

Three-Dimensional Finite Element Analysis of Varying Diameter and Connection Type in Implants with High Crown-Implant Ratio

Sandra Lúcia Dantas de Moraes¹, Fellippo Ramos Verri², Joel Ferreira Santiago Júnior³, Daniel Augusto de Faria Almeida⁴, Cleidiel Aparecido Araujo Lemos², Jéssica Marcela de Luna Gomes², Eduardo Piza Pellizzer²

¹Dental School of Pernambuco, UPE - Universidade de Pernambuco Recife, PE, Brazil

²Department of Dental Materials and Prosthodontics, Araçatuba Dental School, UNESP - Universidade Estadual Paulista, Araçatuba, SP, Brazil

³Pró-Reitoria de Pesquisa e Pós-graduação (PRPPG), USC - Universidade do Sagrado

Coração, Bauru, SP, Brazil

⁴Department of Operative Dentistry, Dental School, UNIFAL - Universidade Federal de Alfenas, Alfenas, MG, Brazil

Correspondence: Eduardo Piza Pellizzer. Rua José Bonifácio, 1193, 16015-050 Araçatuba, SP, Brasil. Tel: +55-18-3636-3297. e-mail: ed.pl@uol.com

The aim of this study was to evaluate the effect of varying the diameter, connection type and loading on stress distribution in the cortical bone for implants with a high crown-implant ratio. Six 3D models were simulated with the InVesalius, Rhinoceros 3D 4.0 and SolidWorks 2011 software programs. Models were composed of bone from the posterior mandibular region; they included an implant of 8.5 mm length, diameter Ø 3.75 mm or Ø 5.00 mm and connection types such as external hexagon (EH), internal hexagon (IH) and Morse taper (MT). Models were processed using the Femap 11.2 and NeiNastran 11.0 programs and by using an axial force of 200 N and oblique force of 100 N. Results were recorded in terms of the maximum principal stress. Oblique loading showed high stress in the cortical bone compared to that shown by axial loading. The results showed that implants with a wide diameter showed more favorable stress distribution in the cortical bone region than regular diameter, regardless of the connection type. Morse taper implants showed better stress distribution compared to other connection types, especially in the oblique loading. Thus, oblique loading showed higher stress concentration in cortical bone tissue when compared with axial loading. Wide diameter implant was favorable for improved stress distribution in the cortical bone region, while Morse taper implants showed lower stress concentration than other connections.

Key Words: dental implant, bone tissue, mechanical stress, finite element analysis.

Introduction

The placement of implants in the posterior mandible with reduced bone availability is a challenge for dental implantology. The options that can facilitate placement of conventional implants include use of bone graft and/or lateralization of the inferior alveolar nerve; however, this modality of treatment is associated with high costs and morbidity. Therefore, the use of short implants may be an alternative, viable and effective treatment option (1).

Short implants with wide diameter may increase survival rates (2); additionally, it is more acceptable than surgical placement of bone grafts in the posterior jaw (3). However, there is concern regarding the longevity of these implants from a biomechanical perspective (4). The incidence of oblique loads at short implants can impact longevity (5), mainly owing to the increase in crown-implant ratio (6), which increases stress concentration in the bone tissue around the implant (7).

In addition to diameter, the connection type is an important factor in the biomechanics of implant placement. Studies have shown that implants with a conical internal connection (Morse taper) exhibit better stress distribution in the bone tissue when compared with external hexagon

implants (8,9); however, this outcome remains controversial, as in one study Morse taper did not reduce the microstrain in the bone tissue around the implants (10). Thus, due to the small number of studies that have investigated the effect of diameter and connection type, the aim of this study was to evaluate the effect of varying the diameter and connection type on stress distribution in the cortical bone tissue for implants with a high crown-implant ratio. Three null hypotheses were tested: (1) there is no difference in stress distribution between regular and wide diameter; (2) different connections produce similar stress distribution outcomes; (3) the loading direction does not influence on the stress distribution.

Materials and Methods

Experimental Design

This study was designed to investigate three variation factor: The difference in diameter (Ø 3.75 mm and Ø 5.00 mm), connection type (external hexagon (EH), internal hexagon (IH), and Morse taper (MT)) and loading condition (axial and oblique). The six models that were simulated are presented in Table 1 and Figure 1. This methodology follows described as previous research (8,9,11).

