EFFECTS OF OCCLUSAL LOADS IN THE GENESIS OF NON-CARIOUS CERVICAL LESIONS – A FINITE ELEMENT STUDY

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ABSTRACT

Aim of the study This study investigated the magnitude and distribution of stress in a maxillary first premolar subjected to normal and heavy occlusal loads, that were directed vertically and horizontally, using Finite Element Analysis. Material and methods A virtual 3D model of a maxillary first premolar was created using the CT images of a 14 year-old patient and the physical and mechanical properties of the dental tissues used in other studies. We obtained 8 scenarios for the vertical loading and 8 scenarios for the horizontal loading. Results The magnitude and distribution of stress were the least favorable in the case of the heavy horizontal loading applied on the intact tooth. Conclusions Our study showed that the intact tooth was the most affected by stress regardless of the loading applied.

Key words: finite element analysis, non-carious cervical lesions, stress, tooth wear.

INTRODUCTION

Non-carious cervical lesions represent the pathological processes of hard dental tissues loss at the cement-enamel junction, that do not involve any bacterial process (1).

In 1991, Dr. Grippo introduced the term “abfraction” to define these lesions and considered stress to be the main factor involved in their genesis (1, 2). The term “abfraction” derives from the Latin words ab-“away” and fractio –“breaking” (2, 3) and means “to break away” (1).

In their studies, Dr. Grippo and Dr. Masi showed that teeth subjected to static occlusal loads wear rapidly as opposed to teeth not subjected to these occlusal loads (4).

Even more studies showed that non-axial occlusal loads are involved in the genesis of stress at the cervical region of the tooth (1, 2, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15).

Non-axial occlusal loads can cause two types of stress in the tooth structure. The first one is the compressive stress located mainly at the surface adjacent to the direction in which the tooth flexure occurs and the second one is the tensile stress, located at the surface opposed to the direction of the tooth flexure (5, 7, 10, 11, 12, 16).

Because of the high prevalence of non-carious cervical lesions, many studies tried to enhance the influence of stress in the etiology of these lesions, using Finite Element Analysis, photoelastic tests, strain gauges and electronic microscopy (16).

This study aims to investigate the stress in a maxillary first premolar (with intact external morphology or with wear) when occlusal loads of normal and excessive magnitude are applied vertically and horizontally, using Finite Element Analysis.
MATERIAL AND METHODS

In order to create a 3D virtual model of a maxillary first premolar, we used the CT images of a 14 year-old patient (Figure 1). Frontal and transverse images of 1.5 mm width were scanned and the data was used to build a 3D virtual model that could be used in the program we applied the Finite Element Analysis.

Figure 1. Images T14- Sections of 1.5mm.

Information regarding material properties such as the elastic modulus of Young and the Poisson’s ratio were collected from the literature and summarized in Tabel 1. All the biological materials represented in the models were considered homogenous and linearly elastic. The values of tensile and compressive stress obtained were compared to the values of Ultimate Tensile and Compressive Strength of these materials, according to Tabel 2.

<table>
<thead>
<tr>
<th>Material</th>
<th>Elastic Modulus of Young (GPa)</th>
<th>Poisson Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enamel</td>
<td>80.35 (17, 18, 19)</td>
<td>0.33 (17, 18, 19)</td>
</tr>
<tr>
<td>Dentine</td>
<td>19.89 (17, 19, 20)</td>
<td>0.31 (17, 19, 20)</td>
</tr>
<tr>
<td>Pulp</td>
<td>0.002 (19, 21)</td>
<td>0.45 (19, 21)</td>
</tr>
<tr>
<td>Periodontal ligament</td>
<td>0.069 (17, 18, 19)</td>
<td>0.45 (17, 18, 19)</td>
</tr>
</tbody>
</table>

Tabel 1. Material properties

Material | Ultimate Tensile Strength (MPa) | Ultimate Compressive Strength (MPa) |
---------|---------------------------------|------------------------------------|
Enamel   | 24 (7)                          | 62 (12, 22)                         |
Dentine  | 90 (23)                         | 193 (12, 22)                        |

Tabel 2. Ultimate tensile and compressive strength for dental tissues

The scanned images were converted into a 3D model using MIMICS Program and were processed in Abaqus/CAE so that they could be studied with Finite Element Analysis. The 3D Virtual model consisted of the upper right first premolar and the alveolar bone represented as a parallelepiped. The premolar comprised of: enamel, dentine and pulp. The periodontal ligament was simulated by creating a uniform outline of 0.3mm width. The alveolar bone was simulated so that the upper limit was positioned 3 mm lower than the cervical limit of the tooth. The cement was not simulated because of its minor dimensions and its lower relevance for this study. The tooth was not rigidly fixed to the bone, because between them we applied the periodontal ligament with an elastic modulus of 0.069 GPa (17, 18, 19).

