Amilcar Chagas Freitas Júnior

Plataforma regular versus switching: estudo mecânico por meio de testes laboratoriais de fadiga e análise de elementos finitos em implantes com hexágono externo e interno.

ARAÇATUBA - SP
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Plataforma regular versus switching: estudo mecânico por meio de testes laboratoriais de fadiga e análise de elementos finitos em implantes com hexágono externo e interno.

Tese apresentada à Faculdade de Odontologia do Câmpus de Araçatuba – Unesp, para a obtenção do Grau de "Doutor em Odontologia" – Área de Concentração em Prótese Dentária.

Orientador : Prof. Dr. Eduardo Passos Rocha

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Dedicatória

Aos meus pais, Regina e Amilcar

Que sempre incentivaram e apoiaram as minhas escolhas. Muito obrigado por terem me ensinado os verdadeiros valores da vida!

Ao meu irmão, David

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RESUMO GERAL

Freitas Júnior AC. Plataforma regular versus switching: estudo mecânico por meio de testes laboratoriais de fadiga e análise de elementos finitos em implantes com hexágono externo e interno [Tese]. Araçatuba: Faculdade de Odontologia da Universidade Estadual Paulista; 2011.

Proposição. O objetivo do presente trabalho foi avaliar a influência do conceito de plataforma *switching* na confiabilidade e modo de falha de restaurações unitárias sobre implante com hexágono externo ou interno na região anterior da maxila. Adicionalmente, análises de elementos finitos foram realizadas para avaliar o padrão de distribuição de tensão dentro do complexo pilar-implante e no tecido ósseo peri-implantar.

Materiais e Métodos. 84 implantes foram divididos em 4 grupos (n = 21) para realização dos testes de fadiga: SWT-EH e REG-EH (implantes de conexão externa com plataforma *switching* ou regular, respectivamente); SWT-IH e REG-IH (implantes de conexão interna com plataforma *switching* ou regular, respectivamente). Análises estatísticas de *Weibull* foram realizadas considerando as missões de 50.000 ciclos a 210N e 300N. Adicionalmente, foram construídos 4 modelos de elementos finitos considerando as mesmas variáveis para obtenção das tensões equivalentes de *von Mises* (σ_{vM}) no complexo pilar-implante e das máximas tensões principais (σ_{max}) no osso peri-implantar.

Resultados. Os valores de Beta para os grupos SWT-EH (1,31), REG-EH (1,55), SWT-IH (1,83) e REG-IH (1,82) indicaram que a fadiga acelerou a falha em todos os grupos. Os valores de confiabilidade calculados para os grupos SWT-EH, REG-EH, SWT-IH e REH-IH foram 0,53 (0,33 - 0,70), 0,93 (0,80 - 0,97), 0,99 (0,93 - 0,99) and 0,99 (0,99 -

1,00), respectivamente. Os modos de falha (fratura do pilar e/ou do parafuso) não variaram em função do desenho da conexão protética (plataforma regular ou *switching*). Dentro do complexo pilar-implante, os maiores valores de tensão (σ_{vM}) foram observados no parafuso (SWT-EH = 190 MPa e REG-EH = 160 MPa) nos grupos com implantes de hexágono externo; enquanto nos grupos com implantes de hexágono interno os picos de tensão estiveram no pilar (SWT-IH = 186 MPa e REG-IH = 88.8 MPa). No osso cortical, os implantes com plataforma *switching* geraram menor tensão (σ_{max}) tanto para conexão externa (SWT-EH = 49.0 MPa e REG-EH = 56.5 MPa) como para conexão interna (SWT-IH = 37.7 MPa e REG-IH = 45.5 MPa).

Conclusões. Os maiores valores de σ_{vM} observados no complexo pilar-implante quando usados implantes com plataforma *switching* (grupos SWT-EH e SWT-IH) resultaram em menor confiabilidade do sistema restaurador apenas para implantes com conexão externa, mas não com conexão interna. Independente do tipo de conexão do implante (externa ou interna), menor estresse ósseo foi observado ao redor de implantes com plataforma *switching*.

Palavras-chave: implantes dentais, plataforma *switching*, biomecânica, confiabilidade, análise de elementos finitos.

ABSTRACT GERAL

Freitas Júnior AC. Regular and switched-platform: fatigue and finite element analysis in implants with external and internal hexagon [Thesis]. Araçatuba: UNESP - São Paulo State University; 2011.

Purpose. The aim of the present study was to evaluate the effect of platform switching concept on reliability and failure modes of anterior single-unit restorations for internal and external hex implants. Additionally, finite element analysis were performed to assess the stress distribution within implant-abutment complex and peri-implant bone.

Materials and Methods. 84 implants were divided in 4 groups (n=21) for fatigue tests: REG-EH and SWT-EH (regular and switched-platform implants with external connection, respectively); REG-IH and SWT-IH (regular and switched-platform implants with internal connection, respectively). Weibull analysis for a mission of 50,000 cycles at 300N was performed. Additionally, 4 three-dimensional finite element models reproducing the characteristics of specimens used in mechanical tests were created to evaluate the equivalent von Mises stress (σ_{vM}) within implant-abutment complex and the maximum principal stress (σ_{max}) in the peri-implant bone.

Results. The Beta values for groups SWT-EH (1.31), REG-EH (1.55), SWT-IH (1.83) and REG-IH (1.82) indicated that fatigue accelerated the failure of all groups. The calculated reliability for groups SWT-EH, REG-EH, SWT-IH and REH-IH were 0.53(0.33-0.70), 0.93(0.80-0.97), 0.99(0.93-0.99) and 0.99(0.99-1.00), respectively. Failure modes (screw and/or abutment fracture) were similar for regular and switched-platform implants. Within implant-abutment complex, the higher peak of stress (σ_{vM}) was observed in fixation screw (SWT-EH = 190 MPa and REG-EH = 160 MPa) for groups with external hex implants; while for groups with internal hex implants was in abutment (SWT-IH = 186 MPa and REG-IH = 88.8 MPa). In the cortical bone, switched-platform implants generated lower peak of stress (σ_{max}) for both external (SWT-EH = 49.0 MPa and REG-EH = 56.5 MPa) and internal (SWT-IH = 37.7 MPa and REG-IH = 45.5 MPa) connections.

Conclusions. The higher levels of stress observed within implant-abutment complex when reducing abutment diameter resulted in lower reliability of the system only for external hex implants, but not for internal hex implants. Lower stress was transferred to peri-implant bone for switched-platform models regardless the type of implant connection (external or internal hexagon).

Key Words: dental implants, platform switching, biomechanics, reliability, finite element analysis.

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LISTA DE ABREVIATURAS

SWT = switching platform

REG = regular platform

EH = external hexagon

IH = internal hexagon

SLF = single load-to-fracture

SSALT = step-stress accelerated life testing

FEA = finite element analysis

3D = three-dimensional

2D = two-dimensional

σ_{vM} = von Mises equivalent stress

σ_{max} = maximum principal stress

SEM = scanning electron microscopy

CAD = computer-aided design

μCT = microcomputed tomography

E = elastic modulus

v = Poisson's ratio

Co-Cr = cobalt-chrome

MPa = megapascal

GPa = gigapascal

mm = milimiters

N = Newtons

β = beta

% = percent

Ø = diameter

º = degree

~ = approximately

e.g. = for example

i.e. = in others words

SUMÁRIO

INTRODUÇÃO GERAL

Para a longevidade clínica de qualquer restauração implanto-suportada é requisito fundamental que seja obtido sucesso nos aspectos mecânicos e estéticos. Dessa forma, não apenas o correto posicionamento do implante, mas também um ótimo volume dos tecidos peri-implantares são fatores a serem alcançados, especialmente quando se trata de reposições unitárias na região anterior da maxila.[1] Como a correta localização dos tecidos moles peri-implantares depende da preservação da altura da crista óssea, os tecidos ósseos são fatores determinantes para o resultado estético final.[2]

Atualmente, sabe-se que o processo de remodelação óssea e gengival é inevitável após a restauração do implante e consequente exposição do mesmo ao meio oral, uma vez que é necessário um espaço para a formação de um epitélio juncional e uma faixa de tecido conjuntivo a partir da junção pilar-implante, onde normalmente se encontra um "microgap".[3] Nesse contexto, é sugerido como pré-requisito para a preservação da integridade das margens gengivais e da papila interdental que a perda óssea não seja superior a 1,5 mm ao longo do primeiro ano pós-restauração do implante, e ≤ 0,2 mm nos anos seguintes.[4]

Entre os recursos disponíveis para minimizar a perda óssea peri-implantar, a restauração do implante com um pilar de menor diâmetro em relação à plataforma protética do implante (conceito de "plataforma *switching*") tem sido utilizado com frequência nos últimos anos.[5, 6] Este conceito foi desenvolvido involuntariamente em meados dos anos 90 quando alguns fabricantes de implantes dentais começaram a produzir e introduzir no mercado odontológico os implantes de diâmetro largo antes de produzir os pilares protéticos correspondentes com as mesmas medidas.[7, 8] Quatorze anos mais tarde, por meio de exames clínicos e radiográficos, foram observados resultados favoráreis em relação à preservação dos tecidos moles e duros em torno daqueles implantes restaurados por pilares de menor diâmetro. Desde então, esta técnica vem sendo difundida e aperfeiçoada por clínicos, pesquisadores e empresas da área de Implantodontia.

