THE ANALYZE BY FINITE ELEMENT OF STRAINS IN PERIODONTAL LIGAMENT AND ALVEOLAR BONE DURING ORTHODONTIC TOOTH MOVEMENT

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ABSTRACT
Orthodontic tooth movement (OTM) is achieved by applying an orthodontic force system to the brackets. The (re)modeling processes of the alveolar support structures are triggered by alterations in the stress/strain distribution in the periodontium. The aim of the present investigation was therefore to use the FEM, for to determine the influence of force magnitude in the stress and strain distribution in the alveolar support structures. Human jaws segments obtained from autopsy were micro CT-scanned and sample-specific finite element (FE) models were generated. The material behaviour of the PDL was considered to be nonlinear and non-symmetric and the alveolar bone was modeled according to its actual morphology. A series of FE-analyses investigated the influence of the moment-to-force ratio, force magnitude, and chewing forces on the stress/strain in the alveolar support structures and OTM. Stress/strain findings were dependent on alveolar bone’s morphology. Because of the nonlinear behaviour of the PDL, distinct areas of tension, and compression could not be detected. Secondary load transfer mechanisms were activated and the stress/strain distribution in the periodontium was concealed by occlusal forces. The finite element method (FEM) has proved to be a valid and reliable technique for the calculation of the local state of deformation and loading of complex structures. Because roots and alveolar bone morphology are patient specific, FE-analysis of orthodontic loading regime should not be based on general models.

Key words: finite element analysis; orthodontics; periodontal ligament; tooth movement

INTRODUCTION
Orthodontic tooth movement (OTM) occurs as a result of site-specific resorption and formation of the alveolar bone. The remodelling processes of the alveolar support structures are triggered by alterations in the stress/strain distribution in the periodontium caused by the intra-alveolar displacement of the roots within the intra-alveolar space. According to the classical OTM theories, symmetric zones of compression and tension are present in the periodontium, but these do not consider the complex mechanical properties of the PDL, the alveolar structures’ morphology, and the magnitude of the force applied.

A common goal for all orthodontists has been to define a force that results in a maximal rate of tooth movement with minimal iatrogenic side-effects. The finite element method (FEM) has proved to be a valid and reliable technique for the calculation of the local state of deformation and loading of complex structures.
However, the validity of the results of FE-analyses is totally dependent on the ability to model the complexity of morphology and tissues material properties of the structures analysed [1, 2].

The aim of the present investigation was therefore to use the FEM: 1) to describe the orthodontic load transfer from the teeth to the alveolus; 2) to determine the influence of force magnitude in the stress and strain distribution in the alveolar support structures; and 3) to study the interactions of occlusal and orthodontic forces.

MATERIALS AND METHODS

A simplified FE-model of a tooth from an experiment described previously (14) was used to evaluate the shape of the tooth socket wall when a translation movement was simulated. Using a microCT (ICT) scanner (ICT40; Scanco Medical, Bassersdorf, Switzerland) two three-dimensional (3D) datasets of the alveolar bone were generated. Using a procedure described previously (12), 3D FE-models were generated comprised alveolar bone, PDL, and for the first sample, canine and first premolar, and for the second sample, first and second molars.

In the simplified model, the force magnitude was set at 100cN and a pure translation movement was achieved by constraining root movement to the mesial-distal direction. For the human-based FE-models, a range of orthodontic loading regimes were simulated in accordance with clinical practice. In the first series of analyses, the effects of a force of 100cN acting on a buccal-lingual direction and two different moment-to-force (M/F) ratio were analysed.

The force was acting in a buccal direction on the premolar and second molar, and lingual on the canine and first molar. The M/F ratio for the canine, first and second molar was chosen to be either 0 or 11, whilst for the premolar 0 or 9 [3, 4]. In the second series of analyses, the influence of force magnitude on the load transfer mechanism was evaluated. A fixed M/F ratio of zero was used for the first premolar, the canine and first molar, whereas the force magnitude was progressively increased up to 400cN in steps of 50cN. In the third series of analyses, occlusal vertical forces ranging from 0 to 20 000cN were superimposed to an orthodontic force of 100cN and a M/F of 0. For each series of analyses the stress and strain distribution in the periodontium, and the resulting tooth movements were ascertained.

Movement was suppressed in all directions for the nodes situated on the bottom edge of each bone segments [5, 6].

RESULTS

The FE-analysis showed that the deformation of the alveolar wall in a buccal-lingual cross-section occurred mostly on the tension side (Fig. 1B, C, upper-right quadrant). The concavity of the alveolar wall was decreasing at X (the area where bone apposition occurs) but it is increasing at Y. When bending of the alveolar bone in a buccal-lingual section was assessed, the deformation at the cervical level was below 1 µ strain in case of tipping (fig. 1, lower-left quadrant) and was approximately 0.1 µ strain in case of translation (Fig. 1, lower-right quadrant).

