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Evaluation of the stress induced on the dental pulp of maxillary central incisor under orthodontic loading at different levels of alveolar bone height– An In-vitro study

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Abstract

Aims and Objectives: To evaluate the overall stress produced on the apical neurovascular bundle and the apical one third of pulp under orthodontic loads at various levels of bone resorption.

Materials and Methods: Five three-dimensional finite element models of the right maxillary central incisor were created and in each of these models' gradual horizontal bone loss simulation was done (0 – 10 mm). Each of these models were then subjected to orthodontic forces of 20g, 60g and 120g using Finite element analysis. The overall stress produced on the apical neurovascular bundle and apical third of pulp was determined by von Mises stress.

Results: The stress manifested at the apical neurovascular bundle was more than that at the apical

third of pulp. The highest apical neurovascular bundle stress was manifested by rotational movement (2.164E-04 MPa for 10 mm bone loss at 0.6N) whereas the lowest stress resulted after translational movements (0.661E-04 MPa for 10 mm bone loss at 0.6 N). High positive correlation was found between the increase in bone loss and the stress generated at neurovascular bundle and apical third of the pulp.

Conclusion: The results indicate that orthodontic forces when applied in the range of 20g, 60g and 120g, do not endanger pulp vitality or compromise pulpal blood flow. Among all the investigated orthodontic tooth movements, stress induced by the rotational movement was the highest and translation movement was lowest. Also, alveolar bone resorption caused increase in the stress value compared with the tooth with normal bone height.

Keywords: Finite element analysis, Neurovascular bundle, Pulpal blood flow, von Mises stress.

Introduction

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] Profit et al proclaimed that light continuous forces have minimal or no effect on dental pulp. On contrary, the reaction of dental pulp to orthodontic forces has been reported to vary from mild hyperemia to complete necrosis in the literature. Various factors contributing to blood flow disturbances are type, duration, and values of applied orthodontic forces as well as anatomic features (i.e., diameter of apical foramen) and patient's age. [2,7,3] Histologic studies have reported depression of pulp tissue respiration, vacuolization, circulatory disturbances, haemorrhage, fibro-hyalinosis and even necrosis as the major pulpal changes that might occur following the application of orthodontic forces to teeth. It can result in periodontal ischemia which may lead to root resorption. [9]

Moreover, cases with loss of periodontal tissues (i.e., advanced periodontitis) have reported higher incidences of irreversible inflammatory pulpal reactions. [2,3]

Regressive histologic changes (i.e., vacuolization, congestion, haemorrhage, fibro hyalinosis) have been reported in the pulpal tissue, and in cases with reduced periodontal support, an increased risk for pulp necrosis has been noted. Hence, forces need to be correlated with other contributory factors such as the level of bone loss and amount of Periodontal ligament to prevent irreversible changes in the neurovascular bundle (NVB) of the pulp.

However, studies have shown that pulpal blood flow seems to improve 3 weeks after intrusion and tends to return to its initial level within 3 months after force application.[2,4] In spite of large variation of orthodontic forces evaluated in studies (from 10 g to 500 g),it is undisputedly accepted that the magnitude of pulp inflammation or injury is directly proportional to that of the applied force.[1,2] Experimental force simulation at various bone levels are indicated to evaluate the effect of axial load absorption and dissipation on pulpal blood flow. Finite element analysis (FEA)is an analysis used to calculate stress and loads in complex structures that is currently widely adopted in biomechanics and the study of the behaviour of biological structures. It enables us to simulate the orthodontic forces applied and the results can be shown on a three-dimensional model which is fabricated using Cone beam computed tomography (CBCT) scan. Despite its limitations (e.g., method based on mathematical principles, linear versus nonlinear analysis), Finite Element Analysis is considered to be a proper method to study in vivo the stress in various tissues (i.e., pulpal tissue, Pulpal Blood Flow).[12]

Since there is very little information regarding the tolerable stress for dental pulp during orthodontic movements under low orthodontic forces and reduced periodontium, therefore, the purpose of the study is to assess the stress in the neurovascular bundle of apical third of the pulp during orthodontic movements (intrusion, extrusion, translation, rotation, and tipping) at different alveolar bone heights with the use of orthodontic forces of 20 g, 60 g, and 120 g using Finite Element Analysis.

