Abfraction: 3D analysis by means of the finite element method

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Objective: Tooth deflections under functional loads are considered to be the etiologic factor of noncarious cervical lesions. There are several studies on the materials used to restore these lesions; however, there are few discussing this phenomenon's etiology from a biomechanic point of view. This study was undertaken to evaluate tooth behavior when forces were applied from different directions. **Method and materials:** A 3D finite element model of a maxillary central incisor was designed. A distributed force of 1.5 N was applied on the palatal side of the crown in five stages, with varying directions progressing from tipping to intrusion. Two separate approaches (displacement and stress) were considered to evaluate the cervical area from a stress perspective. **Results:** The displacement approach resulted in a curved path when compared to a straight line connecting the apical and incisal areas. The maximum deflections were in the cementoenamel junction area. The same area was shown to undergo the maximum of von Mises stress and stress intensity. Patterns of the von Mises stress when evaluated in a mesiodistal direction were in complete agreement with the shape of the cervical lesions (except for the application of the intrusive force, which rules out its effect in producing such lesions). **Conclusion:** Force applications, except for intrusive force, can produce increases in the von Mises stress and tooth deflections that can answer the question of the etiology of noncarious cervical lesions. The highest amounts of deflection and von Mises stress were produced by the 45-degree force application. *(Quintessence Int 2003;34:526–533)*

Key words: abfraction, finite element method, force application, functional loads, stress

CLINICAL RELEVANCE: A noncarious cervical lesion is a challenging area for restorative dentists, researchers who work on new materials, and biomechanics experts. Its etiology can be discussed somewhat accurately but cannot be prevented in many cases. Applying new materials in this region is questionable due to acting forces. Long-term survival of materials used to restore such a lesion should be assessed.

At the same time of moving, teeth flex under various loads. This is an important point in operative dentistry, prosthodontics, and implantology, though it is ignored in orthodontic therapies. This type of reaction to external loads has been interpreted to be the cause of some cervical lesions without signs of caries.

Noncarious cervical lesions are characterized by the loss of hard tissue at the cementoenamel junction.[1] Traditionally, it has been assumed to be due to the effects of abrasion and/or erosion. More recently, researchers have stated a new theory that relates these lesions to cuspal flexure.[1–3] Tooth flexure has been described as a lateral or axial bending under occlusal loading. Tooth flexure produces tensile or compressive strain, causing a disruption of the bonds between hydroxyapatite crystals, leading to the formation of cracks in the enamel and the eventual loss of enamel and underlying dentin.[1,3–6]

Grippo[7] coined the term *abfraction* to distinguish this type of cervical lesion associated with cuspal flexure. The term *dental abfraction* tries to show the presence of tooth fatigue, flexure, and deformation through biomechanic loading of teeth, primarily at the cervical regions of the dentition.[4,7] Xhonga[8] found a significantly higher prevalence of these lesions in patients with bruxism.

According to Burke et al,[9] there is evidence to support the cuspal flexure theory in the formation of cervical lesions: *(1)* Lesions occur in teeth subjected to lateral loads, but the adjacent teeth not undergoing the load remain unaffected; *(2)* lesions are rarely seen in the lingual side of teeth; and *(3)* lesions may occur subgingivally, which would not be the case for erosion or abrasion.

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The concept of occlusally generated stresses is appealing as it can explain the morphology and location of these wedge-shaped lesions. Reports show that deformations due to occlusal loads could produce a tensile and compressive stress in the cervical region. According to Lee and Eakle,[10] these tensile stresses are known as the primary etiologic factor of noncarious cervical lesions.

In complicated structures, it is difficult to achieve an accurate analytic solution. Numeric methods, such as the finite element method of analysis (FEA), can be considered a practical approach. Finite element analysis divides the problem domains into a collection of smaller parts (elements). An overall approximated solution to the original problem is determined. In this method, solutions for each element are combined to obtain a solution to the whole body.[11] Among various methods of assessing deformations produced in different structures, the FEA has proven its efficiency in many ways, from the normal situations concerning the nature of tooth movement under orthodontic loads,[12] to special situations like alveolar bone loss,[13,14] extraoral force systems,[15] and many other fields.

