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Analysis of the Abfraction Lesions Formation Mechanism by the Finite Element Method

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ABSTRACT

Introduction: An abfraction lesion is a type of a non-carious cervical lesion (NCCL) that represents a sharp defect on the cervical part of tooth, caused by occlusal biomechanical forces. The largest prevalence of the NCCL is found on the mandibular first premolar. The goal of the study is, by means of a numerical method – the finite element method (FEM), in an appropriate computer program, conduct a stress analysis of the mandibular premolar under various static loads, with a special reference to the biomechanics of cervical tooth region. **Material and methods:** A three-dimensional model of the mandibular premolar is gained from a μCT x-ray image. By using the FEM, straining of the enamel, dentin, peridontal ligament and alveolar bone under axial and paraxial forces of 200 [N] is analyzed. The following software were used in the analysis: CT images processing–*CTAn program* and FEM analysis–*AnsysWorkbench 14.0*. **Results:** According to results obtained through the FEM method, the calculated stress is higher with eccentric forces within all tested tooth tissue. The occlusal load leads to a significant stress in the cervical tooth area, especially in the sub-superficial layer of the enamel (over 50 MPa). The measured stress in the peridontal ligament is approximately three times higher under paraxial load with regard to the axial load, while stress calculated in the alveolar bone under paraxial load is almost ten times higher with regard to the axial load. The highest stress values were calculated in the cervical part of the alveoli, where bone resorption is most commonly seen. **Conclusion:** Action of occlusal forces, especially paraxial ones, leads to significant stress in the cervical part of tooth. The stress values in the cervical sub-superficial enamel layer are almost 5 times higher in relation to the superficial enamel, which additionally confirms complexity of biomechanical processes in the creation of abfraction lesions.
Key words: abfraction, finite element method, occlusion, stress.

1. INTRODUCTION

Teeth are made of several types of tissue (enamel, dentin, cement, pulp) with various mechanical properties and morphology, which makes analysis of distribution and concentration of stress alongside these structures very complex process (1).

By definition, external forces that act on the body cause internal forces between body particles, so their reduction to a unit of surface represents stress/straining (2).

Stress distribution through a certain structure depends on a shape and mechanical properties of the material through which is distributed, as well as types of stress. Fractures of hard tooth tissue are directly related to stress intensity in a certain period of time (3).

A special clinical appearance called abfraction is in a relation to stress distribution through tooth tissue. Abfraction lesion is a type of a non-carious cervical lesion (NCCL) which represents a microstructure loss of tooth tissue, created under action of occlusal biomechanical forces in the area of the highest stress concentration, that is, in the cervical region.

Constant tension and compression of this area result in severing chemical bonds among hydroxyapatite crystals of enamel and dentin, allowing small molecules to penetrate, which prevent re-establishing of bonds (4,5)

Such a loss of hard tooth tissue in the cervical area Grippo (6) 1991 named abfraction, so that these le-

Figure 1. *Abfraction lessions*

sions could clinically differentiate from lesions caused by erosion and abrasion.

Abfraction lessions are typically shaped as a wedge-shaped tissue defect, with sharp internal and external edges (Figure *1)*. Incidence of non-carious cervical lesion rises with patient's age, which also points out to the tissue fatigue component through a longer period of time (1,7).

The mandibular first premolar is the tooth with highest prevalence of non-carious cervical lesions (7,8,9). A specific morphology and occlusion of this tooth surely significantly affect these results.

2. MATERIALS AND METHODS

Intact mandibular first premolar was scanned by a μCT 1076 SkyScan scanner (Kontich, Belgium)(10,11) at the Center for Translational and Clinic Research, School of Medicine of University of Zagreb. The images were reconstructed using Nrecon (ScyScan) program into transaxial sections. By scanning, then by additional reduction of input data, around 576 horizontal sections 0,0361 [mm] thick, with a clearly visible internal tooth structures (resolution up to 758×758 px in each section) were chosen for the reconstruction of 3D model *(Figure 2)*. Data was analyzed by CTAn program (SkyScan).

