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Uberlândia, 2020

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Orientador: Prof. Dr. Guilherme de Araújo Almeida

Banca Examinadora:
Prof. Dr. Guilherme de Araújo Almeida.
Prof. Dr. Carlos José Soares.
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Coordenação do Programa de Pós-Graduação em Odontologia
Av. Pará, 1720, Bloco 4L, Anexo B, Sala 35 - Bairro Umuarama, Uberlândia-MG, CEP 38400-902
Telefone: (34) 3225-8115/8108 - www.ppgoufu.com - copod@umuarama.ufu.br

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"Sonhe, lute, corra atrás, realize. Mas nunca desista, pois nada e impossível quando temos força, foco e fé"

Lourran Gustavo

SUMARIO

LISTA DE ABREVIATURAS E SIGLAS

CLP: Fissura Labiopalatina

UCLP: Fissura Labiopalatina Unilateral Completa

BCLP: Fissura Labiopalatina Bilateral Completa

RME: Expansão Rápida da Maxila

MARPE: Expansão Rápida Palatina Auxiliada por Mini-Parafusos

FEA: Análise de Elementos Finitos

CBCT: Tomografia Computadorizada de Feixe Cônico

STL: Modelo Estereolitográfico

RESUMO

RESUMO

Introdução: O objetivo deste estudo foi avaliar a distribuição de tensão, deformação e deslocamento na estrutura óssea da maxila durante a expansão rápida palatina em um paciente masculino de 17 anos com fissura de lábio e palato bilateral completa não sindrômica, utilizando expansores com ancoragem dentária e esquelética (MARPE) pelo método de elementos finitos. **Métodos:** Para a geração dos modelos específicos de elementos finitos, foi utilizada uma tomografia computadorizada de feixe cônico, os arquivos DICOM foram exportados para os softwares Mimics, 3-Matic (Materialize) e Patran (MSC Software). Foram gerados três modelos tridimensionais específicos: A) HYRAX: Parafuso hyrax convencional (9mm) (quatro bandas); B) MARPE-DS: Modelo com 3 mini-parafusos (1,8 mm de diâmetro - 5,4 mm de comprimento) e ancoragem dentária (quatro bandas); e C) MARPE-NoDS: Modelo com 3 mini parafusos sem ancoragem dentária. A expansão rápida da maxila foi simulada ativando os expansores transversalmente 1 mm no eixo X. **Resultados:** O HYRAX resultou em níveis mais altos de deformação na região dentoalveolar e deformação nula na estrutura óssea palatina. O MARPE-DS apresentou deformação semelhante na região dentoalveolar que o HYRAX e resultou em 4.000 με no centro da região palatal. O MARPE-NoDS apresentou apenas deformação evidente na região palatina. Altos níveis de tensão na raiz dos dentes de ancoragem foram observados para HYRAX e MARPE-DS. Pelo contrário, o MARPE-NoDS não apresentou tensão na estrutura dentária. **Conclusão:** Nos limites do desenho do estudo, é possível concluir que a distribuição das tensões dos expansores utilizados no BLCP apresentou comportamento expansivo assimétrico. O Hyrax e o MARPE-DS produziram, durante a fase inicial de ativação da expansão, deformações elevadas semelhantes nas estruturas dentoalveolares e no deslocamento dos dentes posteriores superiores. O expansor MARPE-NoDS mostrou tensão restrita no palato. É possível concluir que os dispositivos do tipo MARPE-NoDS tendem a ser a opção mais favorável para expansões estritamente esqueléticas.

PALAVRAS CHAVES: Análise de elementos finitos, Expansão maxilar, Mini-Parafusos ósseos, Fissura labial, Fenda palatina.

ABSTRACT

ABSTRACT

Introduction: This study evaluated the stress distribution in the maxilla bone structure during rapid palatal expansion in a 17 years old male patient with bilateral non-syndromic cleft lip and palate (BCLP), using expanders with dental (HYRAX) and skeletal anchorage (MARPE). Material & Method: For the generation of the specific finite element models, cone beam computed tomography was used, and the DICOM files exported to the Mimics, 3-Matic (Materialise) and Patran (MSC Software) software. Three specific three-dimensional models were generated: A) HYRAX: Conventional hyrax screw(9mm) (four bands); B) MARPE-DS: Model with 3 miniscrews (1.8 mm diameter – 5.4mm length) and dental anchorage (four bands); and, C) MARPE-NoDS: Model with 3 mini screws without dental anchorage. The rapid maxillary expansion was simulated by activating the expanders transversely 1 mm on the X axis. Results: The HYRAX resulted in higher strain levels on the dentoalveolar region and also a null tensile stress at palatal bone structure. The MARPE-DS showed similar stress at dentoalveolar region than the HYRAX, and resulted in 4,000 μƐ at the center of palatal region. MARPE-NoDS only showed evident stress at the palatal region. High stress levels at root anchorage teeth were observed for HYRAX and MARPE-DS. On the contrary, the MARPE-NoDS resulted in no stress on the tooth structure. Conclusion: On the limits of the study design it is possible to conclude that the stress distribution from the expanders used in the BLCP showed an asymmetric expansive behavior. The Hyrax and MARPE-DS produced, during the initial activation phase of expansion, similar high strain at the dentoalveolar structures and the upper posterior teeth displacement. The MARPE-NoDS expander showed restricted strain on the palate.

KEYWORDS: Finite Element Analysis, Maxillary Expansion, Bone Screws, Cleft lip, Cleft palate.

INTRODUÇÃO E REFERENCIAL TEÓRICO

1. INTRODUÇÃO E REFERENCIAL TEÓRICO

A fissura labiopalatina (CLP) é considerada a anomalia craniofacial mais comum na população mundial (Yáñez-Vico *et al*., 2012) e uma das malformações do complexo craniofacial mais graves (Samuel, 2006). Essas malformações envolvem o lábio superior, a crista óssea alveolar e o palato (Marazita *et al*., 2004). Em geral, a CLP causa problemas estéticos e funcionais e impactos psicossociais em diferentes magnitudes, dependendo de sua localização e extensão (Marazita *et al*., 2004).

O CLP afeta aproximadamente 1 de cada 700 nascidos vivos, com uma variabilidade relacionada aos estratos geográficos, étnicos e socioeconômicos (Samuel, 2006).[2] Esse tipo de fissuras é causado por um defeito primário na fusão dos processos nasais medial e lateral da maxila, que formam o palato primário e secundário respectivamente, a partir da sexta semana de vida embrionária. A origem da falha na fusão dos processos palatinos tem um caráter multifatorial, algumas são causadas por um único gene mutante, algumas por um conjunto de alterações cromossômicas e outras por exposição aos agentes ambientais específicos como medicamentos anticonvulsivantes, agrotóxicos e corticosteroides. A grande maioria é causada por uma interação desses fatores (Dixon *et al*., 2011). A frequência de CLP difere por sexo e lateralidade, sob uma proporção de 2:1 entre homens e mulheres, onde a fissura de lábio e palato unilateral completo esquerdo apresenta maior prevalência.

As fissuras labiopalatais podem ser classificadas como parciais ou completas de acordo com sua extensão. Entre as fissuras parciais, existem aquelas que envolvem exclusivamente o lábio ou o palato (duro o mole); e entre as fissuras completas, aquelas que podem ser unilaterais (UCLP) direita ou esquerda ou bilaterais (BCLP).