Material and methods

This study included five patients (mean age 26 ±3 years; 3 Males, 2 Females) with chronic periodontitis having different levels of horizontal bone loss who visited H.K. E's S. Nijalingappa Institute of Dental Sciences and Research, Kalaburagi in need of Orthodontic treatment. By means of cone-beam computed tomography (CBCT), detailed images of both right and left Central incisors and right Lateral incisor were created. Using manual image segmentation technique three-dimensional models of each component (enamel, dentin, pulp chamber, bracket, PDL and surrounding alveolar bone) were generated for each of the 5 patients. All the single component models were assembled into 1 3D model, thus obtaining 5 original models (with 2 central incisors and 1 lateral incisor) with different degrees of bone loss. Each of these 5 original models were replicated and for each of these replicated models the missing bone and PDL was reconstructed, hence obtaining 11 complete original models for each patient without periodontal breakdown. In each of the complete models the right central incisor was guarded while the right lateral incisor and left central incisor was replaced by bone. (Fig. 1)

A circular homogenous horizontal bone resorption was gradually simulated ranging from 0 to 10 mm for each complete model (bone height and PDL gradually horizontally reduced by 1 mm), thus obtaining 11 models for each patient and in total 55 models.

Finite Element Analysis is based on the discretization of a complex model into a number of simpler elements i.e., tetrahedrons, also known as finite elements which are interconnected at discrete points called nodes. In this study all the models were filled with 4-node tetrahedrons. (Table I) The boundary conditions, material properties (elastic constants, young's modulus and Poisson ratio) and the loading protocols were assigned to each finite element. The base of the model containing alveolar bone was considered to have zero displacement, while all other parts of the model were treated as free of boundary conditions. (Table II)

Fig 1: A, Mesh of one complete model; B, Mesh of upper right central incisor; C, mesh of dental pulp of upper right central incisor.

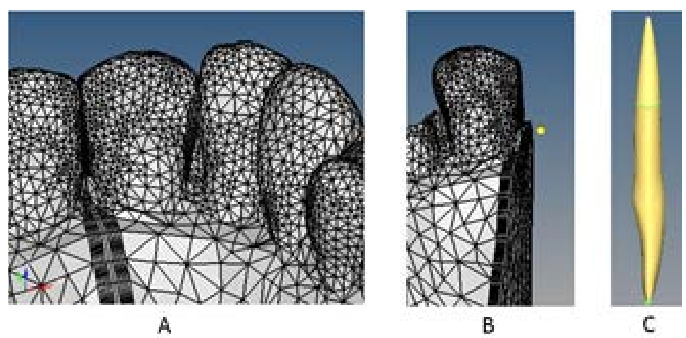

Table 1: Number of elements and nodes.

Model Numbers	Reduction	Number of elements	Number of nodes
1	0	231197	348290
2	1	230093	346982
3	2	228928	345273
4	3	227657	341987
5	4	226482	340238
6	5	225300	339001
7	6	224066	337672
8	7	222818	336482

9	8	221492	335002
10	9	220103	333897
11	10	218638	332764

Table 2: Elastic properties of the materials used in the FEA.

Material	Constitutive equation	Young modulus, E (GPa)	Poisson ratio, v
Enamel	Isotropic, homogeneous, and linear elastic	80	0.33
Dentin / Cementum	Isotropic, homogeneous, and linear elastic	18.6	0.31
Pulp	Isotropic, homogeneous, and linear elastic	0.0021	0.45
PDL	Isotropic, homogeneous, and linear elastic	0.0667	0.49
Cortical bone	Isotropic, homogeneous, and linear elastic	14.5	0.323
Trabecular bone	Isotropic, homogeneous, and linear elastic	1.37	0.3
Bracket	Isotropic, homogeneous, and linear elastic	218	0.33

The Orthodontic tooth movements which were simulated were:20g (for intrusion), 60g (for extrusion, rotation and tipping) and 120g (for translation).