In spite of the presence of various articles dealing with different materials, their applications, advantages, and disadvantages,[16–32] there are few studies dealing with the etiology of these lesions. This study was undertaken to evaluate the cervical area of a tooth under loads from displacement and stress perspectives.

METHOD AND MATERIALS

A three-dimensional (3D) finite element model (FEM) of a maxillary central incisor was designed. The model consisted of 37,884 nodes and 32,768 elements based on Ash's dental anatomy,[33] with minor modifications to obtain the best shape (Fig 1). A 3D brick, isoparametric, octahedral element was chosen to construct the model. The model contained the maxillary central incisor (its crown covered with enamel), its PDL, and spongy and cortical bone (Fig 2). Cementum is a very thin layer and has the same physical properties as dentin; therefore, it seemed unnecessary to define it as a separate layer from the dentin. Each section was given 48 external nodes to enable appropriate modeling. The root was split into 15 levels of varying vertical heights (see Fig 1). According to Coolidge,[34] the PDL is of varying thicknesses in vivo (Table 1) and has been thought to make the model more precise and realistic.

Due to technical reasons, the applied force of 1.5 N was divided into 72 small point forces. The points of force application were parallel to the incisal edge, on the palatal side. The direction of the palatolabial forces ranged between tipping (0 degrees relative to the horizontal line), 22.5, 45, and 65 degrees relative to the horizontal line, and 90 degrees relative to the same line (intrusion).

The boundary condition is an important factor in the FEM, reflecting the manner of movements occurring at the nodes and their relationships. All the nodes at the base of the model were fixed so not to move when subjected to force systems. The analyses were performed on a Pentium III personal computer (ANSYS Version 5.4). Poisson's ratio is the strain in the lateral direction to that in the axial direction when an object is subjected to tensile loading, which increases the length of the object in the direction of the load and decreases the lateral dimensions of the object that are perpendicular to the load. According to experiments,[35] this ratio lies between 0.25 and 0.35 for most of the materials. The highest value for this ratio is 0.50 and shows lack of any volume change of the body while deformation occurs. In other words, any axial deformation will be followed by a lateral deformation. In the present study, the Poisson's ratio of the PDL was assumed to be 0.49, which explains its biologic characteristics rather accurately (Table 2).

Symmetric force applications to the tooth's long axis prevented any rotation tendency.

Two separate approaches were considered for evaluations: *(1)* displacement; and *(2)* stresses.

Output data of the approaches were derived along two paths defined by the nodes of the most prominent part of the labial and palatal sides of the tooth. The path was from the incisal edge down to the apical area. In the last phase of the analysis, another path was defined mesiodistally in the cervical area to assess the stress situation of that region.

The displacements of the nodes along the path were compared with a straight line connecting the incisal edge to the apical area. In this way, any disproportion produced in the displacement of the nodes due to deformation was made clear. The distance formed between the path and the straight line was calculated at the CEJ area as a criterion for the degree of tooth deformation.

Among the criteria used to evaluate the structures under loading to judge the stress state at certain points, was the von Mises stress

$$\sigma_e = (\tfrac{1}{2}\,[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2])^{1/2}$$

and the stress intensity

$$\sigma_1 = \max\,[|\sigma_1 - \sigma_2|, |\sigma_2 - \sigma_3|, |\sigma_3 - \sigma_1|].$$

The aforementioned criteria were traced in the path to show the quality of their changes. The last assessment was to find the von Mises pattern of the cervical area in a mesiodistal direction along the second path.

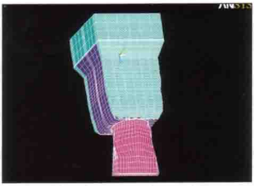


Fig 1 Three-dimensional model of a maxillary central incisor.