Three-Dimensional (3D) Finite Element Modeling

The 3D finite element analysis (FEA) methodology used here follows that of previous studies (8,9,11). Each model was composed of a bone block of the mandibular area around the second molar (2° M) and the trabecular bone in the center was surrounded by 1 mm of cortical bone. Information for the bone block was obtained by computerized tomography already obtained through a database, only used to facilitate the reproduction of details and design of simulated bone tissue. Modeling was performed with InVesalius software (CTI Renato Archer, Campinas, SP, Brazil) and surface simplification was accomplished with Rhinoceros 4.0 software (NURBS Modeling for Windows, Seattle, WA, USA).

The implant design was obtained from a simplified version of the original implant connection (Conexão Sistemas de Prótese Ltda, Aruja, SP, Brazil), with different geometries (external hexagon; internal hexagon and Morse taper), a diameter of \varnothing 3.75 and \varnothing 5 mm and a length of 8.5 mm that included their specific abutments. The implant and abutment geometries were simplified by a 3D computer-aided design software (SolidWorks 2010; SolidWorks Corp, Waltham, MA, USA) and Rhinoceros 4.0 CAD.

The crown was configured from artificial molar tooth (Odontofix Indústria e Comércio de Material Odontológico Ltda., Ribeirão Preto, SP, Brazil) and digitized using a 3D scanner (MDX-20; Roland DG, São Paulo SP, Brazil). Images were exported to Rhinoceros 4.0 CAD software for modeling. Occlusal surface details were added using the SolidWorks CAD software package (SolidWorks). Prosthesis were simulated with a screw for external and internal connection. Morse taper connection received dental prosthesis cemented (cement layer: 0.03 mm thickness) retained. The height of the crown simulated for all models was 15 mm, which resulted in a crown-implant ratio close to 2:1 (high crown-implant ratio).

After modeling the solids, geometries were exported to FEA software for pre- and post-processing (FEMAP 11.2, Siemens PLM, Santa Ana, CA, USA), to obtain meshes of tetrahedral parabolic solid elements

with ten nodes in which different numbers of nodes and elements for each model (Table 1). The mechanical properties of each simulated material were attributed to the meshes by using previously published values in the literature (Table 2) (7-9). All materials were assumed to be homogeneous, isotropic and linearly elastic.

All contacts were simulated as symmetric welds, except for the abutment/implant and single-unit crown contacts that were simulated by symmetric contacts. Constraint

Table 1. Description of models used in this study

Model	Description
1	External hexagon implant (\varnothing 3.75 x 8.5 mm)
2	External hexagon implant (\varnothing 3.75 x 8.5 mm)
3	Morse taper implant (\varnothing 3.75 x 8.5 mm)
4	External hexagon implant (\varnothing 5 x 8.5 mm)
5	External hexagon implant (\varnothing 5 x 8.5 mm)
6	Morse taper implant (\varnothing 5 x 8.5 mm)

Table 2. Mechanical properties of the simulated materials

Material	Elastic Modulus (GPa)	Poisson ratio (ν)	References
Trabecular bone tissue	1.37	0.30	(7)
Cortical bone tissue	13.7	0.30	(7)
Titanium (implant)	110.0	0.35	(7)
Feldspathic ceramic	82.8	0.35	(8)
Zinc phosphate cement	22.4	0.35	(8)
Ni-Cr Alloy (Abutment)	218.0	0.33	(9)