The FEA model was a 3D model with tetrahedral elements resulting in 47548 elements and 68504 nodes. The average size of an element was approximate 0.5mm per surface (Figure 2).

Figure 2. FEA Model.

This study aimed to analyze the effect of tooth wear on the mechanical behavior of an upper first premolar (intact or with tooth wear) subjected to vertical and horizontal loads on normal and excessive value (24).

A- Simulation of vertical loads applied on the upper first right premolar – For these simulations we used 3 versions of horizontal tooth wear, as shown in Figure 3.
Figure 3. FEA Model: a) intact tooth; b) horizontal tooth wear version 1; c) horizontal tooth wear version 2; d) horizontal tooth wear version 3.

The FEA models shown in Figure 3 were prepared for analysis according to Figure 4. A vertical load was applied on a parallelepipedic block that contacted the buccal cusp of the tooth. The root was embedded in the alveolar bone. We created 8 scenarios for this vertical load: 4 using a normal vertical load (F=180 N) and 4 using an excessive vertical load (F=532 N) (24).

Figure 4. Simulation for vertical load

B- Simulation of horizontal loads applied on the upper right first premolar – For these simulations we used 3 versions of lateral tooth wear, as shown in Figure 5.

Figure 5. FEA Model: a) lateral tooth wear version 1; b) lateral tooth wear version 2; c) lateral tooth wear version 3; d) overlapped models.

The FEA models shown in Figure 2 and Figure 5 were prepared for analysis according to Figure 6. A horizontal load was applied using an antagonist tooth, rigidly modeled and with a complementary occlusal surface, which contacted the occlusal surface of the upper premolar. The root of the upper premolar was embedded in the alveolar bone. We created 8 scenarios for this horizontal load: 4 using a normal horizontal load (F=180 N) and 4 using an excessive horizontal load (F=532 N).

Figure 6. Simulation for horizontal load: a) intact tooth; b) lateral tooth wear version 1; c) lateral tooth wear version 2; d) lateral tooth wear version 3.

RESULTS

In the simulations with horizontal tooth wear we quantified the von Mises stress, which is a combination of compressive, tensile and flexural stress, but the compressive stress was prevailing. In the simulations with lateral tooth wear, the prevailing stress was both compressive and tensile.

a- Simulation of normal vertical load, F=180 N

Figure 7 shows the value and distribution of von Mises stress in the upper first premolar, intact and with horizontal tooth.
wear, when we applied a vertical load of 180 N.

Figure 7. Von Mises Stress: a) intact tooth; b) horizontal tooth wear version 1; c) horizontal tooth wear version 2; d) horizontal tooth wear version 3.

The values of von Mises stress in these models were generally under 62 MPa. In the model with the intact premolar, in a limited area of enamel, on the superficial layer, at the buccal cusp, the value of the stress was higher than 62 MPa. In the models with horizontal tooth wear, the values of stress were lower and did not exceed 62 MPa. However, the highest values were found in the oral cervical area.

b-Simulation of excessive vertical load, F= 532 N

Figure 8 shows the value and distribution of von Mises stress in the upper first premolar intact and with horizontal tooth wear, when we applied a vertical load of 532 N.

Figure 8. Von Mises Stress: a) intact tooth; b) horizontal tooth wear version 1; c) horizontal tooth wear version 2; d) horizontal tooth wear version 3.

The values of von Mises stress in these models were generally over 62 MPa, with the highest value in the case of the intact tooth. Regarding the distribution of this stress, in the model with the intact tooth it was found on the occlusal surface, affecting the whole enamel layer. In the models with horizontal tooth wear, the stress found had a lower value than in the model of the intact tooth. In these cases, the highest stress was found in the cervical area of the tooth and its value was in direct proportion to the degree of tooth wear.

c-Simulation of normal horizontal load, F= 180 N

Figures 9 and 10 show the value and distribution of tensile and compressive stress in the upper first premolar intact and with lateral tooth wear, when we applied a horizontal load of 180 N.

Figure 9. Tensile stress: a) intact tooth; b) lateral tooth wear version 1; c) lateral tooth wear version 2; d) lateral tooth wear version 3.

Figure 10. Compressive stress: a) intact tooth;
b) lateral tooth wear version 1; c) lateral tooth wear version 2; d) lateral tooth wear version 3.

The values of tensile stress were generally under 90 MPa, the highest ones being found in the model with the intact tooth. These high values were located on the occlusal surface, at the contact area with the antagonist tooth and on the oral radicular surface.

The values of compressive stress were generally under 193 MPa, the highest ones being found in the model with the intact tooth. These high values were located on the occlusal surface, at the contact area with the antagonist tooth and on the buccal radicular surface.

d-Simulation of excessive horizontal load, F=532 N

Figures 11 and 12 show the value and distribution of tensile and compressive stress in the upper first premolar intact and with lateral tooth wear, when we applied a horizontal load of 532 N.