Ao deslocar a junção pilar-implante da região do perímetro externo do implante em direção ao centro do mesmo, acredita-se que os agentes microbianos provenientes do infiltrado de células inflamatórias ficariam mais afastados dos tecidos peri-implantares e a remodelação óssea causada pelo estabelecimento do espaço biológico seria reduzida.[9] Além disso, haveria também mais espaço para a acomodação dos tecidos moles e duros em torno da região cervical do implante. Sob a perspectiva da bioengenharia, tem sido sugerido que o uso de implantes com plataforma *switching* melhora as características mecânicas em relação à distribuição das cargas oclusais para o osso peri-implantar.[5, 6, 10-13] Mas se por um lado essa modificação no padrão de distribuição das tensões promove um alívio nos tecidos peri-implantares, por outro lado há uma concentrção das tensões nas regiões mais internas do complexo pilar-implante, principalmente no parafuso de retenção do pilar.[5, 10]

Apesar da associação do conceito de plataforma *switching* com menor concentração de tensão no osso peri-implantar e maior no complexo pilar-implante ser defendido na maior parte dos trabalhos previamente publicados, algumas investigações em animais[14] e humanos[15] apontam para resultados distintos, reportando resultados semelhantes para os níveis ósseos em torno de implantes com plataforma *switching* ou regular. Da mesma forma, uma simulação computacional demonstrou ausência de prejuízo mecânico no complexo pilar-implante ao reduzir o diâmetro do pilar em 0,5 mm.[16]

Além de não apresentar um consenso envolvendo estudos *in vitro* e *in vivo*, a literatura pesquisada não fornece ainda um embasamento para responder se o possível aumento de tensão no complexo pilar-implante é suficiente para afetar a confiabilidade a longo prazo da restauração implanto-suportada. Considerando que o principal desafio no desenvolvimento das conexões protéticas reside em reduzir a incidência de falhas mecânicas do sistema restaurador e ao mesmo tempo proporcionar as melhores condições biológicas possíveis aos tecidos peri-implantares, o presente trabalho investigou a influência do conceito de plataforma *switching* no comportamento biomecânico de implantes com hexágono externo e interno. Para isso, este trabalho foi dividido em dois capítulos. No Capítulo 1 foi realizado um estudo para avaliar a probalilidade de falha em função do tempo (teste de fadiga acelerada) a fim de observar a confiabilidade da restauração implanto-suportada variando o desenho da conexão pilar-implante em função do diâmetro do pilar protético (plataforma regular ou *switching*) e o tipo de conexão do implante (hexágono externo ou interno). Adicionalmente, uma simulação computacional (análise de elementos finitos tridimensional) reproduzindo todas as características dos espécimes testados no estudo laboratorial *in vitro* foi realizada para estudar os diferentes padrões de distribuição de tensão em função das variáveis testadas. No capítulo 2 foi realizada uma segunda simulação computacional envolvendo as mesmas variáveis do estudo anterior, porém incorporando nos modelos de elementos finitos tridimensionais as condições clínicas reais não representadas nos modelos laboratoriais do capitulo 1, como a presença do osso peri-implantar (osso cortical e trabecular da região anterior da maxila) e de uma restauração cerâmica livre de metal. Assim, além de avaliar o padrão de distribuição das tensões no complexo pilar-implante, também foi possível avaliar como as tensões foram transferidas aos tecidos peri-implantares em função das novas variáveis incorporadas.

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Capítulo 1 [*]

Biomechanical Evaluation of Internal and External Hexagon Platform Switched Implant-Abutment Connections: An In Vitro Laboratory and Three-Dimensional Finite Element Analysis.

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[*] Este artigo será submetido para a *Revista Journal of Biomechanics*, conforme normas no Anexo A.

1.1 Resumo (Abstract)

The aim of this study was to assess the effect of abutment's diameter shifting on reliability and stress distribution within the implant-abutment connection of anterior single-unit restorations for internal and external hex implants. The postulated hypothesis was that platform-switched implants would result in increased stress concentration within the implant-abutment connection, leading to the systems’ lower reliability on laboratory mechanical testing. For this, eighty-four implants were divided in four groups (n=21): REG-EH and SWT-EH (regular and switched-platform implants with external connection, respectively); REG-IH and SWT-IH (regular and switched-platform implants with internal connection, respectively). Use-level probability Weibull curves and reliability for missions of 50,000 cycles at 210N and 300N were calculated. Four finite element models reproducing the characteristics of specimens used in laboratory testing were created to evaluate the stress distribution (σ_{vM}) at the implant, abutment, and fixation screw. The Beta values for groups SWT-EH (1.31), REG-EH (1.55), SWT-IH (1.83) and REG-IH (1.82) indicated that fatigue accelerated the failure of all groups. The higher levels of σ_{vM} within the implant-abutment connection observed for platform-switched implants (groups SWT-EH and SWT-IH) were in agreement with the lower reliability observed for the external hex implants, but not for the internal hex implants. The reliability 90% confidence intervals (50,000 cycles at 300N) were 0.53(0.33-0.70), 0.93(0.80-0.97), 0.99(0.93-0.99) and 0.99(0.99-1.00), for the SWT-EH, REG-EH, SWT-IH, and REH-IH, respectively. Failure modes (screw and/or abutment fracture) were similar for regular and switched-platform implants regardless of the connection geometric configuration. The postulated hypothesis was partially accepted. The higher levels of stress observed within implant-abutment connection when reducing abutment diameter resulted in lower reliability for external hex implants, but not for internal hex implants. Failure modes were similar when comparing switching and regular platforms.

KEY WORDS: dental implants, platform switching, biomechanics, reliability, finite element analysis.

1.2 Introdução (Introduction)

In the first year after implant insertion and loading, early peri-implant bone loss commonly leads to a reduction in bone height, shown to vary as a function of quality and quantity of bone, implant and abutment designs, implant's surface structure, insertion depths, arch region, and other factors (Manz, 2000; Bozkaya et al., 2004; Hermann et al., 2007). An attempt to hinder this process has resulted in the development of the platform switching concept, which consists in use of an abutment of smaller diameter connected to a implant of larger diameter. This connection shifts the perimeter of the implant-abutment junction inward towards the central axis (the middle of the implant), potentially improving the distribution of forces and placing the implant-abutment gap away from the peri-implant bone (Lazzara and Porter, 2006; Lopez-Mari et al., 2009). It has been suggested that the inward shift of the implant-abutment gap may physically minimize the impact of the inflammatory cell infiltrate in the peri implant tissues, potentially reducing bone loss (Baumgarten et al., 2005; Gardner, 2005; Duarte et al., 2006; Hermann et al., 2007; Cappiello et al., 2008; Luongo et al., 2008; Canullo et al., 2010).

From a biomechanical perspective, previous *in vitro* studies (Maeda et al., 2007; Baggi et al., 2008; Schrotenboer et al., 2008; Rodriguez-Ciurana et al., 2009; Tabata et al., 2010; Vargas et al., 2011) have shown reduced levels of stress on peri-implant bone in platform-switched implants relative to matched implant-abutment diameters. Such potential for crestal bone level preservation has been shown in animal (Becker et al., 2007; Jung et al., 2008; Cochran et al., 2009) and clinical studies.(Hurzeler et al., 2007; Degidi et al., 2008; Canullo et al., 2010).

On the other hand, complications with implant-abutment connections is still a common clinical problem, especially in single-tooth replacements (Jung et al., 2008; Quek et al., 2008; Steinebrunner et al., 2008). When considering platform-switched implants, previous studies (Maeda et al., 2007; Tabata et al., 2010) have shown an increased stress on the abutment and fixation screw, which may compromise the system biomechanical performance. Controversially, several published studies (Bozkaya et al., 2004; Becker et al., 2007; Baggi et al., 2008; Schrotenboer et al., 2008; Crespi et al., 2009; Hsu et al., 2009; Rodriguez-Ciurana et al., 2009; Chang et al., 2010; Vargas et al., 2011) related to the mechanics of platform-switched implants have been restricted to analyzing the stress distribution on peri-implant bone and not on the overall system biomechanical behavior. To date, studies evaluating the mechanical behavior of platform-switched implants considering the stress distribution in implant-abutment complex are scarce and restricted to computer simulations (Maeda et al., 2007; Canay and Akca, 2009; Pessoa et al., 2010; Tabata et al., 2010), which do not consider several clinical variables (influence of fatigue damage accumulation and wet environment) previously reported as important factors to reproduce clinically observed failure modes (Coelho, Silva et al. 2009).

Since the main challenges in the development of implant-abutment connection designs comprises reducing the incidence of mechanical failures while improving the interface between soft tissue and implant-abutment junction (Khraisat et al., 2002; Pjetursson et al., 2004), the evaluation of reliability and failure modes supported by evaluation of stress distribution in each component of platform-switched connections may provide insight into the mechanical behavior of different configurations of implant-abutment connection. Therefore, the present study sought to assess the effect of abutment's diameter shifting (regular and switched-platform) on reliability and failure modes of anatomically-correct maxillary central incisor crowns varying the geometry of implant connection (internal and external hexagon). In order to evaluate the stress distribution within implant-abutment complex (implant, abutment and fixation screw), a three-dimensional finite element analysis was performed considering the variables. The postulated hypothesis was that platform-switched implants would result in increased stress concentration within the implant-abutment connection, leading to the systems' lower reliability when subjected to step-stress accelerated life testing (SSALT).

1.3 Materiais e Métodos (Materials and Methods)

In vitro laboratory study: Single Load-to-Fracture (SLF) and Step-Stress Accelerated-Life Testing (SSALT)

Eighty-four Ti-6Al-4V dental implants (SIN implants, São Paulo, SP, Brazil) were distributed in four groups (n = 21 each) varying the abutment diameter (switched or regular platform) and the type of implant connection (internal or external hexagon) (Figure 1 and Table 1): (1) SWT-EH (switching platform and external hexagon implant); (2) REG-EH (regular platform and external hexagon implant); (3) SWT-IH (switching platform and internal hexagon implant); and (4) REG-IH (regular platform and internal hexagon implant).

All implants were vertically embedded in acrylic resin (Orthoresin, Degudent, Mainz, Germany), poured in a 25-mm-diameter plastic tube, leaving the top platform in the same level of the potting surface. All groups were restored with standardized central incisor metallic crowns (CoCr metal alloy, Wirobond® 280, BEGO, Bremen, Germany) cemented (Rely X Unicem, 3M ESPE, St. Paul, MN, USA) on the abutments, which presented identical height but different diameters (Table 1).

For mechanical testing, the specimens were subjected to 30º off-axis loading. Three specimens of each group underwent single-load-to-fracture (SLF) testing at a cross-head speed of 1 mm/min in a universal testing machine (INSTRON 5666, Canton, MA, USA) with a flat tungsten carbide indenter applying the load on the lingual side of the crown, close to the incisal edge. Based upon the mean load to failure from SLF, three step-stress accelerated life-testing profiles were determined for the remaining 18 specimens of each group which were assigned to a mild (n=9), moderate (n=6), and aggressive (n=3) fatigue profiles (ratio 3:2:1, respectively) (Figure 2) (Nelson, 1990;

Coelho et al., 2009). The prescribed fatigue method was step-stress accelerated life-testing (SSALT) under water (environmental temperature) at 9 Hz with a servo-all-electric system (TestResources 800L, Shakopee, MN, USA) where the indenter contacted the crown surface, applied the prescribed load within the step profile and lifted-off the crown surface. Fatigue testing was performed until failure (bending or fracture of the fixation screw and/or abutment) or survival (no failure occurred at the end of step-stress profiles, where maximum loads were up to 600 N) (Nelson, 1990; Coelho et al., 2009). Use level probability Weibull curves (probability of failure versus cycles) with a power law relationship for damage accumulation were calculated (Alta Pro 7, Reliasoft, Tucson, AZ, USA) (Zhao, 2005). Reliability (90% two-sided confidence bounds) for completion of a mission of 50,000 cycles at 210 N and 300 N load (Paphangkorakit and Osborn, 1997) were determined for group comparisons.

