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ARIEL ADRIANO REYES PACHECO

AVALIAÇÃO DAS DISTRIBUIÇÕES DAS TENSÕES NO LIGAMENTO PERIODONTAL NA RETRAÇÃO DO CANINO SUPERIOR COM CORTICOTOMIAS ALVEOLARES: ESTUDO POR MEIO DO MÉTODO DE ELEMENTOS FINITOS

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Dissertação apresentada ao Programa de Pós-Graduação em Odontologia da Pontifícia Universidade Católica do Paraná, como parte dos requisitos para obtenção do título de Mestre em Odontologia, Área de Concentração em Ortodontia.

Orientador: Prof. Dr. Orlando M. Tanaka

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ARIEL ADRIANO REYES PACHECO

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Orientador(a): Prof. Dr. Orlando Tanaka
Programa de Pós-Graduação em Odontologia, PUCPR

Prof. Dr. Key Fonseca de Lima
Programa de Pós-Graduação em Engenharia Mecânica, PUCPR

Prof. Dr. José Augusto Mendes Miguel
Programa de Pós-Graduação em Odontologia, UERJ

Curitiba, 26 de março de 2015.

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Ariel Adriano Reyes Pacheco
Mestrando em Odontologia – Área de Concentração em Ortodontia
Pontifícia Universidade Católica do Paraná

Orlando M. Tanaka, PhD
Professor Titular do Programa de Pós-Graduação em Odontologia – Área de Concentração em Ortodontia
Pontifícia Universidade Católica do Paraná

Endereço para correspondência:
Prof. Dr. Orlando M. Tanaka
Programa de Pós-Graduação em Odontologia - Ortodontia
Rua Imaculada Conceição, 1155, Prado Velho
Cep: 80215-901 – Curitiba-PR-Brasil
Telefone: 55 41 3271-1637 / Fax: 55 41 3271-1405
e-mail: tanakaom@gmail.com

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RESUMO

INTRODUÇÃO: o objetivo deste estudo foi avaliar por meio do MEF o efeito de diferentes formatos de corticotomias na distribuição e magnitude das tensões no ligamento periodontal na retração do canino superior. **MATERIAL E MÉTODOS:** Foi criado um modelo geométrico de uma hemi-maxila esquerda a partir de uma tomografia computadorizada de um crânio seco no programa Solidworks®, versão 2013 (Dessault Systèmes Solidworks Corp., Concord, Ma) e posteriormente exportada ao programa Autodesk Simulation Multiphysics® 2013, para a realização dos carregamentos de distalização do canino. Foram realizados 5 ensaios: A) sem corticotomias, B) corticotomia com forma de caixa e perfurações na cortical vestibular do canino (CVC), C) CVC + corticotomia com forma circular na cortical vestibular do espaço edéntulo do primeiro pré-molar (CVPM-C), D) CVC + corticotomia com forma quadrada (CVPM-Q) e E) CVC + corticotomia com forma triangular (CVPM-T). **RESULTADOS:** Não houve diferença na distribuição das tensões entre os diferentes formatos de corticotomias. **CONCLUSÕES:** O MEF mostrou que os diferentes formatos das corticotomias para a aceleração do movimento ortodôntico não influenciam na distribuição das tensões no ligamento periodontal durante a retração do canino.

Palavras-chave: Ligamento Periodontal, Análise de Elementos Finitos, Movimentação dentária.

INTRODUÇÃO

Na atualidade existem procedimentos que visam diminuir o tempo de tratamento, com o uso de *brackets* autoligados, fios dobrados por robôs, retração rápida de caninos, utilização de dispositivos de ancoragem esquelética temporária, estimulação física do rebordo alveolar através de correntes elétricas ou magnetos [1-3], corticotomias, corticoincisões feitas com dispositivos como o Propel [4], osteotomias com aparelhos piezoelétricos [5] e administração local ou sistémica de medicamentos.[6,7]

As corticotomias alveolares são procedimentos cirúrgicos, como cortes ou perfurações, limitados a cortical óssea, sem alterar ou modificar o osso trabecular. A técnica consistia em osteotomias nas faces vestibulares e palatinas/ linguais dos dentes a serem movimentados, seguida de outra osteotomia subapical unindo as duas faces e uma fratura liberando os dentes dentro de um bloco ósseo. Este procedimento tinha como objetivo facilitar a movimentação ortodôntica. Entretanto, caiu em desuso pelo alto grau de invasividade e complicações pós-cirúrgicas como a necrose dos blocos ósseos, risco da vitalidade pulpar, risco periodontal e infecção pós-cirúrgica.[2]

Em 1959 a técnica foi reintroduzida por Köle, com refinamentos do protocolo cirúrgico com união das osteotomias supra-apicais e inter-radiculares, preconizando uma luxação e fratura do bloco ósseo para acelerar o movimento ortodôntico,ao adotar princípios de movimentos em blocos independentes. O movimento ortodôntico seria acelerado pela fragilização ou diminuição da resistência mecânica dos alvéolos obtendo-se correções entre 6 a 12 semanas.[8]

Wilcko et al. reintroduziram o uso das corticotomias para facilitar a movimentação ortodôntica, cuja técnica inicialmente foi denominada Ortodontia osteogenicamente acelerada (OOA),[9] e renomeada para Ortodontia osteogenica periodontalmente acelerada (OOPA).[10] Modificações incorporadas à técnica incluíam a não segmentação óssea e a associação à procedimentos de regeneração óssea guiada para diminuir os possíveis efeitos indesejáveis, como a deiscência e fenestração óssea na cortical vestibular, recidiva e reabsorção radicular causada pela tendência expansiva do procedimento.[11-13]

As seguintes indicações para a realização das corticotomias em pacientes ortodônticos são citadas: para acelerar o tratamento como um todo[8], potencializar o tratamento de intrusão de molares superiores no tratamento de extrusões[2] ou mordidas abertas esqueléticas[14], fechamento de espaços em casos de biprotrusão dentoalveolar[15], descompensações para cirurgia ortognática[16], expansão da arcada superior em casos de atresia maxilar[12,17], deficiência alveolar preexistente[12], entre outras. Assim, a corticotomia pode ser uma alternativa a ser considerada em casos limítrofes, podendo atingir as expectativas do paciente com custo menor comparativamente às cirurgias ortognáticas.[2,13]

Contudo, o mecanismo pelo qual as corticotomias aceleram a movimentação ortodôntica ainda não é totalmente compreendido. O aumento local de mediadores químicos da remodelação óssea pela injúria, produzindo uma osteopenia transitória, principalmente no osso trabecular, é um conceito bastante aceito. Nos casos de fechamento de espaços, quando esta remodelação não se limita a apenas ao osso trabecular, mas também inclui o osso cortical, a diminuição da resistência óssea ao movimento ortodôntico também poderia ser um fator colaborativo na aceleração do tratamento.[18]

O método de elementos finitos (MEF), que tem sido utilizado nos estudos biomecânicos da movimentação ortodôntica, consiste num modelo matemático no qual são atribuídos parâmetros de comportamento pré-estabelecidos e permite avaliar as tensões resultantes das cargas aplicadas sobre os corpos (dente, o ligamento periodontal e o osso cortical e trabecular).[19] As tensões no PDL podem ser utilizadas como fator que estimulam modificações no comportamento das células responsáveis pelo remodelamento ósseo na movimentação ortodôntica.[20] Até o presente existem estudos avaliando os efeitos das corticotomias mediante o uso da tomografia *cone beam*[21], micro-tomografía[18,22], radiografias e cortes histológicos em animais[23], mas não existem estudos avaliando a distribuição de tensões no ligamento periodontal com diferentes desenhos de osteotomias sobre as corticais ósseas utilizando o MEF.

Portanto, o objetivo deste estudo foi avaliar por meio do MEF o efeito de diferentes formatos de corticotomias na distribuição e magnitude das tensões no ligamento periodontal na retração do canino superior.

MATERIAL E MÉTODOS

A modelagem foi feita a partir de tomografia tipo *cone-beam* obtida de um crânico seco com dentição permanente completa procedente do departamento de Anatomia da Pontifícia Universidade Católica do Paraná (PUCPR). O tomógrafo utilizado foi o I-CAT (Classic I-CAT, Imaging Sciences, Hatfield, Pa), operado a 120kVp, 0,5 mm de tamanho de ponto focal nominal, gama dinâmica da escala de cinzas de 14 bits, 0,4 mm de tamanho de voxel, produzindo 256 fatias de imagens com 0,25 mm de espessura convertidos em arquivos exportáveis em formato DICOM.

Foi utilizado o programa CAD Simpleware®, Innovation Centre, Exeter, United Kingdom para definir os limites de cada componente anatômico do modelo (osso cortical, osso trabecular, esmalte, dentina e ligamento periodontal). O espaço de 0,25 mm entre as raízes e a superfície do alvéolo dentário foi considerado como a espessura do ligamento periodontal. Com o intuito de simplificação deste processo apenas uma hemimaxila foi considerada, posteriormente no programa Solidworks®, versão 2013 (Dessault Systèmes Solidworks Corp., Concord, Ma) foi corrigido as imagens de superfície geradas pela tomografia para obtenção do modelo geométrico da hemimaxila. Nesta fase são retiradas as superfícies sobrepostas, realizadas a suavização da interseção das superfícies não suaves e corrigidos os espaços vazios gerados pela retirada das vascularizações e nervos. Além disso, são adicionadas ao modelo sólido da hemimaxila, os bracktes, o arco e os tubos. Os diferentes formatos de corticotomias e a remoção do primeiro pré-molar também foram realizados nesta fase. O osso cortical foi isolado antes de realizar os cortes para evitar a sobreposição com o osso trabecular.

A largura da osteotomia e o diâmetro das perfurações são iguais a 1,5 mm. Os *brackets* utilizados foram de canino superior esquerdo com *power-arm* para tração e de segundo pré-molar, e o tubo do primeiro molar todos da prescrição Andrews T2

(Ortho Organizers, Carlsbad, CA, USA) slot 0.022”x0.025”, e o arco de aço inoxidável foi modelado com a dimensão de 0,019 x 0,025 polegada. Todas as dimensões de todos os componentes foram obtidas pelo projetor de perfil da marca Nikon Profile Projector V-16E e Metronics Quadra-Chek 2000. O arco foi dobrado distal ao primeiro molar superior no sentido palatino e fixado na mesial do incisivo lateral permitindo qualquer tipo de flexão e/ou torção.