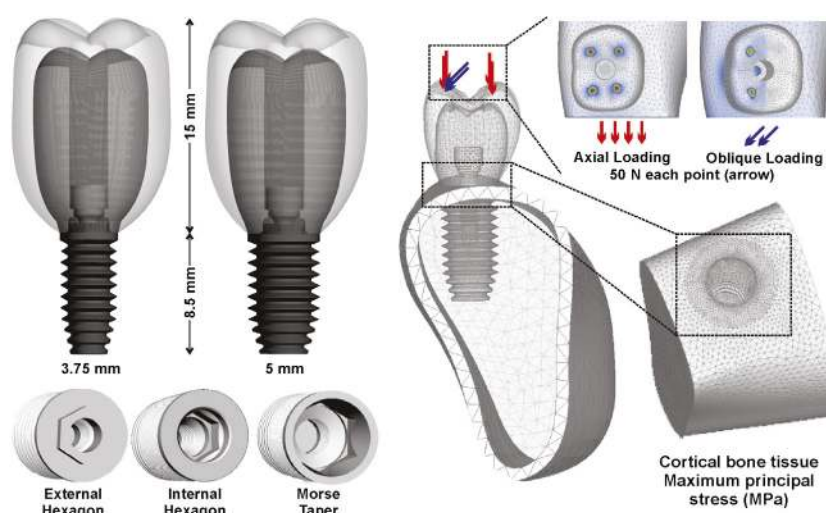


Figure 1. Finite element meshes: connections, diameters, dental implants, bone tissue.

definitions were established as fixed in the axes (x, y and z) at the mesial and distal surfaces of the cortical and trabecular bone. All other model surfaces were unrestricted. The applied axial force was 200 N at a specific four points on the internal slope of the cusps, whereas the oblique load was divided into two loading points applied in the internal slope of lingual cusps with 100 N.

Finally, the analysis was carried out using the FEMAP 11.1.2 finite element software and exported to the NeiNastran 9.2 (Noran Engineering, Westminster, CO, USA) software for calculations at a dedicated workstation (Sun Microsystems Inc., São Paulo, SP, Brazil). Results were entered again in FEMAP 11.1.2 software for visualization and post-processing of the maps. The results were then imported and visualized in the maximum principal stress maps (MPa) to analyze the stress distribution in the cortical bone tissue.

Results

Diameter of Implant

Under axial loading, implants with wide diameter showed a decrease compressive stress in the cortical bone when compared to implants with regular diameter, independently of connection type. This difference is even more evident in oblique loading, since implants

with regular diameter showed increase of tensile stress concentration compared to wide diameter implants (Figs. 2 and 3).

Connection Type

In the axial loading, MT and EH implants showed lower compressive stress than IH implant for regular diameter

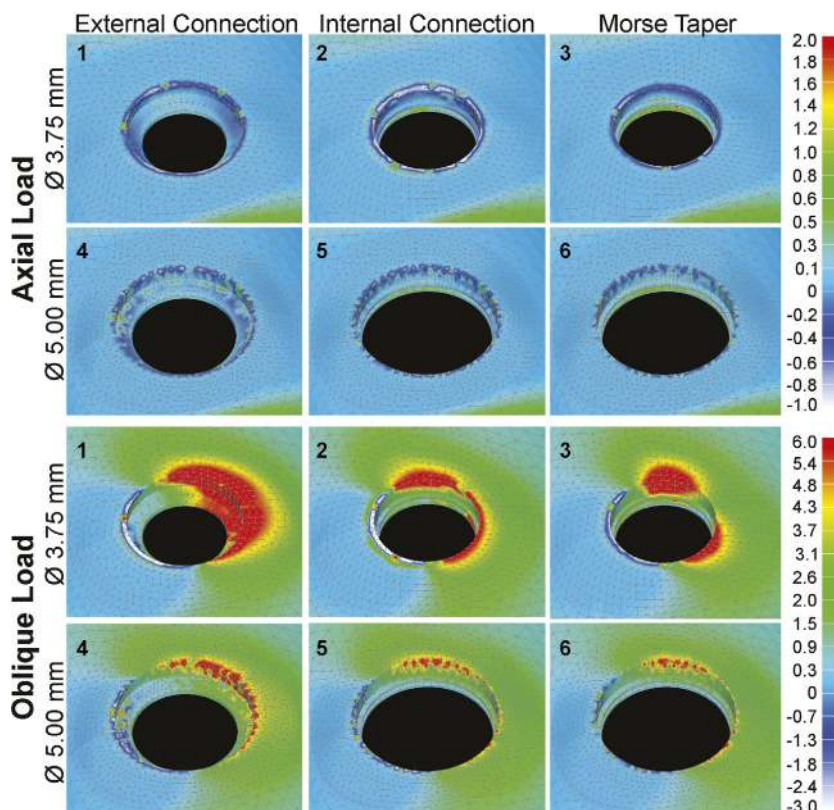


Figure 2. Maximum principal stress values under cortical bone in the models under axial load and oblique load.

