THE EFFECT OF ORTHODONTIC VERTICAL FORCES ON THE DENTAL PULP: A THREE-DIMENSIONAL FINITE ELEMENT ANALYSIS

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ABSTRACT

Aim of the study. In our study we evaluated, by using a three-dimensional Finite Element Model, the effect of intrusive and extrusive forces applied during orthodontic treatment. Material and methods. A tridimensional image of the tooth was obtained, by creating a model with 1379 nodes and 976 finite elements. We selected two clinical situations frequently present during orthodontic treatment: the use of a force aiming to align the teeth according to the vertical dimension, through extrusion or intrusion, which exerts a compression or elongation effect on the periodontal complex. Results. The results showed that the use of high force determined an increased stress especially in the apical third of the root. Conclusions. The use of high forces could determine an increased stress in the apical third of the root and disturbances in pulp circulation or even loss of dental pulp vitality.

Key words: Finite Element Method, orthodontic force, dental pulp necrosis, orthodontic displacement.

INTRODUCTION

Finite Element Method (FEM) is defined as a computerized technique that allows the measurement of stress and tooth displacement by using a predetermined model. This method was first introduced in the aerospace industry and during the last decades has been extensively used in different areas of dentistry, in correlation with procedures that could weak the tooth resistance, leading to a high risk of dental fractures due to malocclusion trauma, cavity preparation, abrasion or endodontic treatment (1-4). If the dental hard tissues lack proper nutrition from the dental pulp due to impaired blood circulation, the elasticity of these structures will decrease; as a consequence, the stress exerted on the tooth during mastication or improper treatment procedures will increase the risk of dental fractures. Therefore, the better understanding of the fracture potential of these forces could assist dental specialists in
eliminating or reducing the clinical factors responsible for this modification (5, 6). FEM is currently considered an ideal method for modeling of tooth supporting tissues and the possibility to record of high stress levels enables the practitioner to assess the risk for biological alterations and to apply the best therapeutic approach (7). The measurements of stress levels developed inside a tooth, alveolar bone and periodontal tissue under occlusal forces were best performed on a three dimensional FEM model of a maxillary central incisor. The recordings showed that a force applied on palatal-labial direction had no effect on the dental pulp but gave maximum stress values at cervical level, which might be a cause of abfraction (8-10). There were also high levels of stress at the apex but on the alveolar bone the force distribution was correlated with insignificant stress levels.

The aim of our study was to evaluate, using a three-dimensional FEM analysis, the behavior of a complex structure formed by enamel-tooth-dental pulp-periodontal ligament – alveolar bone consecutive the application of a vertical force specific to orthodontic movements, as extrusion and intrusion.

MATERIAL AND METHODS

The FEM analysis allows stress evaluation in complex anatomic structures by dividing them into numerical geometric elements. The computer simulation based on FEM was conducted at the Department of Electrical Engineering and Computer in” Petru Maior” University of Tirgu Mureș. For this study an Autodesk Simulation was used, a multipurpose finite element analysis software developed by ALGOR Incorporated in 2009, which is suitable for application with Microsoft Windows. The definition and the creation of the model for a lower premolar using the ALGOR analyzing program consisted of the editing and constructing the tooth and the accompanying structures (dental pulp, periodontal space, alveolar bone), according to morphological and anatomical data. We studied the dental pulp stress value (von Mises stress value) expressed in N/mm2 under extrusion and intrusion forces. A tridimensional image of the tooth was obtained, by creating a model with 1379 nodes and 976 finite elements. We selected two clinical situations that are frequently seen in orthodontic practice: the application of force aiming to align the teeth according to the vertical dimension, produced by extrusion or intrusion, which have a compression or elongation effect on the periodontal complex (Fig. 1). For the accuracy and simplicity of the results, we assumed that all structures are homogenous-isotropic, with linear elasticity and minor deformation displacement.
compression and elongation on the elements of the periodontal structures and the dental pulp.

On a model of a mandibular premolar, in order to reproduce a real clinical situation and an analyze of least favorable conditions, the force value applied in the middle part of the occlusal surface was progressively increased: 100g, 200g, 300g, 400g, respectively: F = 1 N; F = 2 N; F = 3 N; F = 4 N. The following characteristics were measured: Young’s modulus $E$ and Poisson’s ratio ($\nu$). 

RESULTS AND DISCUSSIONS

Results
The most relevant results obtained after FEM analysis is presented in Table 1. The following parameters were evaluated: the values of force stress $\sigma_{zz \text{ max}}$ based on von Mises theory measured at tooth apex; the minimum main stress $\sigma_{zz \text{ min}}$ representing maximum negative values with compression effect at the apex – significant for intrusion; the maximal main stress $\sigma_{zz \text{ max}}$ – maximal positive values with elongation effect specific for extrusion; the maximal displacements on the direction of $Oz - \delta_{zz}$ force at tooth apex. The evaluation of the complex formed by the tooth- enamel-dental pulp is presented in Fig.2 and Fig.3. The displacements produced inside the dental pulp consecutive to extrusion and intrusion orthodontic force stress are described in Fig. 4 and 5. In real situations, the anatomical structures have an anisotropic, non-homogenous and nonlinear behavior therefore must be considered as elasto-plastic materials. Young’s modulus shows the stiffness of the material and describes the way it deforms elastically under axial loading forces. Poisson’s ratio shows the expanding-contracting characteristics of the material.

