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3-D Stress Analysis in First Maxillary Premolar

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A B S T R A C T

The aim of this study was to investigate the stress distribution in a 3-D model of two-rooted tooth (first maxillary premolar) under two different occlusal force vectors by using finite element analysis. In the first model overall force of 200 N was divided into three vectors (cusp to fossa occlusion), and in the second model overall force was divided into 4 vectors (cusp to fossa and cusp to marginal ridge occlusion). The greatest compressive stress was found at the dentino- enamel junction in the cervical area of the both models (about –200 MPa). The greatest tensile stress was found at the vestibular aspect of buccal cusp in second model (about +3 MPa) and in the central fossa of the both models (about +28 MPa). Results indicate that in the both types of occlusal loadings the stress distribution was mainly compression and compressive forces were predominant over tensile stresses. In the second model with 4 vectors, stresses generated in the tooth structure were higher compared to the stresses generated in the first model with 3 vectors.

***Key words**: finite element analysis, first maxillary premolar, stress distribution, two-rooted tooth*

Introduction

Teeth and their periodontal ligaments (PDL) transmit masticatory forces to the alveolar bone. Each tooth consists of different tissues, such as enamel, dentine, pulp and cementum. Therefore the human tooth has been considered as a non-homogenous structure. For that reason it is difficult to understand the role and the mechanism of occlusal load distribution. Moreover, it is important to reveal the role of each tooth and it's PDL and a pathway of the stress distribution, which is conducted along the tooth towards the alveolar bone, as well as the pattern of stress distribution[1]. Human teeth are susceptible to various changes throughout life. The potential for tooth fracture is related to the magnitude of stresses over a period of time[2]. An important factor in stress analysis of human teeth is the clinical response of enamel and dentin during mastication. Different stress values between buccal and lingual enamel require analysis related to functional cusp enamel and non-functional cusp enamel[3]. Cusp fracture of posterior teeth is common phenomenon in dental practice. Recent clinical studies have shown that cervical lesions are most commonly found on the buccal surfaces of premolars[4,5]. Some authors have proposed that large tensile stresses elicited by occlusal loading may cause a loss of tooth structure[6,7]. For maxillary premolars, loadings elicited by contacts in centric occlusion will be transmitted almost along its long axis[7]. The significance of occlusion in clinical practice has not received attention proportional to its importance. The relations of the teeth contacts are important for both, function and stability. The durability of the tooth largely depends on the type of occlusion and type of occlusal stress distribution[8].

In the last two decades many studies have shown how the 2D finite element analysis (FEA) applied to dental mechanics has become a popular numerical method to investigate the critical aspects related to stress distribution[7,9–12]. The use of more detailed 3D models could be helpful to understand critical problems related to the restorative material choice and optimal application procedures. Few studies using 3D models have been described in the literature[1,13–17]. The experimental models of natural teeth should include anatomic variations and the het-

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erogeneous structure of the tooth, which is even more complex in multirooted teeth[18]. Little is known about the 3D distribution pattern over the entire two-rooted first maxillary premolar under occlusal loadings. Conventional methods such as photoelasticity and the strain-gauge methods are inadequate to predict reliable stress distribution in the tooth[19–21]. FEA has been used in dentistry as it represents detailed simulated tooth mechanical behaviour under occlusal loads. Stress, strain and some other qualities could be calculated in every point of the structure. The 3D method permits high efficiency when the biomechanical behaviour of the structure should be evaluated under different loading conditions[13,17]. Teeth differ from each other, and this usually results in large standard deviations of the determined mean values[22]. Teeth variations and different laboratory models result in difficulty to compare different results. Compared with cyclic loadings and other dynamic loadings during different laboratory testings[23], FEA offers several advantages: variables can be changed relatively easily, no costly prototypes are need to be manufactured, and the simulations can be performed in vitro.

The aim of this study was to investigate stress distribution in a 3-D model of a human two-rooted maxillary first premolar, it's PDL, and the surrounding bone tissue under the occlusal loading in two different occlusal conditions by applying the FEA. In order to accurately describe the stress distribution, the aim was also to create a very detailed 3D model consisting of a large number of nodes, elements and connecting surfaces.

Materials and Methods

An intact human maxillary first premolar, which was extracted for orthodontic reason was embedded in the red epoxy resin (Palavit G, Heraeus Kulzer GmbH, Wehrheim, Germany) and sectioned perpendicular to the long axis in 1.3 mm intervals (Isomet™ 1000 Precision Saw, Buehler Ltd., Illinois, USA). Each of the 20 sections was digitally photographed (FujiFilm, FinePix S1 Pro, Kanagawa, Japan). Advancing to cross-sectioning, fixed point has been marked at the bottom of fixating device. The point has been kept visible at all photographs and served as a reference in the x- and y-coordinate system (in-plane coordinate system). Besides, z-coordinate has been determined knowing the distance between each crosssection (1.3 mm), and their sequence. The 3D geometry of the tooth was reconstructed from these cross-sections by using the computer program AutoCAD Mechanical Desktop (v. 4.0, AutoDesk Inc., San Rafael, CA, USA). Detailed information about the creation of this model was described in previously published article[7]. The outline of the periodontal ligament 0.3 mm wide and the surrounding alveolar bone was generated using the outline of the tooth as a guide. The solid model was transferred into a FEA program NASTRAN (v. 2002, MSC Software Corporation, Santa Ana, CA, USA); a 3D mesh was created, and the stress distribution analysis was performed. Boundary conditions have been established on surrounding bone. The bone is clamped (all displacements fixed), thus preventing rigid body displacements in directions of all three coordinate axes. Furthermore, this corresponds to physical conditions, where the displacement of the rest of the structure is negligible. Besides, it was necessary to restrict the motion of tooth in a direction normal to the neighbouring teeth. This has been implemented in the model through appropriate boundary conditions (prevented displacement in the direction of normal to the joint contact surface).

