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CANTILEVER TORQUEADO E CONVENCIONAL PARA VERTICALIZAÇÃO DO MOLAR MESIALMENTE IMPACTADO: ANÁLISE 3D POR ELEMENTOS FINITOS

Porto Alegre
2022

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Orientador: Prof. Dr. Sergio Estelita Cavalcante Barros.

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"Viva como se fosse morrer amanhã,
aprenda como se fosse viver para sempre" ***Mahatma Gandhi***

RESUMO

CEVALLOS, KJ. Cantilever torqueado e convencional para verticalização do molar mesialmente impactado. Análise 3D elemento finito. Dissertação (Mestrado em Clínica Odontológica- Ortodontia) Faculdade de Odontologia, Universidade Federal do Rio Grande do Sul, Porto Alegre, 2022.

Objetivo: Avaliar os efeitos do cantilever torqueado (CT) e convencional (CC), feitos de aço inoxidável (SS) e liga de titânio molibdénio (TMA), na verticalização de molares inferiores impactados mesialmente, utilizando análise tridimensional de elementos finitos. **Métodos:** O modelo tridimensional mandibular incluiu: parte da mandíbula com o segundo molar inferior impactado e inclinado mesialmente, ligamento periodontal (LP), tubo molar, mini-implante e cantilevers. Quatro modelos de método de elementos finitos (CT-SS, CT-TMA, CC-SS e CC-TMA) foram criados para simular diferentes mecânicas de verticalização ancoradas esqueleticamente. A mecânica de CC envolveu um cantilever helicoidal conhecido (0,019 x 0,025"), agindo sobre um tubo molar na face vestibular. A mecânica CT incluía um cantilever torqueado (0,019" x 0,025") capaz de produzir torque mesial de raiz por atuar sobre um tubo posicionado na superfície ocluso-distal do molar, com o slot na direção vestíbulo-lingual. O deslocamento tridimensional do molar e a distribuição de tensão no LP deste dente foram registrados. **Resultados:** O cantilever SS produziu quase o dobro do deslocamento molar quando comparado ao cantilever TMA. A mecânica CT mostrou um deslocamento mesial mais evidente dos ápices da raiz do molar. A mecânica CC teve maior rotação do molar. O momento de verticalização do CT produziu maior extrusão mesial molar, bem como maior intrusão do ápice distal da raiz deste dente. O sistema de deflexão dupla da mecânica do CT induziu uma menor tensão no LP, independentemente da liga metálica. **Conclusões:** O cantilever torqueado proporcionou um momento de verticalização do molar mais eficiente e com menos movimento dentário indesejado e tensão no LP, bem como um local mais acessível para a colagem do tubo molar.

Palavras chaves: Ortodontia, verticalização molar, movimento dentário, aço inoxidável, titânio molibdênio, segundo molar.

ABSTRACT

CEVALLOS, KJ. Torqued and conventional cantilever for uprighting mesially impacted molars: a 3-D finite element analysis. Dissertação (Mestrado em Clínica Odontológica- Ortodontia) Faculdade de Odontologia, Universidade Federal do Rio Grande do Sul, Porto Alegre, 2022.

Objective: To evaluate the effects of the torqued cantilever (TC) and conventional tip-back cantilever (CC) made of stainless steel (SS) and titanium-molybdenum alloy (TMA) on the uprighting of mesially impacted mandibular molars using three-dimensional finite element analysis. **Methods:** The three-dimensional mandibular model included part of the mandible with mesially tipped and impacted mandibular second molar, periodontal ligament (PDL), molar tube, mini-implant, and cantilevers. Four finite element method models (TC-SS, TC-TMA, CC-SS, and CC-TMA) were created to simulate different skeletally anchored uprighting mechanics. CC mechanics involved a known 0.019 X 0.025-in helical cantilever acting on a buccal molar tube. TC mechanics included a 0.019 X 0.025-in cantilever capable of producing mesial root torque by acting on a tube positioned on the molar disto-occlusal surface with the slot in buccolingual direction. Three-dimensional molar displacement and stress distribution on the molar PDL were recorded. **Results:** The SS cantilever produced almost twice as much molar displacement as the TMA. TC mechanics showed more evident mesial displacement of the molar root apexes. CC mechanics had greater molar rotation. TC uprighting moment produced greater molar mesial extrusion as well as greater intrusion of the distal root apex. The dual deflection system of the TC mechanics induced the lowest stress on the PDL, regardless the of metallic alloy. **Conclusions:** Torqued cantilever delivered a more efficient uprighting moment to the molar with less unwanted tooth movement and stress on the PDL, as well as a more accessible site for bonding the molar tube.

Keywords: orthodontics, molar uprighting, tooth movement, stainless steel, titanium molybdenum, second molar.

APRESENTAÇÃO

A presente dissertação com título "**Cantilever torqueado e convencional para verticalização do molar mesialmente impactado. Análise 3D elemento finito.**" está sendo apresentada ao Programa de Pós-Graduação em Odontologia da Universidade Federal do Rio Grande do Sul como parte dos requisitos para obtenção do título de Mestre em Clínica Odontológica/Ortodontia.

O tema é de grande relevância para o desenvolvimento das mecânicas de verticalização, a fim de permitir que os objetivos clínicos de seu uso sejam atingidos de maneira mais segura e eficaz. A presente dissertação contém uma introdução geral ao tema, seguida de um manuscrito e considerações finais. O manuscrito a partir do estudo realizado foi enviado para publicação para o periódico American Journal of Orthodontics and Dentofacial Orthopedics (AJODO) e descrito, com seu respectivo título, a seguir:

Título do artigo:

Torqued and conventional cantilever for uprighting mesially impacted molars: a 3-D finite element analysis.

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1.- INTRODUÇÃO

O segundo molar é de grande importância no desenvolvimento normal da dentição e crescimento facial.[1] Em função disso é necessário que seja feito um diagnóstico e tratamento precoce quando se apresenta impactado.[2] A impactação do segundo molar é relativamente rara na população geral (0,03% a 0,30%), no entanto na população ortodôntica sua ocorrência é mais frequente (2% a 3%).[1, 3-5] A impacção dos segundo molares inferiores pode ser parcial ou total, quando o dente se apresenta totalmente coberto por osso ou tecido mole. Quanto à inclinação mesiodistal, 88% apresentam-se com angulação mesial, 8% vertical e 4% com inclinação distal. [2, 3, 6]

Este distúrbio da erupção pode ser causado por deficiência do comprimento do arco mandibular na região posterior, excesso de tamanho dentário, perda do primeiro molar adjacente, erupção precoce do terceiro molar inferior, erupção ectópica com inclinação excessiva do segundo molar, presença de banda no primeiro molar, fatores genéticos e efeitos indesejados da preservação do espaço por arco lingual passivo ou lip bumper.[2, 4, 5, 7, 8] Quando esta anomalia de erupção não é tratada, ela pode ocasionar problemas nos dentes adjacentes, com alteração periodontal, sinais de inflamação, perda óssea angulada, cáries e sobre erupção dos dentes antagonistas. [9-11]

Métodos cirúrgicos e ortodônticos são aplicados para o tratamento dos segundos molares impactados, no entanto é relevante ter um bom controle de ancoragem para evitar movimentos dentários indesejados durante a mecânica ortodôntica. [4,10-25] O desenvolvimento relativamente recente da ancoragem esquelética tem sido útil neste propósito graças à sua simplicidade de instalação, baixo risco, e movimento dentário eficaz, com mínimo efeito colateral. [4, 10, 11, 18] O mini-implante pode fornecer ancoragem direta e indireta, que permitem várias opções de tratamento, incluindo a estabilização das unidades de ancoragem, sendo que a escolha entre estas formas de ancoragem se dará levando-se em conta a gravidade da impacção, a viabilidade de acesso ao molar impactado, a complexidade do tratamento e os possíveis efeitos colaterais. [11, 16, 18]

Para a verticalização dos molares inferiores, tem se usado nos últimos anos cantilevers incorporados no mini implante. [4, 10, 12, 16, 18] No entanto, os efeitos 3D dos cantilevers ancorados esqueleticamente não foram avaliados e comparados.