O desenvolvimento restrito de estruturas craniofaciais é uma característica comum em pacientes com fissuras labiopalatinas. A causas das limitações do crescimento estão associadas ao efeito restritivo das cirurgias plásticas reparadoras realizadas na primeira infância, a queiloplastia e a palatoplastia (Silva *et al*., 2001). Pacientes com CLP geralmente apresentam mordidas cruzadas dos segmentos anterior e posterior, atresia maxilar severa, além de uma deficiência do terço médio facial com tendência à má oclusão de classe III (Semb *et al*., 2011).

A atresia maxilar do paciente com fissura completa de lábio e palato gera repercussões morfológicas, estéticas e funcionais negativas no desenvolvimento do paciente (Lauris, 2013). Está restrição transversal da maxila ocorre em toda extensão do arco dentário superior; porém, é mais acentuado na região anterior. Deste modo, a distância intercaninos sofre maiores reduções transversais que a distância intermolares. Esta diferença no grau de atresia anterior e posterior mostra-se ainda mais relevante na fissura completa bilateral, representando um desafio importante para a equipe de professionais responsáveis por este tipo de tratamento (Liao *et al*., 2004).

O protocolo de reabilitação para pacientes com CLP prevê frequentemente uma expansão maxilar previamente ao procedimento de enxerto ósseo alveolar secundário, durante a fase tardia da dentadura mista (Freitas *et al*., 2012). A expansão rápida da maxila (RME) é comumente usada para corrigir a atresia maxilar, consiste em um procedimento ortopédico que aumenta o tamanho da arcada dentária maxilar, alinhando os segmentos maxilares e fornece espaço na fissura para receber o enxerto ósseo na região alveolar (Ayub *et al*., 2016). Um dos dispositivos mais utilizados para expansão rápida da maxila é o expansor dentosuportado tipo Hyrax, com um parafuso expansor posicionado transversalmente à sutura palatina com extensões metálicas soldadas às bandas ortodônticas nos dentes de ancoragem (Fernandes *et al*., 2019).

O protocolo RME é um método bem estabelecido para corrigir a deficiência transversal da maxila em crianças; em função de que gera uma expansão esquelética da maxila através da abertura da sutura medial palatina com poucos efeitos dentários indesejáveis (Digregorio *et al*., 2019). No entanto, em pacientes adolescentes e adultos jovens, a expansão palatina não cirúrgica pode resultar em uma inclinação dentoalveolar não controlada devido à resistência esquelética. Consequentemente, esse tratamento pode causar efeitos periodontais desfavoráveis (Lee *et al*., 2014), reabsorções radiculares (Lemos *et al*., 2018), e alta taxa de recidiva do tratamento ortodôntico.

A expansão rápida palatina auxiliada por mini-parafusos (MARPE) foi proposta por Lee et al. (2010) com o objetivo de superar os efeitos indesejáveis dento-alveolares e otimizar o potencial de expansão esquelética de indivíduos em estágios avançados de maturação esquelética (MacGinnis *et al*., 2014). O expansor tipo MARPE, é uma simples modificação de um dispositivo convencional de expansão rápida maxilar, que incorpora mini-parafusos no osso palatino, para garantir a expansão do osso basal subjacente, minimizando a inclinação dentoalveolar (MacGinnis, 2014; Mathew, 2016).

Os efeitos do tratamento de expansão rápida da maxila têm sido extensivamente estudados ao longo do tempo, utilizando diferentes métodos, incluindo a análise tridimensional de elementos finitos (Lee, 2014; Park, 2017; Yoon, 2019).

A análise de elementos finitos (FEA) é um método numérico de simulação computacional que permite avaliar o desempenho biomecânico de estruturas complexas trás a aplicação de uma força externa. O método divide o domínio complexo em um número finito de elementos interconectados por nós (Richmond *et al*., 2005). A cada elemento pode atribuir-se propriedades do material que são determinadas pela situação clínica ou condições do modelo, e forças são aplicadas para simular cargas clínicas. A resposta experimental às forças aplicadas pode ser visualizada e calculada por escalas de cores. A FEA permite uma visualização detalhada da força e rigidez onde as estruturas se dobram, enquanto indica a distribuição de deslocamentos e tensões (Richmond, 2005; Işeri, 1998). Na ortodontia, a FEA pode ser usada para planejar e prever o desempenho biomecânico da força trás a ativação de dispositivos ortodônticos, em estruturas biológicas como o osso, o ligamento periodontal e os dentes (Işeri *et al*., 1998).

Alguns trabalhos (Lee, 2014; MacGinnis, 2014; Park, 2017; Yoon, 2019; Işeri, 1998) tem avaliado o comportamento biomecânico de expansores esqueléticos tipos MARPE, como o estudo do MacGinnis et al. (2015) que compararam a distribuição de forças com um MARPE e um Hyrax convencional para um paciente adulto, usando modelagem por elementos finitos. Eles observaram que o MARPE apresentou forças de tração e compressão direcionadas ao palato, mais próximas do centro de resistência da maxila, o que gera uma expansão mais pura na direção transversal e uma baixa rotação da maxila no sentido horário, uma condição favorável para pacientes com padrões faciais de face longa. Pelo contrário, o Hyrax mostrou-se uma alta concentração de tensão nas estruturas dentarias, o que gera uma alta taxa de deflexão alveolar, aumentado o risco de recidiva do tratamento e os efeitos indesejáveis.

No entanto, há uma falta de evidências consistentes da eficiência do MARPE em pacientes com anomalia craniofacial congênita com fissura labiopalatina, principalmente nos casos de fissuras completas bilaterais. As diferenças entre os efeitos dento-esqueléticos do MARPE e os expansores convencionais, bem como o comportamento biomecânico do MARPE usando ancoragem estritamente esquelética ou associada à ancoragem dentária, durante a expansão maxilar em pacientes com fissura labiopalatina não são claras e precisam de mais pesquisas.

CAPÍTULO

2. CAPÍTULO ÚNICO

ARTIGO 1 - Behavior of three maxillary expanders in cleft lip and palate: A finite element study

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Angela Maria Bautista Patiño; Monise de Paula Rodrigues; Roberto Sales Pessoa; Salomón Yezioro Rubinsky; Ki Beom Kim; Carlos José Soares; Guilherme de Araújo Almeida

Behavior of three maxillary expanders in cleft lip and palate: A finite element study

Angela Maria Bautista Patiño[1,3], Monise de Paula Rodrigues [2], Roberto Sales Pessoa [2], Salomón Yezioro Rubinsky [3], Ki Beom Kim[4] Carlos José Soares [2], Guilherme de Araújo Almeida [1*].

[1] Department of Pediatric Dentistry and Orthodontics, School of Dentistry, Federal University of Uberlândia, Minas Gerais, Brazil.

[2] Department of Operative Dentistry and Dental Materials, School of Dentistry, Federal University of Uberlândia, Minas Gerais, Brazil.

[3] Department of Orthodontics, School of Dentistry, Universidad Nacional de Colombia, Bogotá, Colombia.

[4] Department of Orthodontics, Saint Louis University, St Louis, Mo.

