Finite element analysis of the dental pulp under orthodontic forces

Radu-Andrei Moga,[a] Raluca Cosgarea,[b,c] Stefan Marius Buru,[d] and Cosmin Gruia Chiorean[d]
Cluj-Napoca, Romania, and Marburg, Germany

Introduction: To evaluate the stress at the apical third of the pulp and neurovascular bundle (NVB) during 5 types of orthodontic movement at different levels of bone loss. Furthermore, correlations among bone loss, orthodontic appliances, and stress increase were assessed. **Methods:** Based on cone-beam computed tomography datasets, 10 models of the mandibular second premolar were created. Each of these models was subjected to a gradual horizontal bone loss simulation (0-8 mm). Orthodontic forces of 20 g, 60 g, and 120 g were applied during the finite element analysis (FEA). For each bone loss level, stress values were evaluated with the use of Abaqus at the apical third of the pulp and the NVB. **Results:** The stress manifested at the apical third of the pulp was smaller than that at the NVB. The highest apical NVB stress was found for rotation (0.000546 N/mm^2 for 8 mm bone loss) whereas the lowest stress resulted after translational movements (2.35E−04 MPa for 8 mm bone loss). The FEA showed that Proffit's indicated orthodontic forces did not significantly disturb the pulpal blood flow and damage the apical NVB. Up to a doubling of the NVB stress, bone loss correlated with the force reduction to obtain similar stress levels compared with teeth with no bone loss. **Conclusions:** The present findings indicate that the stress manifested at the apical third of the pulp is smaller than that at NVB. Rotational movements induce the highest stress and translational forces develop the lowest stress related to the physiologic capillary blood pressure. Furthermore, in situations with reduced periodontium, lower forces are needed to reach the maximum tolerable stress compared with teeth with intact periodontium. (Am J Orthod Dentofacial Orthop 2019;155:543-51)

The application of orthodontic forces for specific time periods may induce regressive changes and loss of vitality in the pulp tissue by disturbing the pulpal blood flow (PBF).[1-9] Moreover, higher incidences of irreversible inflammatory pulpal reactions were reported in cases with loss of periodontal tissues (ie, advanced periodontitis).[1,2] Type, duration, and values of applied orthodontic forces as well as anatomic features (ie, diameter of apical foramen) and patient's age contribute to blood flow disturbances.[1,7-9] Orthodontic forces are reported to also induce molecular changes in periodontal ligament (PDL), bone, pulp, and dentin.[2] In addition, periodontal ischemia may lead to root resorption.[8] To prevent irreversible changes in the neurovascular bundle (NVB) and the apical third of the pulp, forces need to be correlated with other contributory factors such as the level of bone loss and amount of PDL.

There is little information regarding the tolerable stress for dental pulp and NVB during orthodontic movements under low orthodontic forces (ie, Proffit forces of 0.1-1.2 N)[10] and reduced peridontium.[6-9] Regressive histologic changes (ie, vacuolization, congestion, hemorrhage, fibrohyalinosis) have been reported in the pulpal tissue, and in cases with reduced periodontal support, an increased risk for pulp necrosis has been noted.[1-4,8,9,11,12] Nonetheless, PBF seems to improve 3 weeks after intrusion and tends to return to its initial level within 3 months after force appliance.[1-9,11-14] Despite a large variation of orthodontic forces evaluated in studies (from 10 g [≈0.1 N] to 500 g [≈5 N]),[2,5-9,11] it is unanimously accepted that the magnitude of pulp inflammation or injury is directly proportional to that of the applied force.[2,4]