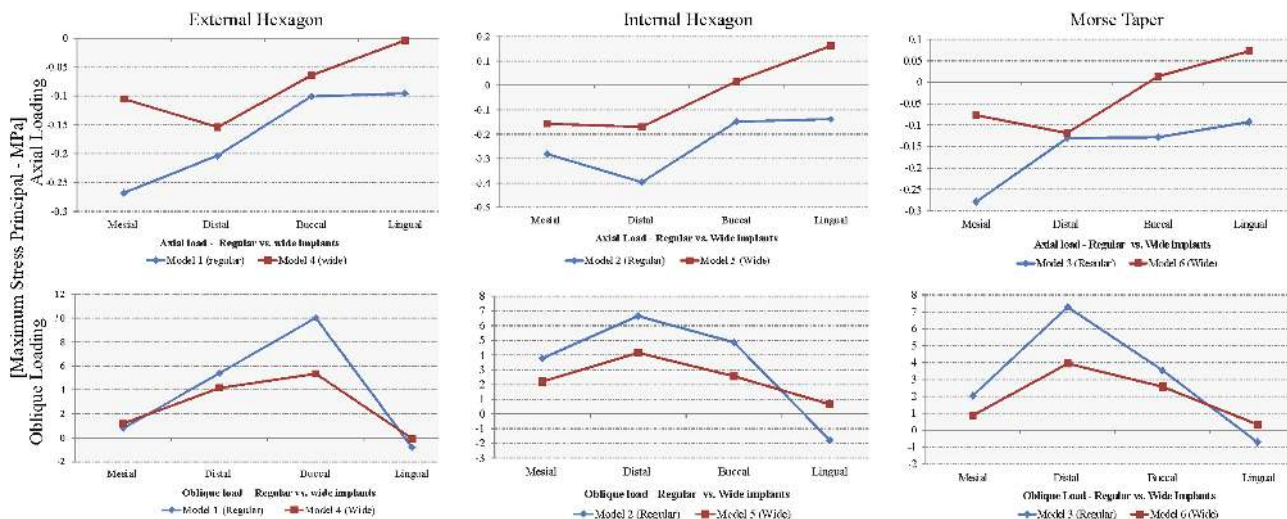


Figure 3. Peak maximum of stress for external hexagon, internal hexagon and Morse taper implant under axial and oblique load.

implants in axial loading, but in the wide diameter implants MT and IH implants showed lower compressive stress than EH (Fig. 4A). Oblique loading showed higher tensile compared to axial loading, EH and IH implants showed a higher tensile stress than MT implants, regardless of the implant diameter (Fig. 4B).

Region and Loading Analysis

In analysis of the different regions (mesial, distal, buccal and lingual) under axial loading, the proximal region (mesial and distal) had a higher compressive stress than the buccal and lingual area for both connection types, with higher compressive stress in the IH implants compared to other connections (Fig. 5A). Regarding oblique loading, higher tensile stress concentration was observed in distal and buccal area, with highest tensile stress in buccal of EH implants (Fig. 5B). Regardless of connection type and diameter, oblique loading showed higher tensile stress

compared to axial loading which presented low compression stress in the analyzed models.

Discussion

The results of this study do not support the first hypothesis tested; regardless of connection type, implants with a wide diameter showed more favorable biomechanical behavior when compared to implants with regular diameter. These results corroborate previous biomechanical studies that found a lower stress concentration for wide diameter implants (9,12-14), especially in short implants (12).