O cantilever helicoidal convencional (CC) é uma das técnicas ortodônticas mais difundidas e utilizadas para a verticalização de molares inferiores, especialmente quando algum grau de extrusão de molares é permitido durante a mecânica de verticalização.[2, 14, 20, 21, 23] Em geral, os cantilevers convencionais são fixados a um tubo ortodôntico posicionado na superfície vestibular do molar inclinado.[21] Entretanto, a maioria dos molares inferiores profundamente impactados e mesialmente inclinados não apresentam exposição adequada de sua superfície vestibular, limitando a colagem de um tubo ortodôntico nesse local.[5, 19, 26, 27] Nesse caso, deve-se considerar a necessidade de intervenção cirúrgica para a exposição da superfície vestibular da coroa do molar, ou de modificação da mecânica de ortodôntica de verticalização para se evitar este procedimento.[19]

Assim, foram propostas técnicas alternativas de verticalização dos molares inferiores envolvendo a utilização de um tubo molar posicionado na direção vestíbulo -lingual, e colado à superfície ocluso-distal do molar impactado. Esta alternativa busca facilitar o procedimento de colagem, bem como a inserção da extremidade distal do cantilever, angulada em 90º, a partir do lado bucal. [16, 19, 24, 26-28]

Recentemente, se propôs uma mecânica de verticalização inovadora com o uso de um cantilever torqueado, ancorado esqueleticamente, e feito de fio retangular de aço inoxidável (.019 x .025”). Nesta técnica, um tubo molar é colado na superfície oclusal, próximo à crista marginal distal do molar mesialmente impactado. O tubo é girado em 90º para permitir que o slot se posicione na direção vestibulo-lingual, possibilitando que um efetivo movimento mesio-distal das raízes seja obtido pela ativação do torque na extremidade ativa deste cantilever. [26] O cantilever torqueado tem sido usado com sucesso em diferentes casos clínicos, especialmente para tratar casos graves de molares inferiores impactados e com inclinação mesial.[26, 27]

Entretanto, o impacto clínico da mudança na localização e orientação do tubo molar, bem como no método de geração do momento de força é difícil de prever e ainda não foi avaliado tridimensionalmente.

Inicialmente, os cantilevers foram feitos de fio retangular de aço inoxidável (SS). [14] A liga de titânio-molibdênio (TMA, Ormco/Sybron, Orange, CA, EUA) só foi introduzida no início dos anos 80 para aplicações ortodônticas.[29] Sua combinação de alta resistência e elasticidade torna-o excelente material para o armazenamento da energia necessária ao funcionamento de molas auxiliares e cantilevers.[29] Apesar desta opção vantajosa, até hoje, os cantilevers de aço inoxidável ainda são utilizados para a verticalização de molares.[4, 10] Embora a técnica de verticalização de molares com cantilever convencional possa ser executada com diferentes ligas metálicas (SS ou TMA), um estudo tridimensional comparando os efeitos mecânicos dos cantilevers de aço inoxidável e TMA para verticalização de molares ainda não foi realizado.

Considerando a ausência de estudos tridimensionais comparando os efeitos mecânicos dos cantilevers convencionais e torqueados ancorados esqueléticamente para a verticalização molar, bem como a ausência de estudos 3D comparando cantilevers tip-back feitos de SS e TMA, esta pesquisa avaliou os efeitos mecânicos produzidos pelos cantilevers torqueados [26, 27] e convencionais, [14, 19, 21, 23] ambos ancorados e feitos de duas ligas metálicas diferentes (SS e TMA), utilizando análise tridimensional de elementos finitos.

2.- OBJETIVOS

2.1.- OBJETIVO GERAL

Avaliar os efeitos do cantilever torqueado (CT) e cantilever convencional (CC), confeccionados em aço inoxidável (SS) e liga de titânio molibdênio (TMA), na verticalização de molares inferiores impactados mesialmente, utilizando a análise tridimensional de elementos finitos.

2.2.- OBJETIVOS ESPECÍFICOS

-Avaliar a quantidade e padrão de deslocamento do molar, gerado pelo cantilever torqueado (CT) e cantilever convencional (CC) durante a verticalização do molar, bem como investigar a influência das ligas de aço inoxidável e de titânio molibdênio neste processo.

-Analisar a tensão principal máxima do ligamento periodontal durante a verticalização do molar com o cantilever torqueado e o cantilever convencional.

-Avaliar os cantilevers quanto à ocorrência de efeitos mecânicos indesejáveis concomitantes à verticalização do molar.

3.- ARTIGO

Este trabalho de dissertação é composto pelo artigo **"Torqued and conventional cantilever for uprighting mesially impacted molars: a 3-D finite element analysis."**

Foi enviado para publicação no periódico *American Journal of Orthodontics and Dentofacial Orthopedics.* O manuscrito, na formatação exigida pelo periódico correspondente, encontra-se a seguir:

TORQUED AND CONVENTIONAL CANTILEVER FOR UPRIGHTING MESIALLY IMPACTED MOLARS: A 3-D FINITE ELEMENT ANALYSIS

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Highlights

- Torqued cantilever provided a more accessible site for bonding the molar tube.
- SS cantilever caused almost twice as much molar displacement as the TMA cantilever.
- Uprighting mechanics with torqued cantilever caused less unwanted tooth movement.
- 3D molar displacement pattern was not influenced by metallic alloy (SS and TMA).
- Torqued cantilever (TC) delivered a more efficient uprighting moment to the molar.

T Torqued and conventional cantilever for uprighting mesially impacted molars: a 3-D finite element analysis

Abstract

Objective: To evaluate the effects of the torqued cantilever (TC) and conventional tip-back cantilever (CC) made of stainless steel (SS) and titanium-molybdenum alloy (TMA) on the uprighting of mesially impacted mandibular molars using three-dimensional finite element analysis. **Methods:** The three-dimensional mandibular model included part of the mandible with mesially tipped and impacted mandibular second molar, periodontal ligament (PDL), molar tube, mini-implant, and cantilevers. Four finite element method models (TC-SS, TC-TMA, CC-SS, and CC-TMA) were created to simulate different skeletally anchored uprighting mechanics. CC mechanics involved a known 0.019 X 0.025-in helical cantilever acting on a buccal molar tube. TC mechanics included a 0.019 X 0.025-in cantilever capable of producing mesial root torque by acting on a tube positioned on the molar disto-occlusal surface with the slot in buccolingual direction. Three-dimensional molar displacement and stress distribution on the molar PDL were recorded. **Results:** The SS cantilever produced almost twice as much molar displacement as the TMA. TC mechanics showed more evident mesial displacement of the molar root apexes. CC mechanics had greater molar rotation. TC uprighting moment produced greater molar mesial extrusion as well as greater intrusion of the distal root apex. The dual deflection system of the TC mechanics induced the lowest stress on the PDL, regardless the of metallic alloy. **Conclusions:** Torqued cantilever delivered a more efficient uprighting moment to the molar with less unwanted tooth movement and stress on the PDL, as well as a more accessible site for bonding the molar tube.