Four nodded tetrahedral elements were applied in the discretization of the tooth morphology, resulting in 1 684 512 elements and 246 510 nodes with a total of 739 530 degrees of freedom. The mechanical properties of the enamel, dentine, bone and periodontal ligaments are shown in Table 1.

TABLE 1
PHYSICAL PROPERTIES OF THE MATERIALS USED IN THE STUDY

Material	Young's modulus (GPa)	Poisson's ratio	Reference
Enamel	80	0.3	(8)
Dentine	18.6	0.31	(22)
Pulp	0.0021	0.45	(27)
Periodontal ligament	0.0689	0.45	(22)
Bone tissue	12	0.3	(22)

Each of various tooth tissue was assumed to be isotropic, homogeneous and elastic under applied loads. The first trial comprised loading of 3 occlusal points acting on the palatal and the buccal cusp (cusp to fossa occlusion), and the second trial comprised loading of 4 occlusal points acting on the palatal cusp and on the marginal ridges (acting on the palatal and the buccal cusp and marginal ridge) (Figure 1 and 2). A total force of 200 N was applied in each trial. The load vectors were applied in such a direction towards the occlusal surface in order to simulate the contacts with antagonistic teeth. In addition, boundary conditions of the model simulated the contact with neighbouring teeth.

Results

Differences were determined for the stress distribution between the two models under different loading conditions (Figure 1 and 2). In the first model the compressive stress values ranged from 0.4206 to 175.222 MPa, and the tensile stress values ranged from 0.2 to 28.2 MPa. In the second model the compressive stress values ranged from 0.4247 to 224.694 MPa, and the tensile stress values ranged from 0.6 to 27.077 MPa. In general, the whole tooth complex was under low compressive stress (about 0.5 MPa). Larger compressive stresses were found in enamel at the force application point and in the cervical enamel and dentine. Tensile stresses were found

Fig. 1. Stress distribution in the tooth with cusp 3 point loading. Color scale show values in MPa.

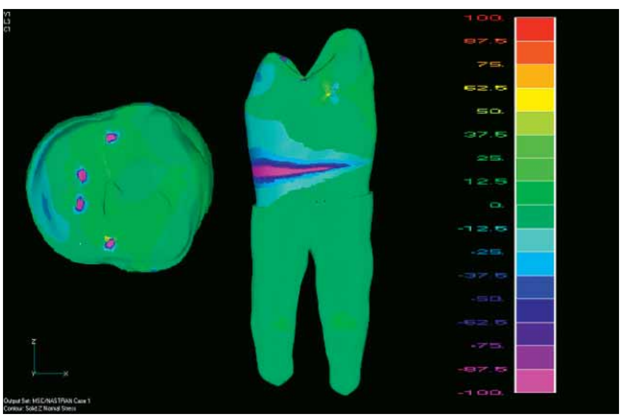

Fig. 2. Stress distribution in the tooth with 4 point loading. Color scale show values in MPa.

in the enamel in the central occlusal area (in the fissure system and in the adjacent area of the enamel) and at the vestibular surface of the buccal cusp. In the second model stress values were higher than in the first model, except for the buccal cervical area where the stress value was lower (Table 2).

Discussion

The FEA is a method in which geometry of the subject to be analysed is described through a certain number of geometrical entities (elements) connected in nodes. The stress and strain distribution is derived from displacements calculated in each node[24]. This method permits response evaluation of a natural system under various loads and conditions[25,26]. The human teeth cannot be represented through the two FEA dimensional model. Therefore, the actual and structural response cannot be simulated without considering the third dimension. In contemporary literature only few studies investigated stress distribution using a 3D FEA models of premolars with two roots, but without the periodontal ligament or the supporting bone tissue[13,15,16,27]. None of the studies demonstrated compressive stress distribution at the cervical region in both, enamel and dentin, which is different from the results of the present study. The reason might be attributed to a less complex finite element models and/or different force vectors applied. Different results could also be caused by a lack of clear definition of the connection between elements of the model, such as dentino-enamel junction at the tooth cervics. For accurate modelling of dentino-enamel connection, it is necessary to join several geometries with different morphology and magnitude, which has been successfully performed in the model, which was used in this study through a large number of elements. The models previously used had 11 165 elements and 7 340 nodes or less versus 1 684 512 elements and 246 510 nodes in the model used in the present study[15,16,28,29]. The present study not only included PDL, pulp and bone tissue, but it also simulated the contacts with neighbouring teeth. Simulation of contacts with neighbouring teeth was found only in one study, but a different tooth had been used for loadings[1].