Short Title: Maxillary expanders in cleft lip and palate: A finite element study

***Corresponding author:**

Guilherme de Araújo Almeida

E-mail: guilhermealmeida@ufu.br

Federal University of Uberlândia

School of Dentistry

Avenida Pará, 1720, Bloco 2G

Uberlândia – Minas Gerais – Brazil, Zip Code: 38405-320

Behavior of three maxillary expanders in cleft lip and palate: A finite element study

ABSTRACT

Introduction: This study evaluated the stress distribution in the maxilla bone structure during rapid palatal expansion in a 17 years old male patient with bilateral non-syndromic cleft lip and palate (BCLP), using expanders with dental (HYRAX) and skeletal anchorage (MARPE). **Material & Method:** For the generation of the specific finite element models, cone beam computed tomography was used, and the DICOM files exported to the Mimics, 3-Matic (Materialise) and Patran (MSC Software) software. Three specific three-dimensional models were generated: A) HYRAX: Conventional hyrax screw(9mm) (four bands); B) MARPE-DS: Model with 3 miniscrews (1.8 mm diameter – 5.4mm length) and dental anchorage (four bands); and, C) MARPE-NoDS: Model with 3 mini screws without dental anchorage. The rapid maxillary expansion was simulated by activating the expanders transversely 1 mm on the X axis. **Results:** The HYRAX resulted in higher strain levels on the dentoalveolar region and also a null tensile stress at palatal bone structure. The MARPE-DS showed similar stress at dentoalveolar region than the HYRAX, and resulted in 4,000 µƐ at the center of palatal region. MARPE-NoDS only showed evident stress at the palatal region. High stress levels at root anchorage teeth were observed for HYRAX and MARPE-DS. On the contrary, the MARPE-NoDS resulted in no stress on the tooth structure. **Conclusion:** On the limits of the study design it is possible to conclude that the stress distribution from the expanders used in the BLCP showed an asymmetric expansive behavior. The Hyrax and MARPE-DS produced, during the initial activation phase of expansion, similar high strain at the dentoalveolar structures and the upper posterior teeth displacement. The MARPE-NoDS expander showed restricted strain on the palate.

Keywords: Finite Element Analysis, Maxillary Expansion, Bone Screws, Cleft lip, Cleft palate.

INTRODUCTION

Cleft lip and palate(CLP) are considered the most common craniofacial anomalies in humans[1] and one of the most severe type of cleft anomaly.[2] These malformations involve the upper lip, alveolar ridge and the palate.[3] In general, CLP causes esthetic, functional, and psychosocial impacts in different magnitudes, depending on its location and extension.[3]

The treatment normally starts in the early childhood with lip and palate repair, requiring the combination with the long and complex orthodontic treatment.[4] The lip and palate reconstruction may influence the maxillary growth, causing anteroposterior, vertical, and transversal maxillary deficiencies.[5] The rehabilitation protocol for patients with bilateral CLP involves frequently maxillary expansion before the secondary alveolar bone graft procedure.[4] Rapid palatal expansion(RPE) is commonly used for correcting the maxillary constriction.[6] This treatment protocol increases the maxillary dental arch, aligning the maxillary segments, and providing space in the alveolar cleft for bone graft.[5] One of the most used devices for rapid maxillary expansion is the hygienic rapid expander (HYRAX), with an expander screw positioned transverse to the palatal suture and metallic extensions soldered to orthodontic bands in the anchorage teeth.[7] The RPE protocol is well-established method to correct transverse maxillary deficiency in children; due to a skeletal maxillary expansion through the opening of the palatal medial suture with few dental undesirable effects.[8] However, in patients late-adolescents and adults, nonsurgical palatal expansion can result in not controlled dentoalveolar tipping due the skeletal resistance. This treatment might consequently cause unfavorable periodontal effects,[9] root resorption,[10] and high relapse rate of orthodontic treatment.

Recently, the use of temporary skeletal anchorage devices as an auxiliary biomechanics therapy for RPE, have resulted in a decreasing of the side effects of conventional maxillary expansion by achieving pure skeletal changes.[11] The miniscrews assisted rapid palatal expander (MARPE), is a simple modification of a conventional rapid maxillary expansion appliance. The main difference is the incorporation of miniscrews into the palatal jackscrew to ensure expansion of the underlying basal bone, minimizing dentoalveolar tipping.[11,12]

The effects of rapid maxillary expansion treatment have been extensively studied over time using different methods, including analysis of three-dimensional finite element analysis.[9,13,14] Finite element analysis (FEA) is an important method to evaluate the biomechanical performance of a complex structure by dividing the complex domain in a finite number of the elements interconnected.[15,16] In orthodontics, the FEA can be used to planning and to predict the performance of the resultant force applied by different devices. When the bone, periodontal ligament and tooth structures are subjected to load, the stress, strain and displacement are resultants. The magnitude of the load, the design of the orthodontic devices and the anchorage method can determine the resultants displacement, strain and stress. FEA allows for detailed visualization of structures bend and twist, while indicating the distribution of displacements, stress and stresses by color scales.[17]

Some studies have analyzed stress distribution in RPE by HYRAX, tooth or tissue bone-borne and bone-borne palatal expanders.[9,11,13,14,17,18,19,20,21] They have demonstrated that different designers, specially of bone-borne expanders have had distinct characteristics of stress distribution[18,19]. According these papers[18,19], HYRAX and tooth bone-borne expanders have resulted in a dentoalveolar buccal inclination as a side effect, when compared with bone-borne appliances[18,19,20]. On the other hand, the arms between the bone-borne screw and the upper posterior teeth used as anchorage sometimes have been considered as determinant to the stability of this type of expanders[21]. In cleft palate, its extension and location may prevent one or the other screw to be positioned, suggesting a possible instability of the expander unless the arms between the upper posterior teeth and the screw was installed. However, the differences between the dentoskeletal effects of MARPE and the conventional expanders, as well the biomechanical behavior of the MARPE using strictly skeletal anchorage(bone-borne) or associated with dental anchorage (tooth bone-borne), during the maxillary expansion in patients with cleft lip and palate is not clear and needs further research.

The aim of this study was to analyze the displacement, stress and strain distribution of the dentoskeletal maxillary structures resulting from the RPE in the complete bilateral CLP, using two different types bone-borne expanders (MARPE) (with or without dental anchorage) and conventional tooth-borne palatal (HYRAX) expander by 3D finite element analysis. The null hypothesis was that in cleft palate individuals, there are no differences in the stress pattern and amount of strain distribution and displacement of the dentoskeletal maxillary structures according to the expanders type used.

MATERIALS AND METHODS

This study was approved by the ethical committee (at the National University of Colombia and Pediatric Hospital *La Misericordia* protocol B.CIEFO-243-18). A cone-beam computed tomography imagen was selected from the tomographic image bank of the Orthodontic Clinic of the Pediatric Hospital *La Misericordia*, Bogotá, DC, Colombia.

A structural nonlinear three-dimensional finite element analysis was created from a cone-beam computed tomography scan (CS9300 Carestream, 90 kV, 15 mA, field of view 10x5 cm, 0.18 mm slice thickness and 0.5 mm voxel dimension) using Mimics software (version 18.0; Materialise, Leuven, Belgium). We used a complete maxilla tomography of a 17-year-old male adolescent, with complete bilateral cleft lip and palate, who received a secondary bone graft (cancellous bone of the iliac crest) before eruption of the permanent canine.

