



ORIGINAL ARTICLE / ОРИГИНАЛНИ РАД

Biomechanical behavior of periodontally compromised dento-alveolar complex before and after regenerative therapy – a proof of concept

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SUMMARY

Introduction/Objective Finite element analysis (FEA) is mathematical method which can be used for the assessment of biomechanical behavior of dento-alveolar complex.

The objectives were to analyze biomechanical behavior changes of teeth and supporting tissues under occlusal load in cases of horizontal and vertical alveolar bone loss, to assess potential impact of tooth displacement and altered stress distribution on further damage, and to evaluate the impact of regenerative periodontal therapy.

Methods Three patient-specific three-dimensional finite element (3D FE) models were developed from the acquired cone beam computed tomography, comprising the patient's upper left canine, first and second premolar, and adjacent bone. Model 1 represented horizontal bone loss. Model 2 included intrabony defect along distal aspect of tooth #24. Model 3 represented situation six months after the regenerative periodontal surgery. Displacement, Von Mises, and principal stresses were evaluated through FEA, under moderate vertical occlusal load.

Results FEA demonstrated that in the model with vertical bone loss significant tooth displacement was present, even though the clinically evident tooth mobility was absent. Biomechanical behavior and stress distribution of teeth and surrounding tissues under moderate occlusal load was much more altered in case with vertical bone loss in comparison with horizontal bone loss. Six months following the regenerative therapy, the values of all evaluated parameters were noticeable reduced.

Conclusion Regenerative periodontal therapy improved the biomechanical characteristics of the affected teeth and the related periodontal structures.

Keywords: periodontal disease; alveolar bone loss; guided tissue regeneration; finite element analysis

INTRODUCTION

Alveolar bone loss is one of the main features of periodontitis. Bone defects may vary in their localization, shape, and extent. Generally, bone destruction may occur in two diverse patterns, as horizontal or vertical bone loss [1]. Horizontal bone loss is the most commonly seen and it is characterized by the linear reduction of bone height around the tooth. The vertical or angular bone defects are those that appear in the oblique direction [1]. Deep vertical (intrabony) defects associated with vertical bone loss are the standard indication for periodontal regenerative therapy [2].

It is evident that tooth with reduced bone support has compromised occlusal force transition to the jaws, and the further damage the residual periodontal tissues may occur [3]. In cases of horizontal or vertical bone loss different stress distribution may be expected. However, what is the outcome of these differences and how much do they affect the tooth? Would the increased stress level further harm

the remaining periodontal tissues? How high is the level of stress in the affected supporting tissues if the tooth does not have clinically evident pathological mobility? There is not enough scientific evidence which could give the answers to these questions.

Several regenerative procedures aiming at repairing the lost periodontal tissues, including the alveolar bone, periodontal ligament (PDL), and root cementum are in daily practice [4]. Although therapy of periodontitis aims to eliminate the periodontal pockets as the main collector of subgingival deposits and microorganisms, we are questioning the influence of the regenerative periodontal therapy on biomechanical behavior of affected dento-alveolar complex. Literature survey demonstrated that the biomechanical aspect of differences between horizontal and vertical bone loss cases has not been analyzed and fully understood so far. Furthermore, benefit in biomechanical behavior after surgical regenerative treatment has not been analyzed. Moreover, it has already been pointed out that clinically evident tooth mobility negatively

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influences the outcome of the regenerative therapy [4]. However, is it also important to analyze the biomechanical behavior of teeth and related structures in periodontally affected sites without measurable tooth mobility?

Three-dimensional finite element (3D FE) method is a very powerful tool which can give insight into the biomechanical behavior of analyzed dento-alveolar complex. It has been widely implemented in research related to dentistry [5–13].

In this study, the first objective was to analyze the stress distribution in cases with horizontal and vertical bone loss with no clinically evident tooth mobility. The goal was to test the hypothesis that in case of vertical bone loss PDL and alveolar bone are affected with higher occlusal stress which could further damage these structures, despite the fact that tooth mobility was not detected. The second aim of the study was to investigate whether regenerative periodontal therapy decreases displacement and stress values in the affected teeth and surrounding tissues. We used 3D FE analysis of three patient specific models developed from cone beam computed tomography (CBCT) in order to mimic the clinical situations.

