Evaluation of cervical abfraction lesions due to occlusal forces in oblique and vertical direction at different alveolar bone heights using finite element analysis: An in-vitro study

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INTRODUCTION

The neck of a tooth crown has an essential role in the contribution of an esthetic smile. It has been observed that this area is usually affected by caries or other conditions. The other conditions havebeen termed as non-carious cervical lesions (NCCL) [1]. These include defects that occur due to mechanical or chemical factors without the involvement of bacteria. Abrasion, abfraction and erosion are the commonly occurs non-carious cervical lesions[2]. Abrasion and abfraction occur dueto mechanical wear of the teeth structure; whereas erosion occurs due to chemical wear of the teethsubsequent to intake of acidic foods and beverages[3]. These lesions occur over a period of time andhence are chronic in nature[4].

The abfraction lesion was described earlier in 1930. Subsequently it was termed as "idiopathic erosive cervical lesion". Grippo JO. 1991[5] introduced the term "abfraction" so as to differentiate abfraction from other defects of teeth that may occur from other causes. "Abfraction can be definedas a physical process resulting from biomechanical occlusal stress concentration at the cervical third of the tooth leading to ditching at the cemento-enamel junction due to crack formation". Occlusal loading forces over a period of time result in tooth flexure followed by loss of enamel and dentin at an area away from the loading forces; especially at the neck of the teeth. These loading forces may occur during mastication, chewing, bruxing[1].

Abfraction occurs at the neck of the tooth crown on the buccal surface as wedge-shape areas withthe depth more than the width. The borders of the abfraction lesion are well defined and sharp. The occlusal and gingival walls of abfraction lesion converge in a pulpal direction to meet in line angle.Abfraction also occurs as hairline cracks, crescent-shaped or saucer-shaped lesions or as striations.Based on the shape of the abfraction lesion, they have been classified as: "C-shaped lesion, V- shaped lesion, and mixed lesions".

It was commonly observed that Abfraction and gingival recession occur together. Most of the times, the abfraction lesions are located in the supragingival area, however; it may also occur in the subgingival area[2]. In other words, these lesions occur at the fulcrum of tooth flexure. It was observed that, abfraction occurred when the occlusal load exceeded the flexure strength of the tooth in cervical area (where the enamel and dentin are thinner causing loss of enamel & dentin).

When the abfraction lesion was observed under scanning electron microscopy (SEM) it showed dentinal damage even in the presence of intact enamel. The smear layer covered the dentinal tubules and hence the dentinal tubules were not visible. In the initial stage of the lesion; dentinal tubules were patent but with progression, the tubules became less in number and were covered by the smear layer. Some scratches were seen on the surface of the lesion, which could be due to the associated abrasion[3].

The incidence of NCCL increases with the increasing age, indicating the effect of tissue fatigue over a prolonged period[6]. The tooth with highest prevalence of NCCL is the mandibular first premolar, which could be due to its specific shape and occlusion[7]. A strong association between abfraction and parafunctional habits was observed.

Previous finite element studies and strain-gauge studies have found that stresses concentrate in the thin cervical enamel area and the magnitude of these stresses exceed the known failure stresses for enamel[8]. The finite element analysis (FEA) has been defined as “a computerized numerical iteration technique used to determine the stress and displacement through a predetermined model”.The theory of abfraction is based on “computer-generated models” and investigations generally with data consisting of case reports, case series, and case studies[9]. However, there was a pitfall in the studies conducted. The forces considered for the analysis were not related to the normal function, hyperfunction (increased) or hypofunction (decreased). In the present study, a normal force of 15 kilograms (kgs) was considered.

The purpose of the present study was to evaluate the abfraction lesions in the cervical region of mandibular first premolar considering 15 kgs occlusal forces, in oblique and vertical direction and to correlate it with different alveolar bone heights using finite element analysis.