1) When a M/F = 0 was simulated and the force level kept at 100cN, all the teeth displayed uncontrolled tipping. Regions of compressive and tensile normal stresses could be identified in the PDL. However, the magnitude of the tensile stresses was significantly higher than the compressive stresses. This was consistent for all the teeth (Fig. 2).

The accompanying strains in the PDL were in the range of 20% to 14%. 
Fig. 1. Sample-specific FE-models – orthodontic loading

Fig. 2. Compressive and tensile normal stresses.

The distinct compression and tension areas seen in the PDL were not present in the adjacent areas of the alveolar bone, except for a thin layer of bone in close contact with the PDL. Areas of tensile stress were well recognizable in the lingual-cervical and buccal-apical alveolar bone. In the buccal-cervical area of the alveolar bone the compressive stresses are barely detectable. The same is seen on the lingual-apical portion of the alveolar bone.

When $M/F'$s of 9 and 11 at 100cN were simulated, all teeth displayed almost perfect translation. As a consequence, the overall displacements of the teeth were smaller than in the case of uncontrolled tipping. In the lingual section of the PDL of the canine and first molar, and on the buccal section in case of the premolar, a nearly uniform distribution of tensile stresses were present, whereas a very mild compression was present on the opposed side of the PDL. In the alveolar bone on the tension’ side the tensile stresses were uniformly distributed with a maximum value of about 0.02MPa (for the premolar), whilst on the opposite side the compressive stresses were by far lower with a maximum value of about 0.001MPa (for the canine).

2) In the second series of experiments, the force level was gradually increased. When the force magnitude was below 150cN, the state of stress/strain and deformation in the PDL was mimicking what had been found in the first series of analyses. In contrast, when force magnitude became larger than 200cN, a small area of compression started to appear in
the PDL at the level of the crest of alveolar bone and in the direction of the force. At a level of 400cN, the peak value of compressive stresses was similar to what was found on the tensile side, nevertheless, the area did not substantially increased in size (Fig. 3). At a force level of 400cN the PDL in the buccal- and lingual-cervical level has been deformed more than 80%. The area where compressive stresses were present was immediately bordered by areas where no compression could be detected.

The compressive stresses in the PDL were transferred to the adjacent alveolar bone, where they were transformed into compressive as well as tensile hoop stresses, as demonstrated in a previous research [7, 8] (Fig. 3, lower row).

Fig. 3. The force level was gradually increased

In the last series of analyses, the influence of the occlusal forces on the stress and strain distribution in the PDL was investigated. When the vertical-occlusive force reached a magnitude up to approximately 500cN, no substantial changes could be detected in the PDL from the scenario where only the orthodontic loading forces were applied. Beyond this level, the loading of the PDL and of the alveolar structures in general became completely different, changing from uncontrolled tipping (because of the orthodontic forces) to pure intrusive movement (because of occlusal forces).

DISCUSSION

Changes in the stress and strain distribution are the triggers for bone modeling that allow the teeth to move when an orthodontic loading regime is applied at the bracket. The present investigation describes how the loading pattern influences the first steps of the mechanotransduction mechanism leading to PDL re-arrangement and bone resorption and formation in relation to OTM.

These findings do not corroborate the simplified view of having tensile and compressive stresses in separate areas of the PDL and alveolar bone [7] which characterized the classical pressure – tension’ theory [8]. Bone formation related to an increased concavity of the alveolar bone wall also could not be confirmed. Moreover, the change in curvature of the alveolar socket could not be compared with long bones [9]. What is presented in this study corroborates what was previously speculated: bone formation is the result of an increase state of load in the alveolar bone and in the stretched PDL fibres, while bone resorption is the results of either an unload state (i.e. direct resorption) or as a consequence of...
hyalinization (i.e. indirect or undermining resorption) in the area where the PDL is undergoing large compressive deformation and the underlying alveolar bone is subjected to local high stress and strain [10].

The present study showed that small forces were enough to produce deformations in the PDL, yet the associated compressive stresses were very mild. However, by increasing force magnitude during uncontrolled tipping the compressive stresses in the PDL increased considerably and compressive forces were transferred to the cervical portion of the alveolar bone. In the present study, an approximation of the true physical properties of PDL was used, where its basic shape with a low-stiffness toe region and a high stiffness slope closely resembled both experimentally (3) and mathematically determined relationships [11].

A limitation of the present study is that the results could not be directly compared with in vivo loading; nevertheless, the calculated amount of deflection of the teeth reflects what has been reported in experimental studies. Nevertheless, a fine tuning of the FE-models and of the material properties of the various tissues is necessary in order to better determine the stress and strain distributions within the whole periodontium and the transition between low and high forces under orthodontic loading.

CONCLUSIONS

The present FE-analyses indicate that following the application of an orthodontics loading regime, alveolar bone modeling cannot be based on the simplified, yet generally accepted, concept of resorption caused by compression, and formation caused by tension.

REFERENCES