The segmentation of the different structures: compact bone, cancellous bone, enamel and dentin of the entire maxilla, was accomplished using image density thresholding[22,23]. Periodontal ligament layer 0.2 mm thick,[24] was imposed on tooth roots by Boolean operations[22]. After segmentation, the 3D triangle-based surface of each maxillary structure was exported in Stereo Lithography (STL) format (Fig 1), which is a file format that stores information about the external topography of CBCT images. The orthodontic bands and connecting arms to the expander was design using 3-Matic software (version 18.0; Materialise, Leuven, Belgium). The STL surface files were imported and meshed in MSC.Patran® 2010 (MSC.Software, Santa Ana, CA, USA) with tetrahedral elements, forming a volumetric element mesh (Fig 2A). This mesh was imported into a finite element analysis software package (MSC.Marc/Mentat, MSC.Software) to perform the structural analysis (Fig 2B). Nodes on top of the bone structure were rigidly fixed in the x-(horizontal), y-(vertical) and z-directions (Fig 2C). All materials were considered linear-elastic, isotropic, and homogeneous. The applied material properties (elastic modulus and Poisson's ratio) were obtained from the literature (Table 1)[9,25-29]. Interfaces between the different structures were considered bonded, except for the parts related to the expander screw, which contact was considered rigid. Three models were generated (Fig 3):

HYRAX model: Conventional hyrax screw with 9mm (PecLab Ltda, Belo Horizonte - MG, Brazil) and four bands (both upper second premolar and second molar);

MARPE-DS model: MARPE SL 9 mm with dental anchorage (PecLab); dental anchorage four banded (both upper second premolar and second molar) supported by 3 mini-screws (PecLab) with a diameter of 1.8 mm and a length of 5.4 mm were placed lateral to the midpalatal area;

MARPE-NoDS model: MARPE SL 9 mm without dental anchorage (PecLab) supported by 3 mini-screws (Peclab) with a diameter of 1.8 mm and a length of 5.4 mm were placed lateral to the midpalatal area.

In Hyrax and MARPE-DS models the left and right second premolars and second molars were banded (bands were meshed using shell elements connected to teeth using bonded interface) and connected with 1.5mm stainless steel wire to the base of the expander screw and the lingual surface of the bands on both sides.

Data processing *requires a high computational* capacity. For this reason, only the dentoalveolar bone region was considered in the three models. Each model consisted of 5502525 elements and 1286756 nodes, and the total data processing time was 120 hour per model.

Expanders were activated transversely (Figure 2D) by 0.1 mm for 10 steps, resulting in a total of 1.0 mm of expansion in *X* direction and were unfixed in *Y* and *Z* directions to prevent interference with the resultant movement. The displacement (mm), von Mises stress (MPa) and Equivalent Elastic Strain (µƐ) distributions were assessed at the maxilla bone and at the anchorage teeth.

RESULTS

The strain distribution (µƐ), for the bone structure for the 3 orthodontic devices are shown in Figure 4. The HYRAX resulted in concentrated strain distribution in the dentoalveolar region bone; however, the resultant strain on the palatal bone structure was null. The MARPE–DS resulted in highest strain located at the palatal middle region, with approximately 4.000 µƐ. The MARPE–DS resulted in similar dentoalveolar region bone strain distribution that in HYRAX. MARPE-NoDS resulted in the highest strain concentrated at the palatal region; although, null strain concentration was observed on the bottom of the dentoalveolar region.

The strain distribution at the left and right side of the buccal alveolar bone are shown in Figures 5 and 6, respectively. On the left side, the HYRAX device resulted in strain concentration peak (≅2.000 µƐ) around the molars region when simulated 1 mm of expansion was applied (Fig 5). The MARPE-DS showed similar strain distribution pattern that HYRAX device, and high strain concentration at the palate bone to the buccal region (Fig 5). The MARPE-NoDS showed a predominant strain distribution at the palatal region bone and practically null strain concentration on the posterior teeth (Fig 5). On the right side, the HYRAX and MARPE-DS showed similar strain concentration at buccal maxilla bone, with much lower strain (≅1.000 µƐ) than that of the left side (Fig 6). This behavior was observed at the MARPE-NoDS where de strain concentration was minimal at whole buccal right side (Fig 6). When comparing the strain concentration between left and right side is evident that this distribution ~~is~~ was asymmetric (Figs 5 and 6).

The von Mises stress distribution on the buccal and lingual surface of the premolar and molar teeth where the orthodontic devices were stabilized are shown on Figure 7 and 8 and Table 2, respectively. The HYRAX device resulted in the highest stress concentration on the dentin cervical region of the buccal and lingual surfaces due the exclusively dental anchorage (Figs 7 and 8). The left and right premolars showed similar highest and similar stress level (≅100 MPa). The left second molar had higher stress (≅115 MPa) compared with right second molar (Table 2). The MARPE-DS demonstrated similar stress distribution than

HYRAX on all premolars and molars teeth, although it was a slightly smaller on the left upper premolar (Table 2). The MARPE-NoDS model showed an insignificant stress concentration on the teeth (6.2 MPa) for premolars and molars (Figs 7 and 8), on both side (Table 2).

Considering the movements of the teeth, the displacement of the left upper second molars was slightly greater than the right side in the Hyrax and MARPE-DS. The displacement of the upper second premolars was similar in the two expanders (Table 2). On the other hand, in the activation of MARPE-NoDS, the displacement of the upper second premolars and molars was practically non-existent (Table 2).

DISCUSSION

The null hypothesis was rejected. The strain distribution of the maxilla bone and the displacement of the teeth involved were different according the maxillary expanders and the type of anchorage used in the cleft lip and palate.

In the RPE, the activation of the expansion screw leads to the generation of an external force that stimulate biomechanical effects on the craniofacial structures. A biological phenomenon known as mechano-transduction is generated in bone by strain/stress resultants[30]. Mechanical stresses applied to cells are translated into chemical signals that elicit adaptive responses according to the frequency, magnitude and intensity of the stimulus[30]. The biomechanical effects generated in the bone are evaluated by external forces can be evaluated by recording strain levels in microstrain (µƐ). The Frost mechano-stat theory established that a normal load between 100-2000 µƐ allows bone maintenance, a slight overload of 2000 to 4000 (µƐ) induces bone formation and values greater than 4000 (µƐ) generate bone resorption due to overload[22].

In our study, despite the presence of a cleft in the palate and the use of 3 mini-screws, it was enough to trigger a stress distribution similar to that found in normal individuals submitted to the action of the same type of expanders[18,19,20]. In the occlusal view, the HYRAX expander, for using a strictly dental anchorage, showed the higher strain at the dentoalveolar region (3200 µƐ) and the null effect on the palatal surface for expansions of up to 1 mm. These results confirm to those of Matsuyama et al[29] who also found more strains in the areas of the posterior alveolar bone, zygomaticoalveolar line and pterygomaxillary connection, while stresses less were seen in the posterior hard palate, midpalatal suture, and anterior alveolar bone. On the other hand, in both skeletal anchorage expanders (MARPE-DS, MARPE-NoDS), the highest strain distribution happened around the miniscrews on the palatal bone (Fig 4). This confirms the findings of a similar studies that concluded that the concentration of strain on the palate is very similar for expanders with skeletal anchorage[9,14,31]. Furthermore, the use of skeletal anchorage during the initial phases of maxillary expansion in patients with cleft lip and palate generated a high concentration of microstrain (greater than 4000 µƐ) in the central region of the palate, able to induce the bone cells activity in the midpalatal suture area. Thus, justifying the skeletal effect of MARPE-type expanders demonstrated in several clinical trials[6,19,20].

According this research, although the MARPE-DS presents skeletal anchorage, its teeth and alveolar strain were very similar to the dentoalveolar results evidenced by the HYRAX[18,19,20]. In contrast, the MARPE-NoDS did not show a significant strain on the upper posterior teeth, limiting its strain concentration to the palate, for activations of up to 1 mm. (Fig 4, Table 2)[18,19,20]. This difference between HYRAX and MARPE-DS with MARPE-NoDS can be explained because the force generated in the initial expansion is transferred by the arms that connect the expander to the teeth[18,19,20]. On the other hand, regardless of the expander used, the strain distribution tended to be more concentrated around the screws and teeth involved as anchorage and smaller at the anterior region of the maxilla, at least during the initial phase of the expansion (Fig 4). Probably, this smaller distribution of stress in the anterior region was influenced by the more posterior positioning of both expanders used due to the presence of clefts in the palate. In this specific case, it was necessary to use the second premolars and molars as dental anchorage; in addition, to the impossibility of installing a fourth mini-implant in the left anterior region of the MARPE-DS and MARPE-NoDS expanders, due to the extension of the gap palate in this patient.