Introduction

Second molar impaction is relatively rare in the general population (0.03 to 0.3%), but is more frequent in the orthodontic population (2% to 3%).[1-4] In general, impacted mandibular second molars are mesially tipped with partial or total impaction.[2,5,6] This eruption disturbance can be caused by posterior mandibular arch length deficiency, loss of the adjacent first molar, early eruption of the mandibular third molar, unfavorable mesial eruption pathway of the second molar, and unwanted effects of E-space preservation by a passive lingual arch or lip bumper.[1,2,7,8] Many techniques and devices can be used to upright impacted molars, which can be tooth- or bone-anchored.[5,9-24] Nowadays, the use of mini-implants to provide direct or indirect skeletal anchorage for mandibular molar uprighting is welcome, avoiding unwanted tooth movements, as well as preparation and stabilization of the anchorage unit.[1,16,24] However, to the authors' knowledge, the 3D effects of skeletally anchored tip-back cantilevers have not been evaluated.

Tip-back cantilever is one of the most widespread and used orthodontic techniques for mandibular molar uprighting, especially when some degree of molar extrusion is allowed during uprighting mechanics.[11,19-21] In general, tip-back cantilevers are attached to an orthodontic tube positioned on the buccal surface of the tipped molar. However, most of the deeply impacted and mesially tipped mandibular molars do not present adequate exposure of their buccal surface, preventing the bonding of a molar tube at this location.[2,17,25,26] In this case, uprighting mechanics must be modified to avoid the need for surgical exposure of the molar buccal surface.[17] For this reason, alternative mandibular molar uprighting techniques involving the bonding of orthodontic accessories on the disto-occlusal surface of the impacted molars have been proposed.[14,17,27-32]

More recently, innovative uprighting mechanics proposed the use of a skeletally anchored torqued cantilever made of stainless steel rectangular wire. In this technique, a molar tube is bonded to the distal marginal ridge of the mesially impacted molar and rotated 90° to direct the slot buccolingually, allowing mesiodistal movement of the roots by cantilever torque activation.[25] The torqued cantilever has been successfully used in different centers, especially to treat severe cases of mesially tipped and deeply impacted mandibular molars.[25,26] However, the clinical impact of changes in the molar tube location and orientation and in the method of generating the force moment is difficult to predict and has not yet been three-dimensionally evaluated.

Initially, tip-back cantilevers were made of stainless steel (SS) rectangular wire.11 Titanium-molybdenum alloy (TMA, Ormco/Sybron, Orange, CA, USA) was only introduced in the early 1980s for orthodontic applications.[33] Its combination of high strength and springiness provides an excellent energy storage for auxiliary springs as cantilevers.[33] However, even today, stainless steel tip-back cantilevers are still used for molar uprighting.[1,13] Although the tip-back cantilever technique can be performed with different metal alloys, a three-dimensional study comparing the mechanical effects of stainless steel and TMA tip-back cantilevers for molar uprighting has not yet been performed.

Considering the absence of three-dimensional studies comparing the mechanical effects of the skeletally anchored torqued and conventional cantilevers for molar uprighting, as well as the absence of 3D studies comparing tip-back cantilevers made of SS and TMA, this research evaluated the mechanical effects produced by torqued[25,26] and conventional tip-back cantilevers,[19-21] both skeletally anchored and made of two different metal alloys (SS and TMA), using three-dimensional finite element analysis.

Material and Methods

The mandibular geometry was obtained from a database of the Information Technology Center (ITC), _________, ___. The technique applied for representation of the physical model was created using the BioCAD protocol,[34,35] which was developed using a CAD software to generate a model extracted from the interpolation of multiple tomographies, maintaining the universal anatomic marks.

CT scans were segmented into an STL mesh using the software Invesalius, version 3.0 (ITC, _______, ___). Then, the meshes were interpolated into a mixed anatomical geometry, using anatomical landmarks guided by an anatomy atlas, which allowed working with real anatomical parameters. This mixed model was converted into a CAD model using the Rhinoceros 5.0 design software (McNeel North America, Seattle, WA). This procedure preserved the anatomical landmarks and created the base model to set up the anatomical geometry under study. The three-dimensional mandibular model used in this study extended from the retromolar area to the permanent canine region and included only the second molar with mesial tipping of 35º, simulating a mesially tipped and impacted mandibular molar (Fig 1). Then, it was imported into the Rhinoceros 5.0 SR8 design software (McNeel North America, Seattle, WA).

The finite element model was generated in the Altair HyperMesh Software (Altair Hypermesh; Altair Engineering, Inc., Detroit, MI) to the meshing process and boundary conditions setup. In this step, the material properties (Table I) and constraints of the model were defined, such as fixation areas, symmetry (mathematical representation of another half of the model) and contacts, relating to the software and the interaction area between meshes (Fig 1). After setting the mesh, materials properties, and boundary conditions, the logic was defined to replicate the model activation, which requires moving the cantilever arm to the mini-implant position, generating reaction forces in the cantilever that tension the bracket and move the tooth.

The geometric model was subjected to mathematical analysis using Altair HyperWorks 2019 (Altair Engineering, Inc., Troy, MI) finite elements tools. The model structures were determined with specific properties (Table I), and the simulated materials had elastic, isotropic, and uniform characteristics. A 0.30 mm thick layer around molar roots was created to represent the periodontal ligament (PDL) as indicated in previous studies and a cortical bone thickness of 2 mm was adopted to represent the mandibular cortical layer.[36,37]

Two skeletally anchored tip-back cantilevers for uprighting mesially impacted second molars, known as torqued cantilever (TC) [25,26] and conventional tip-back cantilever (CC) [19], were analyzed. The performance of both cantilevers was analyzed varying the mechanical properties of their metallic alloys to simulate titanium molybdenum alloy (TMA) and stainless steel (SS) characteristics. Thus, four models (TC-TMA, TC-SS, CC-TMA, and CC-SS) were obtained for comparative analysis (Fig 2). The number of elements was equivalent for all geometries with a slight variation only for the cantilever type. The conventional tip-back cantilever model had more elements due to its longer wire extension, but there was no difference in the number of elements between the different metallic alloys (Table II).

A three-dimensional geometric model of the mini-implant and the molar tube was created with the computer-aided design (CAD model) using the Rhinoceros 5.0 design software (McNeel North America, Seattle, WA). The mini-implant morphological and dimensional characteristics selected for this study were based on a cylindrical mini-implant with a length of 7 mm and a thread diameter of 1.5 mm. To allow easier isolation of the bone-implant block, the mini-implants were inserted at a 90-degree angle to the bone surface. The mini-implant was assumed to be a rigid structure and it was positioned in the interradicular space between the first and second mandibular premolars on the side of the impacted second molar. The molar tube design was simulated using a 0.022 X 0.028-in Edgewise tube, which was positioned at different tooth crown locations for each molar uprighting mechanics. The torqued cantilever (TC) mechanics had the molar tube positioned on the occlusal surface, close to the distal marginal ridge of the mesially impacted second molar. The tube was rotated 90° to direct the slot buccolingually, allowing mesiodistal movement of the roots by cantilever torque activation.[25,26] The usual molar tube position on the buccal surface of the second molar was applied for the conventional cantilever (CC) mechanics.

The cantilevers were created and modeled based on rectangular wires (0.019 X 0.025-in) using the 3D modeling software (Rhinoceros 5.0 SR8; McNeel North America, Seattle, WA). The torqued cantilever was activated by torquing the end of the cantilever that is inserted into the molar tube. The conventional cantilever was activated by opening the helical spring positioned close to the molar tube. In both mechanics, the cantilever activation was such that the distance from the cantilever arm to the mini-implant produced a similar uprighting force on the second molar.

The models were analyzed for the three-dimensional displacement of the second molar, which was produced by the effort of reaction to tensioning of the cantilever structures. To replicate this complex movement, a non-linear static simulation was performed into three simulation steps to represent the large displacement of the cantilever. The first step was responsible for moving the cantilever to the activation position. The second step joined the end of the cantilever arm to the mini-implant, activating a fixed contact between their surfaces. Finally, the third step released the force that displaced the cantilever arm to the mini-implant, transferring the induced tension in the cantilever arm to the tooth. The models were analyzed for 3D molar displacement and maximum principal stress induced on the periodontal ligament. Molar displacement was expressed in millimeters (mm), while stress was recorded in megapascal (Mpa).