Figure 12. Compressive stress: a) intact tooth; b) lateral tooth wear version 1; c) lateral tooth wear version 2; d) lateral tooth wear version 3.

The values of tensile stress were higher than 90 MPa in the FEA model of the intact tooth and were found on the occlusal surface, at the contact area with the antagonist tooth and on the oral radicular surface. In the FEA models with lateral tooth wear, the highest values for the tensile stress had the same distribution, but lower peak.

The values of compressive stress were higher than 193 MPa in the FEA model of the intact tooth and were found on the occlusal surface, at the contact area with the antagonist tooth and on the buccal radicular surface. In the FEA models with lateral tooth wear, the compressive stress with a value higher than 193 MPa were found at the oral cusp, and their distribution was inversely proportional to the degree of tooth wear.

DISCUSSION

Recent research findings provided us with a higher understanding of the mechanisms involved in the genesis of non-carious cervical lesions. Grippo (16) stated that non-carious cervical lesions have a multifactorial etiology that includes stress, friction and biocorrosion, and Donovan, in a review from 2017 (25) declared that these lesions have a complex, controversial and insufficiently understood etiology, probably involving erosion, abrasion and tooth flexure secondary to occlusal loads.

Engineering studies support the “abfraction theory”: tensile stress resulted from non-axial occlusal loads can cause the disruption of bonds between hydroxyapatite crystals and the separation of enamel from dentine (3). Sawlani conducted a study (26) to evaluate the factors involved in the evolution of non-carious cervical lesions and concluded that only the occlusal stress is causing them, without the implication of other factors.
In this study we used the CT images of a 14 year-old patient and obtained a FEA 3D model of an upper right first premolar. Furthermore, we simulated 3 models with horizontal tooth wear and 3 with lateral tooth wear, in the attempt to simulate as many clinical situations as possible.

To these FEA 3D models we applied normal and excessive (bruxism) loads on a vertical and horizontal direction, in the attempt to simulate the occlusal loads developed in the mandibular static positions and the mandibular dynamics.

The aim of this study was to evaluate the value and distribution of stress in the cervical area and the probability of it to be involved in the genesis of non-carious cervical lesions. The stress was considered as tensile and compressive stress and its values were compared to the ones found in other studies (7, 12, 22, 23).

In the simulation of a vertical normal load, when we analyzed the compressive stress, we found its value to be almost the same as the ultimate compressive strength and it was found in the FEA model of the intact tooth at the buccal cusp and in the FEA models with horizontal tooth wear, in the cervical oral region. The values of the von Mises stress in the models with horizontal tooth wear were lower than the ones found in the FEA model with the tooth intact.

In the simulation of an excessive horizontal load, we observed that the FEA model with the intact tooth was the most affected by the value and distribution of the tensile stress developed. The tensile stress whose value was higher than the ultimate tensile strength was found in the model of the intact tooth on the occlusal surface and on the radicular oral surface. In the FEA models with lateral tooth wear, the compressive stress had lower values and were found at the palatal cusp.
lateral tooth wear, the tensile stress had lower values and a similar distribution.

Regarding the **compressive stress**, we found that in the FEA model of the intact tooth, its value was higher than the ultimate compressive strength and it was limited to the occlusal surface and the vestibular cervical area. In the FEA models with lateral tooth wear, the compressive stress was found on the oral surface.

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 (28, 29). 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 (30, 31). They declared that physiological tooth wear has an adaptive feature and assures a good functioning of the oral cavity.

Relating to the distribution of stress, this study showed that stress can be present in other areas in which non-carious cervical lesions have not been frequently found. Similar results regarding the distribution of stress were found by Benazzi (28) in a study in which we simulated stress in a mandibular premolar with Finite Element Analysis and by Rees (33).

This distribution of stress, correlated with the fact that non-carious cervical lesions frequently develop in the vestibular cervical region, suggest that there are other factors involved in the pathogenesis of this lesions, which do not appear in other areas with stress.

Grippo (2) described since 1991, 5 types of abfraction lesions for enamel and 10 for dentine. In this classification, Grippo showed that these lesions can have various shapes and can be found on other dental surfaces than the cervical buccal one, but with a lower frequency.

**CONCLUSIONS**

1. Our study showed that the FEA model with the tooth intact is the most affected by stress, even in the case of a vertical normal load being applied.

2. In the simulation of a vertical normal load, the maximum stress was found on the superficial layer of the enamel, whereas in the simulation of a vertical excessive load, the maximum stress involved the whole width of the enamel layer.

3. The value and distribution of stress were the least favorable in the simulation of the excessive horizontal load in the FEA model with the intact tooth.

4. The fact that we found stress in other areas than the cervical buccal one suggests that there are other factors involved in the genesis of non-carious cervical lesions.

**REFERENCES**