[a]Department of Odontology, Faculty of Dental Medicine, "Iuliu Hatieganu" University of Medicine and Pharmacy Cluj-Napoca, Cluj-Napoca, Romania.
[b]Department of Periodontology, Philipps University Marburg, Marburg, Germany.
[c]Department of Prosthodontics, Faculty of Dental Medicine, "Iuliu Hatieganu" University of Medicine and Pharmacy Cluj-Napoca, Cluj-Napoca, Romania.
[d]Department of Structural Mechanics, Faculty of Civil Engineering, Technical University of Cluj-Napoca, Cluj-Napoca, Romania.
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Address correspondence to: Radu-Andrei Moga, University of Medicine and Pharmacy Cluj-Napoca, Str. Motilor 33, 400001, Cluj-Napoca, Romania; e-mail, randreimoga@umfcluj.ro; randreimoga@yahoo.com.
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To evaluate the effect of axial load absorption and dissipation on PBF, experimental force simulation at various bone levels are indicated.[15,16] The tensile stress, which is the most damaging, is evaluated by means of von Mises stress (used to assess when the material fails or fractures).[17] Finite element analysis (FEA) was largely used for conducting such experiments[14-23] and represents a numeric form of analysis based on the discretization of a model into a number of simpler elements (tetrahedrons and nodes). This method enables to solve complex issues in physics and engineering, thus allowing biomechanical behavior simulations of tissues (eg, load appliance on a tooth). FEA enables study of how the pattern loads are dissipated and absorbed by tissues and assessing the produced stress (eg, tensile and compressive stresses). The accuracy of the FEA results depends on the validity of the input data and preciseness of the analyzed models. Previous studies used models having 475-148,097 tetrahedrons and 726-239,666 nodes,[15,19,20,23-28] investigating various levels of bone height (1-8 mm).[15,16,27-30] Despite its limitations (eg, method based on mathematical principles, linear versus nonlinear analysis), FEA is considered to be a proper method to study in vivo the stress in various tissues (ie, pulpal tissue, PBF). However, to the best of our knowledge, no study has described the stress induced by orthodontic forces in a gradual horizontal bone loss process. In addition, the evidence to describe correlations among the amount of orthodontic forces, the level of bone resorption or amount of present PDL, and PBF is scarce.[30]

Therefore, the aim of the present study was to evaluate the stress in the apical third of the pulp and apical NVB during 5 orthodontic movements (intrusion, extrusion, translation, rotation, and tipping), with the use of small orthodontic forces 20 g (≈0.2 N), 60 g (≈0.6 N), 120 g (≈1.2 N), and a gradual horizontal bone loss of 0-8 mm. Second, a correlations among the degree of bone resorption, the decrease of force magnitude and stress increase in the apical third of the pulp, and NVB was investigated.

MATERIAL AND METHODS

Ten patients (mean age 28.15 ± 1.93 years, 6 female) with treated chronic periodontitis and different levels of horizontal bone loss, and in need of orthodontic treatment, were included in this study. By means of cone-beam computed tomography (CBCT [ProMax 3DS, Planmeca OY, Helsinki, Finland]; field of view 50 × 50 mm, voxel size 0.075 mm), detailed 2-dimensional images of the right mandibular premolars and first molars were created. The distance between 2 slices was 0.075 mm, allowing accurate anatomic registration.[24,31-33]

For each of the 10 patients, 3-dimensional (3D) models of each component (ie, enamel, dentin, pulp chamber, bracket, PDL, and surrounding cortical and cancellous bone) were generated with the use of a manual image segmentation technique. All single-component models were assembled into 1 3D model, thus obtaining 10 original models (1 model per patient, with 1 molar and 2 premolars) with different degrees of bone loss. Each of these 10 original models was then replicated and for each replicated model, the missing bone and PDL was reconstructed, with the aim to obtain 10 complete models without periodontal breakdown (Fig 1, *A*). In each of the complete models the second mandibular premolar (7 single-rooted and 3 with 2 roots) was guarded while the first premolar and molar were replaced by cortical and trabecular bone (Fig 1, *B*). Afterward, in each complete model, a horizontal bone resorption was gradually simulated (0-8 mm bone loss): Bone and PDL were gradually horizontally reduced by 1 mm, thus obtaining for each of the 10 complete models (with reconstructed bone) 8 models with periodontal tissue loss (80 models in total). A circular homogenous horizontal tissue loss per investigated premolar was assumed.

The CBCT image segmentation process was done manually for each slice based on the different gray-scale values and Hounsfield units with the use of AMIRA 5.4.0 (Visage Imaging Inc., Andover, MA) by 1 examiner (R.-A.M.). A clear separation between the dentin and the cement was not possible. The entire cementum layer in the roots area was considered to have the same properties (Young modulus 18.6 GPa and Poisson ratio 0.31) as the dentin.[18] The PDL stretched between to the intra-alveolar bone and the root surface with a thickness[15,16] ranging from 0.16 to 0.24 mm.[19,20] The cortical bone layer had an average length and thickness of 2 mm,[19,20] and the residual bone was trabecular bone.

All models were filled with 4-node tetrahedrons, and each of the 10 complete models had 5,058,673-6,047,378 tetrahedral elements and 950,897-1,062,438 nodes (Fig 1, *B*).[15,19,20,23-28]

FEA is based on the discretization of a complex model into a number of smaller and simpler elements (ie, tetrahedrons) called finite elements, interconnected at discrete points called nodes. The FEA was performed with the use of a software program coded with a finite element method algorithm.