AIM

To evaluate the abfraction lesions due to occlusal forces in oblique and vertical direction at different alveolar bone heights using finite element analysis

OBJECTIVES

1. To evaluate the effect of stress in the cervical region of mandibular first premolar due to occlusal forces in oblique direction with different alveolar bone height using finite element analysis.
2. To evaluate the effect of stress in the cervical region of mandibular first premolar due to occlusal forces in vertical direction with different alveolar bone height using finite element analysis.
3. To correlate the effect of stress in the cervical region of mandibular first premolar with occlusal forces in oblique and vertical direction at different alveolar bone height using finite element analysis.

Methodology

Study design

This was an experimental in-vitro study.

Study setting

Study was conducted in the Department of Periodontology of a recognized dental college in collaboration with a computer laboratory equipped to conduct finite element analysis.

Study sample

A healthy extracted mandibular first premolar was used to obtain six 3D geometric models for Finite Element Analysis.

Softwares

1. SOLIDWORKS 3D CAD solutions
2. Software ANSYS (Swanson Analysis System, Houston PA, USA)

Methods of measurement

1. Stress (Newton per square meter)
2. Displacement

Methodology

1. Development of geometric model
2. Mesh generation
3. Behaviour and properties of physical model
4. Boundary conditions
5. Analysis and evaluation of results

A healthy natural mandibular first premolar tooth extracted for obtaining space for orthodontic treatment was selected. The finite element method was used to study the behaviour of the tooth at the cervical region under occlusal forces of 15kgs in vertical and oblique directions on the tooth.

The three-dimensional solid model generation

The tooth was selected based on its lack of carious lesions and absence of abnormalities, which could simplify interpretation of results of a sound tooth model for finite element analysis. To develop a three-dimensional (3D)-FE model based upon actual geometric dimensions, sequential software processing was performed. The extracted mandibular first premolar was scanned using 3D scanner. Obtained surface contours and meshes were then imported into software and 3D solid model of mandibular first premolar with a tooth length of 19.8mm, crown height of 6.7 mm and root length of 13.1 mm was generated.

Interfacial surface between dentin and enamel were made by lofting technique of the computer-aided design programme according to the anatomy of the natural tooth. Once enamel and dentin 3D volumes were generated, Boolean operations were used to ensure congruence between the related interfacial surfaces. The enamel volume was created by subtracting the dentin volume. Then, the enamel and dentin 3D volume were combined to make a final 3D solid model of the intact mandibular first premolar.

Additionally based on the outer geometry of the model, PDL and alveolar bone were created. The PDL, cortical bone and spongy bone were modeled around the tooth root. Thickness of the PDL, lamina dura and outer cortical bone were assumed to be 0.25mm, 0.4mm and 1.1 mm respectively. The cementum layer was not considered in this model due to small thickness and the properties similar to dentin and the pulp was also disregarded.

1. Development of geometric model

The first step was the creation of 3D geometric model. The tooth along with its surrounding structures was scanned using white light scanner. This gave cloud point data for individual parts. Using this data, 3D models were constructed using SOLIDWORKS 3D CAD solutions. To stimulate functional occlusal forces in oblique and vertical directions, six models were generated. In first model **(Model 1)**, at normal bone height an occlusal load (V) of 15 kgs was applied in oblique direction to the tooth. In second model **(Model 2)**, at 25% reduced bone height an occlusal load (V) of 15 kgs was applied in oblique direction to the tooth. In third model **(Model3)**, at 50% reduced bone height an occlusal load (V) of 15 kgs was applied in oblique direction totooth. In fourth model **(Model 4)**, at normal bone an occlusal load (V) of 15 kgs was applied in vertical direction to the tooth. In fifth model **(Model 5)**, at 25% reduced bone height an occlusal load (V) of 15 kgs was applied in vertical direction to the tooth. In sixth model **(Model 6)**, at 50%reduced bone height an occlusal load (V) of 15 kgs was applied in vertical directions to the tooth.

2. Mesh generations

Geometric models were processed by ANSYS (Swanson Analysis System, Houston PA, USA) software to generate desired 3D-Finite element models.