The overall stress produced on the apical neurovascular bundle and apical one third of pulp under Orthodontic loads at various levels of bone resorption was determined by von Mises stress analysed using Ansys R17.2. Their magnitudes reflected the mechanical behaviour of the neurovascular bundle of the apical third of pulp and were represented numerically as a color-coded projection on geometric model.

Result

The study demonstrated that for all the five types of orthodontic tooth movements, the stress manifested at the neurovascular bundle was higher than that at the apical third of the pulp (Figs 2 and 3). The von Mises mean stress values obtained for different orthodontic tooth movements for gradual horizontal bone resorption are summarized in Table III -V.

For 0.6 N (60g) of force application in the models without horizontal bone loss, the highest stress in the Neurovascular bundle was obtained for rotation movement (0.509E-04 MPa) followed by tipping (0.488E-04MPa), intrusion (0.384E-04MPa) and extrusion (0.325E-04 MPa). Lowest stress value was obtained for translation movement (0.305E-04MPa).

For rotational movement at 0.6N, bone loss of 3 mm led to 50% increase in the stress value. At 6 mm bone loss, the stress value tripled and at 10 mm bone loss it increased by 4.2 times than the stress value at teeth with no bone loss.

For both intrusion at 0.2N and extrusion at 0.6N, there was approximately 1.5 times increase in the stress value for 7mm bone loss and 2.5 times increase for 10 mm bone loss compared with teeth with no resorption.

For tipping movement (0.6N) 1.5 times increase in the stress value was observed for 6 mm bone loss, 2.5 times increase at 9 mm bone loss and 3.5 times increase at 10 mm of bone loss. For translation movement at 1.2N, stress determined at 6 mm bone loss was 1.5 times higher and at 10 mm bone loss the stress was 2.2 times higher compared with teeth having intact periodontium.

The highest and the fastest increase in stress at the apical neurovascular bundle was observed for the rotational movements, followed by tipping movement and the least stress was demonstrated for the translation movement among all the orthodontic movements.

Fig 2. Model with no bone loss—von Mises stress distribution in the apical NVB and apical third of the pulp on maxillary central incisor: A, intrusion (0.2 N); B, extrusion (0.6 N); C, rotation (0.6 N); and D, tipping (0.6 N); E, translation (1.2 N)

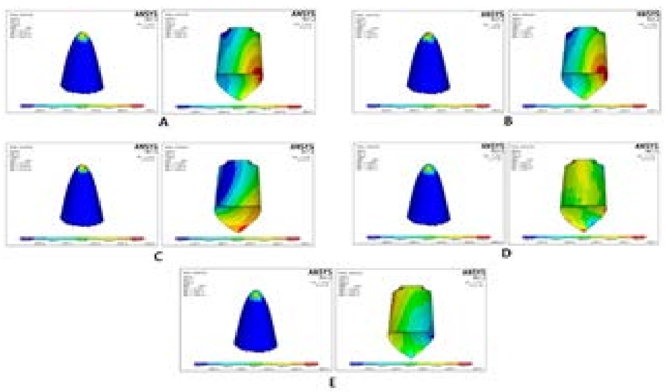

Fig 3. Model with 10 mm bone loss—von Mises stress distribution in the apical NVB and apical third of the pulp on maxillary central incisor: A, intrusion (0.2 N); B, extrusion (0.6 N); C, rotation (0.6 N); and D, tipping (0.6 N); D, translation (1.2 N)