O modelo sólido completo foi transferido para o programa de elementos finitos Autodesk Multiphysics Simulation ® 2013. Nesta etapa é gerado as malhas de elementos finitos, introduzida as propriedades mecânicas (módulo de Young e coeficiente de Poisson) (Tabela 1)[24-26] dos todos os componentes que formam o modelo sólido (esmalte, ligamento periodontal, dentina, brackets, tubo e arco). Nas faces laterais e superior das extremidades da hemimaxila, como condições de contorno, foram restringidas as translações nas direções x, y, z. A magnitude do carregamento aplicado foi de 120 gf de acordo com diretrizes de diferentes trabalhos de distalização de caninos.[27-29]

Tabela 1. Módulo de Young e Coeficiente de Poisson

Material	Módulo de Young (MPa)	Coeficiente de Poisson
Esmalte	84.1	0,20
Ligamento Periodontal	0,059	0,49
Dentina	18.6	0,31
Osso cortical	13.8	0,26
Osso trabecular	345	0,38
Aço inoxidável	200	0,3

Malek, Darendeliler, Swain, 2001. Quian *et al*, 2008. Kojima e Fukui, 2006.

Após uma análise de convergência do campo de tensões definiu-se a malha para realização das análises de MEF.[30] Os comprimentos das arestas dos elementos resultantes desta análise variam entre 0,375 mm e 0,500 mm. A malha resultante (figura 1) é de formada por 1.256.452 elementos tetraédricos lineares e por 113.840 nós. O modelo de elementos finitos do osso cortical e trabecular, do ligamento periodontal, da dentina e do esmalte foram considerados homogêneos, isotrópicos e com comportamento elástico linear. O campo de tensões sobre o modelo de elementos finitos é avaliado de acordo com a teoria da energia de distorção para materiais dúcteis, também conhecido como critério de falha de von Mises. Estas duas tratativas vem sendo utilizadas no campo da ortodontia.[31,32]

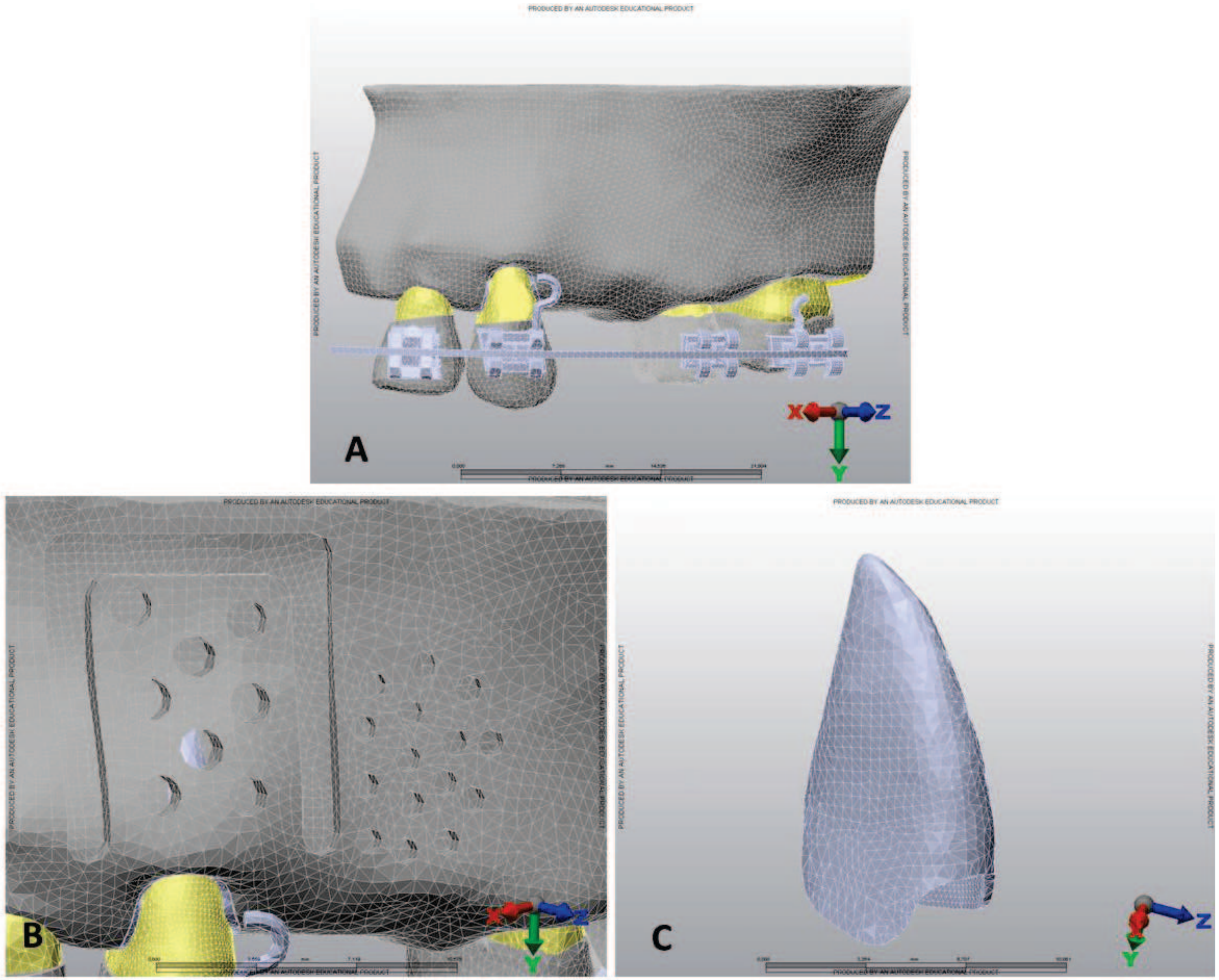

Fig 1. Malha gerada no Autodesk Similation Multiphysics

Foram avaliadas 5 possibilidades de distalização do canino, sem a presença do primeiro pré-molar (Figura 2):

A. Controle: Sem corticotomias, o osso cortical não apresentava nenhum tipo de perfuração.

B. CVC: corticotomia com forma de caixa e perfurações sobre a cortical vestibular do canino.

C. CVPM-C: CVC + corticotomia com forma circular sobre a cortical vestibular do primeiro pré-molar (CVPM).

D. CVPM-Q: CVC + corticotomia com forma quadrada sobre a CVPM.

E. CVPM-T: CVC + corticotomia com forma triangular sobre a CVPM.

Uma vez finalizados os ensaios, as distribuições das tensões foram avaliadas nas faces mesial, distal, vestibular e palatina do ligamento periodontal do canino.

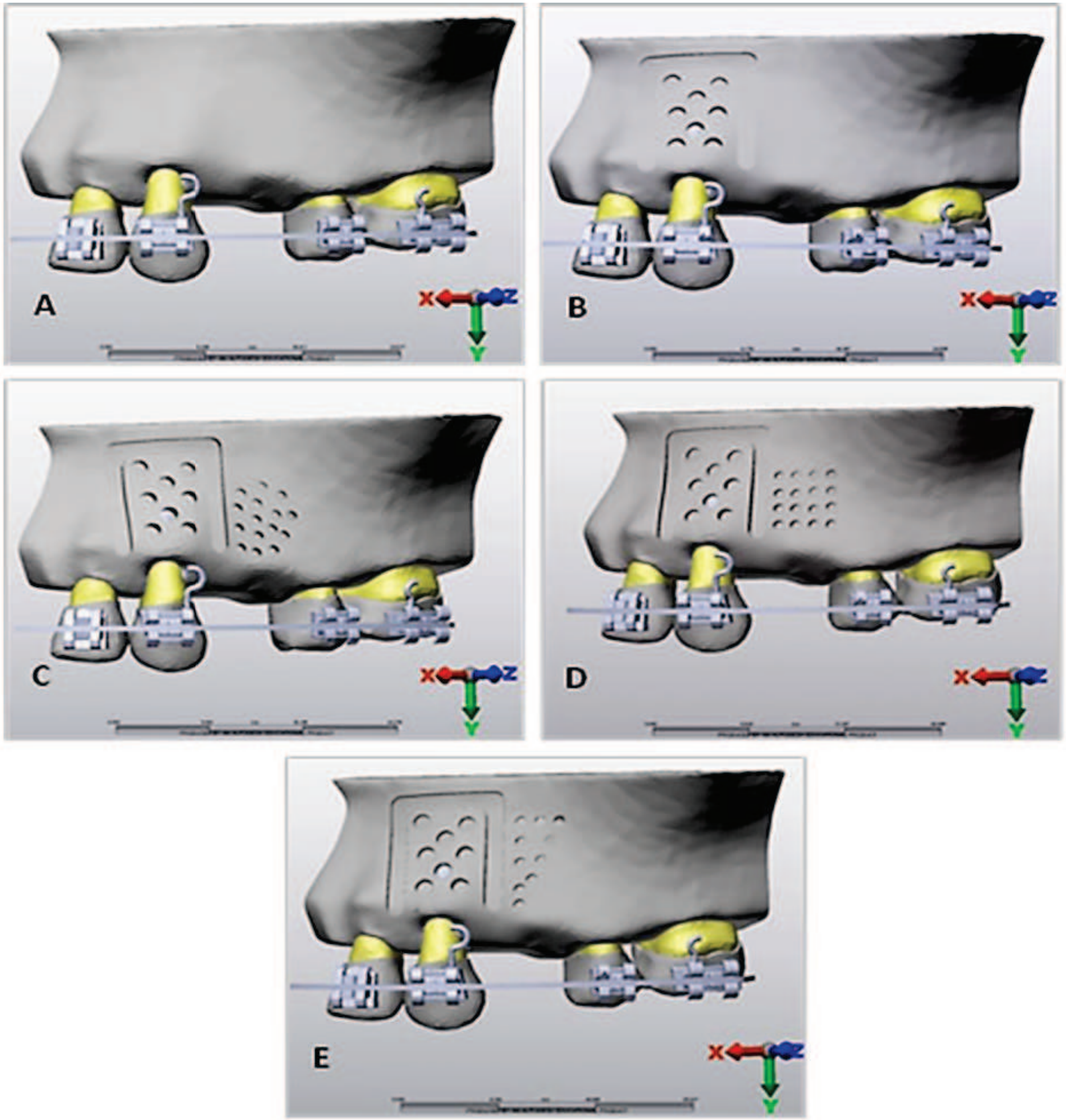

Fig 2. Modelos dos ensaios realizados: **A**. Controle, **B**.CVC, **C**.CVPM-C, **D**.CVPM-Q, **E.**CVPM-T.