Results

The general pattern of 3D molar displacement produced by the same cantilever made with different metallic alloys (SS and TMA) was similar (Fig 3). Although the molar displacement pattern was not influenced by the cantilever material, the SS cantilever produced almost twice as much molar displacement as the TMA cantilever (Fig 3).

3D molar displacement

Both cantilever mechanics produced a total molar displacement that included distolingual rotation, mesiodistal uprighting, extrusion, and lingual tipping. Despite these similarities, TC and CC cantilever mechanics showed some individualities when the 3D molar displacement vectors were distinctly evaluated.

Molar uprighting (Y-axis)

Distal displacement of the second molar was observed in both mechanics, but it was more intense and consistent with a couple moment movement in TC mechanics (Fig 4). In fact, only TC mechanics showed an evident mesial movement of the mesial and distal root apexes of the second molar (Fig 4). In addition, the distal displacement produced by TC mechanics was greater and more concentrated in the tooth crown (Fig 4). This set of differences in tooth displacement may contribute to explain the better performance of TC mechanics for molar uprighting (Supplementary material).

Molar rotation (X-axis)

Three-dimensional molar displacement evaluation showed that both cantilevers (TC and CC) were prone to cause distolingual molar rotation, but with different fulcrum positions (Figs 5 and 6). In general, the rotation fulcrum followed the long axis of the second molar in both mechanics, but it was more distally displaced and buccolingually centralized in CC mechanics than in TC mechanics (Fig 6). Consequently, the molar rotation produced by CC mechanics was more intense and associated with greater buccal displacement of the mesial portion of the second molar (Fig 5).

Molar extrusion (Z-axis)

Second molar extrusion was observed on the buccal side, while the lingual side showed a downward displacement, confirming that the uprighting process in both mechanics was associated with molar lingual tipping (Fig 7). The TC mechanics showed greater mesial extrusion as well as greater intrusion of the distal root apex (Fig 7). Again, this movement composition may help to explain the improved performance of TC mechanics for second molar mesiodistal uprighting.

Stress distribution

The maximum principal stress induced by SS cantilever on the periodontal ligament was greater than that induced by TMA cantilever (Fig 8). Starting from the cervical portion of the periodontal ligament, the tensile stress was predominantly located in mesial surfaces, while the compressive stress was more prevalent in distal surfaces. However, this tensile and compressive stress distribution was prone to invert towards the root apex, characterizing the total periodontal stress resulting from the couple moment produced by the molar uprighting process (Fig 8). In addition, this stress distribution pattern was more evident in TC mechanics than in CC mechanics. The tensile and compressive stresses associated with the distolingual molar rotation could be seen near the furcation area in both mechanics.

Discussion

Finite element analyses were performed between two different tip-back cantilevers for molar uprighting, which were made of two different metallic alloys. Considering Lagravère's recent guidance on the rationale for the FEM study,[38] the authors consider that this three-dimensional study can bring relevant advances to clinical practice and help solve some clinical limitations of conventional tip-back cantilever for uprighting deeply impacted mandibular molars.[25,26] Although the general pattern of 3D molar displacement produced by the same type of cantilever made with different metallic alloys (SS and TMA) was quite similar, the results showed that the SS cantilever produced greater molar displacement and higher stress on the periodontal ligament. These findings can be explained by the higher stiffness and maximum bending moment of stainless steel springs when compared to TMA springs, influencing the release of orthodontic force due to less efficient energy storage.[39,40]

The most widespread biomechanical effects of the tip-back cantilevers involve two-dimensional molar changes, namely molar distal tipping (mesiodistal plane) and extrusion (vertical plane).[16,19,22,24,41,42] However, other less emphasized side effects as molar rotation and buccolingual tipping have also been reported, since tip-back cantilevers act far from the center of resistance of the molar, producing displacement vectors in all three spatial planes.[11,21,43,44] In this study, torqued and conventional cantilevers produced molar displacements that included mesiodistal uprighting, extrusion, distolingual rotation, and lingual tipping. Although the displacement directions were similar for both cantilevers, the three-dimensional evaluation showed that the type of tooth movement was not the same due to mechanical peculiarities inherent to each cantilever, such as line of force action, force moment, rotation center and tipping control.

In the mesiodistal direction (Y-axis), the torqued cantilever produced a distal displacement of the molar that was greater and more concentrated in the tooth crown (distal crown tipping) compared with the conventional cantilever. In addition, only the torqued cantilever produced an evident mesial movement of the mesial and distal root apexes of the second molar. These findings suggest that the force moment produced by the torqued cantilever in mesiodistal direction was associated with a greater root torque effect than that produced by the conventional cantilever, causing immediate mesial root tipping during molar uprighting. Thus, considering that mesial root tipping is often desired to upright mesially impacted molars, the torqued cantilever may be a more advantageous option.[1] In addition, the immediate distal tipping of the crown produced by the torqued cantilever seems to be beneficial for unlocking mesial molar impaction,[25,26] avoiding the need for a two-step uprighting process, which requires distalizing forces from an open-coil spring before cantilever mechanics.[13]

The restricted mesial root tipping in conventional cantilever mechanics may be related to the initial phase of tooth movement that is portrayed by the finite element analysis, not considering the subsequent changes in this force system.[43] It should be considered that during the action of the conventional tip-back cantilever, the play between the molar tube and the rectangular wire allows free mesiodistal inclination of the wire inside the slot, forming two contact areas (mesial/distal) between the slot and the rectangular wire.[45,46] It can be speculated that, when the cantilever is activated, this mesiodistal inclination of the rectangular wire combined to its vertical deflection over the mesial contact area would produce a distalizing force vector, in addition to the couple, which changes the rotation center of the molar, reducing the mesial tipping movement of the root. In fact, when the distal movement of the molar is completely constrained by tying the molar tube to the anterior segment with a ligature wire, the rotation center shifts to a more ideal location (i.e., at the molar tube) during molar uprighting with conventional cantilever, benefiting mesial root tipping movement.[43] In contrast, the third-order moment generated by the torqued cantilever acts on the occlusal molar tube, torquing it without the previously described contact between the conventional cantilever wire and the buccal molar tube in a second-order direction.

Torqued and conventional cantilevers produced distolingual molar rotation (X-axis). The occurrence of distolingual rotation during the uprighting process of mesially tipped molars has already been reported.[17,43,44] However, in this study, the position of the rotation fulcrum was not similar between the evaluated cantilever mechanics. The more distal and buccally displaced fulcrum associated with the conventional cantilever produced greater rotation and buccal displacement of the mesial portion of the second molar. This finding may be associated with the previously discussed distalizing force vector produced by the conventional cantilever, which acts buccally to the center of resistance of the molar, encouraging its distal rotation.[17] Despite the lower potential to cause molar distolingual rotation, a buccal eccentric force can occur even when the molar tube is positioned on the distal marginal ridge of the mesially impacted molar, as in the torqued cantilever due to the buccal position of the mini-implant.16 In this case, an anti-rotation bend can be incorporated at the end of the torqued cantilever to generate a force moment that further minimizes the side effect of distolingual molar rotation.[17] However, when the mesially impacted molar is already distobuccally rotated, distolingual rotation associated with uprighting mechanics may be clinically advantageous.

Molar extrusion is a well-known side effect associated with most uprighting mechanics.[11,16,19,21,22,43,44] Although molar extrusion due to the vertical movement of its center of resistance is an undesirable side effect when the tipped molar has already reached the functional occlusal plane, deeply impacted and mesially tipped molars can benefit from the motion composition involving distal tipping and extrusion.[19,22,24,26] Torqued and conventional cantilevers caused molar extrusion (Z-axis). The torqued cantilever showed greater extrusion of the mesial segment of the molar crown. However, it also produced greater intrusion of the distal root apex. These findings suggest that the torqued cantilever delivered a more efficient uprighting moment to the molar. Thus, the extrusion associated with the torqued cantilever was more mesially located and mostly associated with the moment generated by the couple of force used for molar uprighting.

