Finite Element Method Stress Analysis Caused by Orthodontic Forces

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Summary

The method of finite elements has proved to be successful for analysis of the transmission of forces and stress in biological systems. The aim of this investigation was to determine differences in the distribution of stress and deformation, depending on different levels of application of simple horizontal orally directed forces on the labial surface of the tooth using a mathematical model of the tooth, with equivalent supportive structures, constructed means of the finite element method. An upper canine, extracted for periodontal reasons, was used as a pattern for construction of the model. A three-dimensional model was obtained consisting of 4000 elements in the shape of a hexahedron and 2367 nodes, totalling 7101 grades of freedom. Horizontal orally directed 1 N force, was applied to the model on five different levels of the tooth crown, vertically on its longitudinal axis. Deformation and stress intensity were observed for all the applied forces and equivalent stress calculated, according to the energetic theory of strength (Huber-Mises-Hencky theory).

Key words: *stress, deformation, finite element method.*

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Introduction

The finite element method has proved successful in analysis of the transmission of forces and stress in biological systems (1-15). The problem of the transmission of forces and stress on teeth and surrounding tissue is complex due to the inhomogeneous character of the structures of which they are constructed and irregularity of contour, and also their external form and complex internal morphology. Each tooth consists of several different tissues: enamel, dentine, pulp, cement and the periodontal ligament connected to surrounding bone. Each of the above tissues has essentially different characteristics and properties (16). A true and firm mechanical body, such as the tooth, changes its form under the influence of external forces, during which additional internal forces take place among the molecules in the interior of the body. The changed form is defined as deformation, while the additional forces among the molecules are defined as stress. Final movement of the body, as a whole, or its particular parts, occurs as a result of the external forces (17). All these factors (forces, deformation, stress and movements) are mutually connected. Thus, by determining any one of them the extent, amount, interval and intensity of the remaining physical factors can often be concluded (18). The initial reaction of tissue will be mechanical and will depend, with regard to quality and quantity, on the above characteristics of force, and also the characteristics of the tissue itself on which they are transmitted. Their effect is decisive for the biological reaction which follows the mechanical reaction (5).

There is still insufficient knowledge of the magnitude, direction and distribution of the forces applied in orthodontic therapy and also their effect on the tooth and surrounding supportive structures. Thus, the aim of this investigation was to attempt to determine differences in the distribution of stress and deformation, depending on the different level of application of simple horizontal, orally directed forces on the labial surface of the tooth, using a mathematical model of a tooth with appropriate supportive structures, constructed by using the finite element method. The investigation is one more attempt to approach the problem of the effect of forces on biological tissue by using a biomechanical method, and therefore all obtained results should be interpreted thus.

Sample and methods

An upper canine, extracted for periodontal reasons, served as the pattern for construction of a mathematical model. After the tooth had been well cleaned it was placed in transparent acrylic. Layers 0.5 mm thick were ground off, vertically on the longitudinal axis of the tooth by a paralelometar-freza (Combilabor CL-MF, Hereaus-Hanau). Each section was recorded by a video camera, Sony CCD TRV 825 E Hi 8 mm. Sixty photographs of the tooth sections were taken. The camera was connected to a computer (PC Pentium II 64 Mb RAM, 350 MHz, 8.4 Gb HDD) via a S-VHS cable, and a frame grabber - video adapter used for digitalisation of the photographs (Ima Scan, resolution 1024-768 in PAL format with 625 horizontal lines and 16 Mb video memory). The photographs were digitalised in the ISSA programme, developed by the VAMS company in cooperation with the School of Dental Medicine University of Zagreb. In this way 60 cross-sections of the tooth were defined and registered in BMP format. The defined contours of the cross-sections of the tooth were read into the CAD programme AutoCAD Mechanical Desktop 2.0, where the three-dimensional geometry was defined from the curve of the cross-section of the tooth by "lofting" method.

The drawings were converted into standard IGES format, which ensured their readability in different CAD applications, including the NISA programme, in which calculation was performed by the FEM. Thus a three-dimensional mathematical model of the upper canine was obtained, on which periodontal ligament was modelled for the length of the whole root, 0.25 mm in width. After which supportive bone was modelled. The compact layer modelled was 2 mm thick, with underlying spongy bone Each of the segments was allotted an equivalent isotropic material model, as shown in Table 1. Three-dimensional hexahedron elements were used for modelling, with six nodes and three grades of freedom per node (movements in the direction of three mutually vertical axes). The whole model comprised 4000 elements in the form of a hexahedron, and 2367 nodes, making a total of 7101 grades of freedom for the whole model (Figure 1) (19). Horizontal, orally directed force, strength 1 N was applied to the model on five different levels of the tooth crown, vertically on its longitudinal axis. Deformation and stress intensity was observed for all the applied loads and equivalent stress, calculated according to the energetic theory of hardness (Huber-Mises-Hencky theory). The results of the calculation are shown in figures, registered in GIF format (Figure 2-10).