RESULTADOS

A representação gráfica da análise dos campos de tensões foi avaliada pela visualização da distribuição das tensões de acordo com uma escala de cores, onde a cor com tom azul corresponde a áreas de tensão mais baixas e a cor vermelha corresponde a tensões mais altas. O modelo de elementos finitos foi avaliado utilizando o critério de falha de von Mises.

Utilizaram-se os eixos (x, y e z) como referência para realizar a interpretação dos resultados no programa Autodesk Simulation Multiphysics® 2013, o eixo x representa o plano ântero-posterior ou sagital, o y o plano vertical ou frontal e o z o transversal. Os resultados foram para as simulações se descrevem a continuação segundo a face:

Face mesial (lado de tração)

As distribuições das tensões foram elevadas no terço médio do ligamento periodontal em todos os modelos avaliados. Os padrões de distribuição foram similares em todos. Não havendo diferencia entre todos os formatos de corticotomia como observado na figura 3.

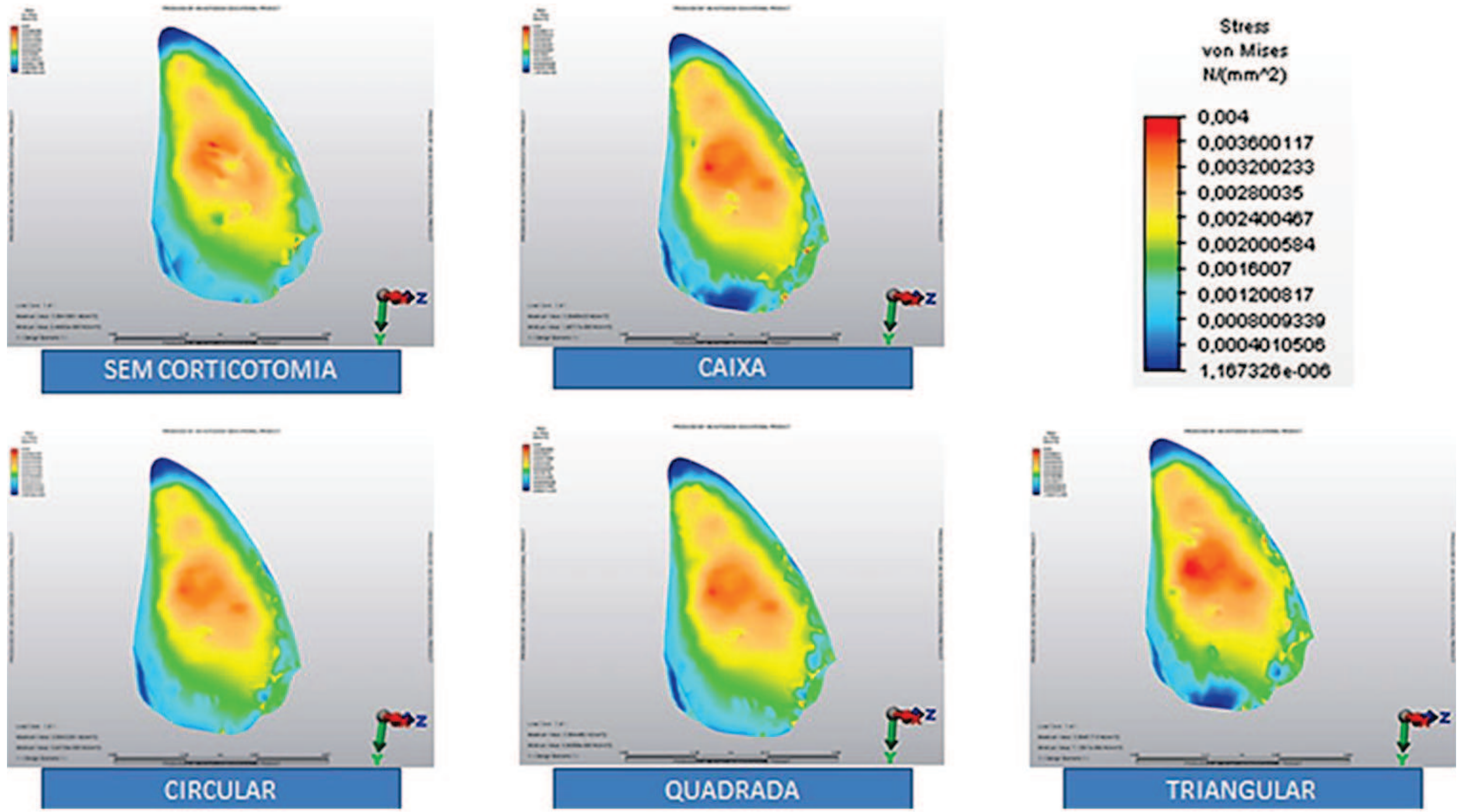

Fig 3. Distribuição das tensões na face mesial do canino.

.**<u>Face distal (lado de compressão)</u>**

O padrão de distribuição das tensões na face distal do canino foram similares em todos os modelos avaliados. Não havendo diferencia entre todos os formatos de corticotomia como observado na figura 4.

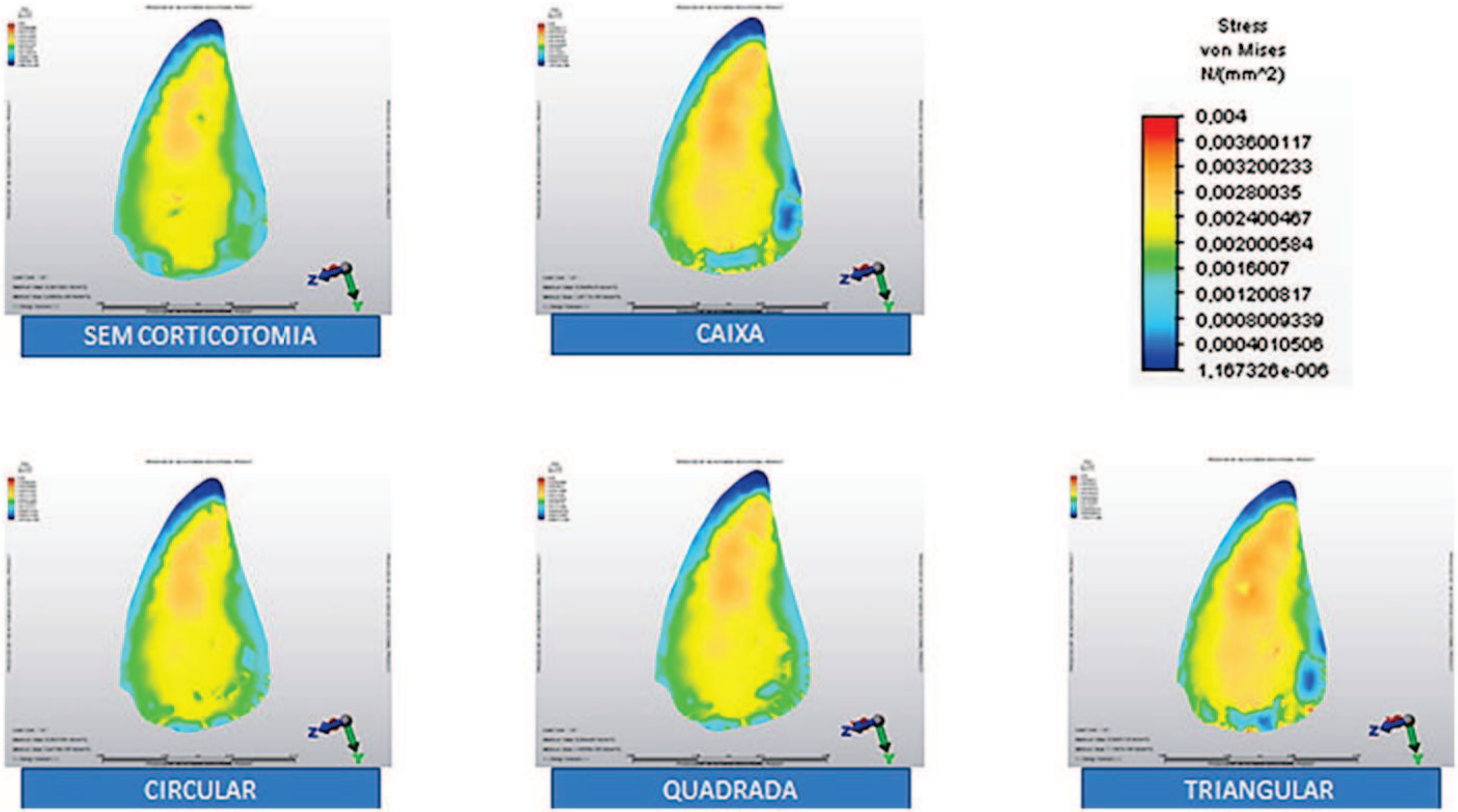

Fig 4. Distribuições das tensões na face distal do canino.

Como observado nas figuras, as superfícies com coloração vermelha indicam os lugares onde ocorreram as tensões elevadas, e representam o valor máximo quando a força foi aplicada. Os valores na escala estão apresentados em Megapascal (MPa) que é igual a N/mm^2 ($1MPa= 1N/mm^2$). Para facilitar a compreensão dos valores de tensão média máxima estes valores foram convertidos em Quilopascal ($kPa= 1000 \times N/mm^2$ ou 1000 x MPa).

Nota-se que os valores de tensão média máxima (Tabela 2) foram similares para todos os modelos, não existindo diferença significante quando a força é aplicada no *power arm* durante a retração de caninos.