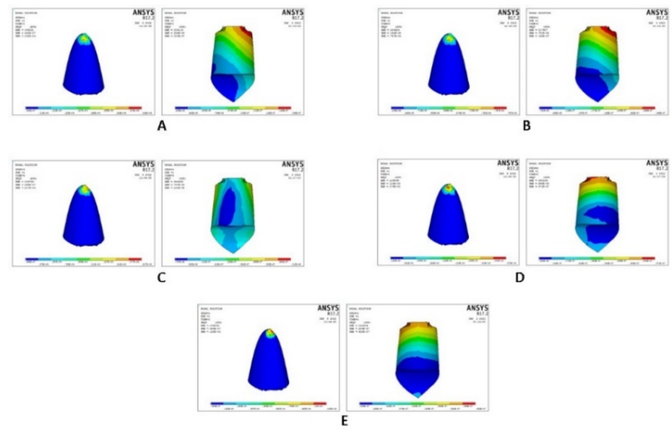

Table 3: von Mises mean stress values in N/mm^2 (MPa) at apical neurovascular bundle and apical one third of pulp for intrusion (0.2 N) and extrusion (0.6 N), for gradual horizontal bone resorption.

Resorption	Intrusion			Extrusion		
PDL and Bone Loss	NVB Stress (MPa) (10^{-4})	NVB Stress increase	Apical Third Stress (MPa) (10^{-8})	NVB Stress (MPa) (10^{-4})	NVB Stress increase	Apical Third Stress (10^{-7}MPa)
0	0.128	1.000	0.621	0.325	1.000	0.135
1	0.140	1.098	0.652	0.362	1.113	0.143
2	0.144	1.125	0.683	0.389	1.197	0.149
3	0.151	1.187	0.793	0.397	1.220	0.159
4	0.158	1.236	0.807	0.404	1.243	0.166
5	0.172	1.344	0.917	0.422	1.298	0.176
6	0.177	1.389	1.060	0.452	1.390	0.189
7	0.180	1.413	1.210	0.462	1.421	0.202
8	0.198	1.552	1.337	0.517	1.590	0.239
9	0.216	1.689	1.420	0.556	1.710	0.297
10	0.295	2.308	1.510	0.794	2.445	0.340

Table 4: von Mises mean stress values in N/mm^2 (MPa) at apical neurovascular bundle and apical one third of pulp for rotation (0.6 N), for gradual horizontal bone resorption.

Resorption	Rotation		
PDL and Bone Loss	NVB Stress (MPa) (10^{-4})	NVB Stress increase	Apical Third Stress (10^{-7}MPa)
0	0.509	1.000	0.241
1	0.600	1.180	0.288
2	0.761	1.496	0.315
3	0.969	1.904	0.361
4	1.246	2.447	0.367
5	1.412	2.786	0.459
6	1.517	2.980	0.574
7	1.623	3.189	0.720
8	1.802	3.541	0.843
9	2.030	3.993	0.912
10	2.164	4.252	1.100

Table 5: von Mises mean stress values in N/mm^2(MPa) at apical neurovascular bundle and apical one third of pulp for tipping (0.6N) and translation (1.2 N), for gradual horizontal bone resorption.

Resorption	Tipping			Translation		
PDL and Bone Loss	NVB Stress (MPa) (10^{-4})	NVB Stress increase	Apical Third Stress (MPa) (10^{-7})	NVB Stress (MPa) (10^{-4})	NVB Stress increase	Apical Third Stress (10^{-7}MPa)
0	0.488	1.000	0.150	0.610	1.000	0.251
1	0.504	1.033	0.165	0.631	1.034	0.269
2	0.537	1.101	0.191	0.675	1.107	0.279
3	0.568	1.164	0.220	0.720	1.181	0.288
4	0.601	1.232	0.253	0.756	1.255	0.301
5	0.641	1.314	0.290	0.827	1.356	0.313
6	0.691	1.416	0.334	0.905	1.483	0.352
7	0.776	1.590	0.343	0.925	1.517	0.377
8	0.862	1.766	0.415	1.030	1.685	0.406
9	1.177	2.412	0.494	1.155	1.893	0.429
10	1.719	3.523	0.562	1.322	2.168	0.615

Discussion

This study was conducted to assess the stress produced at the apical neurovascular bundle and apical one third of the pulp of maxillary central incisor with gradual horizontal bone loss (0 to 10 mm) induced by 5 types of orthodontic tooth movements.

For all the 5 types of investigated orthodontic forces, the stress produced at the apical neurovascular bundle was more than that at the apical third of pulp.