Boundary conditions, material properties (elastic constants, Young modulus, and Poisson ratio), and loading protocols were assigned to each finite element, defining how the model would deform under the applied

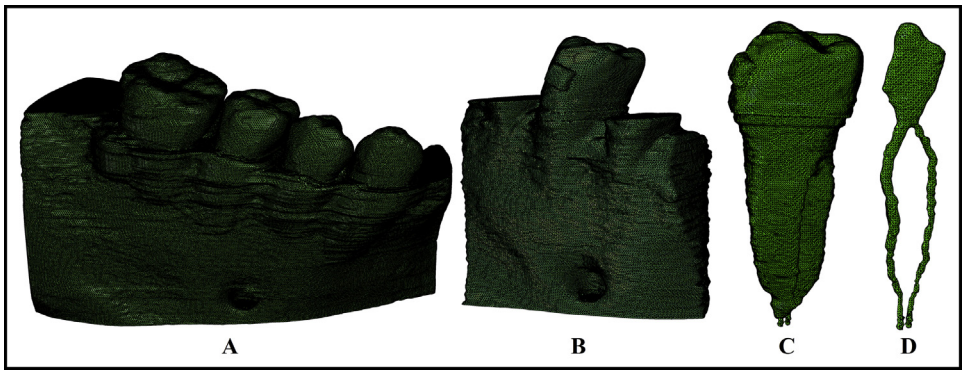

Fig 1. A, Mesh of one complete model; **B,** mesh of second lower right premolar; **C,** mesh of second lower right premolar and apical NVB; **D,** mesh of dental pulp and apical NVB of a 2nd lower right premolar with 2 roots.

loads. The model structures were solved as a series of nodal displacements, and the resulting von Mises stresses (predicting the failure of isotropic materials) were calculated and displayed in ABAQUS 6.11 (Dassault Systemes Simulia Corp., Providence, RI) (Fig 1). Their magnitudes reflected the mechanical behavior of the structures (pulp and NVB) and were represented numerically as a color-coded projection on the geometric model (Figs 3 and 4). The overall stress value of the NVB and pulp under small orthodontic loads at various levels of bone resorption was determined with the use of the von Mises stresses (considered the proper failure criteria for ductile materials).[17]

The elastic constants of all used materials are given in Table I.[10,15-23,34-40] The base of the model containing both the cortical and trabecular bone was considered to have zero displacement. All of the other parts of the model were treated as free of boundary conditions (no boundaries). For simplifying the FEA, it was assumed that the interfaces between all components were perfectly bonded.[21,22,41-46]

The simulated orthodontic movements were: intrusion (20 g [≈0.2 N]), extrusion (60 g [≈0.6 N]), translation (120 g [≈1.2 N]), rotation, and tipping (60 g [≈0.6 N]; Fig 2).

RESULTS

The stress manifested at the apical third of the pulp was smaller than that in the NVB for all 5 types of orthodontic movements (Figs 3 and 4). The von Mises equivalent stress mean values are summarized in Tables II-IV.

In the models without horizontal bone resorption, the highest stress in the NVB for a force of 0.6 N was seen for rotation and intrusion-extrusion movements (1.49E−04 MPa). Lower values were produced by the tipping movement (1.28E−04 MPa), and the lowest values were obtained during translation (0.97E−04 MPa).

In the models with different degrees of horizontal bone resorption, intrusion (at 0.2 N) and extrusion (at 0.6 N) applied at teeth with 4 mm horizontal bone loss determined a 50% increase in the NVB stress. At 6 mm bone loss, the stress doubled, and at 8 mm bone loss the stress was 2.5 times higher compared with teeth with no resorption (Table II).

Translational movements (at 1.2 N) in cases with 3 mm bone loss determined a 50% increase in the NVB stress. Bone loss >5 mm doubled the stress, and at 8 mm bone loss the stress was 2.4 times higher compared with teeth with intact periodontium (Table III).

Rotational movements at 0.6 N led to a doubled level of stress in the NVB at teeth with 2 mm bone loss. The stress tripled at 5 mm bone loss, and the highest stress was seen at 8 mm bone loss: 3.6 times higher than at teeth with no tissue loss (Table III).

When tipping forces of 0.6 N were applied in cases with 1 mm bone loss, a 50% increase in the stress at the NVB was noted. At 4 mm bone loss, the stress doubled, and at 7 mm it tripled. The maximum stress was found at 8 mm bone loss: 3.1 times higher than at teeth with intact periodontium (Table IV).