In the lateral view the strain distribution in dentoalveolar and palate region were similar that occlusal view, according to the type of anchorage (Figs 5 and

6). The expansion was asymmetric, with greater strain concentration on the left side than the right side. This asymmetry can be explained by two factors. The first is the cleft width; where bone strength tends to be lower, when the greater the cleft size. In this study, the most extensive cleft palate was located in the right side. The second factor, as already mentioned, refers to the number of screws used. In the MARPE-DS and MARPE-NoDS expanders, was greater number of screws on the left side, due to the impossibility of installing a second screw on the right side, by the greater extension of the cleft palate in this region. Therefore, as the left side received a greater number of screws, a substantial resistance to the movement of the dentoskeletal structures was found, generating greater strain concentrations. This becomes clear when the side views were observed: the presence of strain distribution was found only in the region of the palate, in which the MARPE-DS and MARPE-NoDS expanders were used. In these expanders, the intensity of the deformation found on the palate, was directly related to the amount of screws used and the bone strength present in each posterior segment, according to the cleft palate extension (Figs 5 and 6, Table 2). This was consistent with previous studies[12,32,33] in unilateral Cleft Lip and Palate (UCLP), where the stress distribution between the cleft and noncleft sides was asymmetric because of differences in the masses and support structures of the minor and major segments of the maxilla. In the other hands, the amount of displacement and deformation at the cleft side tends to be larger than the smaller cleft palate or the noncleft side.

The HYRAX and MARPE-DS resulted in the highest strain around the buccal bone plate, especially at the left second molar area. The presence of arms connected to dental structures (MARPE-DS) generate a high concentration of strain in the dentoalveolar structures of the buccal bone plate, even when associated with skeletal anchorage (Figs 5 and 6, Table 2). These results support the finding of clinical trials that evaluate the periodontal effect in different types of maxillary expanders.[8,18,19,20,34] The rapid maxillary expansion with tooth-tissue-borne and tooth-borne expanders reduced the buccal bone plate thickness of supporting teeth 0.6 to 0.9 mm and increased the lingual bone plate thickness 0.8 to 1.3 mm[34]. Bone dehiscence were induced on the buccal aspect of the anchor teeth, especially in subjects with thinner buccal bone plates[34], which can be explained by the high strain values.

The distribution of stress in the upper posterior teeth was also different, depending on the use or not of dental anchorage. When MARPE-NoDS type expander was used, null displacement was observed due the anchorage of the expander occurred strictly on the skeletal bone tissue (Figs 5 and 6, Table 2). On the other hand, when dental anchorage was used (HYRAX and MARPE-DS), evident stress was generated in the teeth used as dental anchorage (second premolars and upper molars); as well as in the adjacent teeth. In addition, in these expanders, the stress occurred on the buccal and lingual surfaces and in both the coronary and radicular portions. However, the distribution of the stress was not uniform, manifesting in decreasing order from the crown to the root and on the buccal and lingual surfaces, with greater concentration of the lingual surface (Figs 5 and 6, Table 2). This lingual surface is the region where the arms were connected to the expansion screw and the dental structure, for this reason a maximum stress concentration was evidenced in this area. The left side showed the highest stress concentration, due probably to the lower resistance of midpalatal suture to displace, producing the expansion resultant transmitted to the tooth structures[32]. Patients with BCLP during the initial maxillary expansion significantly high buccal inclination in the anchor teeth can be generated. Although the Von Mises stress distribution method is not able to distinguish the type of stress, whether from compression or tension, this finding also confirms the previous observations about the questioned use of conventional HYRAX expander in patients with CLP when high buccal tipping is preexisting[35].

Apparently, the MARPE-NoDS seems to be properly indicated when is necessary the skeletal expansions without dental compromising resultant even in cleft palate individuals. Futhermore, patients that present non-carious cervical lesions, short roots, periodontal disease and posterior teeth with buccal tipping increased are not recommended to increase the stress/strain concentration on the root surface[19]. Considering that the stress/strain distribution in the palate between the MARPE-DS and MARPE-NoDS are similar, it seems logical to assume that the opening capacity of the suture will be the same[29]. Therefore, if the objective of the maxillary expansion with skeletal anchorage is opening of the midpalatal suture without dental effects, the use of arms associated with skeletal expanders could be questionable[18,19,20].

However, in patients with cleft palate this reasoning does not always apply clinically. First, as there may be a limitation in the amount of bone on the palate, the number of screws may be reduced, compromising the stability of the MARPE expander screw, increasing the risk of deflection of the screws used and forcing the need to insert double arms between the screw and a possible dental anchorage[21]. Another aspect to be considered, is that in the presence of fissures in the palate, the gingival tissue present in the palatal area tends to be thicker, preventing the bicortical insertion of the screws and limiting their potential for skeletal anchorage. Again, in these cases, the indication of the MARPE expander should be associated with dental anchorage, preferably by means of double arms[21]. In this case, the suggestion to reduce stress on dental structures would be to involve a greater number of posterior teeth to be used as dental anchorage or to modify the design of the appliance, increasing a mucosal support, as proposed by Moon et al[20].

The use of mini-implants with a larger diameter can be an efficient biomechanical alternative in patients with cleft palate that present limited bicortical anchorage, since reduces the risk of deflection and possible screw[36] fracture and increases the stability of the expansion.

Experimentally testing for rapid maxillary expansion and measuring the stresses and strains in craniofacial structure is very complex and require specialized equipment. The finite element method allows to understand and visualize biomechanical behaviors that of clinical conditions is would be practically impossible. This analysis involves some limitations, such as assumptions and generalizations about tissue behavior. All materials were considered to be isotropic and homogeneous in this study. Although enamel, dentin and bone are anisotropic and considered heterogeneous. On the other hand, this analyze evaluated only the initial stress distribution and displacement patterns, without consideration of the biologic factors contributing to the reaction of the maxillofacial structure.

With variability in numerous factors (eg, shape of the palate and other anatomic structures, cleft width and density of the bones) affecting the biomechanical system of maxillary expansion in BCLP patients, it would be difficult for the FE model to represent every clinical situation. Nevertheless, it can be claimed that FE models suggest what the biologic response will be, especially in patients with similar clefts.

This is the first finite elements study that simulates rapid maxillary expansions in patients with bilateral palatal clefts using different types of skeletal or dental anchorage. At the same way, our FEM model its different to another's precedent studies with FEM in orthodontics, because it simulates the specific properties of each part of the tooth (enamel, dentin and ligament) allowing biomechanical analyzes closer to reality. A future clinicals tries is recommended to assess the effects of the bone-borne expander to evaluate maxillary expansion in Bilateral Cleft Lip and Palate patients.

CONCLUSIONS

Based on the study design of the specific FE analysis of the maxillary expansion in bilateral cleft lip and palate patients treated with HYRAX, Tooth bone-borne, and bone-borne palatal expander the followed conclusion can be draw:

- The distribution of stresses from the expanders used in the BLCP showed an asymmetric expansive behavior.
- The Hyrax and MARPE-DS produced, during the initial activation phase of expansion, similar high strain at the dentoalveolar structures and the upper posterior teeth displacement.

MARPE-NoDS expander showed restricted strain on the palate.