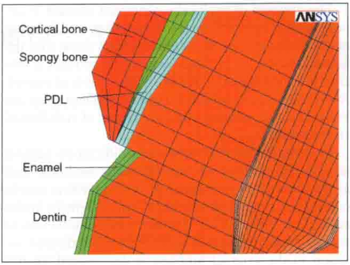


Fig 2 *(right)* The different materials used in the model.

TABLE 1 Geometry of the PDL widths according to Coolidge[34] (mm)

Distance from the alveolar crest	Distal	Lingual	Mesial	Labial
13.0	0.25	0.25	0.22	0.25
10.5	0.18	0.22	0.20	0.22
8.0	0.15	0.20	0.17	0.20
6.5	0.14	0.18	0.16	0.18
5.0	0.15	0.20	0.17	0.20
2.5	0.18	0.22	0.20	0.22
0.0	0.19	0.24	0.21	0.24

TABLE 2 Mechanical properties of the structural elements of the study

Material	Young's modulus (N/mm²)	Poisson's ratio
Cortical bone	3.40×10^4	0.26
Spongy bone	1.37×10^4	0.38
PDL	6.67×10^{-1}	0.49
Dentin	1.80×10^4	0.31
Enamel	8.40×10^4	0.33

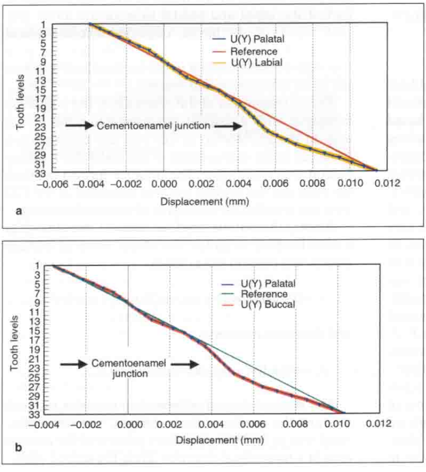


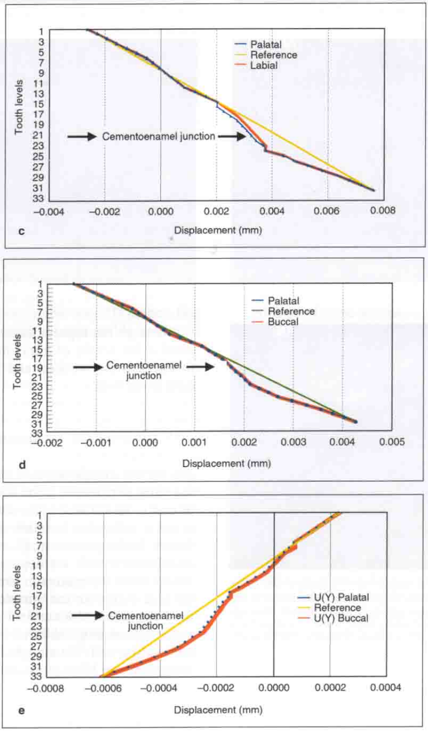
Fig 3 Displacement of the labial and palatal nodes in the direction of the applied force (1.5 N) compared to a straight line connecting the incisal and apical areas: *(a)* Tipping force application (0 degrees); *(b)* 22.5-degree force application; *(c) (facing page)* 45-degree force application; *(d) (facing page)* 65-degree force application; and *(e) (facing page)* intrusive force application (90 degrees).