A less emphasized side effect of uprighting mechanics is the molar lingual tipping because the extrusion force vector is buccally displaced in relation to the center of resistance of the molar. In general, the downward displacement of the lingual aspect of the molar crown was more intense in the conventional cantilever mechanics, suggesting a greater molar lingual rolling associated with this uprighting method. It has been proposed that mini-implants that anchor the uprighting mechanics should be vertically inserted in the bone crest, in the middle of the buccolingual width of the tipped molar, and the orthodontic force should be centered on the distal marginal ridge to contribute to control the buccolingual molar tipping during the uprighting process.[16] Although in this study the mini-implants were inserted perpendicularly to the buccal bone, the torqued cantilever action occurred in the middle of the distal marginal ridge of the tipped molar where the molar tube is bonded. This molar tube location brought the line of force action closer to the center of resistance of the molar, reducing the undesirable tendency for molar lingual rolling due to a vertical eccentric force.

In general, the uprighting of a mesially impacted mandibular molar is more focused on mesial root movement than on uncontrolled distal displacement of the molar, as opening a large space between the second and first molars may not be interesting.[1,25] However, mesial root movement involves an extensive root apex displacement, which has been considered more difficult to achieve than the tooth crown tipping, besides being associated with increased external apical root resorption.[47,48] It should also be considered that the cantilever spring was the molar uprighting technique that generated the greatest strain on the molar roots when four different techniques were compared in a previous study.[42] Thus, the lower periodontal stress produced by the TMA alloy may be preferable to stainless steel, especially if the mesially tipped molar needs to be uprighted primarily at the expense of mesial root movement. Another clinically relevant finding was that the torqued cantilever does not require the addition of helices to achieve the desired load/deflection rate for tooth movement. This is because the activation of a conventional cantilever produces a known vertical deflection of its lever arm, while the torqued cantilever activation produces a torsional deflection of the rectangular wire that occurs along with the vertical deflection.[25] This dual deflection system of the torqued cantilever reduces the load-deflection rate, making the use of helical loops unnecessary.[25] This novel deflection system may have contributed to the slightly lower stress on the periodontal ligament generated by the torqued cantilever. Thus, when the torqued cantilever deflection system occurred in the TMA alloy, the lowest stress of the periodontal ligament was obtained.

In general, on the distal surface of the second molar, both cantilevers produced compressive stress in the cervical area of the periodontal ligament with tensile stress in the apical area. Opposite stresses were produced on the mesial surface. Similar results were also reported by a previous study that evaluated tooth movement produced by a cantilever spring for molar uprighting.[44] However, it should be emphasized that this stress distribution pattern was more evident and clearly defined in the torqued cantilever than in conventional cantilever mechanics. This is likely because the couple moment produced by the torqued cantilever was less affected by the tensile and compressive fields generated by other unwanted force vectors, suggesting a better clinical performance for molar uprighting.

Clinical implications

The findings of this study suggest that the torqued cantilever produces similar biomechanical effects as those produced by the conventional cantilever, with some specific advantages such as a better-defined molar uprighting moment and more controlled unwanted tooth movement. Nevertheless, the greatest clinical advance of the torqued cantilever is to allow uprighting biomechanical effects similar to those produced by the conventional cantilever to be applied to deeply impacted molars, whose buccal surface of the crown is not accessible intraorally.[25,26] Thus, surgical interventions with the specific objective of accessing the buccal crown surface can be avoided, since the distal cusps are usually more accessible without or with less need for surgical exposure.[2,17] In addition, placing a molar tube on the distal marginal ridge in buccolingual direction facilitates the bonding process and buccal insertion of the right-angled distal end of the uprighting cantilever.[17,25,26]

Conclusions

- The three-dimensional molar displacement pattern was not influenced by metallic alloy (SS and TMA).
- The cantilever made of SS produced the greatest amount of molar displacement and the highest stress on the periodontal ligament, regardless of the cantilever type.
- The cantilever type (torqued and conventional cantilevers) influenced the three-dimensional displacement pattern and periodontal stress distribution of the mesially impacted molar.
- Torqued cantilever delivered a more efficient uprighting moment to the molar.
- Unwanted molar movements during the uprighting process were better controlled by the torqued cantilever.
- The dual deflection system of the torqued cantilever contributed to the lowest stress on the molar periodontal ligament, regardless of its metallic alloy.
- Torqued cantilever provides better access for bonding the molar tube, reducing the need for surgical exposure of the buccal surface of the deeply impacted molar.

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Legend to figures

Figure 1 - Mesh of tetrahedral elements in the preprocessing stage.

Figure 2 - FEM models comprising bone, teeth, periodontal ligament, molar tube, mini-implant and tip-back cantilevers. Torqued and conventional cantilevers made of stainless steel (SS) and titanium-molybdenum alloy (TMA) were evaluated (Buccal view).

Figure 3 - Three-dimensional molar displacement produced by the conventional and torqued cantilevers made with different metallic alloys (SS and TMA). Hot colors represent the largest displacements, while the smallest displacements are illustrated by the cold colors (Buccal view).

Figure 4 – Buccal and lingual view of molar displacement produced in mesiodistal direction (Y-axis, molar uprighting) by conventional and torqued cantilevers made with different metallic alloys (SS and TMA). Positive values mean distal tooth displacement, while mesial displacement is represented by negative values.

Figure 5 - Buccal and lingual view of molar displacement produced in buccolingual direction (X-axis, molar rotation) by conventional and torqued cantilevers made with different metallic alloys (SS and TMA). Positive values mean lingual tooth displacement, while buccal displacement is represented by negative values.

Figure 6 - Occlusal view of total molar displacement produced by conventional and torqued cantilevers made with different metallic alloys (SS and TMA). Cold colors represent the rotation fulcrum that occurred during molar uprighting.

Figure 7 - Buccal and lingual view of molar displacement produced in apico-occlusal direction (Z-axis, molar extrusion) by conventional and torqued cantilevers made with different metallic alloys (SS and TMA). Positive values mean upward tooth displacement, while downward displacement is represented by negative values.

Figure 8 – Tensile and compressive stress distribution produced by conventional and torqued cantilevers made with different metallic alloys (SS and TMA) on the molar periodontal ligament. Positive values mean tensile stress, while compressive stress is represented by negative values.

Tables

Table I - Mechanical properties attributed to the structures of the geometric model.

Structures	**Young's Modulus (MPa)**	**Poisson's Ratio**
Tooth	20000	0.3
Periodontal Ligament	0.71	0.4
Cortical Bone	13700	0.26
Trabecular Bone	1370	0.3
Stainless steel	200000	0.3
Titanium	115000	0.35
TMA	69000	0.3

Table II - Number of FEA elements and nodes per model.