Table 1. Displacements and stress value measured for the dental pulp

<table>
<thead>
<tr>
<th>Force [N]</th>
<th>Values of dental pulp stress [N/mm²]</th>
<th>Pulp displacements [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stress in coronal direction $\sigma_{zz \text{ max cor}}$</td>
<td>Stress apical direction $\sigma_{zz \text{ max apex}}$</td>
</tr>
<tr>
<td>1</td>
<td>0,000135 8</td>
<td>-0,000468</td>
</tr>
<tr>
<td>2</td>
<td>0,000272</td>
<td>0,000937</td>
</tr>
<tr>
<td>3</td>
<td>0,000475</td>
<td>0,001405</td>
</tr>
<tr>
<td>4</td>
<td>0,000544*</td>
<td>0,01874*</td>
</tr>
</tbody>
</table>

*significant results
Fig. 2. Modified position of the structure, displacement distribution ($\delta$) for a force $F=4$ N

Fig. 3. Modified position of the structure. Distribution of stress equivalent Von Mises $\sigma$ for a force $F=4$ N

Fig. 4. Displaced position of the dental pulp. Distribution of stress according to force direction $Oz$, $\sigma_{zz}$ for $F=4$ N
Fig. 5. Modified position of the dental pulp. Values of the minimum main stress $\sigma_{2\text{ min}}$, for $F=4$ N

The graphic representation of displacement variations according to force direction on the axis $Oz - \delta_{zz}$ and the maximum stress; stress values on force direction $Oz - \sigma_{zz}$, minimum main stress $\sigma_{2\text{ min}}$ with compression effect of periodontal fibres in the periodontal ligament for a force $F = 4$ N are presented in Fig. 6 and Fig. 7.

Fig. 6. Maximum stress values measured at apical level in the dental pulp.

Stress dupa directia foriei in apex
Stress minim principal in apex

Stress maxim in apex PULPA

Stress maxim in apex PULPA [MPa]

1 2 3 4
Forta [N]
Fig. 7. Stress variation measured inside the dental pulp during application of vertical orthodontic forces.

The dental pulp is directly affected by the way the occlusal forces are distributed during vertical orthodontic forces of extrusion and intrusion and the preservation of the complex represented by the tooth-periodontal ligament–alveolar bone depend on the distribution of the forces that act on the dental pulp during tooth displacement due to orthodontic treatment.

Discussion

The stress developed on the tooth surface during its functionality and the responses of dental structures to load have, been studied by sophisticated methods such as the use of mathematical techniques, the use of photo-elastic systems or laser holographic interferometry (11). The main disadvantages of these methods are the evaluation of only surface stress forces and a poor validation rate, according to the current scientific standards. From this perspective, FEM can be applied for the study of stress levels produced inside the dental structures, with the potential to obtain a mathematic equivalent model of a real tooth (12, 13). Data from the scientific literature consider that a three-dimensional model is more suitable in comparison to confident analysis, due to the fact that tooth structures have no symmetry in their material distribution (14-17). Miura and Maeda (18) conducted a study in which a force of 100N was applied horizontally on the buccal area of a tooth and could almost generate avulsion. Although dental enamel does not have a high resistance to trauma, it shows a good capacity of stress absorption and dissipation, the complex microstructure of this hard tissue based on crystalline prisms forms a protective layer. The forces generated in the cervical area might lead to the damage of periodontal structures either by squeezing of the conjunctive fibers or by fracture of the adjacent alveolar bone. Poiate et al (19) considered that the evaluation of the periodontal ligament injury that occurs due to dental trauma can be accomplished by using elastic models that are suitable to simulate the behavior of the tooth supporting tissues. There are a few data in the literature regarding the values of maximum stress load supported by dental pulp during orthodontic
treatment and clinical studies suggested that trauma as concussion or subluxation might cause pulp necrosis. Tanaka et al (20) showed that the dental pulp can withstand forces up to 2.94MPa without signs of pulp damage. Other studies presented the distribution of stress in the root canal and endodontic system of teeth with endodontic treatment or posts; the results showed no statistically significant differences regarding post deformation, root cement disruption for both study groups, with the highest values of stress being recorded at the surface of radicular dentin wall (21). Furthermore, the removal of dentin did not increase the susceptibility to tooth fracture, but the curvature of the root canal was a major factor for stress concentration (22). These studies recorded maximum stress values during lateral loading in comparison with axial forces, while on the dental pulp small values of stress were noted. This study can be included in the group of current research protocols towards a better understanding of the alterations induces by trauma or injury towards the non-aggressive simulations of real biological phenomena. We used a modern method of computer-aided simulation, represented by FEM, currently considered to offer an accurate identification of the structural stress. In orthodontics, the use of FEM is accompanied by many advantages; it enables the application of forces with different directions and intensities in any area of the examined structure; moreover, it creates the possibility to build a three-dimensional model of the tooth, without need of ethical approval.

**CONCLUSIONS**

1. Based on the results of our study, the use of high forces could determine an increased stress in the apical third of the root, which might lead to circulation disturbances or even loss of dental pulp vitality. However, we considered that there is no conclusive scientific evidence for a relationship between force level and severity of dental pulp tissue reactions.

2. There is a need for further clinical studies to support the theory of a force-dependent reduction of blood-flow in the dental pulp of teeth subjected to orthodontic vertical forces. The direction and magnitude of a traumatic force are important factors for the determination of its consequences on the vital tooth.

3. FEM is a viable method for simulations in biological systems, which unfortunately has some drawbacks that make it difficult to transfer the results into the clinical practice.

**REFERENCES**