The highest value and fastest increase in stress at the apical NVB was produced by rotational movements (5.46E-04 MPa), followed by tipping (3.94E-04 MPA). The translational movement produced the least stress (2.35E-04 MPa for 0.6 N of force) among all of the investigated orthodontic types of movements.

DISCUSSION

This study (as part of a larger FEA research related to orthodontic treatment during the loss of periodontal tissues) evaluated the stress at the apical third of the pulp

Table I. Elastic properties of the materials used in the FEA

Material	*Constitutive equation*	*Young modulus, E (GPa)*	*Poisson ratio, υ*	*References*
Enamel	Isotropic, homogeneous, and linear elastic	80	0.33	18-20,23,34-36
Dentin/Cementum	Isotropic, homogeneous, and linear elastic	18.6	0.31	18,23,34-39
Pulp	Isotropic, homogeneous, and linear elastic	0.0021	0.45	18,23,34,37,39
PDL	Isotropic, homogeneous, and linear elastic	0.0667	0.49	15,16,18,36,37,39
Cortical bone	Isotropic, homogeneous, and linear elastic	14.5	0.323	17,19,20-22,25,36,37,40
Trabecular bone	Isotropic, homogeneous, and linear elastic	1.37	0.3	17,19,20-22,36,37,40
Bracket (Cr-Co)	Isotropic, homogeneous, and linear elastic	218	0.33	21,22

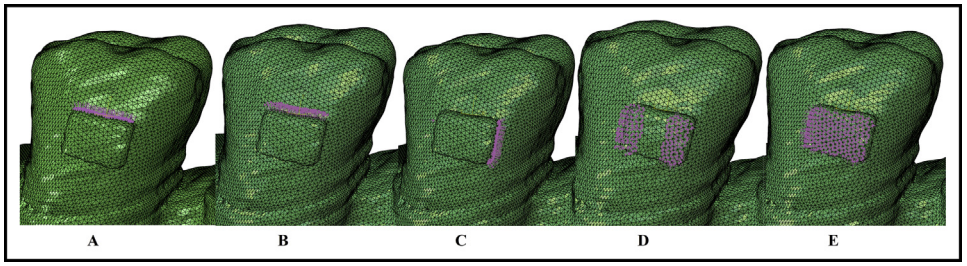

Fig 2. Model with application of orthodontic loads: **A,** intrusion (0.2 N); **B,** extrusion (0.6 N); **C,** translation (1.2 N); **D,** rotation (0.6 N); and **E,** tipping (0.6 N).

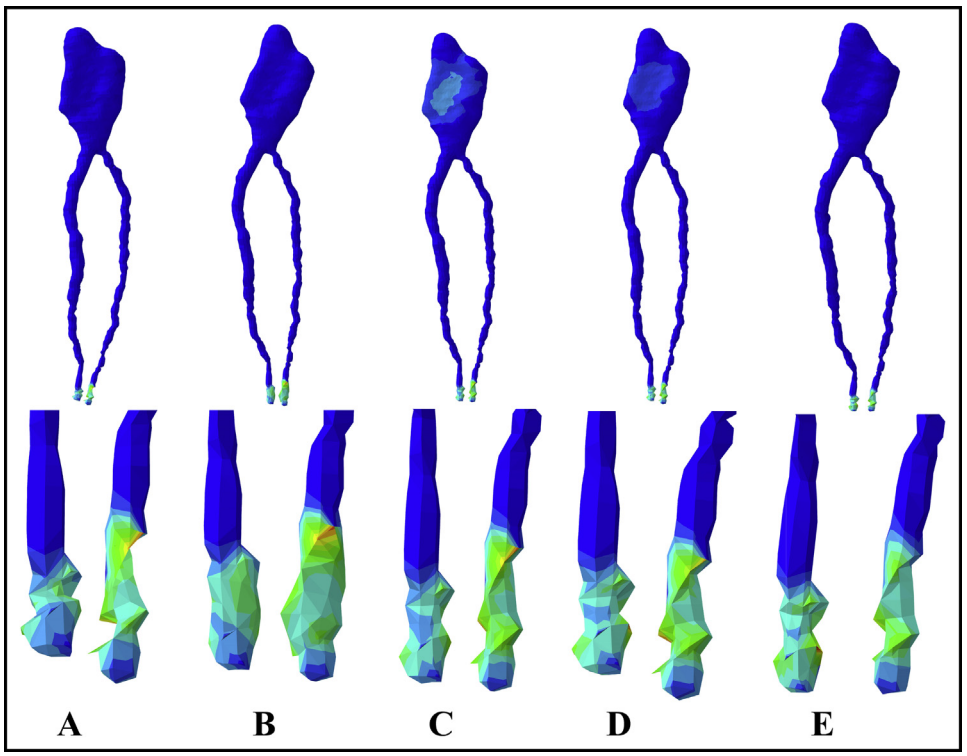

Fig 3. Model with no bone loss—von Mises stress distribution in the apical NVB and apical third of the pulp on 1 premolar: **A,** intrusion (0.2 N); **B,** extrusion (0.6 N); **C,** translation (1.2 N); **D,** rotation (0.6 N); and **E,** tipping (0.6 N).