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FIGURES:

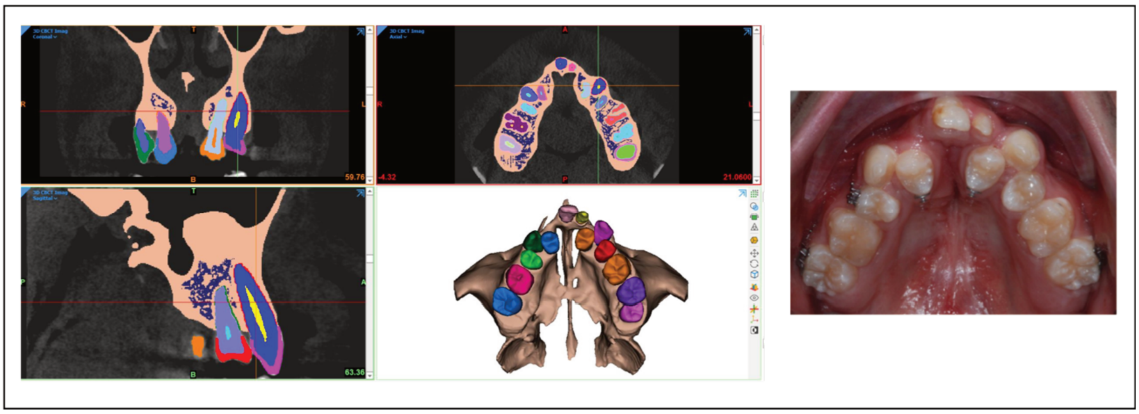

Figure 1. Segmentation with Mimics software of the image obtained by computed tomography of the patient with cleft lip and palate.

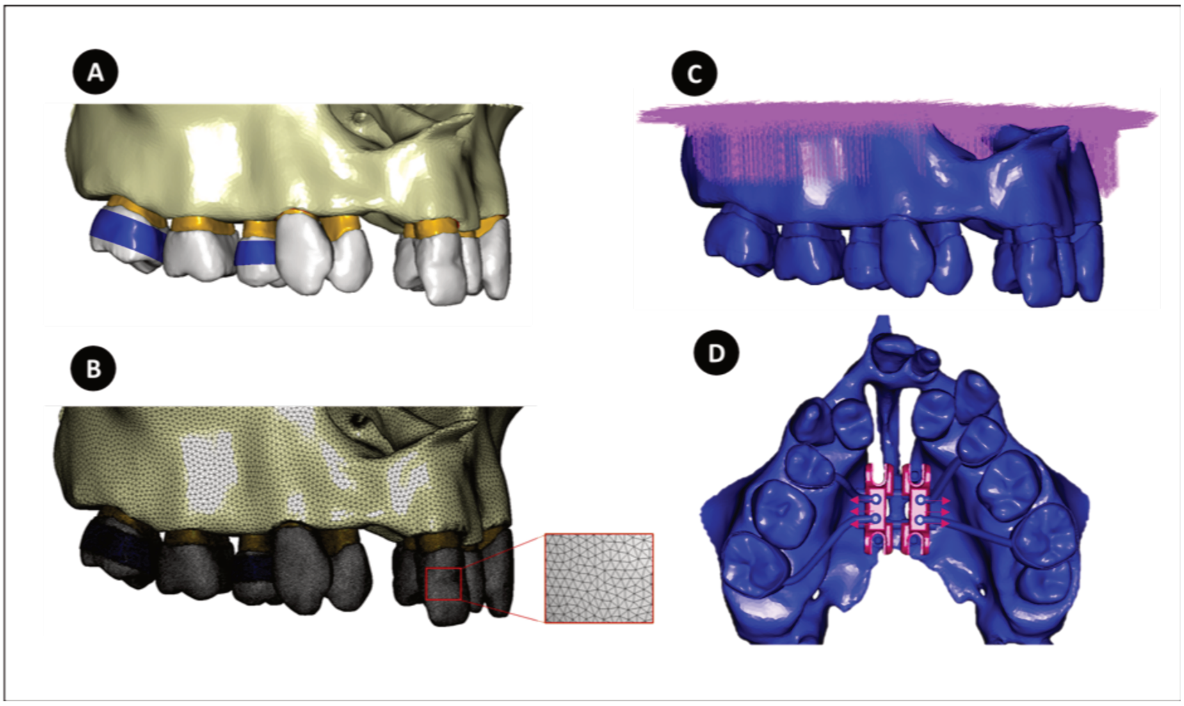

Figure 2. Generation of specific models by finite elements. A) 3D reconstruction of the dental and bone structure using Mimics and 3-Matic. B) Mesh created with Mimics, 3-Matic and Patran software. C) Bone fixation in the XYZ axis D) Non-linear analysis simulating of the expansion in *X* axis.