Tabela 2. Tensão média máxima

Formatos	Módulo de Young (KPa)
Controle	4.1
CVC	4.07
CVPM-C	4.22
CVPM-Q	4.44
CVPM-T	4.5

DISCUSSÃO

O MEF é uma ferramenta matemática útil para avaliar as características mecânicas de tecidos de uma forma não invasiva [33], esta ferramenta é proveniente da área da engenharia, usa modelos matemáticos permitindo visualizar e calcular os níveis de tensão sobre elementos ou corpos geométricos quando sometidos à carga [34] caso do ligamento periodontal, analisado no presente trabalho.[35,36]

O osso cortical é formado microestruturalmente pelo ósteon, osso intersticial, canal Haversiano, canal de Volkman e canalículos ósseos. A parte mineralizada possui um comportamento isotrópico transversal, mas quando associado aos fragmentos de tecido mole como vasos e nervos, a matriz óssea é influenciada pela parte líquida conferindo propriedades anisotrópicas que devem ser consideradas. No nosso trabalho, todos os componentes foram considerados como materiais homogêneos e isotrópicos conforme outros estudos. [31,32]

Recentemente estão sendo estudadas as propriedades do osso, as quais são altamente influenciadas pela porosidade, forma e comprimento dos poros ósseos, propriedades mecânicas da matriz óssea e as constantes elásticas da matriz. Estas caracterizações alteram os valores do módulo de Young e coeficiente de Poisson mostrando a anisotropia do osso cortical. [37] No nosso estudo o ligamento periodontal foi considerado como isotrópico e linear de acordo com outros estudos [20,31,38,39], alguns estudos experimentais apresentam modelos de ligamento periodontal anisotrópicos e viscoelásticos [19,35,40]. Ambas as situações descritas podem ser fatores limitantes em nosso estudo.

A aplicação das cargas utilizando-se um *bracket* com *power-arm* de translação de Andrews aproxima o centro de resistência do canino resultando numa distribuição mais uniforme da carga aplicada sobre o ligamento periodontal e originando um movimento de translação como demostrado pelo MEF no estudo de Ammar et al.[31], em concordância com os resultados de nossos ensaios.

A aceleração da movimentação ortodôntica após as corticotomias é de 3 a 4 vezes maior do que a movimentação no tratamento convencional, podendo movimentar um dente de 1 a 2 milímetros por semana, mais rápido do que a movimentação no tratamento convencional, de 1 a 2 milímetros por mês. [5,41,42]

O pico da movimentação ocorre nos dois primeiros meses e termina diminuindo no quarto mês, quando termina o fenômeno de aceleração rápida.[3,43] O fenômeno é observado com frequência após cirurgias ortognáticas e após os procedimentos cirúrgicos que visam acurtar o tempo de tratamento ortodôntico. O *turnover* ósseo aumenta [3] e o movimento dentário é acelerado.[11,44]

A injúria óssea produzida pelas incisões deve ser de magnitude suficiente para que possa produzir o fenômeno desejado. Isto pode ser obtido pelo aumento de incisões em diferentes lugares ou fazendo com que as injúrias ao osso sejam mais invasivas. [45] Baseando nesses princípios cirúrgicos visamos realizar os ensaios com diferentes formatos de corticotomias, para observar se sob o ponto de vista mecânico existia alguma diferença no carregamento inicial na retração do canino quando a força era aplicada no *power arm*. Estas diferenças não foram observadas.

O formato das perfurações nas corticotomias não exercem nenhuma influencia sobre o resultado como descrito por Wilcko et al.,[12] no nosso estudo não existiram diferenças nos ensaios entre os diferentes formatos realizados e a distribuição das tensões sobre o ligamento periodontal. Isto pode ser observado nos valores obtidos de tensão média máxima, os quais praticamente não diferem um do outro.

No lado de compressão a superfície do ligamento periodontal todos os formatos apresentaram superfícies vermelhas em toda a extensão do ligamento periodontal, sugerindo um movimento de corpo do canino quando a força foi aplicada no *power arm,* como apresentado no trabalho de Ammar et al.[31]

Forças de magnitude baixa podem produzir deformações no ligamento periodontal, mais as tensões associadas são baixas.[35] Isto aconteceu na CVPM-T e CVC, que apresentaram áreas de coloração avermelhada de maior extensão, mas as tensões observadas são consideradas muito baixas como para confirmar que existiu alguma diferença quando comparada com CVPM-Q, CVPM-C e o controle.

Dentre as limitações deste procedimento encontram-se a movimentação de dentes anquilosados e o movimento dentário através de osso não vital como ocorre em pacientes com osteonecrose.[13] As contraindicações das corticotomias são: a doença periodontal ativa, dentes com problemas endodônticos não tratados, fumadores, pacientes que utilizaram corticosteroides por tempo prolongado ou que utilizam medicamentos possam diminuir a densidade óssea como os bifosfonatos.[2,12,46] As complicações cirúrgicas mais frequentes são edema, secção radicular, equimose, e infecções. Em pacientes com algum risco cardíaco o procedimento deve ser realizado com cautela pelo risco de bacteremia transitória que acontece após o procedimento cirúrgico.[10,17,47]

A simples necessidade de acelerar o tratamento ortodôntico não é uma justificativa suficiente para realizar a corticotomia, pois não existem estudos suficientes para validar este procedimento. [2,3]

CONCLUSÕES

O MEF mostrou que os diferentes formatos das corticotomias para a aceleração do movimento ortodôntico não influenciam na distribuição das tensões no ligamento periodontal durante a retração do canino.

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2. ARTIGO EM INGLÊS

TITLE PAGE

STRESS DISTRIBUTION IN THE PERIODONTAL LIGAMENT DURING CANINE RETRACTION USING ALVEOLAR CORTICOTOMIES: A FINITE ELEMENT METHOD STUDY.

Ariel Adriano Reyes Pacheco, DDS
Master in Dentistry-Orthodontics
Pontifical Catholic University of Paraná

Orlando M. Tanaka, PhD
Professor of the Graduate Program in Dentistry - Orthodontics
Pontifical Catholic University of Paraná

Correspondence:
Prof. Dr. Orlando M. Tanaka
Graduate Program in Dentistry - Orthodontics
Immaculada Conceição, 1155, Prado Velho Street
CEP: 80215-901 - Curitiba-PR-Brazil

Phone: +55 41 3271-1637
Fax: 55 41 3271-1405
e-mail: tanakaom@gmail.com

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ABSTRACT

INTRODUCTION: the objective of this study was to evaluate the effect of different corticotomy formats on the distribution and magnitude of stress in the periodontal ligament during retraction of the maxillary canine, using the finite element method (FEM). **METHODS:** a geometric model of the left side hemi-jaw was created from a computed tomography scan of a dry skull using SolidWorks® software version 2013 (Dassault Systèmes SolidWorks Corp., Concord, MA), and subsequently exported to Autodesk Simulation Multiphysics® 2013 software in order to recreate the loads during canine distalization movement. Five trials were performed: **(A)** without corticotomies; **(B)** box-shaped corticotomy and perforations in the cortical bone of the canine (CVC); **(C)** CVC + circle-shaped corticotomy in the cortical bone of the edentulous space of the first premolar (CVPM-C); **(D)** CVC + square-shaped corticotomy (CVPM-Q); and **(E)** CVC + triangle-shaped corticotomy (CVPM-T). **RESULTS**: There was no difference in stress distribution among the different formats of corticotomies. **CONCLUSIONS**: Using FEM, we showed that the different formats of corticotomies used to accelerate orthodontic tooth movement did not affect stress distribution in the periodontal ligament during canine retraction.

Keywords: Tooth Movement, Finite element method, Periodontal Ligament.

INTRODUCTION

Currently, different procedures or devices to reduce the time of treatment are available. These include physical stimulation of the alveolar ridge by electric currents or magnets, rapid canine retraction, self-ligating brackets, wires bent by robots, temporary skeletal anchorage devices,[1-3] corticotomies, corticisions made with devices such as the Propel,[4] osteotomies using piezoelectric devices,[5] and local or systemic administration of drugs.[6,7]

Corticotomies are surgical procedures such as cuts or perforations that are limited to the cortical bone, and do not produce changes or modifications to the trabecular bone. This technique involves osteotomies on the facial and palatal/lingual sides of the teeth to be moved, which is followed by a subapical osteotomy joining the two fractured faces, and releasing the teeth within a bone block. This procedure was intended to facilitate the orthodontic movement. However, it fell in disuse because of the high degree of invasiveness and postsurgical complications such as necrosis of bone blocks, pulp vitality and periodontal risks, and post-surgical infections.[2]

In 1959 the technique was reintroduced by Kole,[8] with a series of refinements of the surgical procedure such as union of supra-apical and inter-radicular osteotomies to dislocate and fracture the bone block in order to accelerate orthodontic movement; thus, adopting the principles of movements of independent blocks. The orthodontic movement was accelerated by embrittlement, or by decreasing the mechanical strength of the walls, which resulted in major movements corrected in between 6 to 12 weeks.[8]

Wilcko et al.[9] reintroduced the use of corticotomies to facilitate orthodontic movement. Their initial technique was called “accelerated osteogenic orthodontics” (AOO),[9] and later was renamed as “periodontally accelerated osteogenic orthodontics” (PAOO).[10] Technical modifications included the inclusion of non-bone fractures, and guided bone regeneration procedures to minimize possible side effects such as dehiscences or fenestrations of the cortical bone, as well as recurrence and root resorption caused by the expansive tendency of the procedure.[11-13]

Corticotomy is indicated in orthodontic patients for the following aspects: to accelerate the treatment as a whole;[8] to enhance treatment intrusion of upper molars in the treatment of extrusions,[2] or skeletal open bites;[14] space closure in cases of dentoalveolar biprotrusion;[15] decompensations for orthognathic surgery; [16] expansion of the upper arch in cases of maxillary atresia;[12,17]and preexisting alveolar deficiency,[12] among others. Thus, this technique can be an alternative for borderline cases, because it fulfills patient's expectations and has lower costs compared to orthognathic surgery.[2,13]

However, the mechanism by which corticotomies accelerate orthodontic tooth movement is not fully understood. Local increase in chemical mediators of bone remodeling caused by the injury, which produces transient osteopenia, particularly in the trabecular bone, is a widely accepted concept. In cases of closing spaces, when remodeling is not limited to the trabecular bone, but also includes cortical bone tissue, tooth movement due to decreased bone strength could also be a factor in accelerating the treatment.[18]

The finite element method (FEM), which has been used in biomechanical studies of orthodontic movement, is a mathematical model to which preset performance parameters are assigned, allowing the evaluation of the resulting stress loads applied on bodies (tooth, periodontal ligament and cortical and trabecular bone).[19] Tensions in the periodontal ligament can be used as a factor that stimulate changes in the behavior of cells responsible for bone remodeling in orthodontic tooth movement.[20] To date, studies have evaluated the effect of corticotomies with the use of cone beam tomography,[21] microtomography,[18,22] radiography and histological sections of animals, [23] but studies evaluating stress distribution in the periodontal ligament using different formats of osteotomy on the cortical bone and applying FEM are lacking.

Therefore, the aim of this study was to evaluate the effect of different corticotomy formats in the distribution and magnitude of stress in the periodontal ligament during retraction of the maxillary canine, using FEM.