3. Behaviour and properties of physical model:

Six 3D solid models were meshed with tetrahedral elements. The number of elements and nodes varied according to the model. All models were assumed to be fixed at the mesio-distal cross section of alveolar bone, with no rotation or translation allowed in any direction. The mandibular bone sectional edges, which restricted the displacement along the Z axis. All nodes on the lower surface of the cortical bone were constrained in all directions (X, Y and Z), preventing rigid body displacement, as the boundary conditions for all models. The materials from the different structures in the models were assumed to have homogenous, isotropic, linear elastic properties, represented by Young's modulus of elasticity and the Poisson's ratio as shown in Table 1

4. Boundary condition

15 Kilograms (Kgs) of occlusal load was applied in oblique and vertical direction to the mandibularfirst premolar.

5. Analysis and evaluation of results

The processing stage or solution analysis was performed with Solid Works 2015 software, and this software was also used in the post processing for the visualization and evaluation of the results. Results were obtained in the form of Von Mises stresses depicted as colour coded contour maps where each contour represents a particular magnitude of the stress subjected individually on various component.

RESULTS

A healthy extracted mandibular first premolar was used to obtain six 3D geometric models for Finite Element Analysis. It was scanned using 3D scanner. The images obtained along with the surface contours and meshes were then imported into the SOLIDWORKS 3D CAD solutions software and 3D solid model of mandibular first premolar with a tooth length of 19.8mm, crown height of 6.7 mm and root length of 13.1 mm was generated.

To stimulate functional occlusal forces in oblique and vertical directions, six models were generated. In **first model**, at normal bone height an occlusal load (V) of 15 kgs was applied in oblique direction to the tooth. In **second model**, at 25% reduced bone height an occlusal load (V)of 15 kgs was applied in oblique direction to the tooth. In **third model**, at 50% reduced bone heightan occlusal load (V) of 15 kgs was applied in oblique direction to tooth. In **fourth model**, at normalbone an occlusal load (V) of 15 kgs was applied in vertical direction to the tooth. In **fifth model**, at 25% reduced bone height an occlusal load (V) of 15 kgs was applied in vertical direction to thetooth. In **sixth model**, at 50% reduced bone height an occlusal load (V) of 15 kgs was applied in vertical directions to the tooth.

The resultant stresses were obtained in the form of von Mises stresses. The tracing of von Mises stresses field was represented in the form of color-coded bands with the help of ANSYS software. Red color represented the highest stresses. Orange, yellow, light green, green, light blue, blue and dark blue colors represented the stresses in the descending order following red color.

In FEM analysis **Model 1** with no bone reduction, with 15 kgs oblique loading, the equivalent stress value observed in Pulp was 0.6675 MPa and maximum deformation was