Clinically, a lower stress concentration may contribute to lower marginal bone loss around the wide diameter implants (15,16). Thus, the use of implants with wide diameter should be indicated, especially when a discrepancy in the crown-implant ratio may directly increase stress concentration in the bone tissue (7). There are situations in which the lack of adequate bone thickness can preclude the use of

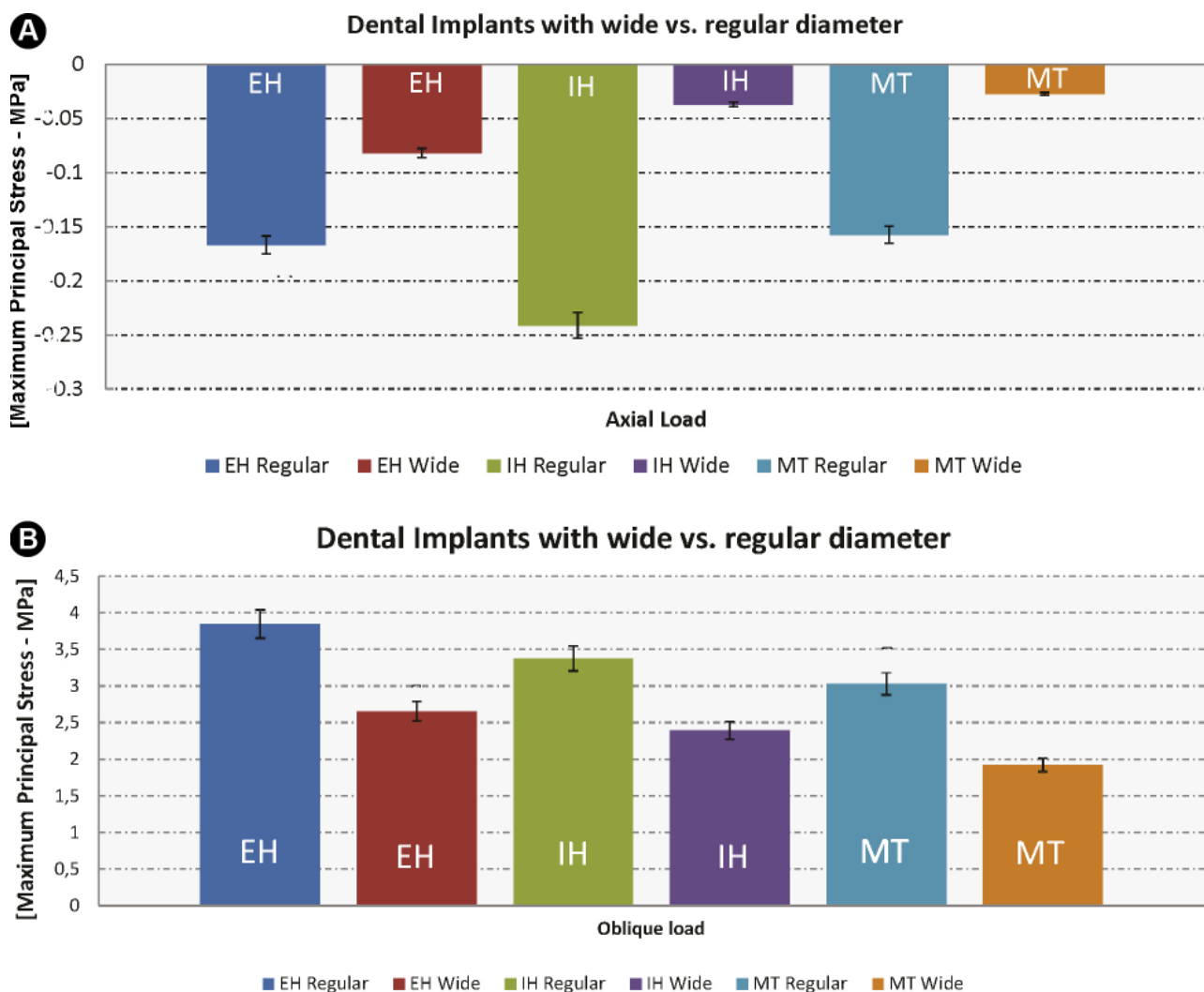


Figure 4. Means of stress in the cortical bone tissue in models with different connections and different diameter under axial load (A) and oblique load (B).

implants with a wide diameter, making it necessary to instead perform bone grafting (17); however, bone grafting in the mandibular region is associated with increased risk of complications and morbidity, which may limit its surgical benefits (17,18). Thus, in situations where it is not possible to the use wide diameter implants, the alternative approach may involve using the most suitable connection type from a biomechanical point of view.