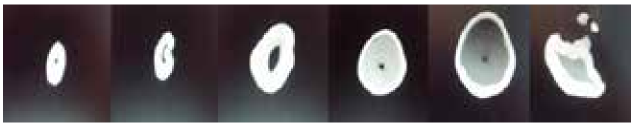

Figure 2. *Micro CT images of the mandibular first premolar*

Based on the μCT section, pre-processing of the data and generating a volumetric 3D CAD tooth model was conducted. For that purpose, program packages *Matlab, CreoParametic 1.0* was used.

This way, two 3D solid models of enamel and dentin were obtained, which are in mutual contact alongside the entire dentin enamel junction. On the other side, the pulp is modeled as an empty space, since Young's modulus of pulp elasticity is negligibly small in relation to adjacent structures. The peridontal ligament is modeled as a membrane 0.3 mm thin, which surrounds the root of the tooth, which corresponds to real anatomic values (12), and additionally a segment of the alveolar bone is modeled (Figure 3).

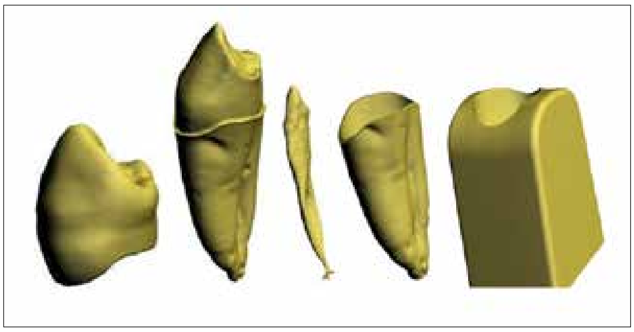

Figure 3. *Three-dimensional volumetric tooth tissue models reconstructed from μCT images; (a) enamel, (b) dentin, (c) pulp, (d) periodontal ligament (e) reconstructed segment of the alveolar bone*

Previously modeled 3D volumetric tooth structures are linked in one unit–a complex model. Mutual relation of elements as well as boundary conditions are defined. Using *AnsysWorkbench, a* finite element mesh of the complex model is formed and the tooth model is divided into finite elements, namely: for volumetric bodies Solid187, for contact areas Targe179 and conta174, and for boundary conditions and area of the force action a Surf154 type net. The size of the basic element of meshed model was 0.1 mm, so that the model consisted 747157 knots and 439113 elements (Figure 4).

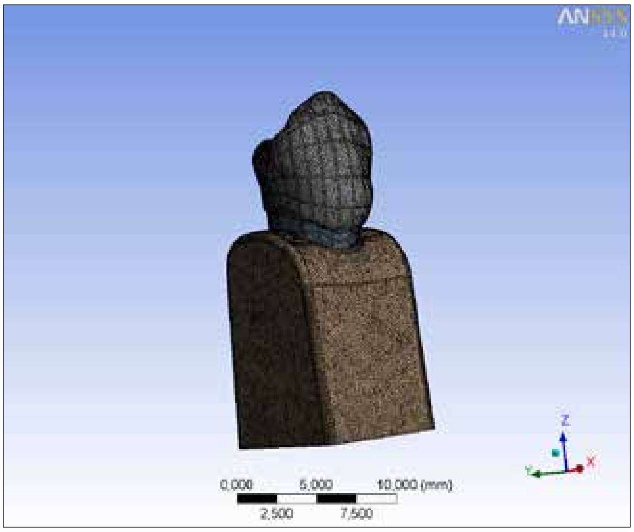

Figure 4. *Image of the finite elements mesh*

Characteristics of the materials used in the research, obtained after a detailed literature research are, given in *Table 1.* For the purpose of the analysis, it was assumed that all materials are isotropic, homogenous and linearly elastic.