0.0463mm. The equivalent stress value observed in Dentin was 127.13 MPa and maximum deformation was 0.0642mm. In PDL, the equivalent stress value observed was 6.58 MPa and maximum deformation was
0. 0599 mm. In Enamel, the equivalent stress was 44.208 MPa and maximum deformation was 0.0707 mm. In Mucosa, the equivalent stress observed was 21.502 MPa and maximum deformation was 0.0614 mm. In Cancellous bone, the equivalent stress was 7.885 MPa and maximum deformation observed was 0.0510 mm. In Cortical bone, the equivalent stress was 124.95 MPa and the maximum deformation was 0.0435. (Table 2, Figure1)
In FEM analysis **Model 2** with 25 % bone reduction, with 15 kgs oblique loading the equivalent stress value observed in Pulp was 0 MPa and maximum deformation was 0 mm. The equivalent stress value observed in Dentin was 154.55 MPa and maximum deformation was 0.014632 mm. In PDL, the equivalent stress value observed was 3.3277 MPa and maximum deformation was 0.099311 mm. In Enamel, the equivalent stress was 112.05 MPa and maximum deformation was 0.0163 mm. In Mucosa, the equivalent stress observed was 15.963 MPa and maximum deformation was 0.0456 mm. In Cancellous bone, the equivalent stress was 8.2683 and maximum deformation observed was 0.0449 mm. In Cortical bone, the equivalent stress was 162.04 MPa and the maximum deformation was 0.0453. (Table 3 Figure 2)
In FEM analysis **Model 3** with 50% bone reduction, with 15 kgs oblique loading the equivalent stress value observed in Pulp was 0 MPa and maximum deformation was 0 mm. The equivalent stress value observed in Dentin was 300.71 MPa and maximum deformation was 16.298 mm. In PDL, the equivalent stress value observed was 18.68 MPa and maximum deformation was 12.15 mm. In Enamel, the equivalent stress was 980.4 MPa and maximum deformation was 17.84 mm. In Mucosa, the equivalent stress observed was 31.398 MPa and maximum deformation was 0.14 mm. In Cancellous bone, the equivalent stress was 179.15 and maximum deformation observed was 0.216 mm. In Cortical bone, the equivalent stress was 75.28 MPa and the maximumdeformation was 0.0435. (Table 4, Figure 3)
In FEM analysis **Model 4** with no bone reduction, with 15 kgs vertical loading the equivalent stress value observed in Pulp was 0.255 MPa and maximum deformation was 0.0528 mm. The equivalent stress value observed in Dentin was 103.1 MPa and maximum deformation was 0.0564 mm. In PDL, the equivalent stress value observed was 0.0210 MPa and maximum deformation was 0.0563mm. In Enamel, the equivalent stress was 33.991 MPa and maximum deformation was 0.0578 mm. In Mucosa, the equivalent stress observed was 5.018 MPa and maximum deformation was 0.0615 mm. In Cancellous bone, the equivalent stress was 1.6691 MPa and maximum deformation observed was 0.0606 mm. In Cortical bone, the equivalent stress was 62.681 MPa and the maximum deformation was 0.0587mm. (Table 5, Figure 4)
In FEM analysis **Model 5** with 25% bone reduction, with 15 kg vertical loading the equivalent stress value observed in Pulp was 0 MPa and maximum deformation was 0 mm. The equivalent stress value observed in Dentin was 144.66 MPa and maximum deformation was 0.74806 mm. In PDL, the equivalent stress value observed was 2.47 MPa and maximum deformation was 0.71835mm. In Enamel, the equivalent stress was 48.43 MPa and Maximum deformation was 0.7799 mm. In Mucosa, the equivalent stress observed was 17.17 MPa and maximum deformation was 0.0626 mm. In Cancellous bone, the equivalent stress was 1.34 MPa and maximum deformation observed was 0.0617 mm. In Cortical bone, the equivalent stress was 11.99 MPa and the maximum deformation was 0.0598 mm. (Table 6, Figure 5)
In FEM analysis **Model 6** with 50% bone reduction, with 15 kgs vertical loading the equivalent stress value observed in Pulp was 0 MPa and maximum deformation was 0 mm.

The equivalent stress value observed in Dentin was 371 MPa and maximum deformation was 0.23 mm. In PDL, the equivalent stress value observed was 0 MPa and maximum deformation was 0.17 mm. In Enamel, the equivalent stress was 35.04 MPa and Maximum deformation was 0.25 mm. In Mucosa, the equivalent stress observed was 13.02 MPa and maximum deformation was 0.0625 mm. In Cancellous bone, the equivalent stress was 3.5979 MPa and maximum deformation observed was 0.0616 mm. In Cortical bone, the equivalent stress was 530.89 MPa and the maximum deformation was 0.0597 mm. (Table 7, Figure 6)

Table 1: Material, Young's modulus of elasticity and Poisson's ratio

Material	Young's modulus	Poisson's ratio
Enamel	80000	0.33
Dentin	18600	0.31
Pulp	0.2	0.45
PDL	0.069	0.45
Cancellous	1970	0.25
Cortical	15,750	0.33