Further, this study rejected the second hypothesis, as

there was a significant difference in stress distribution between the connection types. Specifically, Morse taper implants were biomechanically more favorable than other connections, especially during oblique loading. External hexagon implants under oblique loading showed greater stress in the cortical bone tissue, regardless of the diameter. Biomechanical superiority of Morse taper implants has been reported in the literature (8,9). This connection has a favorable design with greater internal stability than that

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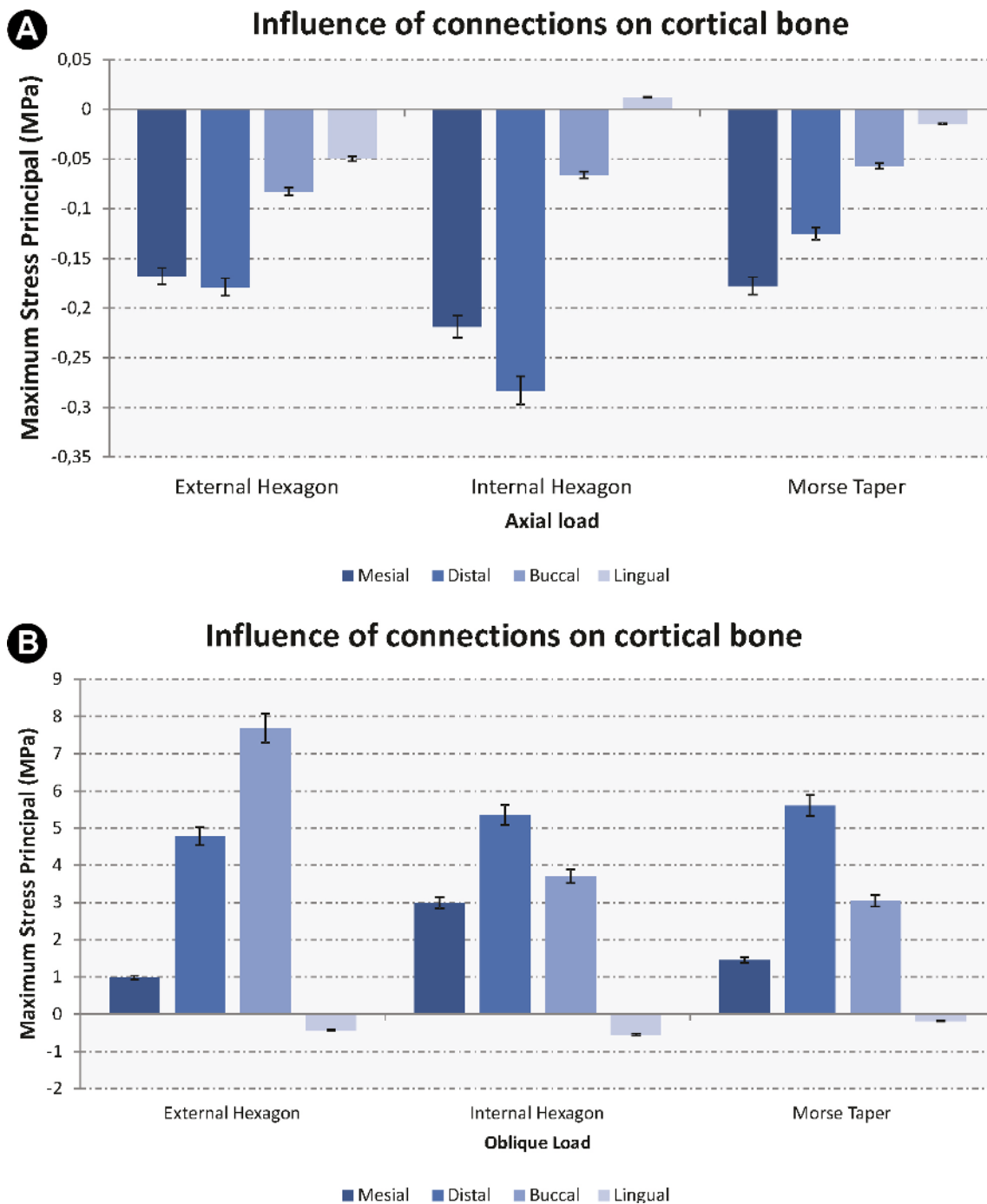


Figure 5. Means of stress in the different regions of cortical bone tissue with different connections.

of other connection types (owing to better mechanical imbrication), which allows centralization of stress on the implant body and reduces stress in the cortical bone region (8,9).