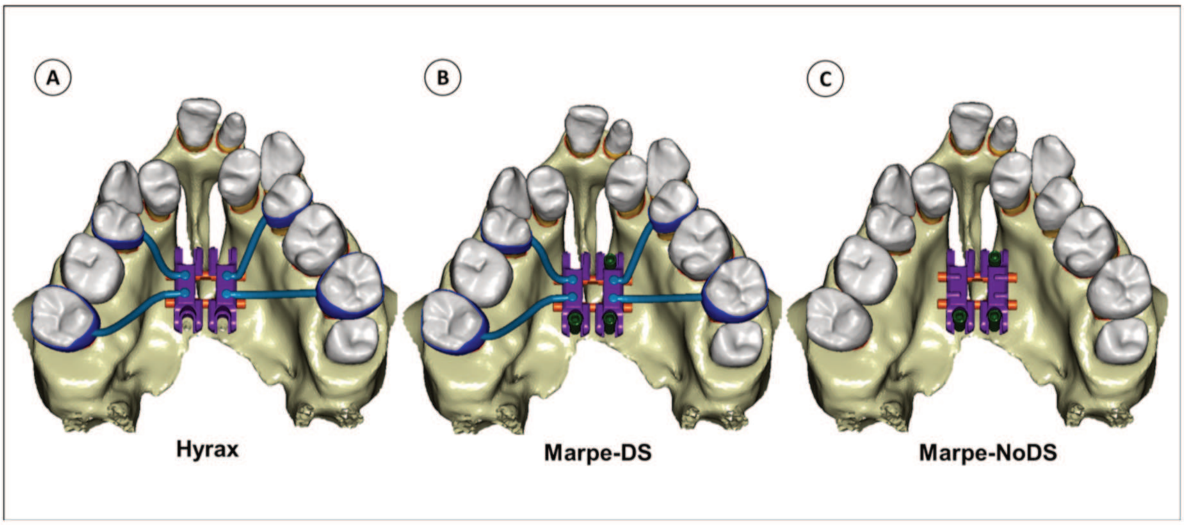

Figure 3. Specific models by finite elements. A) HYRAX B) MARPE-DS C) MARPE-NoDS

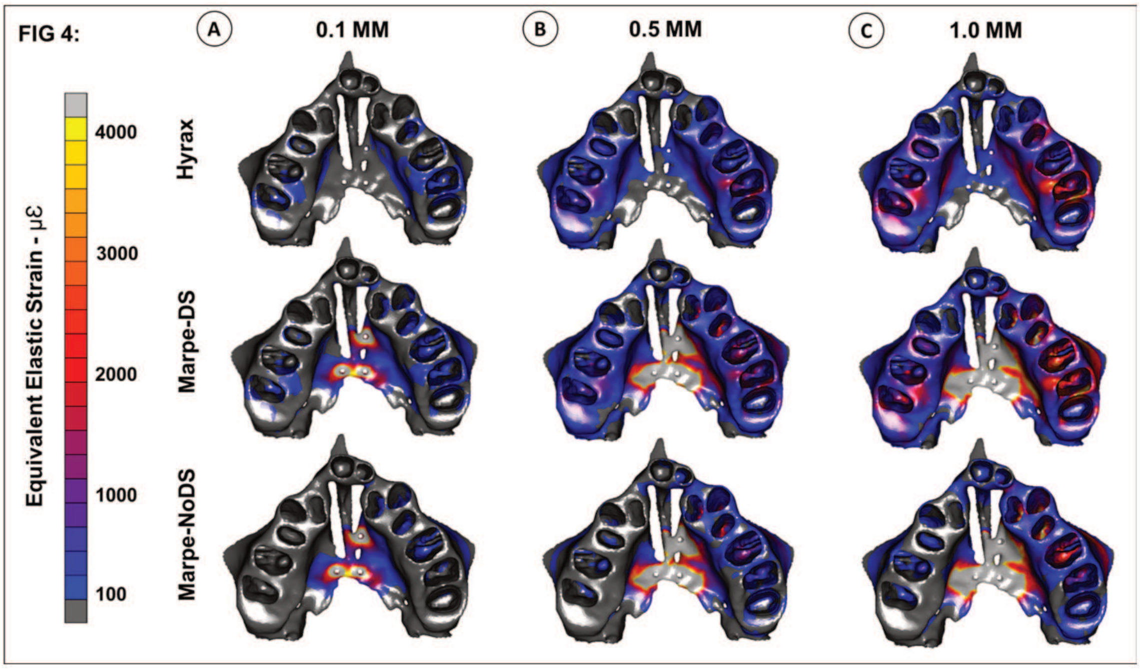

Figure 4. Strain distribution (με), for the bone structure of the 3 orthodontic devices.

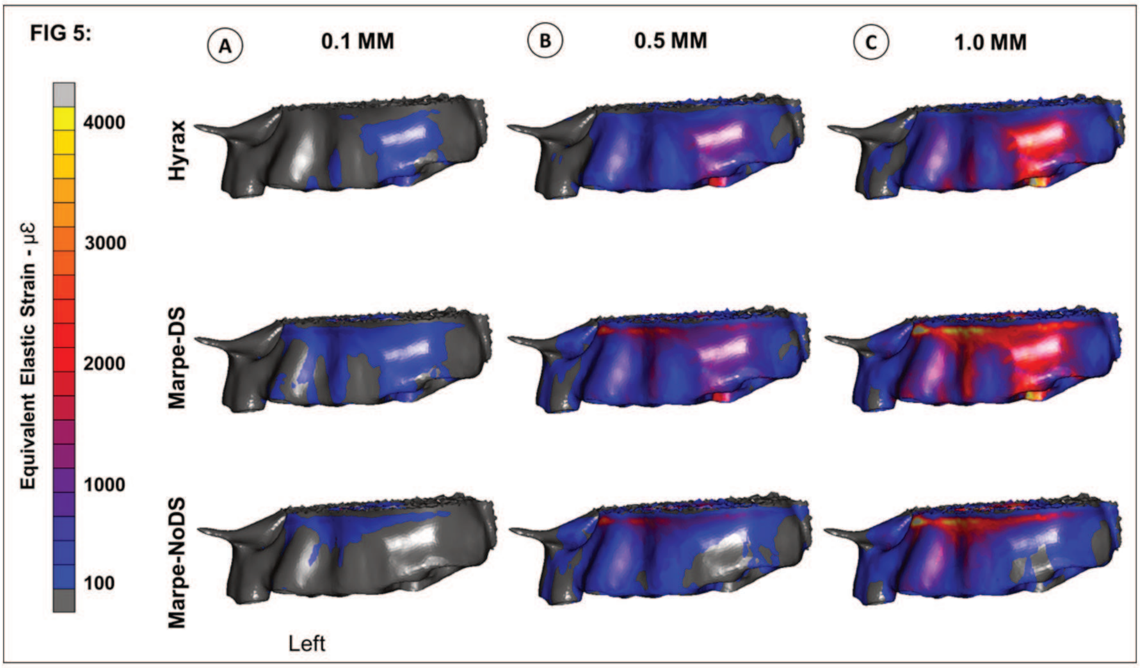

Figure 5. Left side of the Strain distribution in the vestibular alveolar bone.

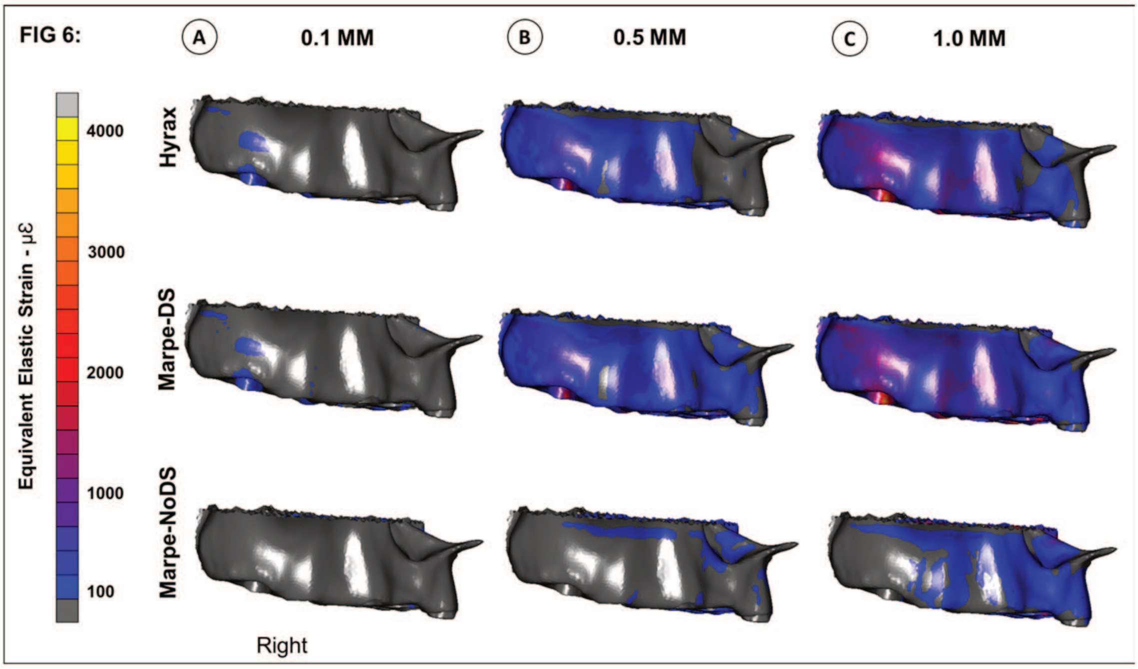

Figure 6. Right side of the Strain distribution in the vestibular alveolar bone.