MATERIALS AND METHODS

Our model was made from cone-beam tomography images obtained from a dry skull with permanent teeth, at the Department of Anatomy at the Catholic University of Paraná (PUCPR). An I-CAT scanner (CAT-I Classic, Imaging Sciences, Hatfield, PA), operated at 120 kVp, 0.5 mm nominal focal spot size, 14 bit dynamic range gray scale, 0.4 mm voxel size, which produced 256 bit image slices of 0.25 mm thickness converted into exportable files in DICOM format, was used for our study.

To define the anatomical limits of each component of the model (i.e., cortical bone, cancellous bone, enamel, dentin, and periodontal ligament) we used Simpleware® CAD program (Innovation Centre, Exeter, United Kingdom). The 0.25 mm spacing between the root and the tooth socket surface was regarded as the thickness of the periodontal ligament. In order to simplify the process only one hemi-maxilla was considered. The images obtained by the tomography scan were exported to SolidWorks® software version 2013 (Dassault Systèmes SolidWorks Corp., Concord, MA) for surface correction to create the geometric model. In this phase, the overlapped surfaces are removed, the intersections of the surfaces are smoothened and the empty spaces created by the remotion of the nerves and vascularization are corrected. The tube, the arch and the brackets are added to the solid model. The different formats of corticotomies and the remotion of the first premolar were also performed in this phase. The cortical bone was isolated before the cutting procedure to avoid any overlapping with the cancellous bone.

The diameter of the perfurations and the width of the osteotomies are equal to 1.5 mm. Brackets and an orthodontic arch segment were also modeled in this program. Prescription type T2 Andrews brackets with power-arm for left upper canine traction were used as references for modeling the brackets and tube (Ortho Organizers, Carlsbad, CA, USA) with a slot of 0.022 x 0.025 inch The arch segment was modeled with a stainless steel arch of 0.019 x 0.025 inch. The measures for the modeling were obtained using a Nikon Profile Projector V-16E and a Metronics Quadra-Chek 2000 digital readout.

The solid was exported to the finite element program Autodesk Multiphysics Simulation ® 2013. A finite element mesh was created for each of the model components (i.e., cortical bone, cancellous bone, periodontal ligament, enamel, dentin and steel) were assigned a parameters by entering their mechanical properties (values of Young's modulus and Poisson's ratio). (Table 1). As boundary conditions, the translations of the x, y and z axes were restrained in the lateral faces and the upper extremity of the hemi-maxilla. The amount of force applied to the power-arm to simulate canine retraction was 150 gf. [48]

Table 1. Young Module & Poisson´s Coefficient

Material	Young Module (MPa)	Poisson´s Coefficient
Periodontal Ligament	0.059	0.49
Enamel	84.1	0.2
Dentin	18.6	0.31
Cortical Bone	13.8	0.26
Trabecular Bone	345	0.38
Stainless Steel	200	0.3

Malek, Darandelier & Swain, 2001. Quian *et al*, 2008.Kojima e Fukui, 2006.

After a convergence analysis of the stress, the mesh was defined to perform the finite element analysis. The variation in the size of the edges of the elements were between 0.375 mm. and 0.500 mm. The final mesh (figure 1) was formed by 1.256.452 linear tetrahedral elements and 113.840 nodes. The model was considered as homogeneus, isotropic and with a linear elastic behaviour. The stress fields over the finite element model were measured according to the von Mises criteria for ductile materials. These types of considerations are currently being used in the orthodontics.[31,32]

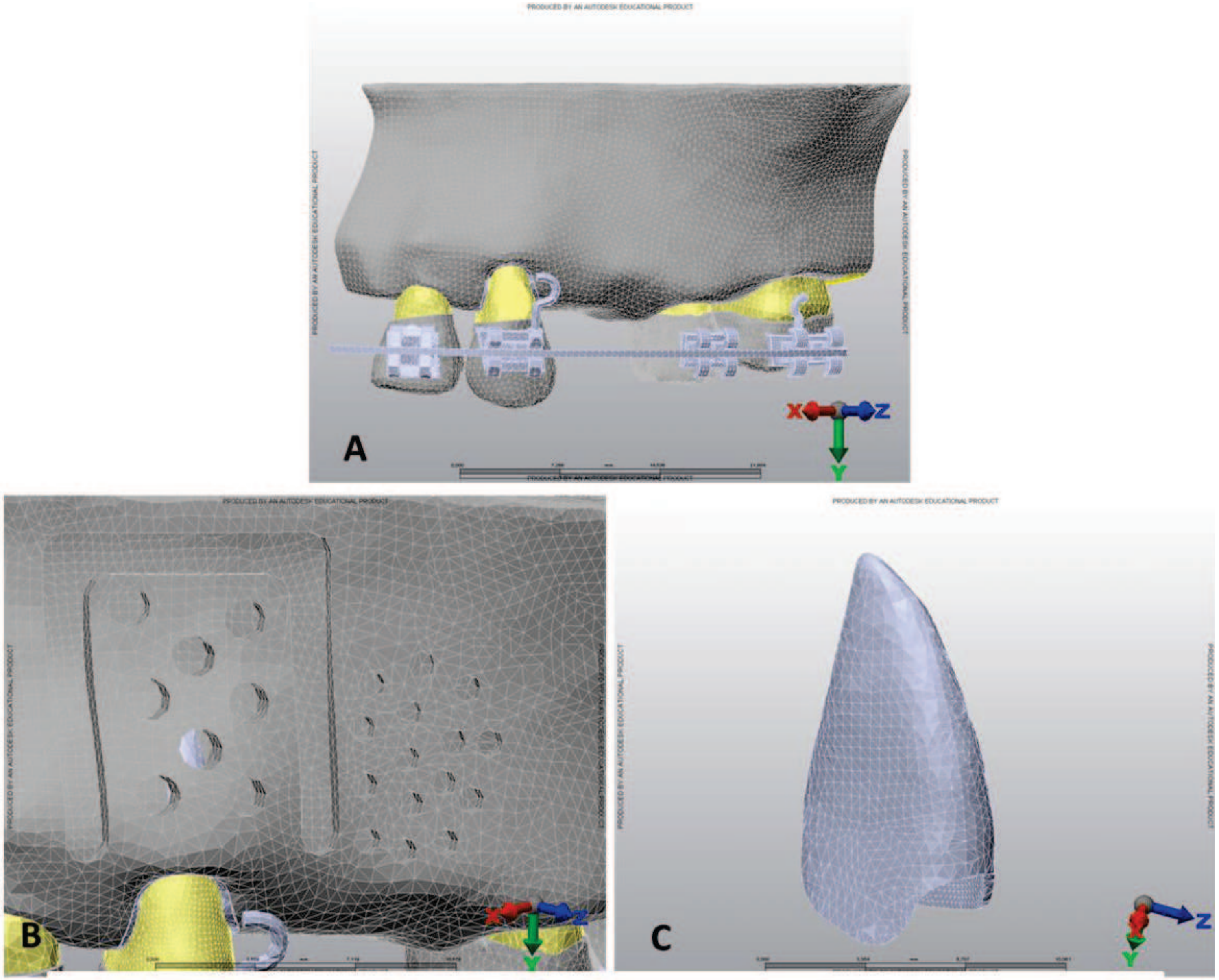

Fig 1. Mesh created using the Autodesk Simulation Multiphisics

Five distalization possibilities of canine without the presence of the first premolar were assessed (Figure 2):

(A) Control: No corticotomies, and no drilling in the cortical bone.

(B) CVC: Box-shaped corticotomy and perforations in the cortical bone of the canine.

(C) CVPM-C: CVC + circle-shaped corticotomy in the cortical bone of the first premolar (CVPM).

(D) CVPM-Q: CVC + square-shaped corticotomy in the CVPM.

(E) CVPM-T: CVC + triangle-shaped corticotomy in the CVPM.

After completing the tests, distributions of stress were evaluated in the mesial, distal, buccal, and palatal sides of the canine periodontal ligament.

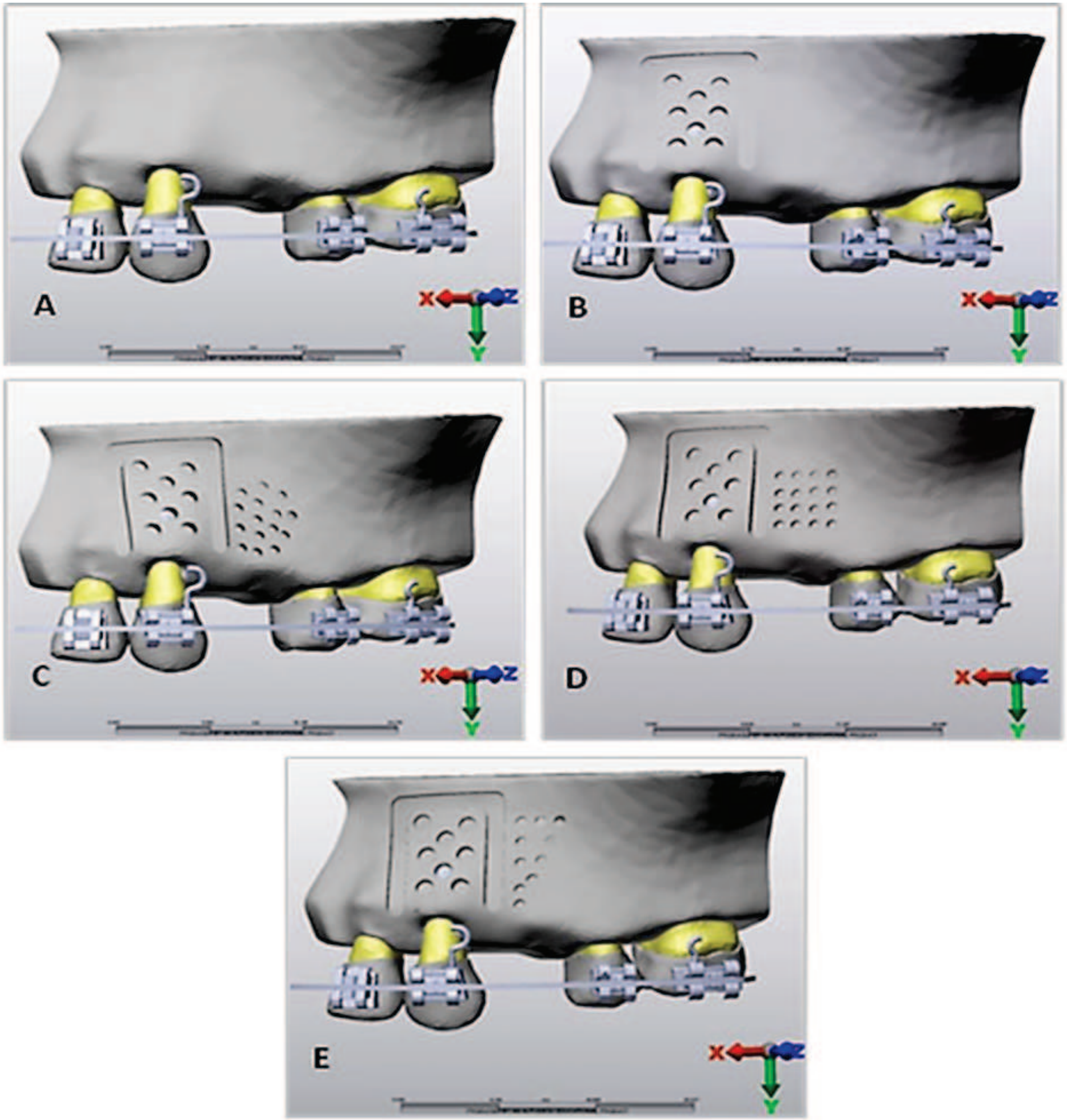

Figure 2. Testing Models: A.Control, B.CVC, C.CVPM-C, D.CVPM-Q, E.CVPM-T.