The unfavorable biomechanical behavior of the external hexagon implant may be due to the connection being out of the implant, which reduces the centralization of stress in the implant body, especially in the oblique loading (8); further, it might contribute to increased stress in the bone tissue around the implant neck due to close contact with the cortical bone. Additionally, the width and/or height of the hexagon can contribute to the increase in stress concentration in the bone tissue region (19). Therefore, the use of external hexagon implants should be avoided, especially in situations where there is an increase in the crown-implant ratio (7,20), or in cases where use implants with a wide diameter is not feasible, since stress concentration in the cortical bone could exceed the physiological limits and consequently accelerate the bone resorption process, which could compromise the rehabilitation.

Regarding the applied loading, it was possible to observe higher stress concentration in the region of the cortical bone tissue for the oblique when compared to axial loading, rejecting the third hypothesis. These results are consistent with the literature (7-9,12,21). This fact may be due to oblique loading tends to increase stress concentration on (compression) and against (tensile) the loading direction (8). Oblique loading should be considered more harmful to bone tissue, which may contribute to higher values of bone resorption over time. Thus, it is important to perform a rigorous occlusal adjustment to transfer the centric contacts allowing a distribution in the long axis of the implant, avoiding an oblique overload in the peri-implant region (7).

In addition to the factors analyzed in this study, other variables can compromise the biomechanical behavior of implant-supported prostheses, such as the increase in occlusal force relative to the direction of loading (22). However, all models analyzed in this study showed development of compressive and tensile stresses within physiological limits for human cortical bone (72 – 76 MPa for tensile stress, 140 – 170 MPa for compressive stress) (21).

The finite element method has been used in dentistry to achieve greater understanding of biomechanical behavior and can be carefully extrapolated to clinical settings (23). Thus, when combined with well-designed clinical studies, the results of the current study could guide new strategies for addressing challenges associated with managing stress distribution in implant dentistry. However, the results should be interpreted with caution due to limitations such as factors related to the methodology, computer simulation

and linearity elastic analysis, which consider bone tissue to be isotropic and homogenous and apply static occlusal loading (24,25). Therefore, additional controlled and randomized clinical studies should be conducted in order to fully explore and evaluate the clinical implications of various biomechanical parameters in implant dentistry.

Within the limitation of this study can conclude that the increase in diameter was favorable for improved stress distribution in the cortical bone region, regardless of the connection type. Morse taper implants were associated with lower stress concentration than other connections, especially during oblique loading.

Resumo

O objetivo deste estudo foi avaliar o efeito da variação do diâmetro e dos tipos de conexão na distribuição do estresse no osso cortical para implantes com a proporção coroa-implante. Seis modelos 3D foram simulados com os programas InVesalius, Rhinoceros 3D 4.0 e SolidWorks 2011. Os modelos foram compostos de osso da região mandibular posterior. Foram incluídos implantes de 8,5 mm de comprimento, diâmetro Ø 3,75 mm ou Ø 5,00 mm, e tipos de conexão como hexágono externo (EH), hexágono interno (IH) e cone Morse (MT). Os modelos foram processados usando os programas Femap 11.2 e NeiNastran 11.0 e usando uma força axial de 200 N e força oblíqua de 100 N. Os resultados foram registrados em termos da tensão principal máxima. O carregamento oblíquo mostrou alta tensão no osso cortical em comparação com a carga axial. Os resultados mostraram que os implantes com maior diâmetro apresentaram distribuição de tensões mais favorável, independentemente do tipo de conexão, enquanto que os implantes cone Morse apresentaram melhores distribuição de tensões comparado aos outros tipos de conexão, especialmente no carregamento oblíquo. Assim, os implantes de maior diâmetro foram mais favoráveis para distribuição das tensões na região de tecido ósseo cortical, enquanto que os implantes cone Morse apresentam menores concentrações de tensões do que as outras conexões.

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