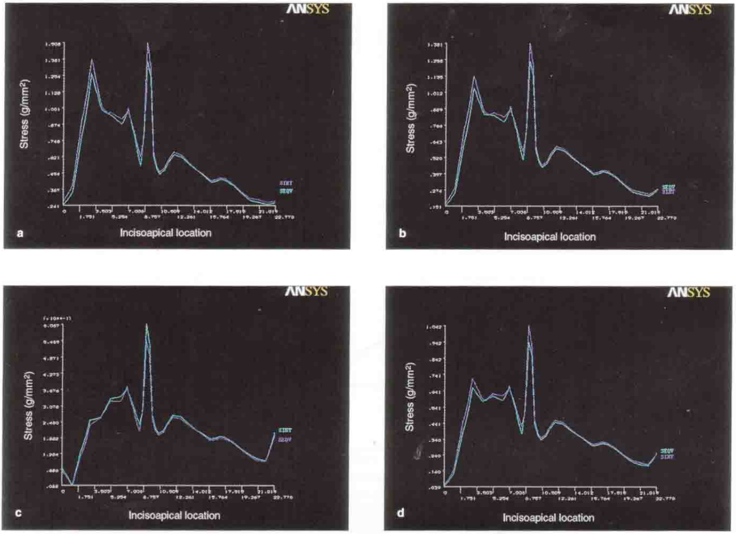
RESULTS

The output data were divided into two main groups according to displacement and stress.

Displacement

Output data for displacement in the palatal and labial sides of the tooth are the same, showing the reliability of the model presented. Displacement results showed some irregularities in the cervical area compared to a straight line passing from the incisal and apical area. Simple analytic geometric rules were employed to evaluate the output data to find out whether or not they were located in a straight line. At first assessment, the difference between the findings of cervical area displacement and the reference line was calculated. Figures 3a to 3e show the behavior of the tooth in different load cases. The decreases found ranged between 2% in intrusion and 13% in 45-degree force application, with a mean value of 8.11% from the reference line. The patterns of the tooth behavior were almost the same in different load cases except for the intrusion force application.





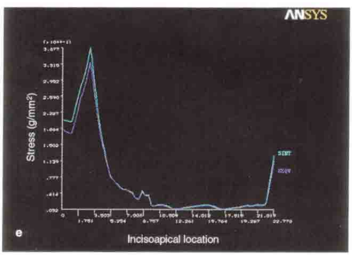


Fig 4 von Mises stress and stress intensity assessment of the nodes along the labial path: *(a)* Tipping force application (0 degrees); *(b)* 22.5-degree force application; *(c)* 45-degree force application; *(d)* 65-degree force application; *(e)* an intrusive force application (90 degree). SINT = stress intensity; SEQV = von Mises stress.

Although the highest amount of deflection was located a few tenths of a millimeter incisal to the CEJ, this area is the weakest and the most susceptible to hard tissue loss.

Stress

Among the criteria used to evaluate a structure from the stress perspective is the von Mises stress and stress intensity. To the best of the authors' knowledge, there is not a maximum bearable stress reported for living tissues. In the present study, output data for the aforementioned criteria are depicted in Figs 4a to 4e. The results show the maximum stress intensity in the cervical area except for the intrusion movement. These figures show that the cervical region was the area of some deformities, exhibited by their displacement in comparison with the straight line and also the area of maximum von Mises stress and stress intensity.

DISCUSSION

Any type of stress (tensile, compressive, or shearing), when sufficient in magnitude, can inflict damage on tooth structure.[36,37] It is known that lateral force acting on a tooth at the fulcrum creates tension and compression of equal magnitudes on both sides.[36] Tooth structure, particularly the enamel, has a far greater compressive strength than tensile strength.[38] Lambrechts et al[39] reported frequent findings of enamel cracks at the cervical enamel under tensile stress. Stereomicroscopic studies,[39] on the other hand, clearly demonstrated evidence of hydroxyapatite crystal disruptions caused by the stress.

Although tensile stress is the major etiologic factor in cervical lesions, it is not to be miscomprehended that all cervical lesions are caused by this stress or that tensile stress is the only factor involved. Stress-induced and abrasion lesions may share a similar morphologic feature.[36] A relationship between bruxism and dental erosion has been suggested by Xhonga.[8] It is estimated, in a group presenting wedge-shaped cervical lesions, that 97% of the population under study had parafunctional disorders.[41] Recent finite element studies[42,43] have shown higher strains adjacent to CEJ, which is in complete agreement with the findings of the present study.