Figure 1: Interpretation Score of Von Mises Stresses

Table 2: Showing tooth material data with respect to Model 1

100% oblique	Maximum Deformation (mm)	Maximum Equivalent Stress Megapascal (Mpa)
Total	7.07E-02	127.13
Pulp	4.63E-02	0.66715
Dentin	6.42E-02	127.13
Periodontal ligament	5.99E-02	6.58E-02
Enamel	7.07E-02	44.208
Mucosa	6.14E-02	21.502
Cancellous	5.10E-02	7.885
Cortical	4.35E-02	124.95

Figure 2: Stress distribution in relation to Model 1

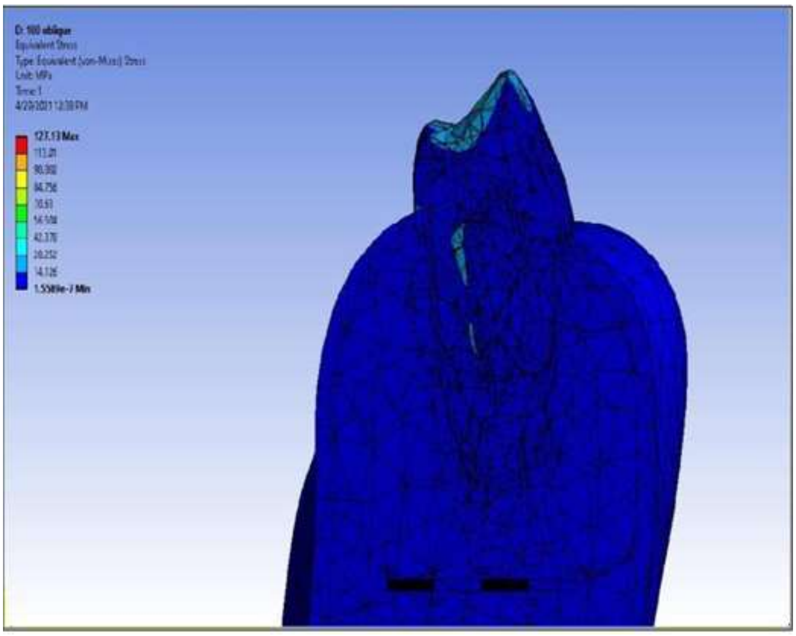


Table 3: Showing tooth material data with respect to Model 2

25% oblique	Maximum Deformation (mm)	Maximum Equivalent Stress (Mpa)
Total	1.6398	162.04
Pulp	0	0
Dentin	1.4632	154.55
Periodontal ligament	0.99311	3.3277
Enamel	1.6398	112.05
Mucosa	4.56E-02	15.963
Cancellous	4.49E-02	8.2683
Cortical	4.53E-02	162.04