RESULTS

The graphic representation of the stress fields was assessed visualizing the distribution according to a predefined color scale. In this scale, the blue color corresponded to low stress areas, while the red color corresponded to high stress areas. The von Mises criteria usad used.

We used x, y, z axis as references to perform the interpretation of the results in Autodesk Simulation Multiphysics® software, the x axis represented the sagittal plane, the y axis represented the frontal plane and the z axis represented the transverse plane. Results of the simulations are described in relation to the farthest side:

Mesial face (traction side)

We observed high stress distribution in the middle third of the periodontal ligament in all of the assessed models. The distribution patterns were similar in all. There were no differences between the test models, as observed in figure 3.

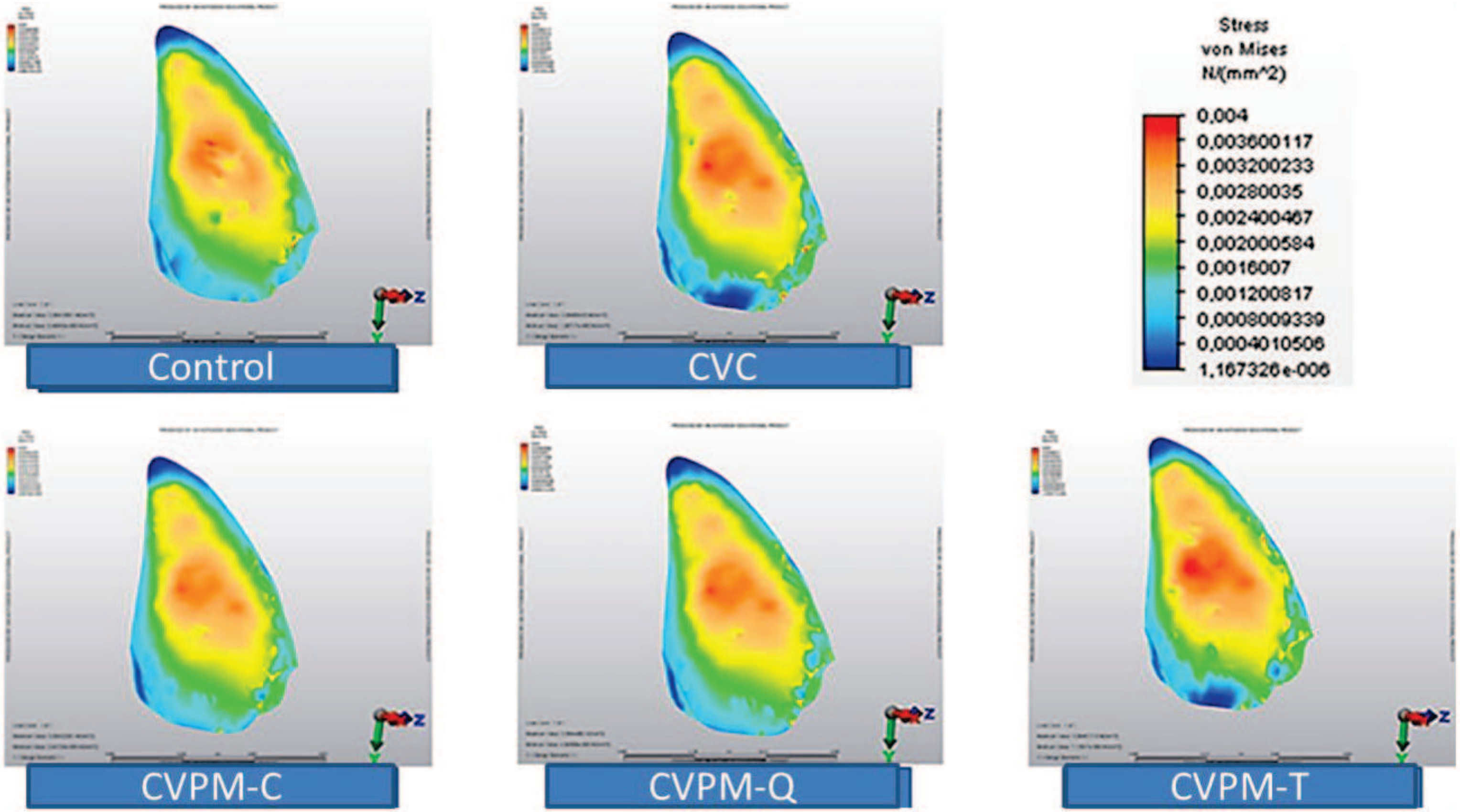

Figure 3. Stress distribution in the mesial face of the canine.

<u>Distal face (compression side)</u>

The stress distribution pattern in the distal face of the canine was similar in all of the test models. There were no differences beteween the corticotomies as observed in figure 4.

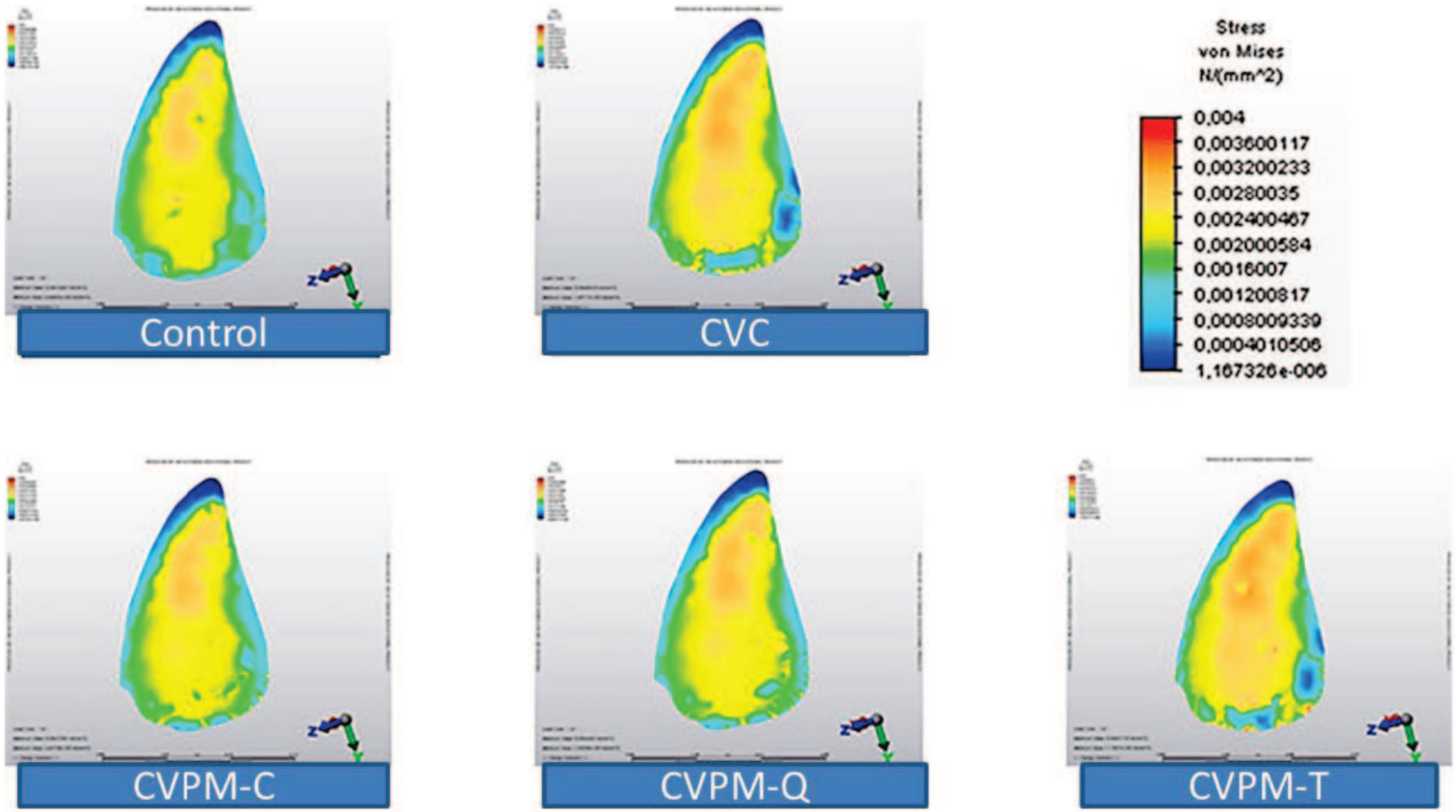

Figure 4. Stress distribution in the distal face of the canine.

As observed in figures 3 and 4 the surfaces with red coloration indicate the locations were high stress occurred, they represent the maximum value when the force was applied. The values in the scale are presented in Megapascals (MPa), which is equal to a N/mm^2 (1MPa= 1N/mm^2). In order to ease the comprehension of these values, we converted them to Kilopascals(kPa= 1000 x N/mm^2 or 1000 x MPa).