Macro images of failed samples were taken with a digital camera (Nikon D-70s, Nikon, Tokyo, Japan) and utilized for failure mode classification and comparisons between groups. In order to identify fractographic markings and characterize failure origin and direction of crack propagation, the most representative failed samples of each group were inspected first under a polarized-light microscope (MZ-APO stereomicroscope, Carl Zeiss MicroImaging, Thornwood, NY, USA) and then by scanning electron microscopy (SEM) (Model S-3500N, Hitachi, Osaka, Japan) (Parrington, 2002; Manda et al., 2009).

Three-Dimensional Finite Element Analysis (3D-FEA)

Four virtual 3D models were created using computer-aided design (CAD) software (SolidWorks 2010, Dassault Systèmes SolidWorks Corp., Concord, MA, USA) following design and dimensions observed in groups SWT-EH, REG-EH, SWT-IH and REG-IH. Each 3D CAD model represented all characteristics of the implant-abutment connection in order to reproduce the experimental conditions prevailing as a result of the mechanical tests (Figure 1). The solid components of the models consisted of a maxillary central incisor crown (Co-Cr alloy), a 50 μm-thick (Li et al., 2006) resin cement layer (Rely X Unicem), an abutment (titanium alloy), a fixation screw (titanium alloy), an implant (titanium alloy), and a cylinder created in the CAD software with the same dimensions of the plastic tubes used in the *in vitro* laboratory study (Figure 3). The anatomically correct crown was generated from microcomputed tomography images in *.dicom* format (μCT40, Scanco Medical AG, Bruttisellen, Switzerland) and its cementation surface was designed to fit the abutments in all groups. The implant insertion hole in the cylinder (acrylic resin) was obtained by a Boolean subtraction.

The components were assembled, imported into FEA software (Ansys Workbench 12.0, Swanson Analysis Inc., Houston, PA, USA), meshed (Figure 3C) (number of parabolic tetrahedral elements (de Almeida et al., 2010) between 254,513 and 288,543; and number of nodes between 433,816 and 492,803) and tested for convergence (6%) (Huang et al., 2008) prior to mechanical simulation.

The FEA model assumptions were that: (1) all solids were homogeneous, isotropic and linearly elastic; (2) there were no slip conditions (perfect bonding) among components (set implant-abutment-screw, elastic modulus (E) = 110 GPa and Poisson's ratio (v) = 0.35)(Huang, Fuh et al. 2009); (3) there was a uniform cement layer (E = 8 GPa, v = 0.33) (Coelho et al., 2009); (4) there was a crown (E = 220 GPa, v = 0.30)(Erkmen, Meric et al. 2011) with similar dimensions (13 mm height with a mesiodistal width of 8.8 mm and buccal-lingual width of 7.1 mm) in all FEA models; (5) there were no flaws in any components; (6) there was a six-degrees-of-freedom (full) constraint on the bottom and lateral surface of the cylinder of acrylic resin (E =

1.37 GPa, $v = 0.30$)[*]. As in the mechanical tests, one 30º off-axis load (300 N) was applied on the lingual side of the crown, close to the incisal edge. Regions of higher von Mises equivalent stress (σ_{vM}) were determined within implant-abutment connection for all models.

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[*] Manufacturer's information

1.4 Resultados (Results)

In vitro laboratory study (SLF and SSALT)

The SLF mean ± standard deviation values for group SWT-EH was 1090.01 N ± 140.49 N, 1204.95 N ± 49.78 for group REG-EH, 960.69 ± 113.85 for group SWT-IH and 818.8 N ± 105.85 N for group REG-IH.

The step-stress accelerated fatigue allows estimation of reliability at a given load level (Table 2). The calculated reliability with 90% confidence intervals for a mission of 50,000 cycles at 300 N showed that the cumulative damage from loads reaching 300 N would lead to restoration survival in 53% of specimens in group SWT-EH, whereas 93% would survive in group REG-EH. These values depict a statistically significant difference between groups SWT-EH and REG-EH. On the other hand, the overlap between the upper and lower limits of reliability values in groups SWT-IH and REG-IH indicates no statistically significant difference in reliability of implant-supported restorations with internal connections, regardless of abutment diameter (switching or regular platform). For the given mission, a survival of 99% of the specimens would be observed in both groups (SWT-IH and REG-IH). As shown in Table 2, from 99% to 100% of the specimens would survive given a mission of 50,000 cycles at 210 N, indicating no statistically significant difference in reliability among all groups.

The step-stress derived probability Weibull plots at a 300 N load are presented in Figure 4. The Beta (β) values and associated upper and lower bounds derived from use level probability Weibull calculation (probability of failure *vs.* number of cycles) of 1.31 (0.75 - 2.28) and 1.83 (1.01 - 3.32) for platform-switched implants (groups SWT-EH and SWT-IH, respectively), and β values of 1.55 (0.78 - 3.06) and 1.82 (1.02 - 3.25) for regular platform implants (groups REG-EH and REG-IH, respectively) indicated that fatigue was an accelerating factor for all groups. The Beta value describes failure rate changes over time ($\beta < 1$: failure rate is decreasing over time, commonly associated with "early failures" or failures that occur due to egregious flaws; $\beta \sim 1$: failure rate that does not vary over time, associated with failures of a random nature; $\beta > 1$: failure rate is increasing over time, associated with failures related to damage accumulation) (Silva et al., 2008; Coelho et al., 2009; ReliaSoft, 2010).

Failure Modes

All specimens failed after SLF and SSALT. Failure modes for all groups are presented in Table 3. For restorations over external hex implants (groups SWT-EH and REG-EH) screw fracture at the third thread region was the chief failure mode (Figure 5C). In these specimens, abutments and implants were intact after mechanical tests. For restorations over internal hex implants (groups SWT-IH and REG-IH), screw and abutment fracture (Figure 6 B and C) were observed in all specimens after mechanical tests. No implant fracture was observed in any group.

Observation of the polarized-light and SEM micrographs of the screw's fractured surface allowed the consistent identification of fractographic markings, such as compression curl, fatigue striations and dimples, which allowed the identification of flaw origin and the direction of crack propagation (Figure 7). As per our imaging analysis of the specimen's fractured surface, all fractures were characterized by material tearing and exhibited gross plastic deformation, suggesting ductile fractures (Figures 6 C and 7 A,B). The resulting ductile fractures occurred as stresses exceeded the material yield strength leaving telltale fractographic marks that indicated crack propagation from lingual to buccal (Figure 7 C), where occlusal forces naturally occur in the anterior region. Although a part of metallic components may fail in a brittle manner, ductile fracture morphology is frequently observed in our specimens away from the origin. For example, *compression curl* is a fractographic feature representative of flexure failures and results from a traveling crack changing direction as it enters a compression field (Quinn, 2007). Usually it evidences fracture origin at the opposing tensile side (Figure 7 D). At higher magnifications (from 500x to 2,500x), fatigue striations were observed (Figure 7 E). They emanated outward from the origin and marked successive positions of the advancing crack front (Parrington, 2002). Also in a higher magnification (1,500x) a dimpled surface appearance created in some areas on the fractured surface was observed, exemplifying a typical ductile fracture in metal alloys, commonly created by microvoid coalescence (Parrington, 2002).

3D-FEA

The values for σ_{vM} within implant-abutment complex (implant, abutment and fixation screw) are presented in Table 4, and showed that the stress distribution on abutment and screw was strongly influenced by the abutment diameter (regular and switched-platform) and type of implant connection (external and internal hexagon). When reducing the abutment diameter, an increase in the σ_{vM} of 41% was observed in the abutment connected to external hex implant (SWT-EH), while an increase in the σ_{vM} of 53% was observed in the abutment connected to internal hex implant (SWT-IH). In the fixation screw, increases of 20% and 12% were observed in the σ_{vM} for SWT-EH and SWT-IH, respectively. No relevant differences in the levels of σ_{vM} were observed in the implant body when considering the variables of this study.

The highest level of stress was observed in the fixation screw for all models. In the fixation screw, the peak of σ_{vM} was concentrated at the third thread region in all groups (Figure 5), whereas in the abutment the peak of σ_{vM} was located on the lingual region at the cervical collar (Figure 6A).

1.5 Discussão (Discussion)

The concept of platform switching is increasingly sought because it can be advantageous in several clinical conditions. Previous studies (Duarte et al., 2006; Cappiello et al., 2008; Luongo et al., 2008; Canullo et al., 2010) have demonstrated that platform-switched abutments may not only reduce the early peri-implant bone loss and increase the biomechanical support available to the implant, but also may improve esthetics. Baumgarten and coworkers (Baumgarten et al., 2005) suggested that the platform switching technique is useful when shorter implants are used, when implants are placed in esthetic zone, and when a larger implant is desirable but prosthetic space is limited. However, as per our laboratory and mechanical simulation results, such attempt to minimize the bone remodeling and resorption and simultaneously improve esthetics by reducing abutment diameter may result in higher stress concentration in the connection components. Our simulation findings are in agreement with other recent FEA studies (Maeda et al., 2007; Tabata et al., 2010).

Considering the relevance of a fatigue resistant implant-abutment connection for the long-term clinical success, the present study evaluated the effect of platform switching concept for external and internal hex implants in the reliability of maxillary central incisor crowns using SSALT. Our results showed that fatigue damage accumulation accelerated the failures of all tested designs, as evidenced by the resulting $\beta > 1$ (also called the Weibull shape factor). Furthermore, a statistically significant lower reliability (given a mission of 50,000 cycles at 300 N load) was found for platform-switched implants with external hex (SWT-EH), but not for platform-switched implants with internal hex (SWT-IH).

These findings may be explained based in the association among stress distribution and system's reliability around the weakest component of the implant-abutment connection: the fixation screw. The higher levels of stress (σ_{vM}) in the abutment screw observed for the external hexagon connection was associated with a lower reliability after mechanical testing for both regular and switched-platform systems (300N load simulation). However, it can be assumed that the slight increase (11.57%) in stress levels (σ_{vM}) observed in the fixation screw when reducing abutment diameter over an internal hex implant (SWT-IH) was not significant to result in lower mechanical reliability. The lower values for reliability observed in groups SWT-EH and REG-EH were due to lower loads initiating prosthetic component failure when compared to groups with internal hex implants (SWT-IH and REG-IH).