Models	Cantilevers			
	Torqued Cantilever (TC)		Conventional Cantilever (CC)	
	SS	TMA	SS	TMA
Number of elements	3.360.166	3.360.166	3.741.574	3.741.574
Number of nodes	838.210	838.210	1.056.579	1.056.579

Figures

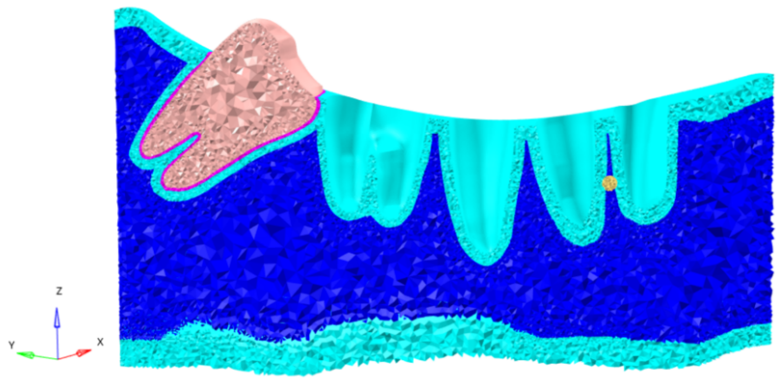
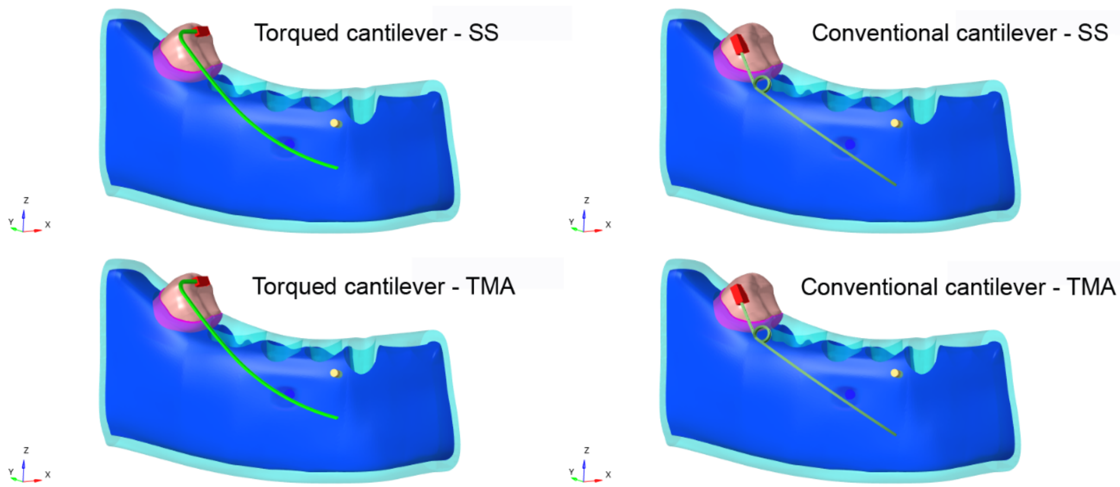


Fig 1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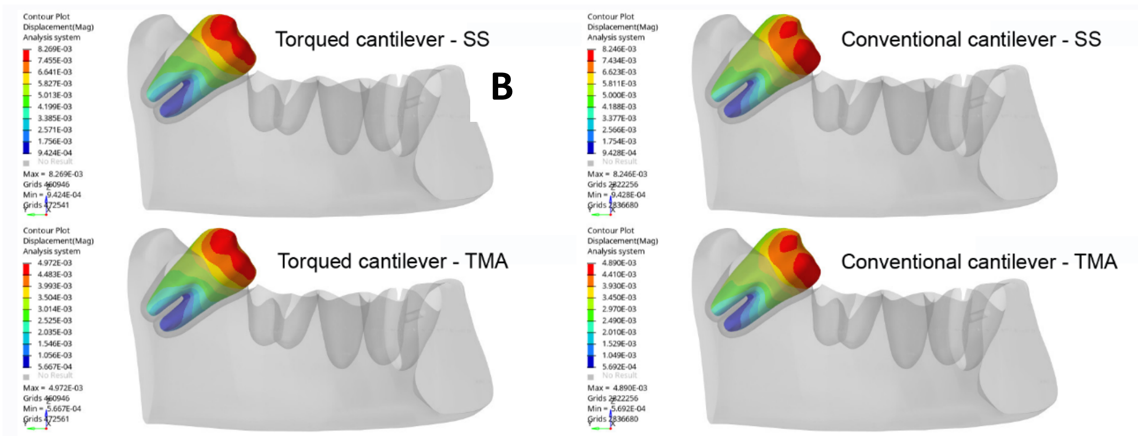
Conventional cantilever - SS
Torqued cantilever - TMA
Conventional cantilever - TMA

Fig 2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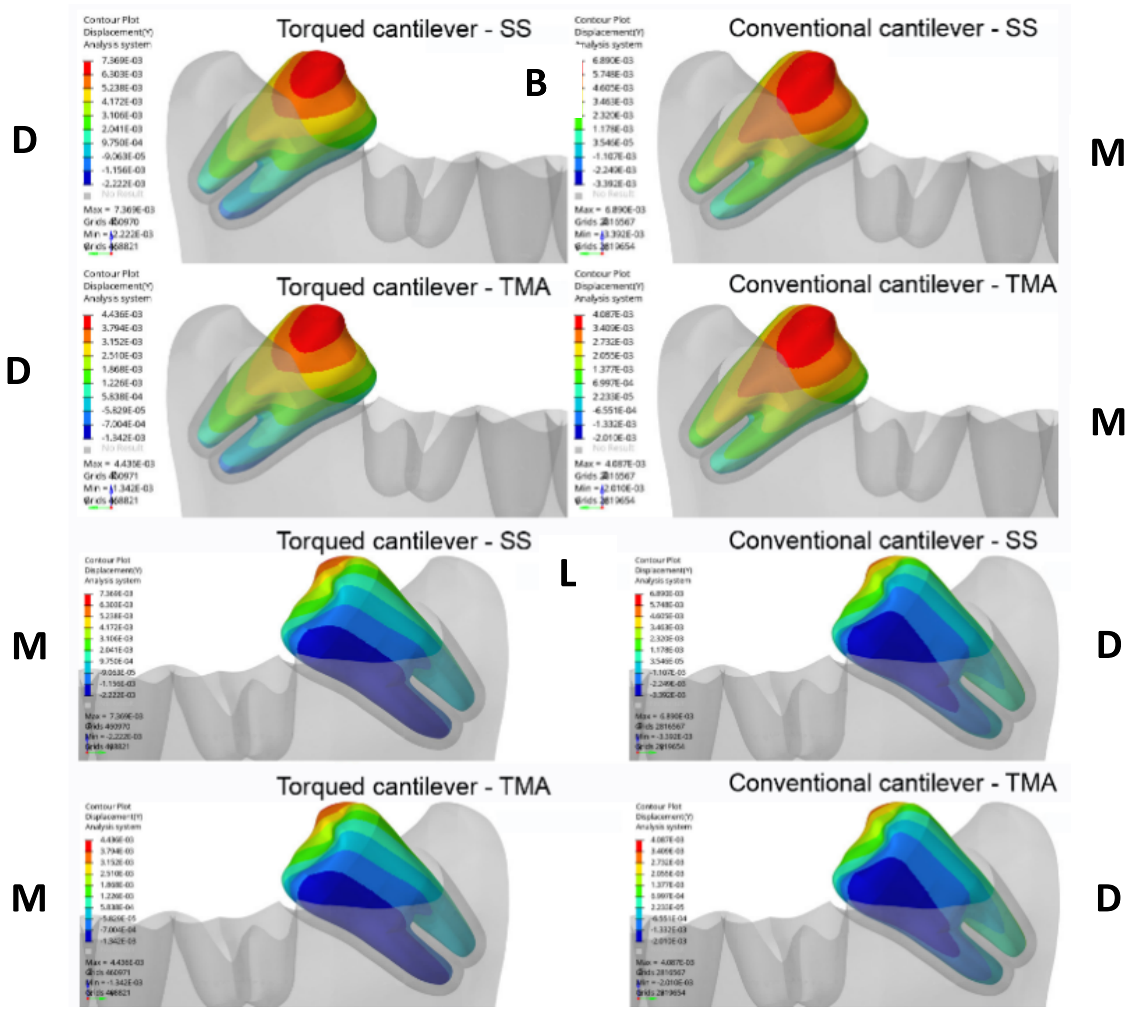
Conventional cantilever - SS
Torqued cantilever - TMA
Conventional cantilever - TMA