Note that values for maximum stress (Table 2) were similar in all the test models, therefore, there was no difference between them when the force was applied to the power arm during canine retraction.

Table 2. Maximum Stress	
Test Models	**Young Module (KPa)**
Control	4.1
CVC	4.07
CVPM-C	4.22
CVPM-Q	4.44
CVPM-T	4.5

DISCUSSION

The FEM is a useful mathematical tool to evaluate the mechanical characteristics of tissues. This tool is derived from the engineering field, and uses mathematical models to calculate the voltage levels of elements or geometrical bodies when they are subjected to loads,[34] as is the case of the periodontal ligament analyzed in this study.[35,36]

Cortical bone is formed by microstructural functional known as osteons. These units contain interstitial bone, Haversian and Volkmann canals, and bone canaliculi. The mineralized portion of the bone has a transverse isotropic behavior, but when it is associated with soft tissues, such as vessels and nerves, the bone matrix is influenced by the liquid part, giving anisotropic properties to the bone that must be considered. In our study, all components were considered homogeneous and isotropic materials, according to other studies.[31 32]

Bone properties, such as the mechanical properties and elastic constants of the matrix, are highly influenced by the porosity, size and shape of the pores size of the bone. In our study the periodontal ligament was also considered as linear and isotropic , but some studies are presenting the anisotropy of this component. [19,35,40] Since these characteristics change the values of Young's modulus and Poisson's ratio, showing the anisotropy of both metrials,[37] they may be a limiting factor in our study.

In agreement with the results of our tests, a previous report using FEM by Ammar et al.[26] showed that the application of the load using an Andrews power-arm bracket near the center of the canine resistance resulted in a more uniform distribution of load applied to the periodontal ligament, and produced translational movement.

The acceleration of orthodontic movement after corticotomies is 3 to 4 times faster than the movement obtained with conventional treatments. The former can move a tooth 1 to 2 mm per week; while with conventional treatments, the movement is 1 to 2 mm per month.[5,41,42]

The peak of movement occurs in the first two months and decreases in the fourth month, with the end of rapid acceleration.[3,43] This is observed frequently after orthognathic surgery, and after surgical procedures to shorten orthodontic treatment time. The increased bone turnover[3] and tooth movement is accelerated.[11,44]

Bone injury caused by the incisions should be of sufficient magnitude to produce the desired phenomenon (i.e., tooth movement). This can be achieved by increasing the number of incisions in different places or producing more invasive injuries to the bone. [45] Based on these surgical principles, we carried out tests with different corticotomy formats to assess if from a mechanical point of view there was any difference in the initial load necessary to retract the canine when force was applied to the power arm. We did not observe any difference in the initial load in our tests.

In our study, there were no differences between the tests performed using different shapes of corticotomies and the stress distribution on the periodontal ligament. This is in agreement with the study of Wilcko et al[12] who showed that the format of the perforations in corticotomies have no influence in the outcome. The CVPM-T and CVC were the types of corticotomies that caused high stress in the periodontal ligament in both the traction (i.e., mesial) and in the compression (i.e., distal) sides. Using corticotomies, the mesial surface of the middle third on the side of traction showed higher stress concentrations than the control and CVPM-Q and CVPM-C, which showed lower voltages.

The compression side surface of the periodontal ligament using CVC and CVPM-T corticotomies showed red areas throughout the extent of the periodontal ligament, suggesting canine body movements when force was applied to the power arm, as shown in a Ammar et al.[31]

Although CVPM-T and CVC presented areas of greater reddish extent, the tensions observed are considered very low, confirming that there were differences compared to CVPM-Q, CVPM-C and control corticotomies.

Limitations of corticotomies include movement of ankylosed teeth, and movement of teeth through non-vital bone, as it occurs in patients with osteonecrosis.[13] Contraindications for the performance of corticotomies include active periodontal disease, teeth with untreated endodontic problems, smoking, patients who used corticosteroids for long periods of time, or used drugs that can decrease bone density, such as bisphosphonates.[2,12,46] The most common surgical complications of corticotomies are swelling, root section, bruising, and infection. In cardiac patients the procedure should be performed with caution because of the risk of transient bacteremia after surgery.[10,17,47]

The simple need to accelerate orthodontic treatment is not a sufficient justification to perform a corticotomy, because there are not enough studies to validate this procedure.[2,3]

CONCLUSIONS

The FEM shows that different formats of corticotomies for accelerated orthodontic movement do not affect the distribution of stress in the periodontal ligament during retraction of the canine.

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3. Anexos.

<u>Face vestibular</u>

Não foram observadas diferenças entre os modelos dos formatos das corticotomias, a coloração na face vestibular foi azulada em quase toda a extensão do ligamento periodontal, mostrando uma baixa magnitude.

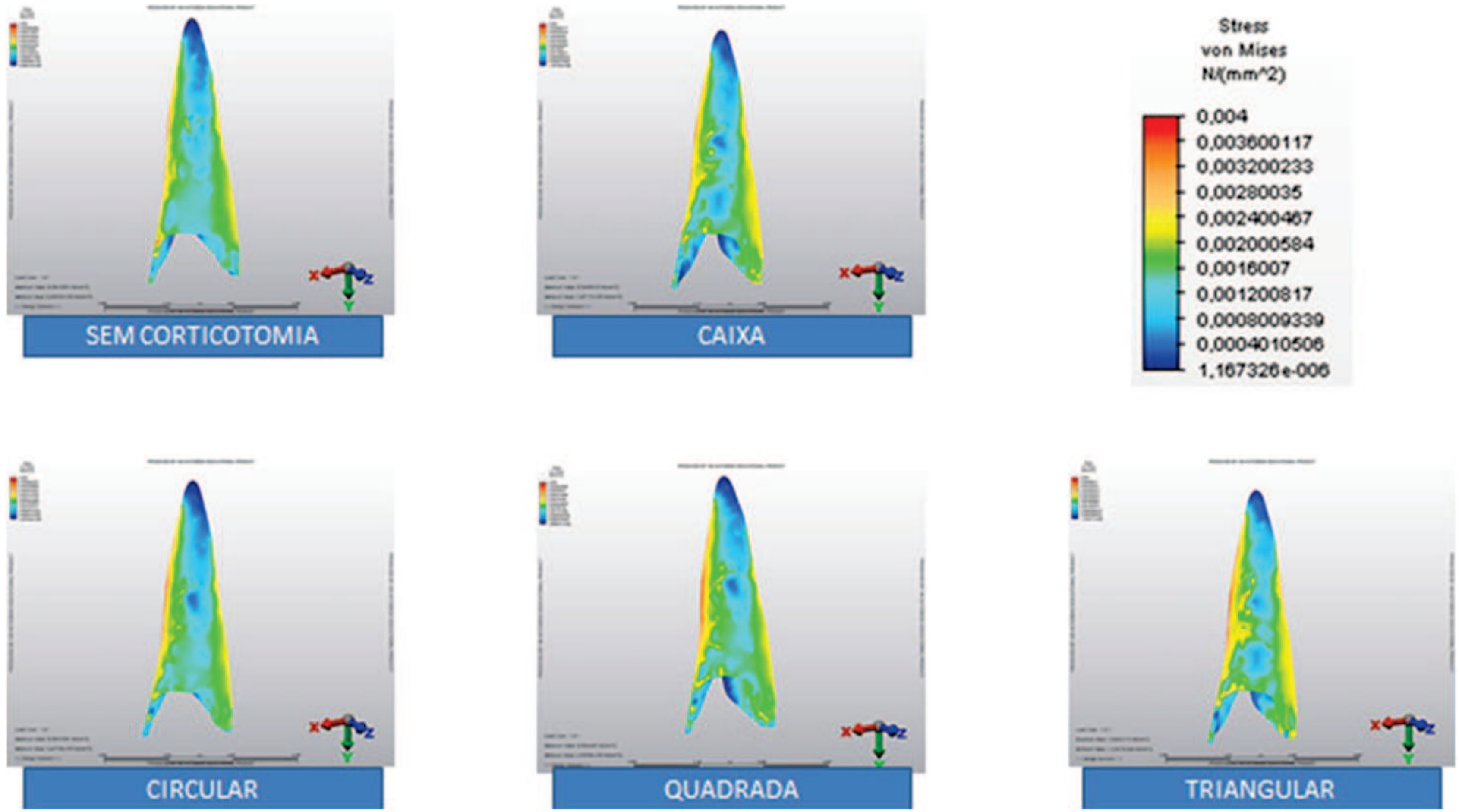

Fig 5. Distribuições das tensões na face vestibular do canino.

Face palatina

Não houve diferenças nesta face entre os diferentes modelos quando sometidos à carga, a coloração azul e distribuição das tensões foi similar em todos.