Worth noting is that all previous considerations were performed under mission of 50,000 cycles at 300 N load. If a mission of 50,000 cycles at 210 N load is considered (mean value for incisal bite force) (Paphangkorakit and Osborn, 1997), the cumulative damage from loads reaching 210 N would lead to restoration survival of 99% to 100% of the specimens after 50,000 cycles. Thus, under normal occlusion conditions, almost all tested specimens would present satisfactory fatigue endurance in the wet environment used in the present study. In an attempt to simulate the oral environment, fatigue in water was performed, which has been suggested as an important service-related cause of failure in metals (Parrington, 2002). In order to address the question of mechanical performance of regular vs. switched-platform restoration performance in both external and internal connections, we utilized a metallic crown, which eliminated the restorative crown material failure and evidenced the mechanical performance of the different groups.

Screw fracture at the third thread region was the chief failure mode in all groups. Those resulted as the upper part of the implant's connection in contact with the fixation screw under off-axis loading causes the presence of a lever around the third thread region of the screw (Figure 5). Moreover, fracture of the abutments were also observed in groups with internal hex implants. Those fractures were always located on the lingual side at the narrower region below the cervical collar. Despites the location of the peak of σ_{vM} at the external region of the cervical collar (Figure 6), the fracture occurred in the narrower region of the abutment because this was the weakest point of the component. It has been previously reported that the failure location is related to the design characteristics of the implant-abutment combination, which is commonly located in the threaded region or areas that represent a critical point for prosthetic component's endurance due to the shift in geometry along its length and subtle alteration in cross-sectional area (Quek et al., 2008).

Despite the stress distribution observed in the 3D-FEA being obtained from single static loading, such as in SLF tests, which does not represent the cyclic loading observed in oral environment and in fatigue tests (SSALT), our results suggest improved stress distribution within the implant-abutment connection of regular-platform models regardless of the methodology (*in vitro* study or finite element analysis). Thus, the improved stress distribution may presumably be the reason for better mechanical behavior of internally connected systems compared to the externally connected counterparts. Concerning the geometry of implant connection (internal vs. external), higher reliability was observed in specimens with internal connection regardless of the abutment diameter. These findings are in agreement with other studies that pointed that deep joints show increased stability favoring structural strength of implant systems (Khraisat et al., 2002; Maeda et al., 2006; Steinebrunner et al., 2008) It should be noted, however, that due to engineering design constraints such as minimum wall thickness for proper mechanical performance of each of the different connection systems, differences in both external and internal features of the implant, abutment, and screw designs will exist. While from a research standpoint it is highly desirable that only the connection is changed with the connecting screw and implant remaining the same, such interplay is unfeasible for when one is attempting to make clinically relevant comparisons (implants presenting the same diameter, length, and crown size) between external and internal connections in most commercially available systems, as alterations in the implant external shape is usually performed by manufacturers in order to maintain tolerances for appropriate fit and wall thickness for the internal connection robustness.

According to the literature (Gardner 2005), there are potential limitations for using platform-switched implants, e.g. the need for components that have similar designs (the screw access hole must be uniform) and the need for enough space to develop a proper emergence profile. Considering that the replacement of single-unit edentulous spaces in the anterior region with implant-supported restorations is a challenging scenario in terms of long-term success and esthetics, it is crucial to acknowledge the functional and mechanical limitations of the implant-abutment connections. Therefore further *in vivo* and *in vitro* investigations of the implant-abutment reliability combined with finite element analysis are warranted.

1.6 Conclusões (Conclusions)

The postulated hypothesis that platform-switched implants would result in increased stress concentration within the implant-abutment connection, leading to the systems' lower reliability on laboratory mechanical testing was partially accepted. The higher levels of stress observed within implant-abutment connection when reducing abutment diameter resulted in lower reliability for external hex implants, but not for internal hex implants. Failure modes were similar when comparing switching and regular platforms.

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Figuras

1.8 Lista de Figuras (Legend of Figures)

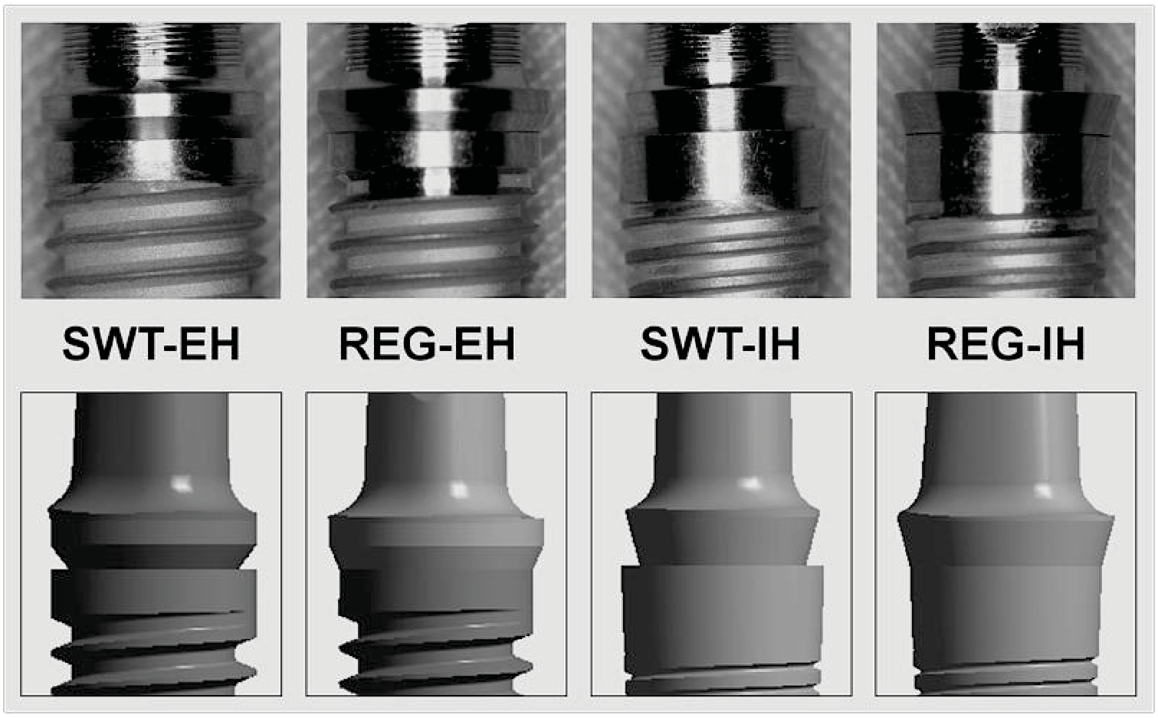

Figure 1. Implant-abutment connections to be used in the mechanical tests (upper) and finite element analysis (lower): SWT-EH and - REG-EH (switching and regular platform connected to a external hex implant, respectively), SWT-IH and - REG-IH (switching and regular platform connected to a internal hex implant, respectively).

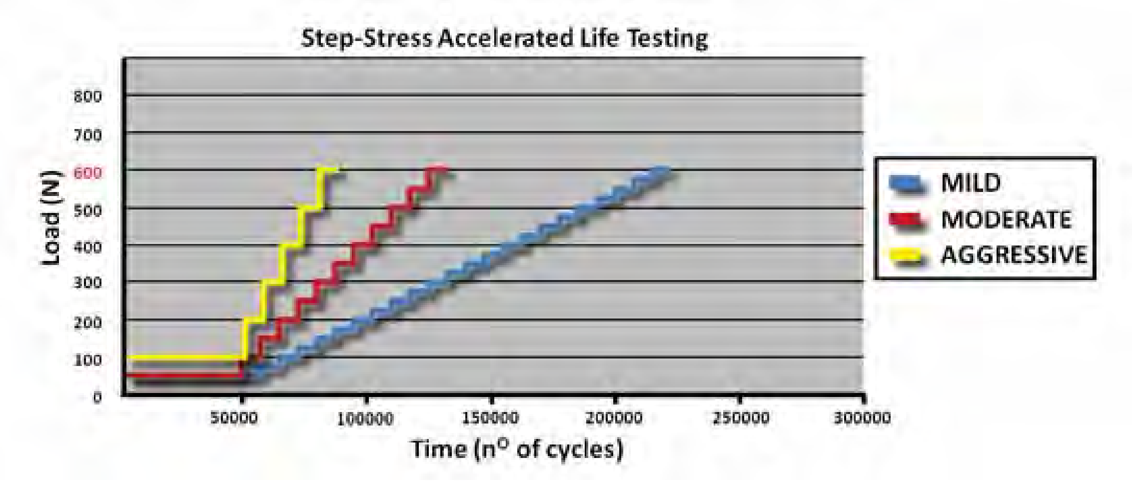

Figure 2. Step-stress profiles utilized for fatigue testing. Note that the loads started in the neighborhood of 50-100 N ending up to 600 N.

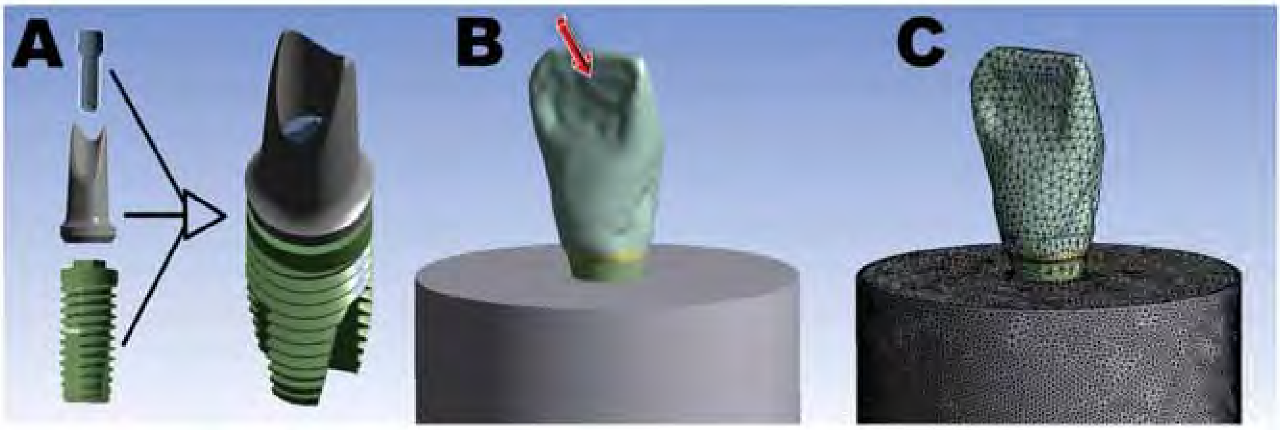

Figure 3. **(A)** 3D CAD models of the implant-abutment complex including fixation screw, abutment and implant. **(B)** Complete CAD model with a cement-retained implant-supported restoration into the acrylic resin cylinder. The red arrow represents a 30º off-axis load (300 N) applied on the crown surface. **(C)** Finite element mesh of the model.