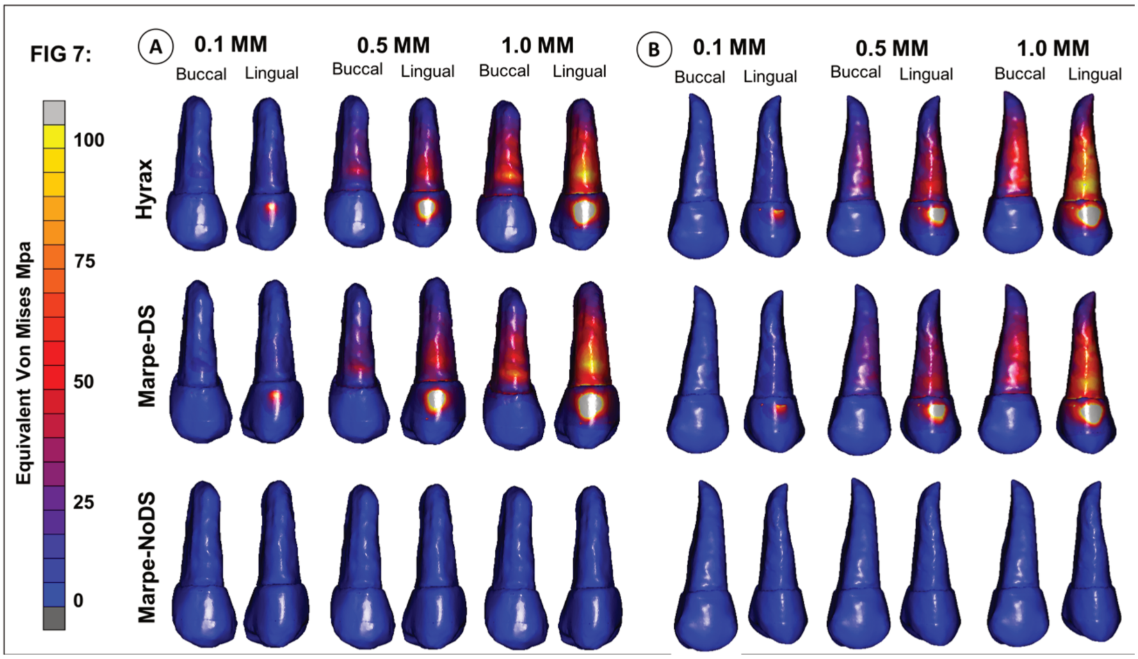

Figure 7. Von Mises stress distribution on the buccal and palatal surfaces of premolar teeth where orthodontic devices were stabilized. A) Right maxillary second premolar B) Left maxillary second premolar

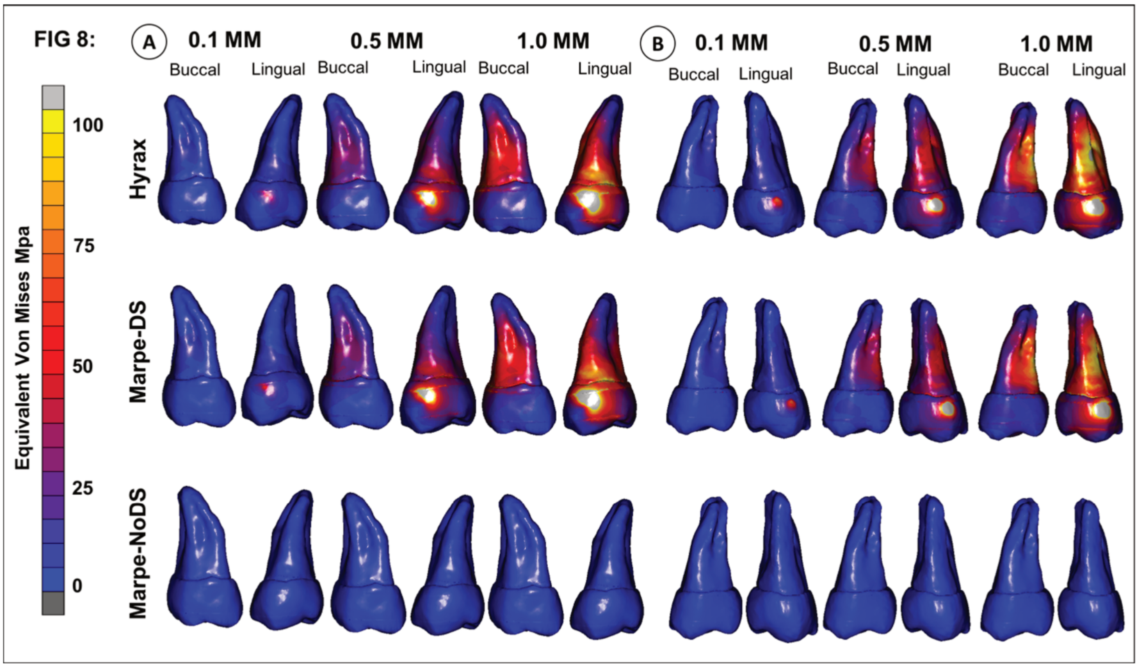

Figure 8. Von Mises stress distribution on the buccal and palatal surfaces of molar teeth where orthodontic devices have been stabilized. A) Right maxillary second molar B) Left maxillary second molar.

TABLES:

TABLE 1: Material properties and elements used in the present study**.**

Structure	Elastic Modulus (MPa)	Poissons's ratio	References
Enamel	84 100	0.30	21
Dentin	18 600	0.31	22
Periodontal ligament	50	0.45	23
Trabecular bone	1370	0.30	24
Cortical bone	13700	0.30	24
Miniscrew (titanium)	110 000	0.30	25
Expander and Band (Stainless steel)	200 000	0.30	9

Table 2. Von Mises stress distribution and displacement in dentin of molar and premolar teeth where orthodontic devices have been stabilized.

Devices	**Equivalent von Mises Stress (MPa)**				**Displacement (mm)**			
	Premolar		**Molar**		**Premolar**		**Molar**	
	Left	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
Hyrax	103.7	101.2	114.3	86.6	0.23	0.24	0.32	0.2
Marpe-DS	89.3	100	108.3	86.2	0.25	0.24	0.33	0.2
Marpe-NoDS	6.2	0.4	6.2	1.1	0.05	0.00	0.03	0.00

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ANEXO

ANEXO 1:

Centro de Investigación y Extensión
Facultad de Odontología
Sede Bogotá

UNIVERSIDAD NACIONAL DE COLOMBIA

Bogotá D.C., 28 septiembre de 2018. **[B.CIEFO-243-18]**

Doctores

GUILHERME DE ARAUJO ALMEIDA
Profesor.
Universidade Federal de Uberlândia

CARLOS JOSÉ SOARES
Profesor.
Universidade Federal de Uberlândia

SALOMÓN YEZIORO RUBINSKY
Docente
Facultad de Odontología – Sede Bogotá.
Universidad Nacional de Colombia

Asunto: Concepto Comité de Ética y Metodología de la Investigación.

Respetados Profesores:

Cordialmente les informo que el Comité de Ética y Metodología en Investigación de la Facultad, en su sesión del día 20 de septiembre, Acta 17-18, luego de revisar el trabajo titulado: "EVALUACIÓN BIOMECÁNICA (SIMULACIÓN COMPUTACIONAL) DE LA EXPANSIÓN MAXILAR DE PACIENTES CON LABIO Y PALADAR HENDIDO UNILATERAL Y BILATERAL NO SINDRÓMICO: UN ANÁLISIS CON ELEMENTOS FINITOS", presentado por la estudiante ANGELA MARIA BAUTISTA PATIÑO y dirigido por ustedes, realizó las observaciones y recomendaciones pertinentes, y emitió el concepto de **AVALADO**, dado que el proyecto cumple con todos los requerimientos éticos y metodológicos.

Con un cordial saludo,

Paula Alejandra Baldión.

PAULA ALEJANDRA BALDIÓN ELORZA
Presidenta del Comité de Ética y Metodología
Facultad de Odontología Universidad Nacional

Copia: ANGELA MARIA BAUTISTA PÁTIÑO - Estudiante

SESQUICENTENARIO UNIVERSIDAD NACIONAL DE COLOMBIA

[Página **1** de 1]
Elaboró:J.D.J.G

Carrera 30 No. 45-03
Edificio 210, Oficina 311
Conmutador: (57-1) 316 5000 Ext. 16011-16012
Bogotá D.C., Colombia
ceninvext_fobog@unal.edu.co

Patrimonio de todos los colombianos