Fig 3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Conventional cantilever - SS
Torqued cantilever - TMA
Conventional cantilever - TMA
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Torqued cantilever - SS
Conventional cantilever - SS
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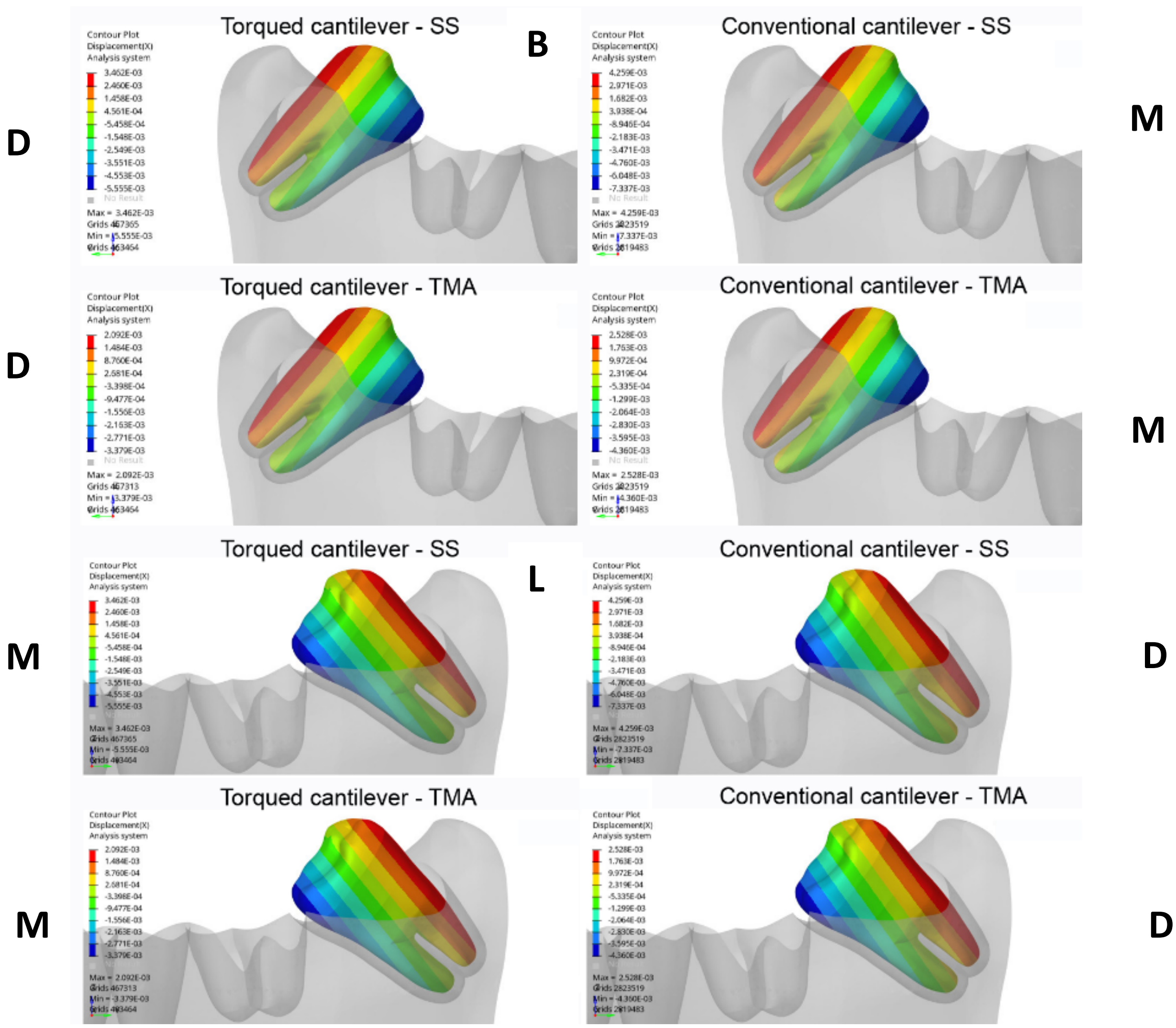
M
D
Contour Plot
Displacement(Y)
Analysis system

Fig 4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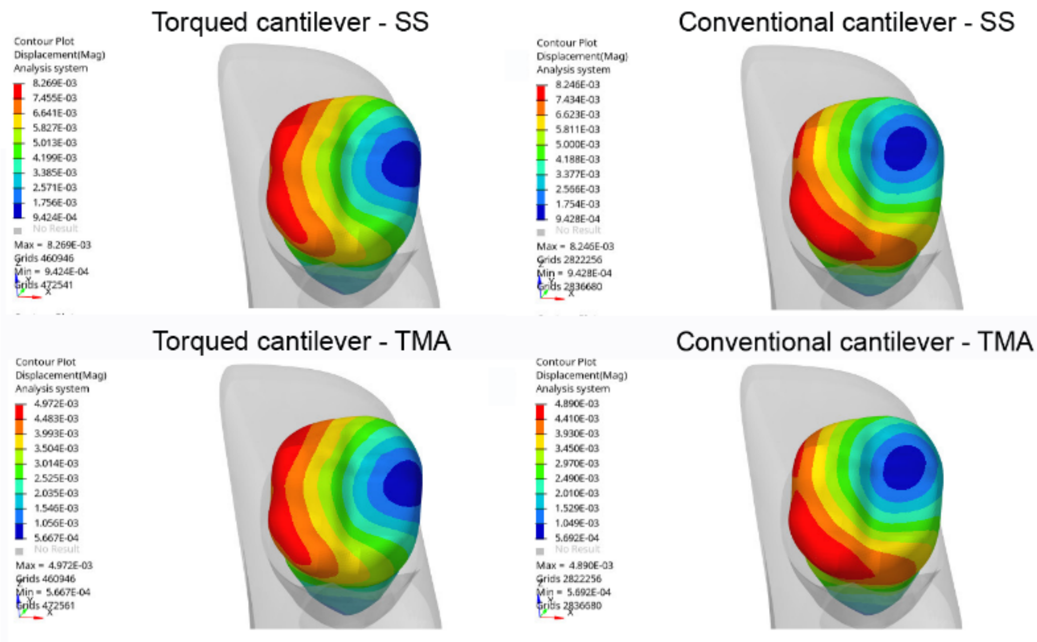
M
D

Fig 5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Conventional cantilever - SS
Torqued cantilever - TMA
Conventional cantilever - TMA
Contour Plot
Displacement(Mag)
Analysis system
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Min = 9.424E-04
Max = 8.246E-03
Min = 9.428E-04
Max = 4.972E-03
Min = 5.667E-04
Max = 4.890E-03
Min = 5.692E-04