Figure 3: Stress distribution in relation to Model 2

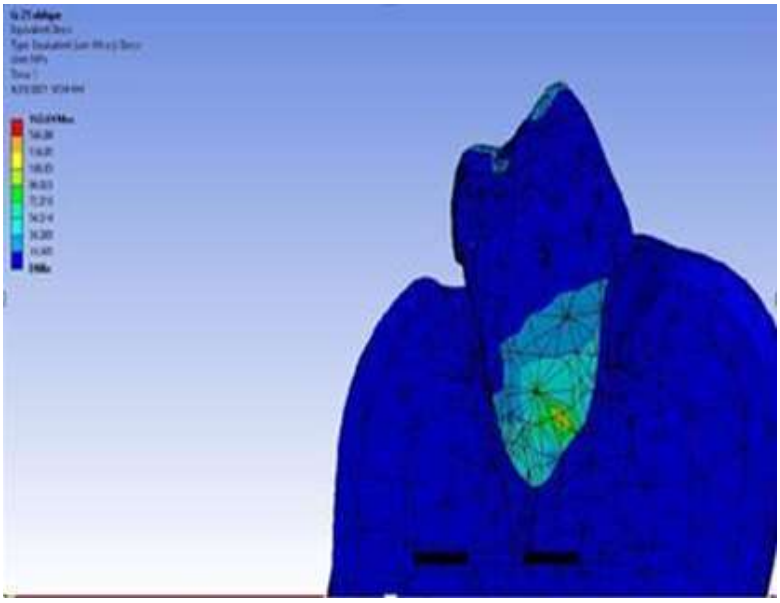


Table 4: Showing tooth material data with respect to Model 3

50% oblique	Maximum deformation (mm)	Maximum equivalent stress(Mpa)
Total	17.846	980.4
Pulp	0	0
Dentin	16.298	301.71
Periodontal ligament	12.156	18.681
Enamel	17.846	980.4
Mucosa	0.14338	31.398
Cancellous	0.21616	179.15
Cortical	4.35E-02	75.287

Figure 4: Stress distribution in relation to Model 3

Table 5: Showing tooth material data with respect to Model 4

100%	Maximum deformation(mm)	Maximum equivalent stress (Mpa)
Total	6.15E-02	103.1
Pulp	5.28E-02	0.25534
Dentin	5.64E-02	103.1
Periodontal ligament	5.63E-02	2.10E-02
Enamel	5.78E-02	33.991
Mucosa	6.15E-02	5.018
Cancellous	6.06E-02	1.6691
Cortical	5.87E-02	62.681

Figure 5: Stress distribution in relation to Model 4

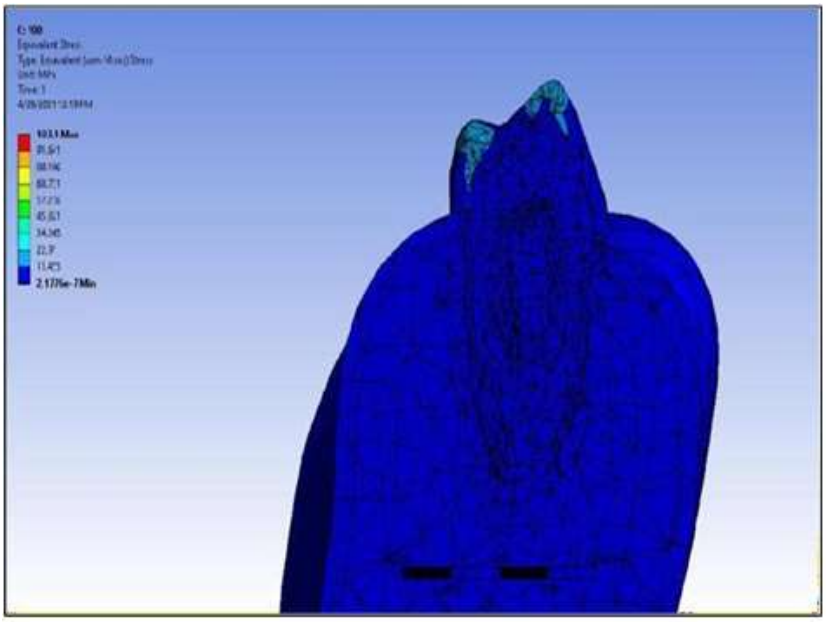


Table 6: Showing tooth material data with respect to Model 5

25%	**Maximum deformation (mm)**	**Maximum equivalent stress (Mpa)**
Total	0.7796	48.47
Pulp	0	0
Dentin	0.7486	14.67
Periodontal ligament	0.7185	2.471
Enamel	0.7796	48.47
Mucosa	6.26E2	17.15
Cancellous	6.17E2	12.33
Cortical	5.98E2	11.95