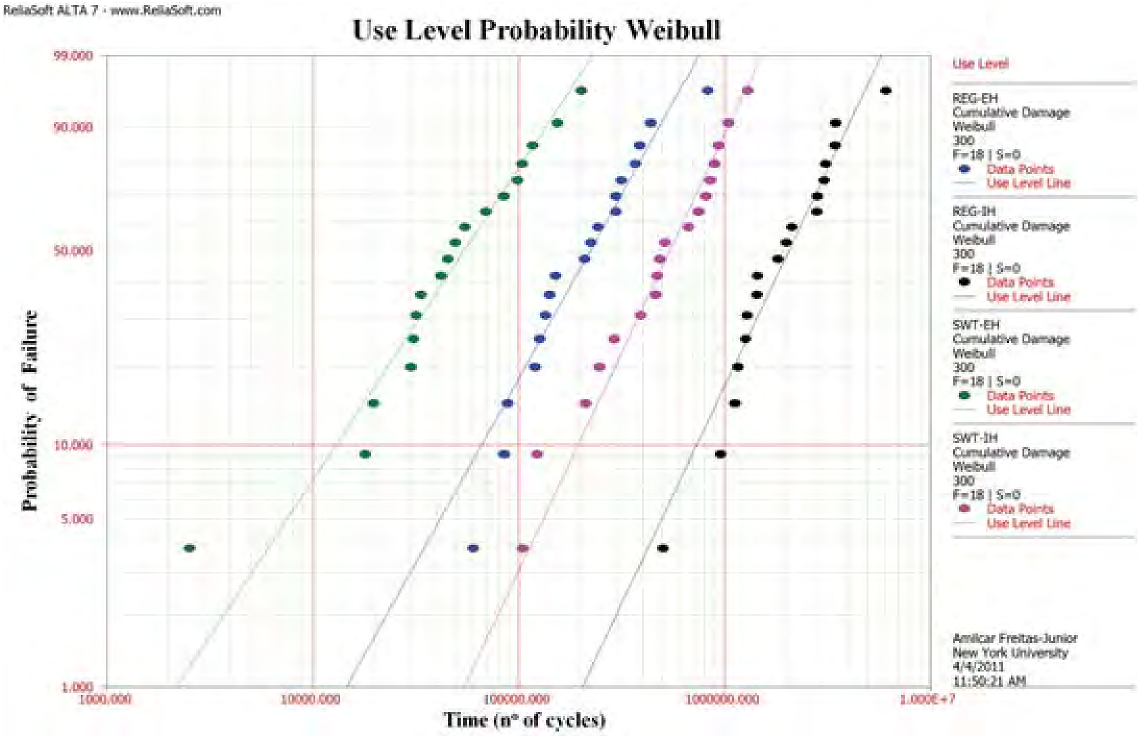

Figure 4. This graph shows the probability of failure as a function of number of cycles (time) for tested groups simulating a mission of 50,000 cycles at 300 N. Note the left position of the SWT-EH group (green) relative to REG-EH group (blue), and SWT-IH group (pink) relative to REG-IH group (black), which indicates the need for more cycles to failure in regular-platform groups compared to the switched-platform groups.

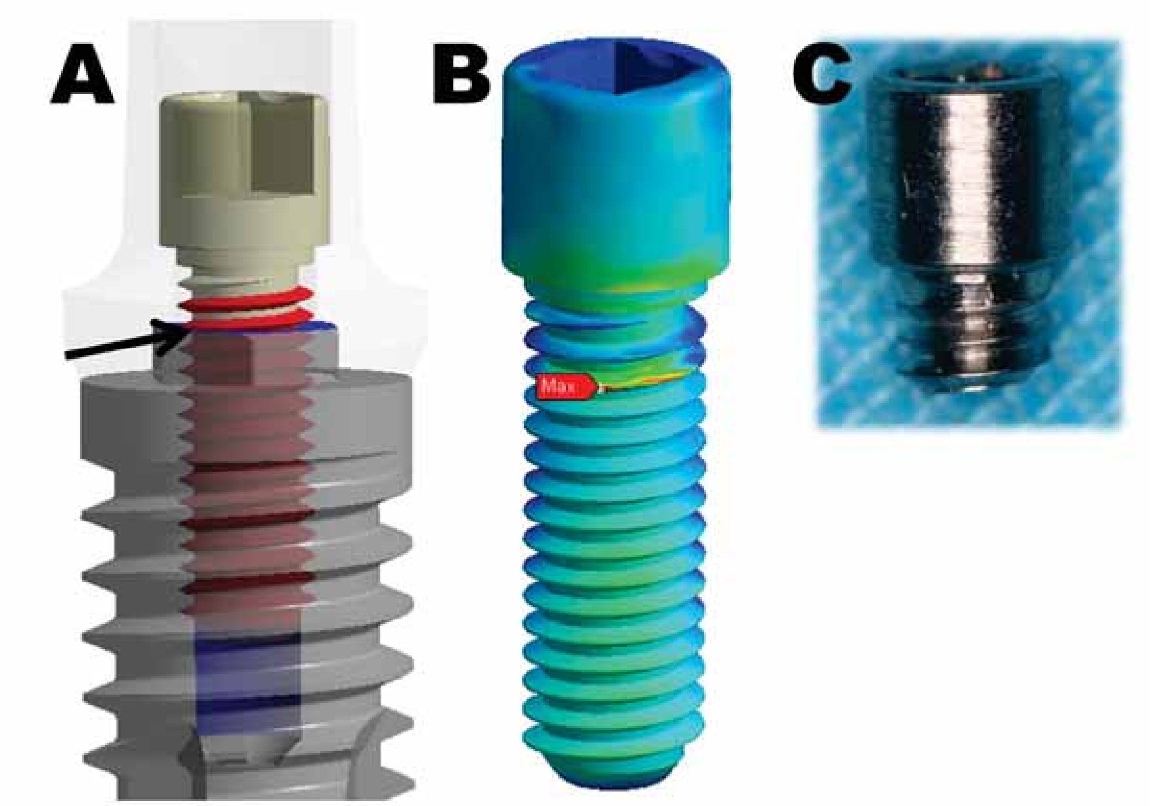

Figure 5. Images illustrating the peak of stress for the fixation screw in all groups. **(A)** 3D CAD model with abutment in transparency showing the contact area (black arrow) at the third thread region of the screw. **(B)** Peak of von Mises equivalent stress (σ_{vM}) at the third thread region of the screw. **(C)** Macro picture of the screw fractured at the third thread region.

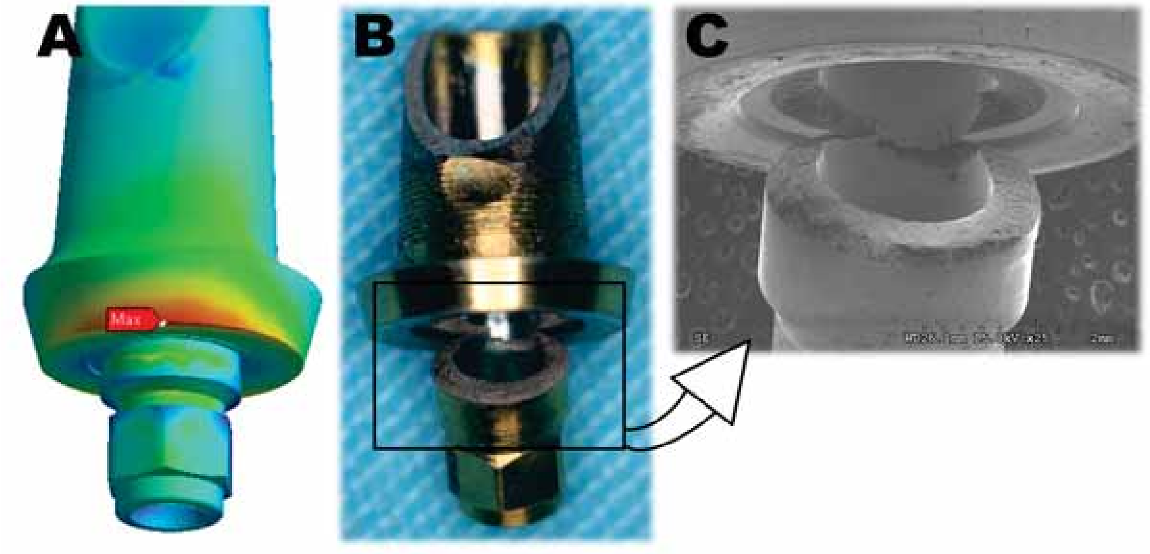

Figure 6. Images illustrating the peak of stress for the abutments. **(A)** Peak of von Mises equivalent stress (σ_{vM}) located on the lingual region at the cervical collar of the abutment. **(B)** Macro picture of an abutment fractured at the cervical collar region. In all specimens, the fracture occurred in this region. **(C)** SEM micrograph of the region of fracture.

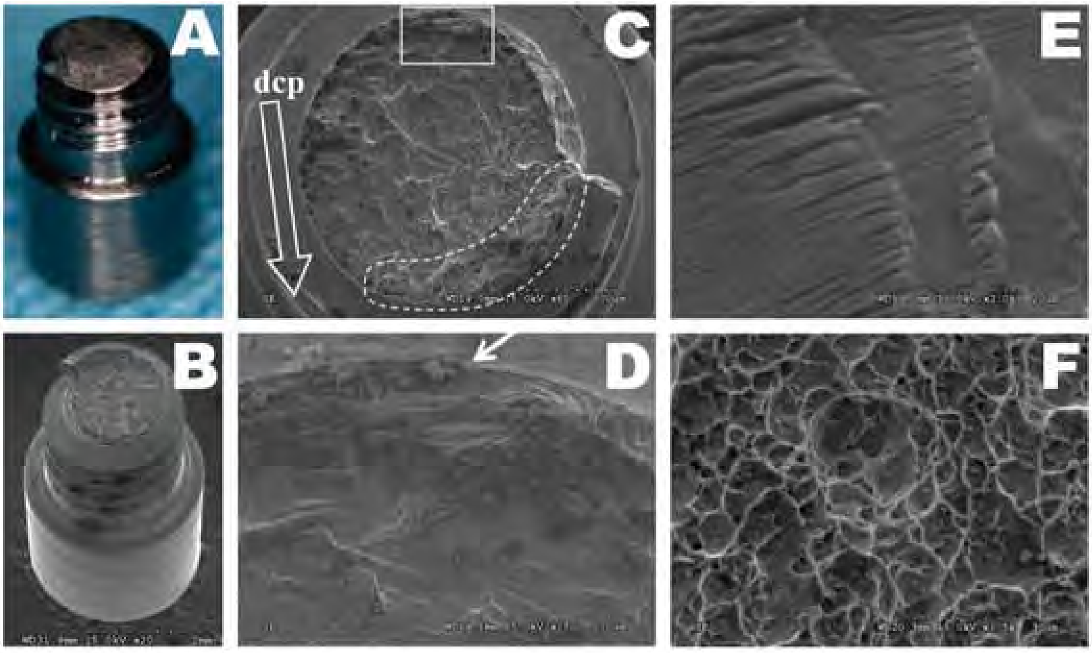

Figure 7. Representative fractured screw after SSALT depicting: **(A** and **B)** Macro image and SEM micrograph, respectively, showing a fracture occurring at the third thread region viewed from the screw's long axis. **(C)** is a SEM micrograph (60x) of the fractured surface of sample shown in (B). The white dotted circle shows a compression curl which evidences fracture origin at the opposing tensile side (white box), indicating the direction of crack propagation (dcp) (white arrow). **(D)** is a higher magnification (250x) of the boxed area in (C) showing the fracture origin. **(E** and **F)** are higher magnifications (2,000x and 1,500x, respectively) of the fractured surface showing typical fractographic features of metallic materials: (E) fatigue striations and (F) dimpled surface appearance.