Results and discussion

The choice of Young's module and Poisson's coefficient was particularly important in the construction of the mathematical model, i.e. determination of the mechanical characteristics of the material of which the structures included in the model were constructed. A large number of different values can be found in the literature for the mechanical characteristics of material used in biomechanical investigations (20-23). Therefore, in order to obtain a clearer picture of such mutually different values, separate tables were produced for Young's module (Table 2) and Poisson's coefficient (Table 3). The module of elasticity, i.e. Young's module, represents the ratio of stress and deformation, and for bone, enamel and dentine is in the order of magnitude GPa, i.e. 10^9 Nm^{-2}, while for the periodontal ligament the order of magnitude 10^6 Nm^{-2}.

Table 2 shows that great differences for these values can be found in the literature. Such differences are primarily the result of different methods by which they were determined, i.e. depending on whether they were examined by compressive, tensile, pressure or ultrasound method. Differences even occurred within each method, depending on the speed and direction of the applied force, or on the frequency, when the examination was performed by ultrasound method. Another important factor that influences the value of module elasticity is dampness of the examined material. Different results are obtained when the mechanical characteristics are determined on a preserved and dried specimen and again different when a fresh and physiologically damp specimen is used. The strength on tension and compression and module elasticity in the process of tension and compression varies between fresh and preserved specimens from 1% to 6% (17). The results of analysis of the mechanical characteristics of enamel, dentine and bone depend on the type and structure of the examined material, followed by the relationship of the organic and inorganic part and age. Differences between the values of the module elasticity for bone are small. Values for dentine range from 11.76 - 20.7 x 10^9 Nm^{-2}. The greatest differences in the values of module elasticity are those for periodontal ligament, which occur because of the choice of sample, i.e. its intactness. In healthy, intact periodontal ligament hydraulic effect has an important role. The values of Poisson's coefficient (Table 3) for enamel, which can be found in the literature, range from 0.30 to 0.33. The differences of these values for dentine are negligible and range from 0.30 to 0.32. Such small differences have no influence on the final result. In all available reviewed investigations Poisson's coefficient for pulp was used, value 0.45, which indicates its structure of mainly connective tissue. However the authors probably partially disregarded the fact that the remaining area of the pulp chamber and root canal is filled with tissue liquid and blood. As the liquid is not compressive its Poisson coefficient is 0.50.

In this investigation the individual structures of the tooth were not taken into account. The tooth was treated as a whole and the average value of Poisson's coefficient was taken of 0.30. In the literature the values of Poisson's coefficient for periodontal ligament vary and range from 0.30 to 0.49. The value of 0.30 is in fact for enamel, while the value of 0.49 relates to soft tissue. Because of the liquid with which the connective tissue of the periodontal ligament is permeated, the optimal value of Poisson's coefficient should be 0.49. Therefore, this value was used in the present investigation. The liquid which fills the closed space also has an influence on the value of Poisson's coefficient for bone. Thus, the minimal value found was 0.30, which shows that the coefficient was determined on isolated bone structure, while the value of 0.38 includes the liquid within the bone cavity. Taking this into account in the present investigation the value of Poisson's coefficient chosen for both cortical and spongy bone was 0.30.

In this investigation horizontal orally directed force, strength 1 N was applied on five different levels of the tooth crown, vertically on its longitudinal axis. The result of the effect of such force is simple leaning-tipping of the tooth (34-37). During such movement the angle of the longitudinal axis of the tooth changes. The most frequent clinical situation, in which such an effect of force and tooth movement occurs, is retrusion of the frontal teeth, helped by the labial arch on a removable orthodontic appliance (activator or active plate).

With the application of force strength 1 N below the tooth apex, the greatest stress was recorded of 2.58 MPa, located exclusively at the place of the force effect and its intensity decreased in concentric circles (Figure 2, 3). If force strength 1 N effects the labial surface of the tooth 2 mm under its apex, the maximal stress amounts to 2.62 MPa and occurs at the place of the effect of the force. In this experiment stress of 0.75 MPa was also recorded in the area of the neck of the tooth and on the oral and palatal side (Figure 4, 5). Force strength 1 N, which effects the labial surface of the tooth 4 mm under its apex causes maximal stress of 0.49 MPa at the place of the force application. Stress of 0.14 MPa was recorded in the area of the labial surface beneath the place of the effect of force, and also on the palatal side of the tooth (Figure 6, 7).

In the fourth experiment force strength 1 N was applied in a horizontal direction 6mm from the tooth apex. The result was maximally recorded stress of 0.37 MPa at the place of the force effect. Stress of

0.11 MPa was recorded on the whole circumference of the tooth beneath the place of the application of force (Figure 8, 9). As a result of the effect of force strength 1 N on the neck of the tooth maximal stress of 0.40 MPa occurred at the place of the force effect (Figure 10, 11).

Finally, it is important to point out that in the present investigation the duration of the effect of force was unimportant, and therefore the results can only be applied in the initial phases of the effect of force on the tooth. It should be emphasised that the finite element method does not give completely precise results and on the whole does not represent the true condition, but rather is one more attempt to approach this problem.