Material	Young`s modulus of elasticity [MPa]	Poisson koefficient	Literature source
Enamel	84 000	0.30	12
Dentin	18 600	0.31	12
Periodontal ligament	50	0.49	13
Alveolar bone	13700	0.30	14

Table 1. *Material characteristics*

The load is distributed to regions that correspond to antagonists contacts in the central occlusion (Figure 5a). For the purpose of presenting actions of the paraxial load, a laterotrusive movement of the mandibular first premolar, at 40° angle on the external side of the buccal cusp (14, 16) (Figure 5b) was simulated. The values of the maximum simulated load were 200 [N] (3,17,18), and it is assumed that the character of force action is static.

The tooth tissue tension values were calculated by the Finite Element Method, which proved to be an adequate method for predicting the biomechanical behavior of the tooth under load (19). The analysis was done in the *AnsysWorkbench 14.0* program package. There are various criteria to grade stress in

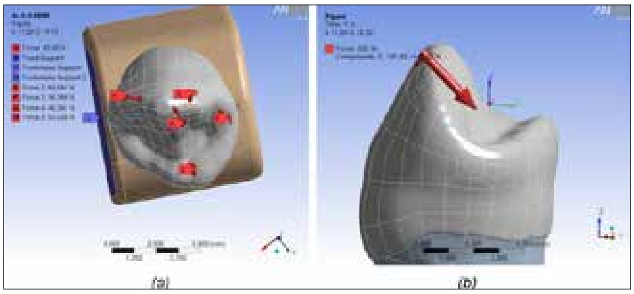

Figure 5. *Image of contact tooth regions in (a) central occlusion (b) laterotrusion*

a material, and with it, to evaluate possible material breaking. In bodies of complex morphology, such as teeth, it is a very rare occurrence to find a single type of stress (straining, compressive or shearing). Almost always, it is a case of combined action of the aforementioned stresses, which results in complex stress. For that reason, in order to show the complex stress the hypothesis of the highest distortion energy (Von Mises stress) was used, which allows determining the total of resulting stress in every point of the observed object – tooth element.

3. RESULTS

Results obtained by the finite element method are represented in the form of relevant images where the stress values are presented through a color scale, which allows a clear visual image with numeric stress

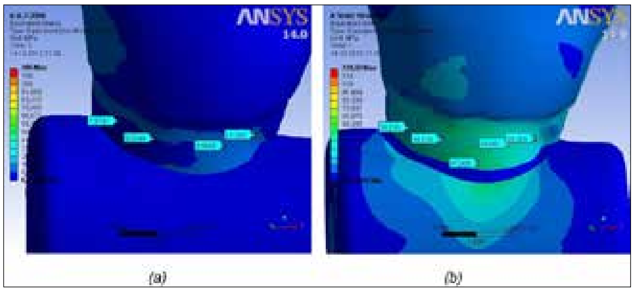

Figure 6. *Stress distribution in the cervical part of the tooth under (a) axial (b) paraxial load of 200 [N]. The values of Von Mises stress in the cervical part of the tooth are almost 5 times higher under the paraxial than under axial load.*

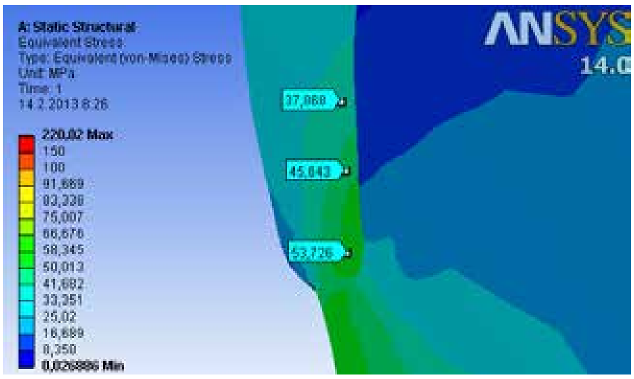

Figure 7. *Stress distribution on the sagital section of the intact tooth under paraxial load of 200 [N]. It was noted that stress values in the cervical part of the tooth are higher in the sub-superficial than in the superficial area of the enamel, which suggested that the initial breaking off of the enamel might happen exactly in these layers.*