Figure 6: Stress distribution in relation to Model 5

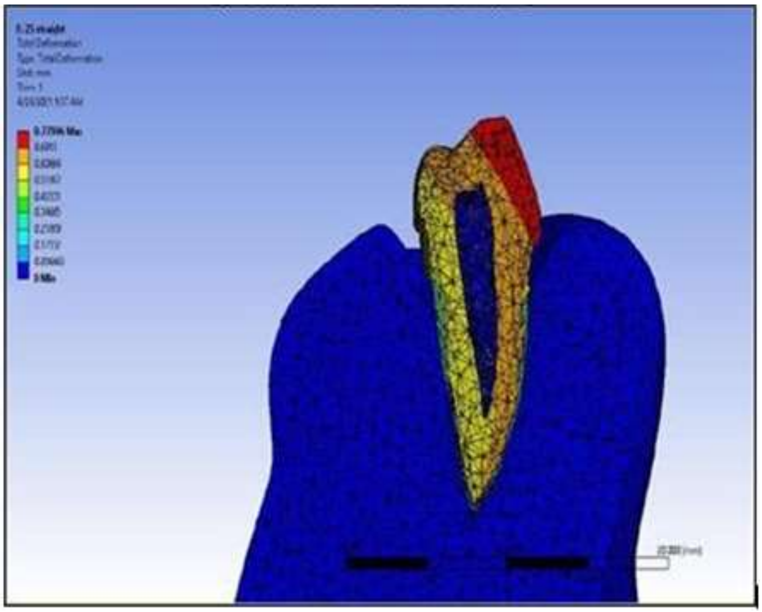
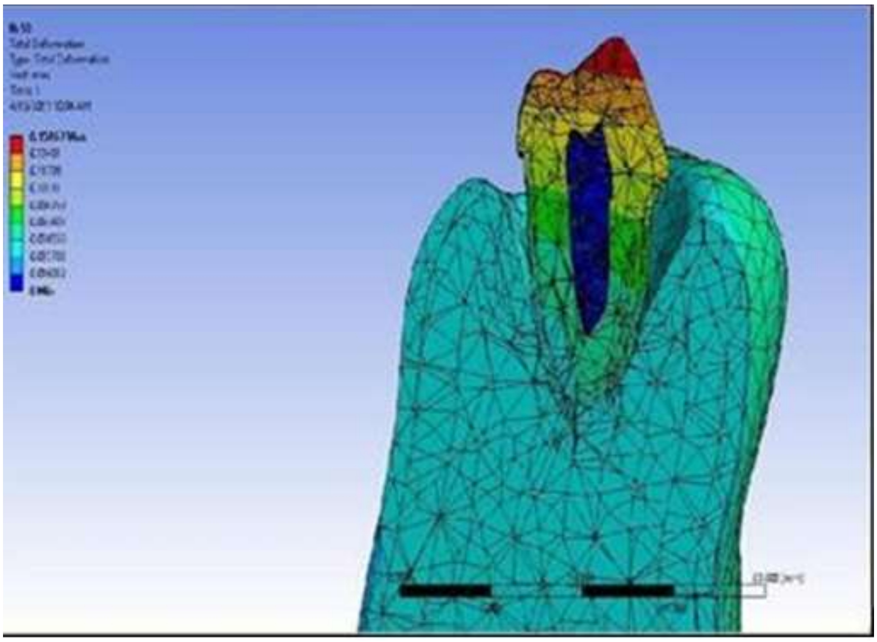


Table 7: Showing tooth material data with respect to Model 6

50%	Maximum deformation (mm)	Maximum equivalent stress (Mpa)
Total	0.25222	530.89
Pulp	0	0
Dentin	0.2302	371
Periodontal ligament	0.17378	0
Enamel	0.25222	35.043
Mucosa	6.25E-02	13.025
Cancellous	6.16E-02	3.5979
Cortical	5.97E-02	530.89

Figure 7: Stress distribution in relation to Model 6



DISCUSSION

Abfraction can be defined as “a physical process resulting from biomechanical occlusal stress concentration at the cervical third of the tooth leading to ditching at the cemento-enamel junction due to crack formation”. It is considered as “a fatigue failure of hard tooth tissues resulting from occlusal loading which leads to tooth flexure”.[1] The neck portion of the tooth crown is an integralpart of the tooth, which has a significant contribution in an esthetic.