The reported physiologic value for capillary blood pressure is 0.0020-0.0047 N/mm^{2}and tolerable stress for periodontal ligament is 0.015-0.026N/mm^2. In this study the highest stress was manifested by the rotational movement at 10 mm bone loss (2.164E-04 MPa) which is 9.25 times lower than reported physiologic blood pressure and 69.3 times lower than tolerable stress for periodontal ligament. Among all the types of orthodontic tooth movements, at 0.6 N force, lowest stress was produced by translation movement i.e., 0.305E-04 MPa for 0 mm bone loss and 0.661E-04 MPa for 10 mm bone loss. Also, when translation force of 1.2N was applied on the maxillary central incisor, NVB stresses produced were 0.610E-04 N/mm^2 at 0 mm bone loss, 0.827E-04 N/mm^2 at 5mm bone loss and 1.322E-04 N/mm^2 at 10 mm bone loss. The stress values reported for all other investigated orthodontic tooth movements were also lesser than the recorded physiologic blood pressure for both in case of intact periodontium and with bone loss, i.e., for intrusion (0 mm bone loss, 0.128E-04 N/mm^2 ~156 times lower; 10 mm bone loss, 0.295E-04 N/mm^2 ~ 67.7 times lower), for extrusion (0 mm bone loss, 0.325E-04N/mm^2 ~ 61.5 times lower; 10 mm bone loss 0.794E-04 N/mm^2 ~ 25 times lower, for tipping (0 mm bone loss, 0.488E-04 N/mm^2 ~ 40.9 times lower; 10 mm bone loss, 1.719E-04 N/mm^2 ~ 11.6 times lower) and for translation (0 mm bone loss, 0.610E-04 N/mm^2 ~ 32.7 times lower; 10 mm bone loss, 1.322E-04 N/mm^2 ~ 15 times lesser). Hence, it can be concluded that stress values obtained are physiologically tolerable and does not compromise the pulp vitality or pulpal blood flow.

Moga et al [1] evaluated the stress in the apical third and apical neurovascular bundle during 5 types of orthodontic movements (intrusion, extrusion, tipping, rotation and translation) in the lower premolar with gradual horizontal bone loss of 0-8 mm. They obtained highest apical neurovascular bundle stress for rotational movements (5.46E-04 MPa) and lowest after translation movement (0.97E-04 MPa) at 0 mm bone loss. The results obtained in this study is in accordance with the results obtained by Moga et al [1] except for the fact that the stress generated by tipping force is more than the stress produced by intrusive-extrusive movements in the present study. Similar results were obtained by Jeon et al [20] where they evaluated the apical stress in Periodontal ligament for 1st maxillary molar using translation force at various degree of bone levels and obtained stress levels of 0.000445 N/mm^2 at 1.2N (3mm bone loss), 0.000403 N/mm^2 at 1.1N (6mm bone loss) and 0.000371 N/mm^2 at 3mm (no bone loss).

On contrary, in the study conducted by Vikram et al [13]to assess the apical stress at maxillary incisors, lower stress levels were reported (extrusion 0.1x10^{-7} N/mm^2, intrusion 0.286x10^{-8} N/mm^2, tipping 0.468x10^{-8}N/mm^2 and rotation 0.263x10^{-7} N/mm^2) at a lower force application of 0.1N. On the other hand, Geramy et al (2002) [6], obtained higher stress values in the periodontal membrane for force application of 1N [i.e., intrusion 0.115-0.185 N/mm^2, tipping 0.026-0.722 N/mm^2] for maxillary central incisor. In another study conducted by Hemant et al[17, 18], stress value of 0.01337 – 0.02006 N/mm^2 was obtained for intrusion and 0.0144 – 0.01646 N/mm^2 for tipping for the force application of 0.2-

1N.Variations obtained in the reported values of stress might be the consequence of different anatomic bony composition of maxilla and mandible, single or multirooted teeth or analysing stress at a given bone level