Tabelas

1.9 Lista de Tabelas (Tables)

Table 1. Characteristics of the components used in the present study.

Components	**SWT-EH**	**REG-EH**	**SWT-IH**	**REG-IH**
Implant	External hex (SUR 5011) 5.0 mm diameter by 11.5 mm length Ø prosthetic platform = 5.0mm	External hex (SUR 5011) 5.0 mm diameter by 11.5 mm length Ø prosthetic platform = 5.0mm	Internal hex (SIHS 5511) 5.0 mm diameter by 11.5 mm length Ø prosthetic platform = 5.5mm	Internal hex (SIHS 5511) 5.0 mm diameter by 11.5 mm length Ø prosthetic platform = 5.5mm
Abutment	Cemented (Al 4151) Ø platform = 4.1 mm	Cemented (Al 5051) Ø platform = 5.0 mm	Cemented (Al 4501) Ø platform = 4.5 mm	Cemented (Al 5501) Ø platform = 5.5 mm
Screw	fixation screw (PTQ2008)	fixation screw (PTQ2008)	fixation screw (PTQH16)	fixation screw (PTQH16)

Table 2. Calculated reliability (upper and lower limits) for tested groups given two different missions: 50,000 cycles at 300 N load and 50,000 cycles at 210 N load. The number of symbols (* and †) depicts statistically homogeneous groups considering 90% two-sided confidence bounds (confidence level = 0.9).

Output	**SWT-EH**	**REG-EH**	**SWT-IH**	**REG-IH**
50,000 cycles @ 300 N	0.53 (0.33 - 0.70)*	0.93 (0.80 - 0.97)**	0.99 (0.93 - 0.99)†	0.99 (0.99 - 1.00)†
50,000 cycles @ 210 N	0.99 (0.94 - 0.99)†	0.99 (0.98 - 0.99)†	1.00 (0.99 - 1.00)†	1.00 (0.99 - 1.00)†

Table 3. Failure modes after mechanical testing (Single-Load-to-Fracture (SLF) and Step-Stress Accelerated Life-Testing (SSALT)) according to the used failure criteria.

Groups	**SWT-EH**	**REG-EH**	**SWT-IH**	**REG-IH**
SLF **(n = 3)**	Screw: 3 fracture Abutment: 3 intact Implant: 3 intact	Screw: 3 fracture Abutment: 3 intact Implant: 3 intact	Screw: 3 fracture Abutment: 3 fracture Implant: 3 intact	Screw: 3 fracture Abutment: 3 fracture Implant: 3 intact
SSALT **(n = 18)**	Screw: 18 fracture Abutment: 18 intact Implant: 18 intact	Screw: 18 fracture Abutment: 18 intact Implant: 18 intact	Screw: 18 fracture Abutment: 18 fracture Implant: 18 intact	Screw: 18 fracture Abutment: 18 fracture Implant: 18 intact

Table 4. Von Mises equivalent stress (σ_{vM}) in MPa within the implant-abutment complex.

Component	**Implant**	**Abutment**	**Screw**
SWT-EH	228	182	365
REG-EH	225	129	305
SWT-IH	216	166	270
REG-IH	216	108.3	242

Capítulo 2 [*]

Stress Distribution on Internal and External Platform Switched Implant-Abutment Connection. A 3D Finite Element Analysis.

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[*] Este artigo será submetido para a *Revista The International Journal of Oral & Maxillofacial Implants*, conforme normas no Anexo B.

2.1 Resumo (Abstract)

Purpose: The aim of this study was to test the hypothesis that switched-platform implants used as anterior single-unit restorations would result in different stress patterns within implant-abutment complex and peri-implant bone when compared with regular platform implants on both external or internal hexagon connection configurations.

Materials and Methods: Four anatomically-correct three-dimensional finite element models were created varying the abutment diameter and the geometry of implant connection: REG-EH and SWT-EH (regular and switched-platform implants with external hexagon, respectively); REG-IH and SWT-IH (regular and switched-platform implants with internal hexagon, respectively). Qualitative and quantitative analysis based in maximum principal stress (σ_{max}) and von Mises equivalent stress (σ_{vM}) were performed in Ansys Workbench.

Results: In the prosthetic components, the higher peak of stress (σ_{vM}) was observed in the fixation screw (SWT-EH = 190 MPa and REG-EH = 160 MPa) for groups with external hex implants. For internal hex implants, peak stresses were observed in the abutment (SWT-IH = 186 MPa and REG-IH = 88.8 MPa). In the cortical bone, switched-platform implants generated lower stress levels (σ_{max}) on both external (SWT-EH = 49.0 MPa and REG-EH = 56.5 MPa) and internal (SWT-IH = 37.7 MPa and REG-IH = 45.5 MPa) configurations.

Conclusions: As hypothesized, different patterns of stress distribution were observed within implant-abutment complex and peri-implant bone. When reducing the abutment diameter, higher levels of stress (σ_{vM}) were observed in abutment and fixation screw, while lower levels of stress (σ_{vM} and σ_{max}) were observed in peri-implant bone regardless the implant connection (external or internal hexagon).

Key Words: finite element analysis, platform switching, biomechanics, stress.

2.2 Introdução (Introduction)

A challenge scenario for the short- and long-term success in dental implantology is to design an implant-abutment connection with a geometry that will minimize stress concentration within the implant-abutment complex and peri-implant bone. Recently, studies have shown that applying the platform switching concept seems to somewhat stabilize the crestal bone loss around implants.[1, 2] This concept consists in the placement of smaller-diameter abutment on wider-diameter implant in order to inwardly reposition the implant-abutment gap region, placing it further away from the peri-implant bone.[3, 4] While such repositioning has the potential of maintaining the septic reservoir that results from the implant-abutment gap further away from bone, such configuration may result in increased levels of stress within the implant-abutment complex and the peri-implant bone.[2, 5]

In an attempt to minimize the mechanical problems related to implant-abutment connections, the literature demonstrates that the internal connection shows better performance in laboratorial tests,[6, 7] anti-rotational stability,[6-8] reduced rate of abutment screw loosening and fracture,[8, 9] and lower stress transferred to the bone[10-12] when compared to the external connection.

Concerning the stress distribution within implant-abutment connection, several studies have evaluated the mechanical behavior of switched-platform implants.[2, 5, 13] Tabata and coworkers[2] used two-dimensional finite element analysis (2D-FEA) to report a higher stress concentration in the crown and fixation screw when varying implant diameter as a function of abutment dimension. While valuable complex 3D-FEA studies have also been performed,[5, 13, 14] simplifications in the anatomy of the restorative components (absence of crown, use of simple cylindrical implant without a screwed surface, and others) on these investigations have limited their extrapolation to clinical scenarios. Certainly, the presence of friable materials such as ceramic (veneer layer and zirconia core of metal-free restorations) and resin cement layer may influence the stress distribution on implant-supported restoration and surrounding structures.

Considering the importance of anatomically-correct representation of all structures involved in FEA simulations to more close reproduce the clinical conditions, and that the main challenge in the development of implant-abutment connection designs relies on reducing the incidence of mechanical failures while improving the interface between soft tissue and implant-abutment junction,[15, 16] the present study sought to test the hypothesis that switched-platform implants used as anterior single-unit restorations would result in different stress distribution patterns within implant-abutment connection and peri-implant bone in comparison with regular platform implants regardless the implant connection (external or internal hexagon).

2.3 Materiais e Métodos (Materials and Methods)

An anatomically correct 3D model of the anterior region of the maxilla was created and assembled to the set implant-abutment-crown within a computer-aided design (CAD) software (SolidWorks 2010, Dassault Systèmes SolidWorks Corp., Concord, MA, USA). The implant insertion hole in the maxillary bone was obtained by a Boolean subtraction.

Four 3D models were created with CAD software (SolidWorks 2010) varying the abutment diameter (platform switching or regular) and the geometry of implant connection (external or internal hexagon) (Table 1 and Figure 1A,B): (1) SWT-EH (switched-platform and external hex implant); (2) REG-EH (regular platform and external hex implant); (3) SWT-IH (switched platform and internal hex implant); and (4) REG-IH (regular platform and internal hex implant). In all models, the implants were restored with an anatomically-correct central incisor crown generated from microcomputed tomography images in *.dicom* format (μCT40, Scanco Medical AG, Bruttisellen, Switzerland). The crown height was 13 mm, with mesiodistal width of 8.8 mm and buccal-lingual width of 7.1 mm. The crowns were created with their cementation surface subtracted to fit the abutments in all groups.

Thus, the solid components of the 3D CAD models consisted of the cortical and trabecular bone, implant (titanium alloy), abutment (titanium alloy), fixation screw (titanium alloy), crown (LAVA system, 3M/ESPE, St. Paul, MN, USA), and a 50 μm-thick[17] resin cement layer (Rely X Unicem, 3M/ESPE, St. Paul, MN, USA) (Figure 1C,D). The materials were considered isotropic, homogeneous and linearly elastic and their mechanical properties (elastic modulus and Poisson's ratio) were incorporated according to the specific literature (Table 2).[18-20] A finite element (FE) software (Ansys Workbench 10.0, Swanson Analysis Inc., Houston, PA, USA) was used to determine the regions of interest and generate the finite element mesh (Figure 1E). A parabolic tetrahedral interpolation solid element with 0.40 mm elements was used for meshing.[21] The mesh refinement was established based on the convergence of analysis (6%).[1, 14, 18] The models showed between 518,220 and 561,333 nodes and 341,601 and 371,869 elements.