However, this critical area of the tooth crown may get affected by microbial lesions like caries, abrasion due to faulty tooth brushing, or non-carious lesions. The lesions that occur in the cervicalportion of the teeth without the involvement of bacteria are termed as non-carious lesions(NCCL)[1]. Observations from recent studies have provided explanations to understand the underlying mechanisms that lead to the development of non-carious cervical lesions. Soares PO, Grippo JO. 1991[10] “stated that non-carious cervical lesions have a multifactorial etiology that includes stress, friction and biocorrosion”. Donovan TE, et al. 2017[11] declared that “these lesions have a complex, controversial and insufficiently understood etiology, probably involving erosion,abrasion and tooth flexure secondary to occlusal loads”.

The “abfraction theory” stated that “tensile stress resulting from non-axial occlusal loads can cause the disruption of bonds between hydroxyapatite crystals and the separation of enamel from dentine” based on the observations of engineering studies[12]. In a study, Sawlani K, et al. in 2016[13] evaluated the factors involved in the evolution of non-carious cervical lesions. They concluded that abfraction occurred mainly due to occlusal stress and other factors did not have any role in it.The present study was conducted to evaluate the abfraction lesions in the cervical area of mandibular first premolar considering 15 kgs occlusal forces, in oblique and vertical direction andto correlate it with different bone heights at CEJ, cervical 1/3rd of the root surface and at cervical 2/3rd of the root surface.

In Model 1, there was no bone reduction under 15 kgs loading in oblique direction, maximum stress and deformation was observed in Dentin. In Model 2, there was 25 % bone reduction under 15 kgs loading in oblique direction, maximum stress and deformation was observed in Enamel. This is the first study evaluating the maximum stress and deformation on Dentin and Enamel. In Model 3, there was 50 % bone reduction under 15 kgs loading in oblique direction, maximum stress and deformation was observed in Cortical bone.

In Model 4, there was no bone reduction under 15 kgs loading in vertical direction, maximum stress and deformation was observed in Dentin. In Model 5, there was 25 % bone reduction under 15 kgs loading in vertical direction, maximum stress and deformation was observed in Enamel. InModel 6, there was 50 % bone reduction under 15 kgs loading in vertical direction, maximum stress and deformation was observed in Cortical bone. The findings from this study were similar to the study done by Vandana et al (2016) [14] and Lee SY, et al. (2002)[15].

Donovan TE, et al. (2017)[11] reported that “vertical heavy occlusal loads are involved in the progression of non-carious cervical lesions”, whereas Litonjua LA, et al. (2004)[16] said that “there is no connection between vertical occlusal loads and these lesions”. The present study showed thatthere is a correlation between the value of occlusal vertical loads and the value of stress in the cervical area.

According to this study, the stress has its greatest value in the FEA model of the intact tooth. Similar results were obtained with Finite Element Analysis by Benazzi S, et al. (2013)[17] Other experts which rely on their clinical experience have stated that the intact tooth is the least favorable for the distribution of occlusal loads in dental tissues, because of the premature contacts and occlusal interference [18, 19]. They declared that “physiological tooth wear has an adaptive feature and assures a good functioning of the oral cavity”.

In this study, it was observed that stress distribution can also occur in other areas in which non- carious cervical lesions have not been frequently found. These observations were similar to the results reported by Benazzi S, et al. (2013)[17]. This suggests that there are other factors involved in the pathogenesis of this lesions.

CONCLUSION

In the present study, higher stress values in the cervical region of the tooth for normal occlusal load was observed. The effect of these stresses increases over a period of time resulting in abfraction with advancing age, along with other wasting diseases of the teeth. In a healthy tooth, when forces are applied in oblique and vertical direction maximum stress and deformation was seen in Dentin. In 25 % bone reduction in diseased tooth, the maximum stress and deformation was seen in Enamel. In 50 % bone reduction in diseased tooth, the maximum stress and deformation was seen in Cortical bone. Hence, we conclude that healthy Periodontium is necessary for uniform distribution of occlusal forces and thereby minimize occurrence of Abfraction lesions.

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