One of the aims of the present study was also to assess the correlation between magnitude of force, amount of bone loss and stress increase at the NVB and at apical third of pulp. The present study reported a gradual increase in the NVB and apical third stress with the increase in the bone loss level for all the 5 types of orthodontic tooth movement. Among all the tooth movements, rotation reported the maximum and fastest increase in the stress level with increase in bone loss (i.e., 0.509E-04 N/mm^2 at 0 mm bone loss) which increased by 50% at 3 mm bone loss (0.969 E -04 N/mm^2), tripled at 6 mm bone loss (1.517E-04 N/mm^2) and became 4.2 times at 10 mm bone loss (2.164E-04 N/mm^2) and the translational movement showed the slowest yet steady increase in the NVB stress value (0.610E-04 N/mm^2 at 0 mm bone loss) which doubled at 9 mm bone loss to 1.155E-04 N/mm^2. Other investigated tooth movements also reported steady increase of NVB stress value with increasing level of bone loss. Similar results have been obtained through the studies conducted by various authors also. In the study conducted by Kumar et al[3], at 4 mm bone height they reported increase in stress value by 6 times for intrusive force and 5 times for tipping force when compared with 12 mm bone height. Ghuloom et al [33] conducted a study to investigate the translational movement of maxillary 1st molar for 3 levels of bone loss (2.5, 5 and 6.5 mm) and found that less force was required to achieve stress level similar to those reported in areas without bone loss (i.e., 80% of initial force of 3 N for 2.5 mm bone loss, 60% for 5 mm bone loss and 35% for 6.5 mm bone loss. Results showed that alveolar bone loss caused increased stress production under the same load compared with healthy bone support and hence, lower forces are needed to reach maximum tolerable stress compared with teeth with intact periodontium.

Since, it is difficult to measure stress in the dental pulp experimentally, hence in this study Finite element analysis was used to determine the equivalent von mises stress. Although in reality, anatomic structures exhibit inhomogeneous, anisotropic and non-linear behaviour but in order to perform the FEA, the structures in the models were assumed to be homogeneous, isotropic with linear elasticity and with small deformations and displacements. Hence, in order to obtain precise and reliable results, advanced and non-linear analysis have to be conducted. Hemant et al in his study reported that stress distribution due to low orthodontic forces in the PDL varies when analysed by linear or non-linear methods. They showed that in a non-linear analysis the values of the compressive and tensile stress were increased, indicative of less force requirement to obtain similar stress levels. Although, it is also reported that all the materials are expected to exhibit linear elastic behaviour under low orthodontic forces (up to 0.6 N) and therefore, this study provides reliable quantitative assessment of the stress values. Also, in the clinical practice, different types of orthodontic movements are often combined together and only in rare circumstances single tooth movement is induced. Considering this fact and also the above-mentioned model assumptions to conduct the present study, it can be assumed that it might have influenced the accuracy of the results obtained. Hence, in order to validate the present results, more clinical studies are needed to be done.

The results of the present study indicates that when forces are applied in the range of 20g, 60g and 120gm, no significant disturbance in the PBF is seen and it does not endanger the pulp vitality. However, a history of dental trauma may lead to disturbance in the pulpal blood flow and loss of pulp vitality during orthodontic treatment regardless of the amount of bone loss. Few studies have also reported short duration biochemical and biological tissue alterations due to depressed pulp tissue respiration and found a positive correlation between the age of participant and amount of tissue respiratory depression.[29]

Hence, it can be presumed that higher orthodontic forces in cases of advanced bone loss have higher effect on apical NVB and PBF and suitable modifications should be done in the force system in cases of bone loss.

Conclusion

From the present finite element study, we can conclude that:

1. The stress produced at the neurovascular bundle is more than that at the apical third of the pulp.
2. Among all the investigated orthodontic tooth movements, rotational movement induced highest stress and translational movement induced the lowest stress compared with the physiologic capillary blood pressure.
3. High positive correlation is found between the increase in bone loss and the stress generated. Hence, lower forces are needed to reach the maximum tolerable stress compared with teeth with intact periodontium.
4. When Orthodontic forces are applied in the range of 20 g, 60 g, 120 g, they are physiologically tolerable and do not compromise pulp vitality or the pulpal blood flow.

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