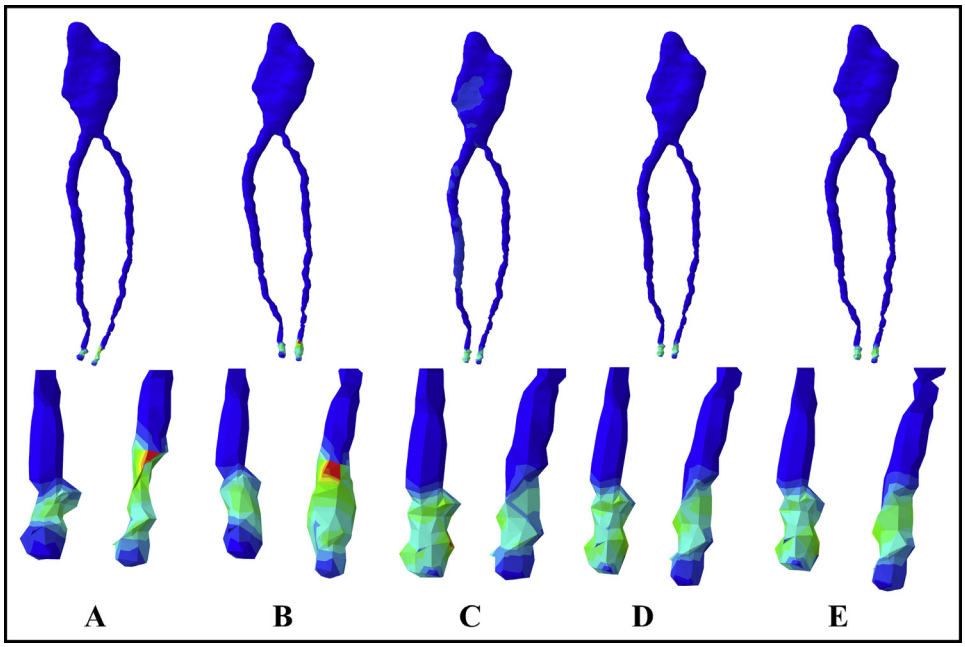

Fig 4. Model with 8 mm bone loss—von Mises stress distribution in the apical NVB and apical third of the pulp on 1 premolar: **A,** intrusion (0.2 N); **B,** extrusion (0. 6 N); **C,** translation (1.2 N); **D,** rotation (0.6 N); and **E,** tipping (0.6 N).

Table II. The highest apical NVB von Mises mean stress values in N/mm^2 (MPa) for intrusion (0.2 N [≈ 20 g]) and extrusion (0.6 N [≈ 60 g]), for gradual horizontal bone resorption

Resorption	*Intrusion*			*Extrusion*		
PDL and bone loss	*NVB stress (MPa)*	*NVB stress increase*	*Apical third stress (MPa)*	*NVB stress (MPa)*	*NVB stress increase*	*Apical third stress (MPa)*
0 mm	4.97E−05	1	4.34E−06	1.49E−04	1	1.30E−05
1 mm	5.91E−05	1.19	5.25E−06	1.77E−04	1.18	1.57E−05
2 mm	6.50E−05	1.31	5.82E−06	1.95E−04	1.3	1.75E−05
3 mm	6.85E−05	1.38	6.00E−06	2.05E−04	1.37	1.80E−05
4 mm	7.46E−05	1.5	6.46E−06	2.24E−04	1.5	1.94E−05
5 mm	8.24E−05	1.66	7.13E−06	2.47E−04	1.65	2.14E−05
6 mm	8.80E−05	1.77	7.56E−06	2.64E−04	1.77	2.27E−05
7 mm	1.11E−04	2.24	9.49E−06	3.33E−04	2.23	2.85E−05
8 mm	1.26E−04	2.53	1.07E−05	3.77E−04	2.52	3.20E−05

and apical NVB induced by 5 types of orthodontic movements with low forces at a second lower premolar with gradual horizontal bone loss of 0-8 mm.