In order to simulate the mean value of incisal bite force in man, one oblique load (30º) was applied on the lingual surface of the crown (210 N) (Figure 1D).[22] As characterization of the boundary condition a displacement equal to zero was established on the three Cartesian axes ($x = y = z = 0$) and were fixed to the mesial and distal sides of the models.

Considering that the implant-abutment complex consists of a ductile material (titanium alloy), the von Mises equivalent stress (σ_{vM}) were obtained for the implant, abutment and fixation screw. On the other hand, as the cortical and trabecular bone are friable materials (non-ductile materials), the maximum (σ_{max}) principal stress was also obtained to better understand the influence of platform switching concept on peri-implant bone.[23]

2.4 Resultados (Results)

The stress (σ_{vM}) values within implant-abutment connection (implant, abutment and fixation screw) and in the peri-implant bone (σ_{max} and σ_{vM}) are presented in Tables 3 and 4, respectively. The results of the higher stress levels for each structure within implant-abutment complex were grouped in an illustrative chart for comparison between groups (Figure 2).

Considering the different abutment diameters (platform switching vs. regular) in the same scenarios, the differences in the stress levels were relevant for both internal and external connections. The alterations in the stress levels as a function of abutment diameter were more evident in the abutment component. When reducing the abutment diameter, an increase of 71.17% was observed in the σ_{vM} for abutment connected to external hex implant (SWT-EH), while an increase of 109.45% was observed in the σ_{vM} for abutment connected to internal hex implant (SWT-IH). In the fixation screw, increases of 18.75% and 20.16% were observed for the σ_{vM} for SWT-EH and SWT-IH, respectively.

Within the implant-abutment connection, the highest stress levels for switched-platform models were located in the abutment (at the bottom region of the lingual flange), while for regular models these were located in the platform and cervical threads of the implants (Figure 3). For the fixation screws, the peak of σ_{vM} was concentrated in the region of the third thread for all groups.

Considering an overview of the models, the peak of stress (σ_{max} and σ_{vM}) was concentrated on the lingual flange near the implant-abutment junction. Then, the loads were transmitted to peri-implant bone generating high stress concentrations on the lingual region of the cortical bone (Figure 4).

Regardless the analysis criterion adopted for evaluating the stress levels in cortical and trabecular bone - σ_{max} or σ_{vM} - the models with switched-platform implants (SWT-EH and SWT-IH) showed lower stress levels compared to non-switched-platform implants (REG-EH and REG-IH). For both implant connections (external and internal hex), the peak of σ_{max} in the cortical bone decreased 13.28% and 17.15% with the switched-platform model compared to the regular platform model, respectively. Considering σ_{vM}, these stress values in cortical bone were 19.12% and 13.42%, respectively. In the trabecular bone, it was also observed a decrease in σ_{max} and σ_{vM}, but with lower degrees of variation.

2.5 Discussão (Discussion)

One of the most challenging aspects of implant therapy is the placement and subsequent restoration in the aesthetic zone, in which the level of peri-implant bone support and the soft-tissue dimensions are factors suggested to be critical for the aesthetic outcome.[2, 24] Thus, the concept of platform switching was developed in an attempt to hinder the process of bone remodeling and resorption, especially during the first year after prosthetic restoration in two-piece implants. In agreement with previous studies,[1-4] our results showed decreased stress concentration in the peri-implant bone around switched-platform configurations, especially in the cortical bone. Presumably, these results can be explained because the peaks of stress related to a reduced-diameter abutment are located far away from the cortical bone. Our results showed that the use of switched-platform abutments horizontally shifted the higher peaks of stress towards the central axis of the implant, improving the distribution of forces from the implant-supported restoration to the peri-implant bone. Conversely, the use of switched-platform abutments increased the stress concentration in the set implant-abutment-fixation screw. These findings are in agreement with most of the previous mechanical studies, [2, 5, 13] but not with Pessoa et al.[14]. Pessoa et al.[14] did not report significant biomechanical drawback when reducing the abutment diameter. However, they considered an horizontal mismatch of only 0.5 mm in switched-platform implants, while in the present study we tested a more pronounced horizontal mismatch (~ 1.0 mm).

Concerning the geometry of implant connection, higher levels of σ_{vM} within implant-abutment connection when using external hex implants regardless abutment diameter were observed. As in the present study the modeled structures (implants and prosthetic components) were a reproduction of those commercially fabricated by the manufacturer, all implants presented 5.00 mm diameter by 11.5 mm length, and the prosthetic platform in internal hex implants were 0.5 mm larger than in external hex implants. Thus, the diameter of implant's prosthetic platform should also be considered for the stress concentration on peri-implant bone. Therefore, when considering stress distribution on peri-implant bone, no comparisons involving groups of implants with different geometry for implant connection (external or internal hexagon) were performed in the present study. It should be noted that due to engineering design constrains such as minimum wall thickness for proper mechanical performance of each of the different systems does result in differences in both external and internal features of the implant, abutment, and screw designs. While from a research standpoint it is highly desirable that only the connection is changed with the connecting screw and implant remaining the same, such interplay is unfeasible for when one is attempting to make clinically relevant comparisons (implants presenting the same diameter, length, and crown size) between external and internal connections in most commercially available systems, as alterations in the implant external shape is usually performed by manufacturers in order to maintain tolerances for appropriate fit and wall thickness for the internal connection robustness.

Regarding the bone-to-implant interface, the current study considered the implants fully osseointegrated. Therefore, the bone-to-implant interface was assumed to be bonded in our finite element models. For this, a Boolean operation into the CAD software (SolidWorks 2010) was performed to establish the implant insertion in the maxilla. All these structures were meshed based in a convergence study accomplished in the models to verify the influence of element size on the obtained results. Thus, convergence was assumed to be achieved when the peak von Mises equivalent stress (σ_{vM}) and maximum (σ_{max}) principal stress did not vary by more than 6%.[1, 14, 18]

Although most of the published work have reported favorable aspects as regards stress distribution in peri-implant bone when reducing the abutment diameter,[1-4] some animal[25] and clinical[26] studies showed no difference in bone levels around platform-switched and non-switched-platform implants. Therefore, there is no consensus between authors about the platform switching concept and some aspects involving the biological aspects related to this subject need to be better explained.

2.6 Conclusões (Conclusions)

The postulated hypothesis that switched-platform implants used as anterior single-unit restorations would result in different stress distribution within implant-abutment complex and peri-implant bone was confirmed. When the implant-abutment junction was horizontally repositioned inwardly and away from the peri-implant bone (concept of platform switching), increased levels of stress were observed within implant-abutment complex, while decreased levels of stress were observed in the peri-implant bone.

ACKNOWLEDGEMENTS

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Figuras

2.8 Lista de Figuras (Figures)

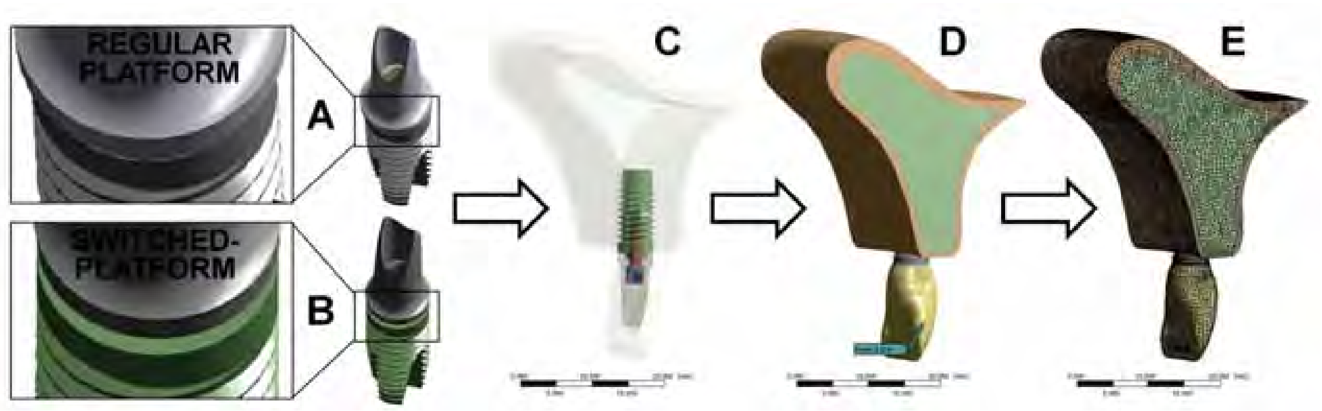

Figure 1. Three-dimensional finite element models of **(A)** regular and **(B)** switched-platform implants. **(C,D)** Solid components of the 3D CAD models (implant, screw, abutment, cement-retained crown, cortical and trabecular bone). In (D) is possible to note the load applied on the crown surface. **(E)** Finite element mesh of the model.

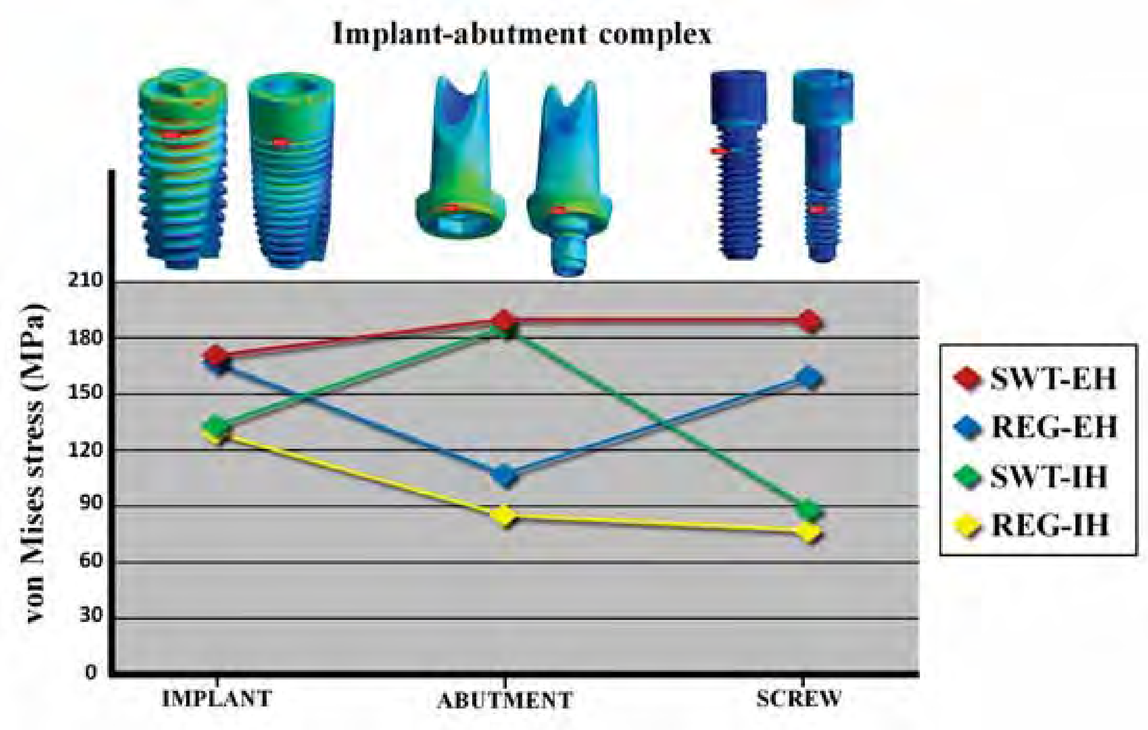

Figure 2. Chart showing σ_{vM} values (MPa) for implant, abutment and fixation screw in the models SWT-EH (red), REG-EH (blue), SWT-IH (green) and REG-IH (yellow). The pictures above the graphic of lines show the peak of stress for each structure considering external (left) and internal (right) hex implants.