Fig 6

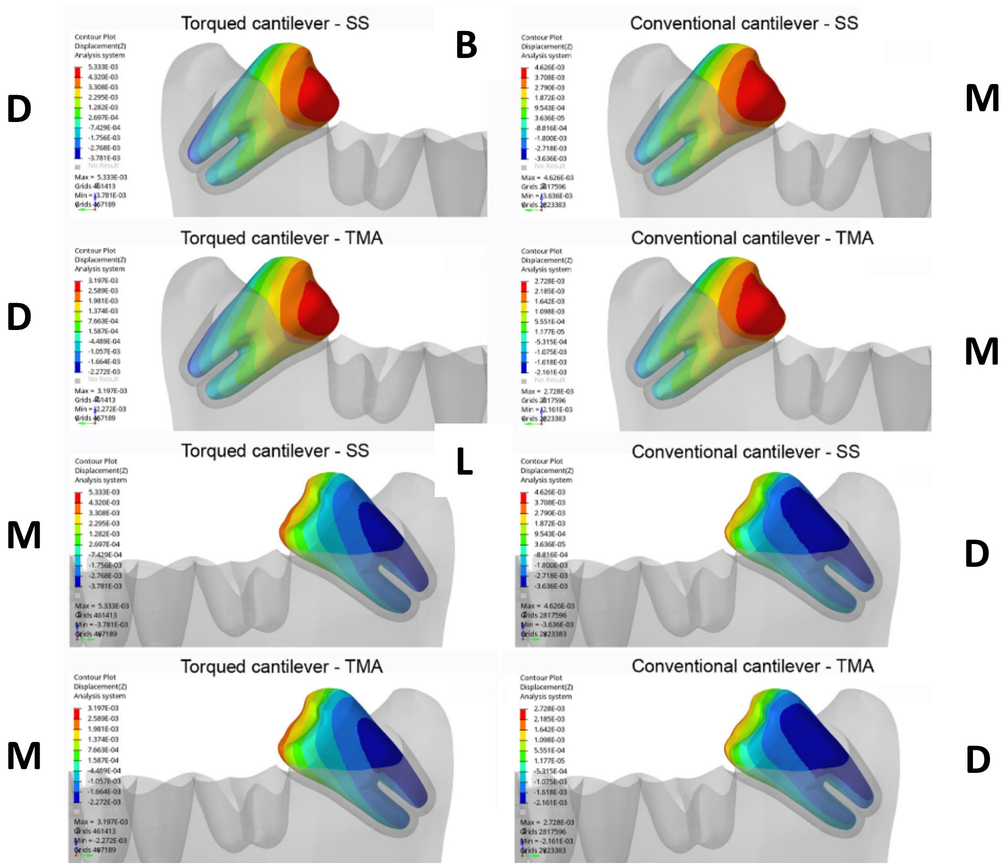
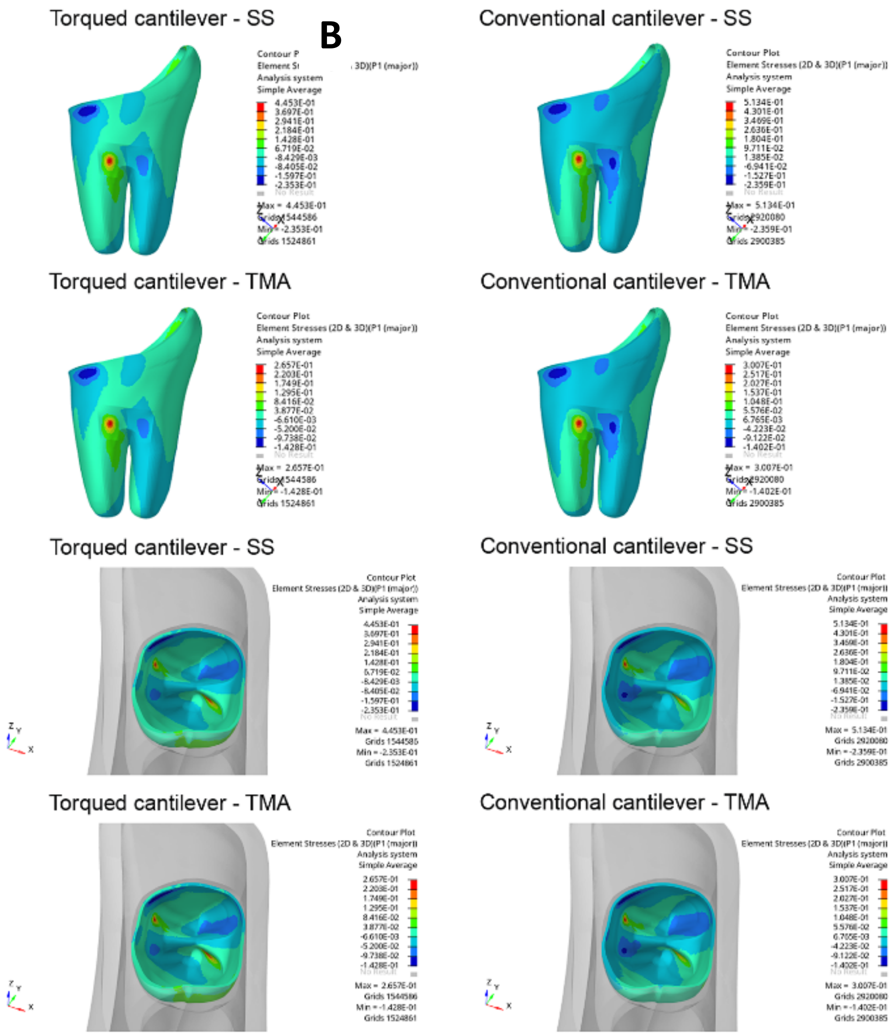

Torqued cantilever - SS
Conventional cantilever - SS
Torqued cantilever - TMA
Conventional cantilever - TMA
Torqued cantilever - SS
Conventional cantilever - SS
Torqued cantilever - TMA
Conventional cantilever - TMA
B
L
D
M
D
M
M
D
M
D

Fig 7



Torqued cantilever - SS
B
Contour P
Element St 3D)(P1 (major))
Analysis system
Simple Average
4.453E-01
3.697E-01
2.941E-01
2.184E-01
1.428E-01
6.719E-02
-8.429E-03
-8.405E-02
-1.597E-01
-2.353E-01
No Result
Max = 4.453E-01
Grids 1544586
Min = -2.353E-01
Grids 1524861
Conventional cantilever - SS
Contour Plot
Element Stresses (2D & 3D)(P1 (major))
Analysis system
Simple Average
5.134E-01
4.301E-01
3.469E-01
2.636E-01
1.804E-01
9.711E-02
1.385E-02
-6.941E-02
-1.527E-01
-2.359E-01
No Result
Max = 5.134E-01
Grids 2920080
Min = -2.359E-01
Grids 2900385
Torqued cantilever - TMA
Contour Plot
Element Stresses (2D & 3D)(P1 (major))
Analysis system
Simple Average
2.657E-01
2.203E-01
1.749E-01
1.295E-01
8.416E-02
3.877E-02
-6.610E-03
-5.200E-02
-9.738E-02
-1.428E-01
No Result
Max = 2.657E-01
Grids 1544586
Min = -1.428E-01
Grids 1524861
Conventional cantilever - TMA
Contour Plot
Element Stresses (2D & 3D)(P1 (major))
Analysis system
Simple Average
3.007E-01
2.517E-01
2.027E-01
1.537E-01
1.048E-01
5.576E-02
6.765E-03
-4.223E-02
-9.122E-02
-1.402E-01
No Result
Max = 3.007E-01
Grids 2920080
Min = -1.402E-01
Grids 2900385
Torqued cantilever - SS
Conventional cantilever - SS
Torqued cantilever - TMA
Conventional cantilever - TMA

Fig 8

4.- CONSIDERAÇÕES FINAIS

A partir deste estudo tridimensional pode-se fundamentar a aplicação desta nova técnica de verticalização do molar, que inclui a utilização de um cantilever torqueado, pois o mesmo demonstrou ser prático e capaz de produzir efeitos mecânicos de verticalização mais eficientes, além de proporcionar um melhor controle de movimentos indesejados do molar durante o referido processo. Apesar de não existir uma diferença no padrão do deslocamento do molar, proporcionado pelo cantilever de aço inoxidável (SS) e liga de titânio molibdênio (TMA), o SS produz maior quantidade de deslocamento e maior tensão no ligamento periodontal. Por fim, a técnica executada com o cantilever torqueado apresenta uma praticidade clínica diferenciada em relação ao cantilever convencional por permitir a colagem do tubo na superfície oclusal exposta do molar impactado, reduzindo a demanda por cirurgia destinada à exposição da superfície vestibular deste dente.

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