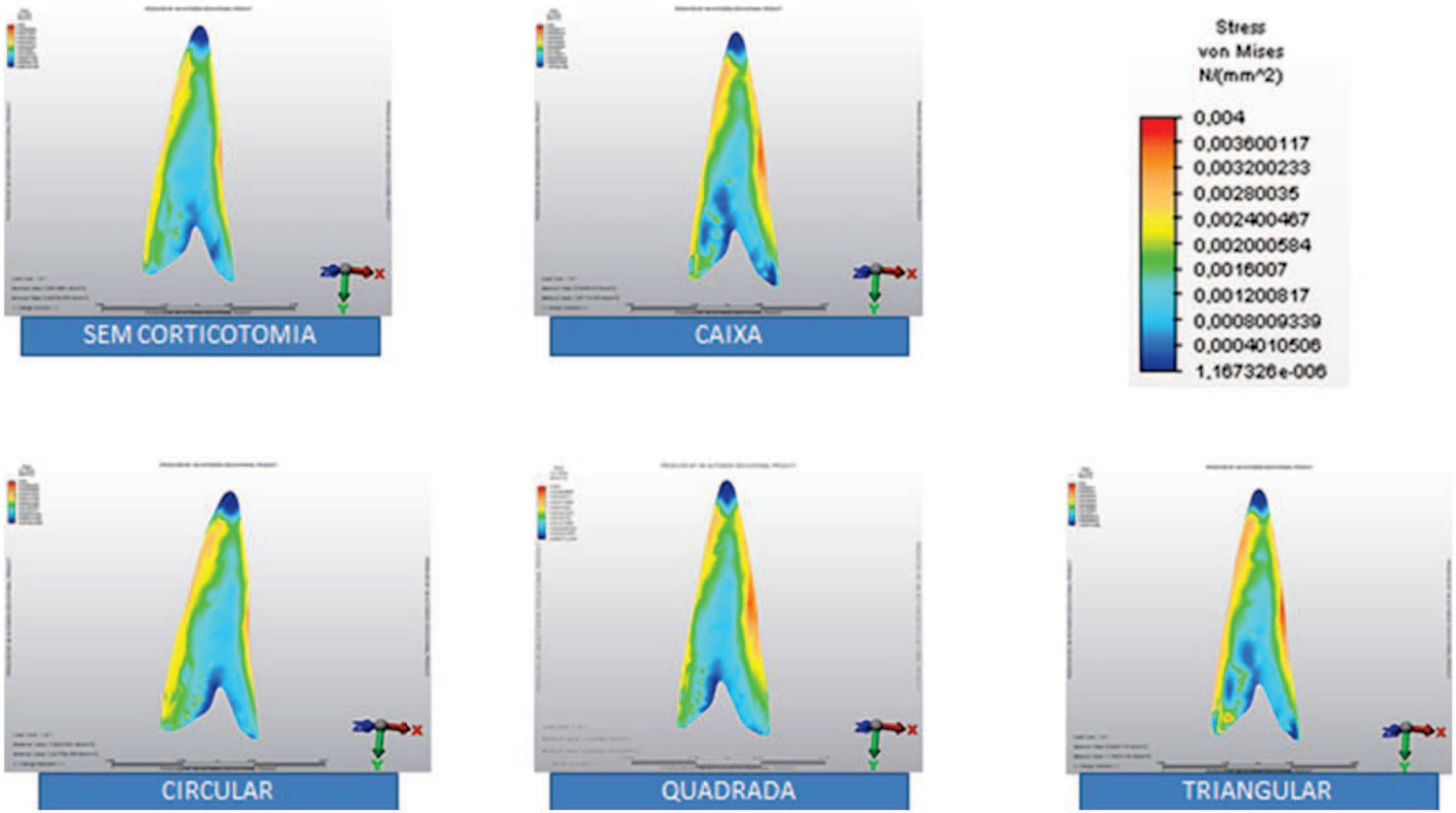

Fig 6. Distribuições das tensões na face palatina do canino.

4. Supplement.

Buccal face

There were no differences between the test models, as observed in the other faces, the coloration of the buccal faces is similar in all test models. The stress distribution is blue colored in almost the whole buccal face, represent low magnitude stress.

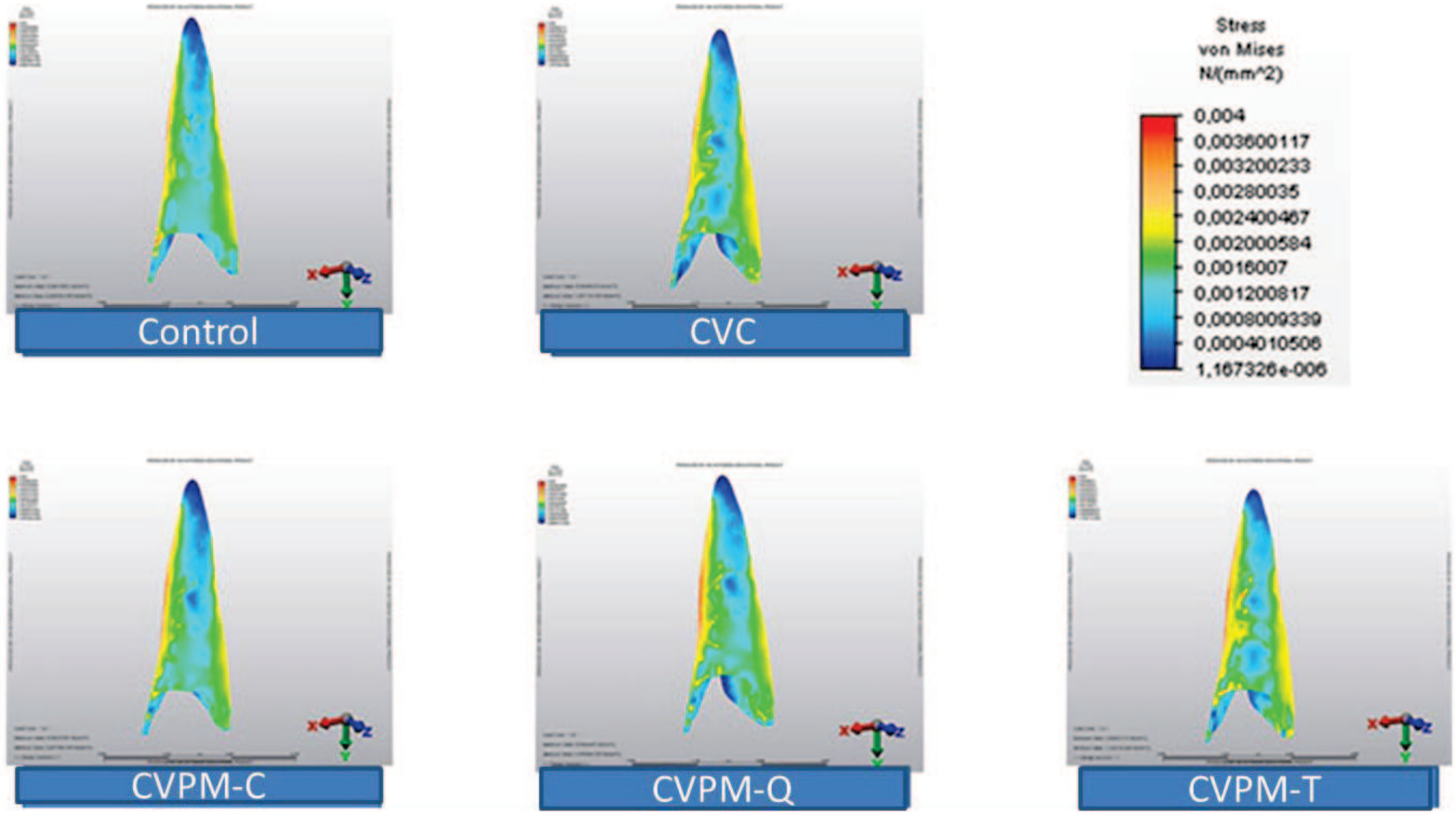

Figure 5. Stress distributions in the buccal face of the canine.

Palatal face

There were no differences between the test models, as observed in the other faces, the coloration of the palatal faces is similar in all test models. The stress distribution is blue colored in almost the whole buccal face, represent low magnitude stress.

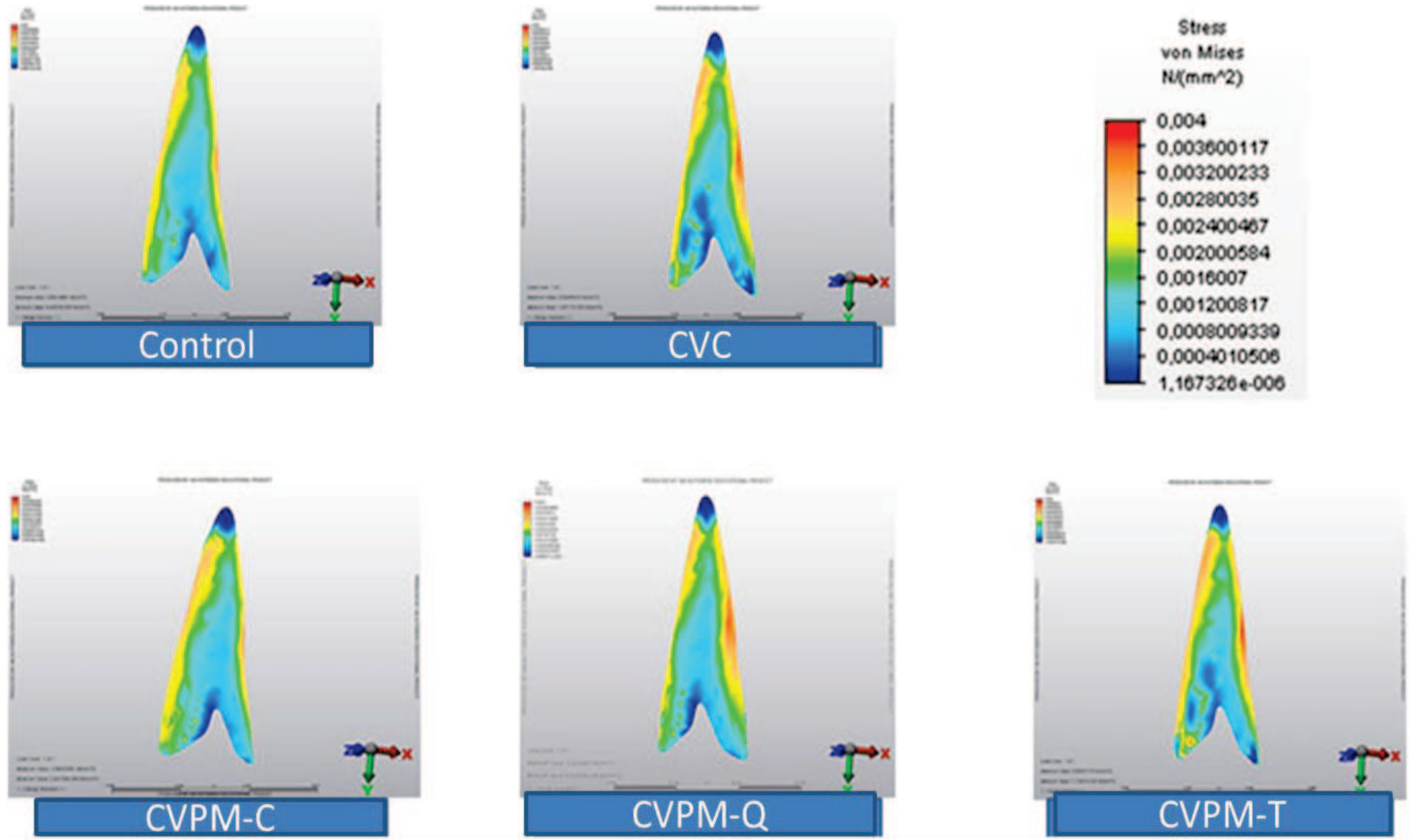

Figure 6. Stress distributions in the palatal face of the canine.

Highlights:

- Stress distribution in PDL during canine retraction assessed by finite element method.
- Five test models were assessed; four of them represented different corticotomy models.
- Test models showed no differences in stress distribution patterns.

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