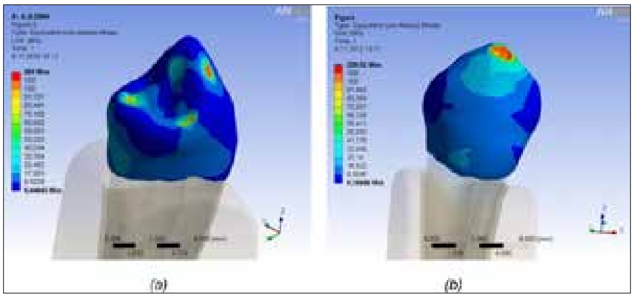

Figure 8. *Stress distribution in the enamel under (a) axial and (b) paraxial load of 200 [N]. Maxumum values of Von Mises stress obtained on the tooth model are spotted in the enamel under the paraxial load in the contact region.*

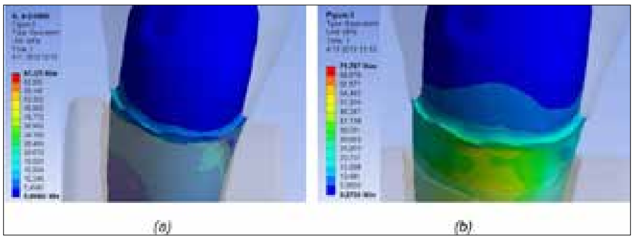

Figure 9. *Stress distribution in the dentin under (a) axial and (b) paraxial load of 200 [N]. There is a significant difference in the stress of the cervical part of dentin under axial in relation to paraxial load.*

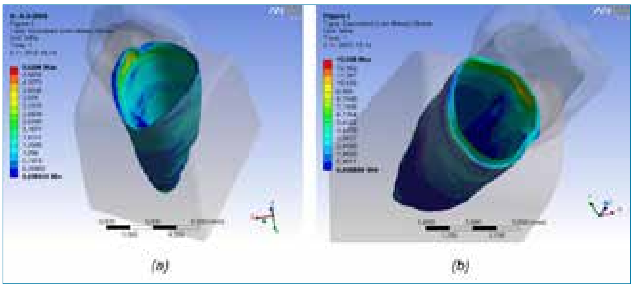

Figure 10. *Stress distribution in the peridontal ligament under (a) axial and (b) paraxial load of 200 [N]. Stress values in the peridontal ligament under paraxial load are almost three times higher than the ones in the central occlusion.*

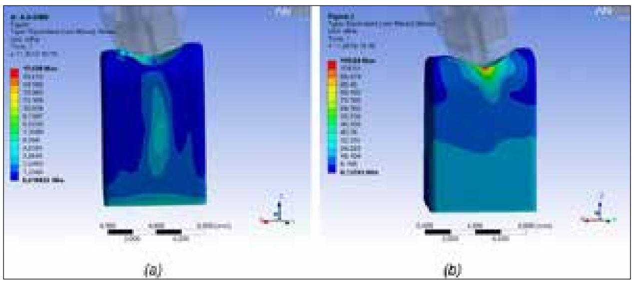

Figure 11. *Stress distribution in the alveolar bone under (a) axial and (b) paraxial load of 200 [N]. The measured stress under paraxial load is almost ten times higher than the ones in the central occlusion. The highest bone stress is spotted alongside the upper edge of the alveolar socket.*

values (the left side of the image). It is necessary to mention that the given selected values represent extreme calculated values.

4. DISCUSSION

This research presents effects of two types of occlusal load on the intact tooth. Since the contact surface and masticatory force intensity are extremely variable, two types of occlusal contacts (Figure 5 a and 5 b) were chosen in order to show effects of a favorable and unfavorable situation for the tooth and surrounding tissues.

Results of this research show that calculated stress values on tested models are higher with eccentric forces in all tooth tissues. Maximum load on the tooth model under both types of loads are spotted in contact regions, that is, region of force action, and under axial load measured 205 [MPa] *(Figure 8 a)*, and under paraxial load 220.02 MPa *(Figure 8 b)*.