TABLE 2
MAXIMUM STRESS VALUES IN MPA IN DIFFERENT PARTS OF THE TOOTH

	3 point loading	4 point loading
Palatal cervical area	–175.222 MPa	–224.694 MPa
Buccal cervical area	–76.4147 Mpa	–17.6418 MPa
Occlusal fossa	+28.2008 Mpa	+27.0774 MPa
Buccal cusp	+0.2374 Mpa	+3.0777 MPa
Vestibular root	–0.6311 MPa	+0.6067 MPa
Bone tissue	–0.4206 MPa	–0.4247 MPa
Other parts of the tooth	–0.5334 MPa	–0.9261 Mpa

positive sign indicates tensile stress (+), negative sign indicates compressive stress (–)

Differences between stress distribution in the two different models confirm that position of contacts on the occlusal surface and the direction of loading may contribute to the development of different stresses.

Most of the failure of dental materials used for tooth restorations was caused by tensile stress[28]. Occlusal adjustment of teeth occlusal surfaces should be performed to prevent it[7]. The results of this study showed that the enamel and dentin in the cervical area and the occlusal enamel are the parts bearing the highest stress, which is in agreement with other authors[1,2,6,8]. The results of this study also show that tensile stress was smaller than compressive stress, which is also in agreement with other studies[1,15,16,28]. However, comparison of stress distribution between various FEA studies is difficult because of different morphology and/or teeth tested, as well as different loadings and vectors used.

The 200 N loads used in this study were chosen, as average chewing force, which is supposed to be the one third of the maximum biting force[30]. Axial test simulations predicted that tooth fracture might occur between 700 and 800 N under compressive load[16].

The tensile character of stresses inside the enamel in the fissure system might contribute to the development of initial caries. Larger tensile stresses causing disruption of the bonds between the hydroxyapatite crystals and leading to separation of the enamel[6]. Compressive character of stress in cervical area of the tested tooth might lead to separation between enamel and dentine[13]. The stress concentration is mainly due to the combination of axial and bending stresses in compression. The compressive stresses were considerably higher at the palatal cervical area and smaller at the buccal cervical area in the second trial, compared to the first trial. This could be the result of tooth bending caused by a perpendicular component of loadings to the longitudinal axis. Results of Goel et al.[13] showed low compressive stress values located in the cervical enamel area (5.67 and 6.25 MPa), while Verdonschot et al.[27] demonstrated only stress distribution within a filling material. Ausiello et al.[15] found stresses of 100 MPa at the cervical region, but only within dentine, while the compressive stress values within enamel were significantly lower. Stress values for occlusal surface were also higher in the study of Ausiello et al.[15], compared to our results, although no distinction between compressive and tensile stress was made. They presented values in Von Mises, the physical parameter that combines the effects of each of the normal and shearing stresses into a single one. The results of the present study demonstrate both compressive and tensile stress distribution at the occlusal surface. Therefore, the results of the present study add to better understanding of stress distribution in the upper first premolar and its supporting structures under occlusal loads applied at the two most common antagonistic contact areas. Furthermore, the newly developed 3D FEA model and the results obtained by this research might be referent values for future investigation of stress distribution within various types of reconstructions and prosthodontic appliances on the first maxillary premolar.

Conclusion

The FEA model used in this study visualized stress distribution in the intact two rooted first maxillary premolar during occlusal loading. Results indicate that both, 3 point and 4 point loadings presented stress distribution mainly as compression. In the case of cusp to marginal ridge occlusion (4 point loading), stresses generated in the tooth structure were higher compared to the stresses generated in the case of cusp to fossa occlusion (3 point loading).

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3-D ANALIZA NAPREZANJA PRVOG GORNJEG PREDKUTNJAKA

SAŽETAK

Svrha ovog rada je istražiti raspodjelu naprezanja na trodimenzionalnom modelu dvokorjenskog zuba (prvi gornji predkutnjak) uzrokovanu dvjema različitim okluzalnim vektorima sile koristeći metodu konačnih elemenata. Na prvom modelu sila od 200 N je podijeljena u 3 vektora (kontakti kvržica i fisura), a na drugom modelu je sila podijeljena u 4 vektora (kontakti kvržica i fisura te kvržice i marginalnog grebena). Najveći tlačno naprezanje je na caklinsko-cementnom spoju u području vrata zuba u oba modela (oko –200 MPa). Najveći vlačno naprezanje je na vestibularnoj strani bukalne kvržice na drugom modelu (oko +3 MPa) i u središnjoj jamici oba modela (oko +28 MPa). Rezultati upućuju da je u oba tipa okluzijskog opterećenja raspored naprezanja uglavnom tlačno naprezanje i takvo naprezanje dominira nad vlačnim. Na drugom modelu sa 4 vektora naprezanje u zubu je veće u usporedbi sa naprezanjem proizašlim iz modela sa 3 vektora.