The stress at the apical third of the pulp was shown to be lower than at the NVB for all 5 types of investigated orthodontic forces (Tables II-IV). In addition, the highest apical NVB stress was found for rotational movements at 8 mm bone loss (0.000546 N/mm^2), with a value 3.66 times lower than the reported physiologic capillary blood pressure.[26,41] The lowest NVB stress resulted after translational movements at 8 mm bone loss (0.000235 N/mm^2; Table III). For the highest evaluated translational force (1.2 N [≈ 120 g]), the second lower premolar exhibited NVB stresses ranging from 0.000194 N/mm^2 (no bone loss) to 0.000292 N/mm^2 (3 mm bone loss), and 0.000420 N/mm^2 (6 mm bone loss). The present results (Table III) corroborate those obtained by Jeon et al.[27] They evaluated the apical stress in the PDL for the first maxillary molar, using translational forces and various degrees of bone levels, and obtained stress levels of 0.000445 N/mm^2 at 1.2 N (3 mm bone loss), 0.000403 N/mm^2 at 1.1 N (6 mm bone loss), and 0.000371 N/mm^2 at 3 N (no bone loss). The fact that Jeon et al reported stress values for a multirooted

Table III. The highest apical NVB von Mises mean stress values in N/mm^2 (MPa) for translation (1.2 N [≈120 g]), for gradual horizontal bone resorption

Resorption	*Translation*		
PDL and bone loss	*NVB stress (MPa)*	*NVB stress increase*	*Apical third stress (MPa)*
0 mm	1.94E−04	1	1.75E−05
1 mm	2.30E−04	1.18	2.04E−05
2 mm	2.59E−04	1.33	2.29E−05
3 mm	2.92E−04	1.51	2.59E−05
4 mm	3.04E−04	1.57	2.81E−05
5 mm	3.48E−04	1.79	3.30E−05
6 mm	4.20E−04	2.17	4.08E−05
7 mm	4.34E−04	2.24	4.14E−05
8 mm	4.69E−04	2.42	4.54E−05

maxillary molar (3 roots with more PDL surface) that are similar to those obtained here for a lower premolar (7 teeth single-rooted and 3 teeth double-rooted, less surface with PDL) is due to the different anatomic bony composition of the maxilla with more cancellous bone and the mandible with thicker cortical bone needing higher forces to induce translation. Nonetheless, Jeon et al needed an almost 3 times higher force compared with our study (3 N vs 1.2 N) to translate the maxillary molar with no bone loss, inducing a slightly higher but physiologically still tolerable stress compared with that obtained here (0.000371 N/mm^2 vs 0.000194 N/mm^2).[27] It seems that despite a more favorable bony architecture with more cancellous bone, much higher forces are needed and to translate multirooted teeth (≥3 roots) with intact periodontium compared with single- or double-rooted teeth.

As expected, lower stress levels (extrusion 0.00000001 N/mm^2, intrusion 0.00000000286 N/mm^2, tipping 0.00000000468 N/mm^2 and rotation 0.0000000263 N/mm^2) were reported in studies assessing the apical stress at maxillary incisors with intact periodontium and the use of lower forces (10 g [≈0.1 N]) compared with those applied in the present study (20 g [≈0.2 N], 60 g [≈0.6 N], 120 g [≈1.2 N]).[26] Contrary to these, higher stress values were reported by Geramy et al (force 1 N, stress for intrusion 0.115-0.185 N/mm^2, stress for tipping 0.026-0.722 N/mm^2),[15,16] Hemanth et al (force 0.2-1 N, stress for intrusion 0.01337-0.02006 N/mm^2, stress for tipping 0.0144-0.01646 N/mm^2),[19,20] and Kumar et al (force 1 N, stress for intrusion 0.074-0.315 N/mm^2, stress for tipping 0.08-0.66 N/mm^2)[28] for maxillary central incisors with no to 8 mm bone loss. Differences in the reported stress values may be due to the various tooth anatomies with different PDL surfaces for model assumptions (maxillary central incisor vs mandibular second premolar) or the fact that the authors analyzed the stress at a given bone level (Hemanth et al[19,20] and Vikram et al[26]: no bone loss) and not at a gradually simulated bone loss as in our study (0-8 mm). The forces used in the above-mentioned studies are similar to those applied in the present study: For advanced bone loss (8 mm), Geramy et al[15,16] and Kumar et al[28] used 1 N for tipping and intrusion, whereas in studies evaluating the stress at teeth with no bone loss the applied forces were <0.8 N (Hemanth et al:[19,20] 0.2-0.8 N [≈20-80 g]; Vikram et al:[26] 0.1-0.35 N [≈10-35 g]).

