prótese/implante extra-curto e tecido ósseo. Entretanto, a união de implantes contíguos pode dificultar a higienização e provocar complicações biológicas como a peri-implantite (OGAWA et al., 2010).

Conclui-se que a conexão protética exerceu influência no comportamento biomecânico do sistema prótese/implante, sendo que a conexão HE apresentou melhor comportamento biomecânico quando comparada à CM, com melhores resultados observados quando da esplintagem das coroas.

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## ANEXO A – Normas para publicação no periódico The International Journal of Oral & Maxillofacial Implants

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