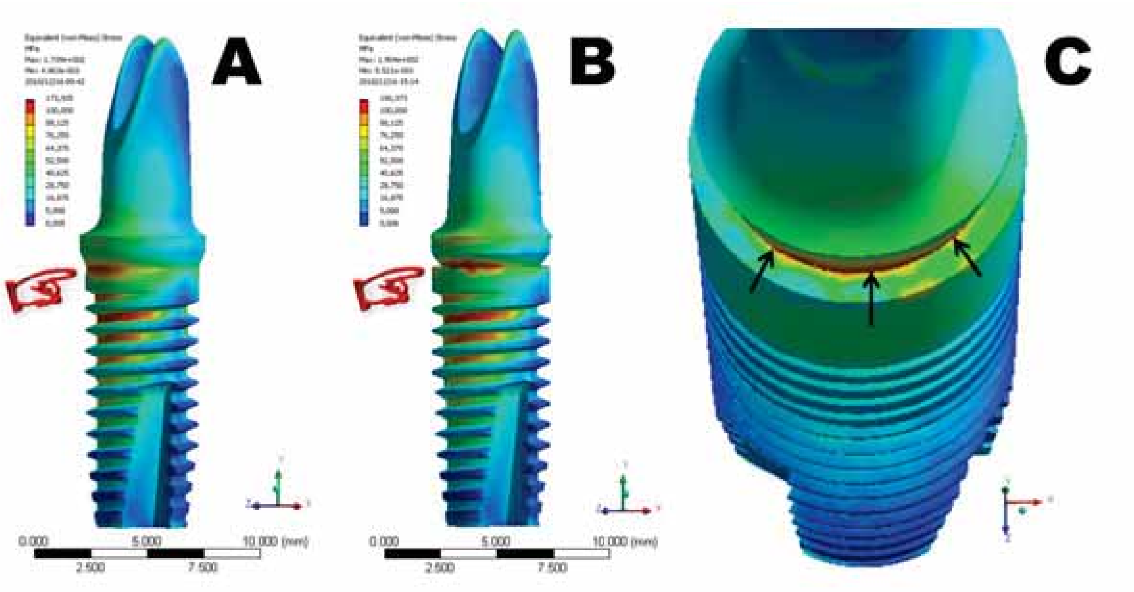

Figure 3. Stress distribution within implant-abutment complex. For **(A)** regular platform implants, lower σ_{vM} values (MPa) were observed at implant-abutment junction (lingual side) compared to **(B)** switched-platform implants. The pointers in (A) and (B) show high stress concentration in the implant-abutment junction for switched-platform connections compared to regular platform, in which the stress is widespread. In **(C)** the black arrows show the high peak of stress (areas in red-orange) repositioned inwardly and away from the outer edge of the implant platform.

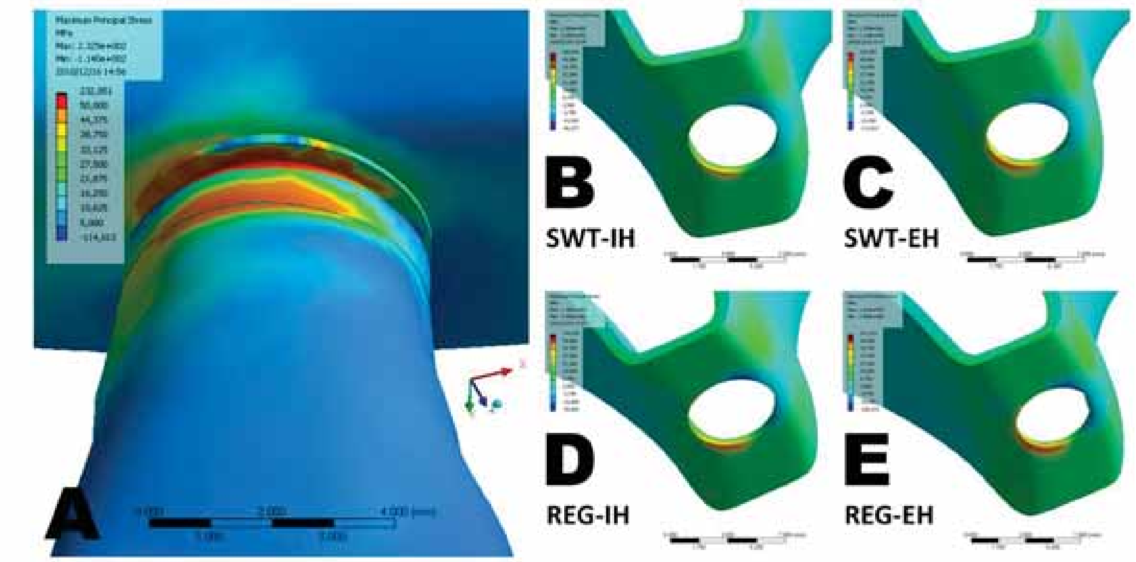

Figure 4. (A) Stress distribution on the implant-abutment junction in a switched-platform model. The stress magnitude (MPa) is showed in the vertical bar by colour scale (red, ↑ stress value; blue, ↓ stress value). Thus, the higher levels of stress were observed on the lingual region of the structures. **(B**, **C**, **D** and **E)** Stress distribution in the cortical bone for all models showing higher peak of stress in the lingual side, where occlusal forces naturally occur.

Tabelas

2.9 Lista de Tabelas (Tables)

Table 1. Characteristics of implants and prosthetic components (SIN implants, São Paulo, SP, Brazil) modeled in the study.

Components	**SWT-EH**	**REG-EH**	**SWT-IH**	**REG-IH**
Implant	External hex (SUR 5011) 5.0 mm diameter by 11.5 mm length Ø prosthetic platform = 5.0mm	External hex (SUR 5011) 5.0 mm diameter by 11.5 mm length Ø prosthetic platform = 5.0mm	Internal hex (SIHS 5511) 5.0 mm diameter by 11.5 mm length Ø prosthetic platform = 5.5mm	Internal hex (SIHS 5511) 5.0 mm diameter by 11.5 mm length Ø prosthetic platform = 5.5mm
Abutment	Cemented (Al 4151) Ø platform = 4.1 mm	Cemented (Al 5051) Ø platform = 5.0 mm	Cemented (Al 4501) Ø platform = 4.5 mm	Cemented (Al 5501) Ø platform = 5.5 mm
Screw	fixation screw (PTQ2008)	fixation screw (PTQ2008)	fixation screw (PTQH16)	fixation screw (PTQH16)

Table 2. Mechanical properties of the materials modeled in the study.

Material	Elastic Modulus (GPa)	Poisson's ratio	References
Implant	110	0.35	Huang et al. (2008)
Abutment	110	0.35	Huang et al. (2008)
Fixation Screw	110	0.35	Huang et al. (2008)
Crown (coping)	205	0.19	Coelho et al. (2009)
Crown (veneer)	70	0.19	Coelho et al. (2009)
Resin Cement	8	0.33	Coelho et al. (2009)
Cortical Bone	13.8	0.26	Huang et al. (2008)
Trabecular Bone (type III)*	1.6	0.30	Kao et al (2008)

* Type of bone present in the anterior region of the maxilla.

Table 3. Von Mises equivalent stress (σ_{vM}) in MPa on implant-abutment connection.

Component	Implant	Abutment	Screw
SWT-EH	171	190	190
REG-EH	169	111	160
SWT-IH	132	186	89.4
REG-IH	129	88.8	74.4

Table 4. Maximum principal stress (σ_{max}) and von Mises equivalent stress (σ_{vM}) in the cortical and trabecular bone.

Group	**Cortical Bone**		**Trabecular Bone**	
	$\boldsymbol{\sigma}_{\mathbf{max}}$ (MPa)	$\boldsymbol{\sigma}_{\mathbf{vM}}$ (MPa)	$\boldsymbol{\sigma}_{\mathbf{max}}$ (MPa)	$\boldsymbol{\sigma}_{\mathbf{vM}}$ (MPa)
SWT-EH	49.0	64.7	10.9	9.52
REG-EH	56.5	80.0	12.0	9.70
SWT-IH	37.7	49.7	2.75	8.65
REG-IH	45.5	57.4	2.83	9.14

Anexos

3.1 Anexo A

Normas da revista ***"Journal of Biomechanics"*** selecionada para publicação do artigo do Capítulo 1 (*Biomechanical Evaluation of Internal and External Hexagon Platform Switched Implant-Abutment Connections: An In Vitro Laboratory and Three-Dimensional Finite Element Analysis.*).

Journal of Biomechanics

Affiliated with the American Society of Biomechanics, the European Society of Biomechanics, the International Society of Biomechanics, the Japanese Society for Clinical Biomechanics and Related Research and the Australian and New Zealand Society of Biomechanics.

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Guide for Authors

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C. Theses

van Werff, K., 1977. Kinematic and dynamic analysis of mechanisms. A finite element approach. PhD. thesis, Delft University Press, Delft.

D. Proceedings

van Soest, A. J., van den Bogert, A. J., 1991. Criteria for the comparison of direct dynamics software systems to be used in the field of biomechanics. In Proceedings of the 3rd International Symposium on Computer Simulation in Biomechanics. University of Western Australia, Perth.

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3.2 Anexo B

Normas da revista ***“The International Journal of Oral & Maxillofacial Implants”*** selecionada para publicação do artigo do Capítulo 2 (*Stress distribution within implant-abutment complex and peri-implant bone considering platform switching concept for internal and external connections. A 3D finite element analysis*).

The International Journal of Oral & Maxillofacial Implants

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