In the present study, the highest NVB stress (0.000546 N/mm^2 induced by rotation) for teeth with reduced periodontium was 3.66 times lower than the reported physiologic values for capillary blood pressure (0.0020-0.0047 N/mm^2)[26,41] and lower than the tolerable stress for PDL (0.015-0.026 N/mm^2).[19,20] For teeth with intact periodontium, the NVB stress obtained here was 10-40 times lower than the reported physiologic values for capillary blood pressure: for intrusion 0.0000497 N/mm^2, ∼40 times lower; for extrusion 0.000149 N/mm^2, ∼13.42 times lower; for translation 0.000194 N/mm^2, ∼10.30 times lower; for rotation 0.00015 N/mm^2, ∼13.33 times lower, and for tipping 0.000128 N/mm^2, ∼15.62 times lower). These results confirm that the forces applied here, which are in the range indicated by Proffit[10] (20 g, 60 g, 120 g), are physiologically tolerable and do not compromise pulp vitality or the PBF.

Moreover, with the use of linear analysis, the present results showed that up to 8 mm bone loss, the apical NVB stress would not exceed the maximum reported tolerable values.

Hemanth et al showed that the stress values calculated by means of nonlinear analysis were 30% higher than those obtained by means of a linear analysis.[19,20] Based on these data, even if the quantitative results obtained here would increase by 30% when analyzed by means of a nonlinear FEA, they would still be lower than the reported physiologically tolerable stress range.[19,20] However, the nonlinear FEA analysis has only been recently used in this field and its reliability and accuracy in studying biologic structures has still to be established.[42,43]

We analyzed our models with the use of CBCT datasets, and FEA is an established method in endodontics for providing accurate anatomic models of tissues.[24,31-33] FEA is a reliable method for constructing hypotheses to be tested in clinical research, and because the stress in the dental pulp and NVB are difficult to be measured experimentally, the

Table IV. The highest apical NVB von Mises mean stress values in N/mm^2 (MPa) for rotation (0.6 N [≈60 g]) and tipping (0.6 N [≈60 g]), for gradual horizontal bone resorption

Resorption	*Rotation*			*Tipping*		
PDL and bone loss	*NVB stress (MPa)*	*NVB stress increase*	*Apical third stress (MPa)*	*NVB stress (MPa)*	*NVB stress increase*	*Apical third stress (MPa)*
0 mm	1.50E−04	1	1.33E−05	1.28E−04	1	1.10E−05
1 mm	2.66E−04	1.78	2.39E−05	1.99E−04	1.55	1.77E−05
2 mm	3.05E−04	2.03	2.65E−05	2.14E−04	1.67	1.86E−05
3 mm	3.19E−04	2.13	3.14E−05	2.37E−04	1.85	2.10E−05
4 mm	3.59E−04	2.4	3.34E−05	2.50E−04	1.95	2.22E−05
5 mm	4.22E−04	2.82	3.92E−05	2.72E−04	2.13	2.42E−05
6 mm	4.63E−04	3.09	4.22E−05	3.04E−04	2.38	2.68E−05
7 mm	5.00E−04	3.34	4.40E−05	3.57E−04	2.79	3.12E−05
8 mm	5.46E−04	3.64	5.04E−05	3.94E−04	3.09	3.43E−05

FEA is a proper method to determine the equivalent von Mises stress. However, its precision depends on the subdivision of the mesh.

The models investigated here had 40 times more tetrahedral elements and 4.43 times more nodes than those analyzed in previous studies, thus assuming a high model accuracy.[15,19,20,23-28]

To perform the FEA, several assumptions were made: the structures in the model were assumed to be homogeneous, isotropic, with linear elasticity, and with small deformations and displacements, as in previous studies.[17,19,21-23,25,41,44] In reality, anatomic structures exhibit inhomogeneous, anisotropic, and nonlinear behavior (material and geometric) and should be modeled as elastoplastic porous materials with a complex microstructure.[19-21,44] However, such an approach would involve complex FEM enhanced with advanced nonlinear experimentally calibrated equations. Developed models based on this approach are rather scarce in the literature, and, to obtain accurate and reliable results, advanced nonlinear analyses have to be conducted.[42,43] Moreover, from the clinical point of view, different types of orthodontic movements are often combined and only seldom is a single movement induced. Considering all above-mentioned arguments and the fact that the total set of model assumptions may have influenced the accuracy of the clinical reproduction for in vitro analyses, the present results need to be interpreted with care. In addition, for evaluating biomechanical behavior and validating the present results, more clinical studies are needed.