Several force vectors may act simultaneously on living tissues in a 3D space. It is not appropriate to analyze one plane, while ignoring the other planes because the structure is not symmetric. Based on these facts, two-dimensional (2D) models cannot represent the real situation of a 3D body. In this way, 2D models like those of Takahashi et al[44] are not expected to show real situations well.

PDL is the most important tissue in the evaluation of any tooth movement. Its role cannot be ignored while trying to achieve a real situation. Rubin et al[45] tried to analyze the stress distribution in a human mandibular first molar, without modeling the PDL. Although using a 3D model is superior to a 2D model, ignoring PDL can influence results seriously. The model presented in the present study is as similar as possible to the real situation described earlier.

The presence of large values of the strains in the enamel adjacent to the CEJ is explained with the following reasons: *(1)* It is thinner than the other regions; *(2)* the enamel rod arrangement is less intertwined near the CEJ than in other regions; and *(3)* the weaker bond between the enamel and the dentin in the cervical area also may contribute to the occurrence of high strains in the enamel.[46] The tight bond of the dentinoenamel junction enables the natural tooth to distribute stress into the more elastic dentin in order to minimize the damage from the local stresses on the enamel that result from occlusal contacts.[47] Evaluating the von Mises stress of the cervical area in a mesiodistal direction revealed an almost similar pattern in all force directions except for the intrusive force application (Figs 5a to 5c).

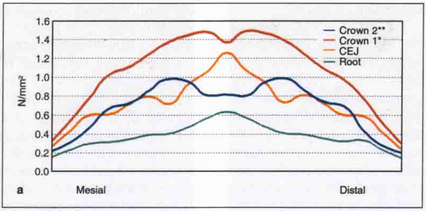
Braem et al[39] described the development process of the stress-induced lesions from the initial cracking stage of the outer cervical enamel to the subsequent advancement of the destructive process in the dentin.

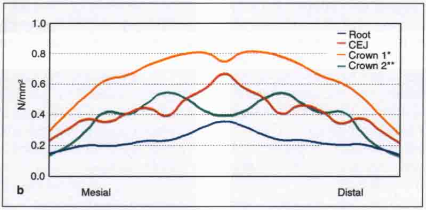
A close study of these figures can reveal some important points that can confirm some clinical findings and are in complete agreement with Burke et al.[39]

1. The patterns are the same as and similar with the overall shape of the lesions mesiodistally.
2. In spite of the presence of higher stresses in the crown in comparison with the CEJ, the enamel rods are thinner in the CEJ, and the lesions start from this area.
3. It can be assumed that once the bond between enamel and dentin starts to disrupt, the lesion continues to develop due to the presence of higher stress values in the incisal part of the CEJ.
4. High amounts of stress in the first layer of the crown can be the reason for restorative material failure in this area.
5. Curve shapes of the intrusive movement show that this kind of force does not have any effect on the etiology of these lesions.

CONCLUSION

Force application causes an elastic deformation in the teeth that was clearly shown by the FEA. The simplest interpretation of less displacement of the nodes in the CEJ and the adjacent areas is that the tooth containing these nodes had been flexed in this area, providing less displacement in comparison with the reference line. The output for von Mises stress and the stress intensity confirmed the former results. Although the exact location of maximum deformation is not in the cervical region, due to the reduced thickness of the enamel rods in the CEJ, it shows the disruption of the enamel, thus resulting in the wedge-shape lesions found in this area. Incisal extension of these lesions was also explained by the von Mises stress output.





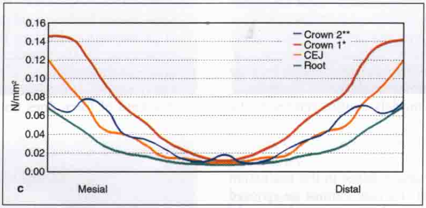


Fig 5 von Mises stress of the cervical area in a mesiodistal direction: (a) Tipping force application (0 degrees); (b) 45-degree force application; (c) intrusive force application (90 degrees). CEJ = cementoenamel junction; * = first crown layer adjacent to the CEJ, ** = second crown layer.

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