The result of high stress values on a small surface, the contact region, is in accordance with Anusavice's (21) claim who, with that, explains wearing out of occlusal composite fillings.

The action of occlusal forces led to a significant stress in the cervical region of the tooth. The calculated Von Mises stress in the cervical tooth part under axial load is not high and measure up to 12 MPa (Figure 6 a), whereas the stresses in the same part of the tooth under paraxial load are significantly higher and measure over 50 MPa *(Figure 6 b),* which corresponds the results of the study of Poiata et al (22).

The elasticity modules of enamel and dentin are different, so the occlusal load is dominantly transferred through the enamel because of a far greater hardness (23). Significantly lower values of Von Misses stress are measured in the dentin in relation to the enamel and measured 67.72 for axial *(Figure 9 a)* and 71.78 MPa for paraxial load *(Figure 9 b)*. The highest stress is spotted in the crown and the cervical part of the tooth and reduces towards to tooth apex.

By analyzing forming mechanisms of abfraction lesions Rees and Hammadeh (24) presented a theory of a possible undermining of the enamel due to stress concentration on the dentin enamel junction.

The results of this research confirm observations of aforementioned authors, since the values of calculated stress in the cervical part of the tooth are higher in the sub-superficial than in the superficial region of the enamel *(Figure 7),* which indicates that breaking of the bonds between enamel prisms might occur in these layers exactly. Cervical lesion progression can additionally be improved through erosion and abrasion. Also, microscopic studies show that the sub-superficial enamel is structurally inferior, with a lower percentage of a mineral component, a higher percentage of protein and higher porosity compared to the superficial layer (25).

The periodontal ligament (PDL) is an extremely important tissue in tooth movement evaluation. The role of the PDL cannot be ignored in an attempt of imitating a real situation. Maximum stress values in the PDL are spotted alongside the upper edge of the ligament, in cervical part of tooth, for both types of load. The calculated stress under load in the central occlusion equals ≈ 5 MPa *(Figure 10 a)*, whereas under the paraxial load it is almost three times higher and equals ≈ 13.5 MPa *(Figure 10 b)*. The calculated values are not high thanks to the fact that the PDL is made of discrete collagen fibers, which allows a high-elasticity behavior under load, that is, works as a stress-absorber (26). A small difference between spotted stress intensity under two types of load proves that the PDL well absorbs paraxial forces.

In the alveolar bone, the highest stress was registered alongside the top of the tooth socket. The calculated bone stress under paraxial load equals ≈ 112 MPa *(Figure 11 a)* and are almost ten times higher than under axial load whose values equal ≈ 17 MPa *(Figure 11 b)*. This results clearly presents the mode of transmission eccentric occlusal forces onto surrounding alveolar bone structures, as well as their role in the possible creation of bone resorption.

5. CONCLUSIONS

The largest influence on stress intensity has the type of loading the teeth. Calculated stress values on tested models are higher with eccentric occlusal forces in all tooth tissues.

Occlusal load, besides in the contact region, leads to occurrence of significant stress in the cervical part of the tooth. Stress values in the sub-superficial layer of the cervical enamel are almost 5 times higher in relation to superficial enamel.

Stress under occlusal forces is dominantly transferred through the enamel where the highest stress values were measured.

Stress calculated under paraxial load in the periodontal ligament is almost three times higher than stress obtained in the central occlusion.

Stress calculated under paraxial load in the alveolar bone is almost ten times higher than stress obtained in the central occlusion. The highest stress in the bone is spotted along the top edge of the alveolar socket.

This research give a clear image of stress distribution in one moment of tooth straining, and represents a good basis for observation and conclusion of cause-effect links during creation of lesions, but still many questions will remain open. They rely on the fact that the acting force in this research is assumed as a static, not a dynamic occurrence, with a relatively large number of repetitions, as it is in reality.

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CONFLICT OF INTEREST: NONE DECLARED.

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