Stress distribution in the PDL with the use of low orthodontic forces varies when analyzed by linear or nonlinear methods. Hemanth et al[19,20] showed that the compressive and tensile stress levels were increased in a nonlinear analysis, indicating that less force is required to obtain similar stress levels in a nonlinear than in a linear analysis. However, for a qualitative analysis such as the one conducted in this study, a linear elastics analysis seemed to be more appropriate because of its simplicity in formulation and accuracy in detecting stress and strain concentrations.[42,43] Under low-intensity loading conditions (up to 0.6 N), all materials are expected to exhibit linear elastic behavior,[42,43] and the analysis would therefore provide a reliable quantitative estimation. Nonetheless, this assumption does not reproduce accurately the clinical situation and represents an inherent limitation of the present study.

A more complex FEM could be developed considering the partial interaction between materials, but this implies complex nonlinear bond-slip relationships to model the interfaces. As previously mentioned, the qualitative analysis represented the main concern of the present study, and in the absence of rigorous constitutive equations to model the interfaces between the materials, we considered that such an analysis was not justified for our purpose and chose a linear analysis.[26-30,45]

A common clinically relevant question refers to the indicated amount of orthodontic force needed to obtain the desired orthodontic movements without endangering the pulp vitality. In addition, it would be clinically helpful to establish the correlations among the amount of the orthodontic forces, the level of bone loss and PDL, and the induced apical stress.

Therefore, a further aim of the present study was to assess the correlations among the degree of bone resorption, the decrease of force magnitude and increase in stress at the apical third of the pulp, and the NVB. The present results indicate that up to a doubling of the NVB stress, bone loss correlated directly with the force reduction for all 5 types of orthodontic movements (Tables II-IV). Similarly, Ghuloom et al reported a correlation among the NVB stress, bone loss, and force

reduction for the translational movement.[30] They investigated the translational movement of a maxillary first molar for 3 levels of bone loss (2.5, 5, and 6.5 mm) and logically showed that less force was required to create stress levels similar to those obtained in areas without bone loss (80% of the initial force of 300 g [≈3 N] for 2.5 mm bone loss, 60% for 5 mm bone loss, and 35% for 6.5 mm bone loss). Nonetheless, lower translational forces were obtained in the present study to induce similar stress levels: For situations with 2 mm bone loss, only 67% of the initial force of 1.2 N (120 g) was required, and for 5 mm bone loss only 21% of the initial force was needed (Table III).[30] Intrusion and extrusion movements at 2 mm bone loss required only 70% of the initial applied force, and in cases with 5 mm bone loss only 35% (Table II). Tipping movements at 2 mm bone loss required 33% of the initial force to determine similar stress levels to those in areas with intact periodontium, whereas at 4 mm bone loss only 5% of the initial force was needed (Table IV). The variability between the stress values obtained in the present study (0.2-1.2 N) and those reported by Ghuloom et al[30] is due to different study protocols (second lower premolar for gradual bone loss of 0-8 mm in our study vs first maxillary molar for bone loss of 0-6.5 mm with 300 g translational force) and analyzing teeth with different anatomy (second lower premolar model with 950,897-1,062,438 nodes and 5,058,673-6,047,378 elements in our study vs maxillary first molar model with 3097 nodes and 2521 elements).[30] Clinically, these results indicate that in situations with reduced periodontium, lower forces are needed to reach the maximum tolerable stress compared with teeth with intact periodontium.

Nonetheless, more information on the tolerable NVB stress and orthodontic loads without damaging the PBF in situations with reduced PDL is needed. The present results of the FEA analysis are in concordance with Proffit's reported orthodontic forces indicating no significant disturbance of the PBF.[10] However, in case of a previous PBF disturbance, orthodontic loads may affect pulp vitality regardless of the amount of PDL.[1-4,6,12] Rotational movement induced the highest NVB stress (doubled at 2 mm and tripled at 6 mm bone loss; Table IV), thus representing the most aggressive type of force that may affect the PBF. It seems appropriate to assume that higher orthodontic forces in cases with advanced bone loss have higher effect on the apical NVB and PBF.

This emphasizes the importance of applying lower forces (Proffit recommended up to 1.2 N)[10] in appropriate activation intervals in adult patients.[1-4,6,7,15,16]

CONCLUSIONS

1. The stress manifested at the apical third of the pulp is smaller than that at NVB. Rotational movements induce the highest stress and translational forces the lowest stress compared with the physiologic capillary blood pressure.
2. In situations with reduced periodontium, lower forces are needed to reach the maximum tolerable stress compared with teeth with intact periodontium.

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