METHODS

A CBCT image of a 38-year-old man was used to create a patient specific 3D FE models. The patient was in good systemic health, nonsmoker, with generalized severe chronic periodontitis. The patient was thoroughly informed about the purpose of the study and gave his written consent before clinical examination. The study was approved by the Ethics Research Committee of the School of Dental Medicine, University of Belgrade, Serbia (ethics approval N° 36/41).

Surgical procedure

Six weeks following the initial periodontal therapy, the patient underwent a periodontal surgery for the debridement of all periodontal defects with probing depth ≥ 6 mm. Periodontal clinical parameters were assessed using a manual periodontal probe graded in millimeters (PCPUNC-15; HU-Friedy, Chicago, IL, USA): probing pocket depth (PPD), gingival recession, and clinical attachment level (CAL), whereas only the deepest site per tooth was reported (tooth #23: PPD = 3 mm, CAL = 2 mm; tooth #24: PPD = 8 mm, CAL = 8 mm; tooth #25: PPD = 4 mm, CAL = 3 mm). After application of local anesthesia, intrasulcular incisions were performed from the distal aspect of the tooth #23 to the distal aspect of the tooth #27. A full-thickness flap was reflected buccally and palatally. The denuded roots were thoroughly debrided using ultrasonic devices and hand instruments. Exposed roots were chemically prepared with 24% EDTA gel (PrefGel®, Biora, Malmö, Sweden and Straumann, Basel, Switzerland) and rinsed thoroughly with sterile saline before the application of enamel matrix derivative (EMD) (Emdogain gel®, Biora and Straumann). Subsequently, a three-wall

intrabony defect along the distal aspect of tooth #24 was reconstructed using bovine porous bone mineral granules (BioOss®, particle size 0.25–1 mm; Geistlich Pharma, Wolhusen, Switzerland). Flaps were repositioned and sutured using the standard procedure. A post-operative visit was scheduled in seven days when the sutures were removed. Six months following the surgery periodontal clinical parameters were assessed (tooth #23: PPD = 3 mm, CAL = 2 mm; tooth #24: PPD = 3 mm, CAL = 4 mm; tooth #25: PPD = 3 mm, CAL = 3 mm).

Cone beam computed tomography scanning

Imaging was performed using a high resolution CBCT device (SCANORA 3Dx, SOREDEX, Tuusula, Finland). The patient was scanned twice, before periodontal surgery and six months following the surgical procedure. Examinations were performed using an 80 × 100 mm field of view, 0.25 mm voxel size, 90 kV tube voltage, and 10 mA tube current and 2.4 s scanning time. All the scans were stored in the standard DICOM format for the further analysis.

Finite element analysis

Development of the finite element models

In total, three patient-specific 3D FE models were developed from the acquired CBCT scans (Figure 1a–c). The models comprised the patient's upper left canine, first and second premolar, and adjacent alveolar bone. For each tooth, we considered its enamel, dentin, pulp chamber, and PDL, while the root cementum was neglected. Mimics software version 10 (Materialise, Leuven, Belgium) was used for the reconstruction of the FE models from the CBCT scans through the following steps. The masks of cortical, trabecular bone and teeth were generated respectively. The Mimics STL+ model was used to convert all the masks into the stereolithography (STL) format. In order to optimize the quality of the triangle meshes for the further FEA, we used the REMESH module attached to Mimics software. At last, by using Geomagic Studio 10 software (Geomagic GmbH, Stuttgart, Germany) we assembled the extracted parts into the three models. A PDL as the 200 μm -thick shell was additionally generated. Bone level adjacent to teeth #23 and #25 did not differ in all three 3D FE models. Likewise, bone level adjacent to tooth #24 was the same in Model 1 and Model 3, while the detailed description of the models is as it follows:

Model 1 represents horizontal bone loss in region #23, #24, and #25 (Figure 1a). It was constructed based on the CBCT scans of the patient's upper jaw before the surgery (Figure 1d), but with certain changes, the vertical bone defect (intrabony defect), which was localized along the distal aspect of tooth #24, was reconstructed by applying the properties of cancellous and cortical bone in order to simulate horizontal bone loss. This model was created in order to examine the differences in displacement and stress distribution between the horizontal (Model 1) and vertical (Model 2) bone loss patterns, and to compare with the

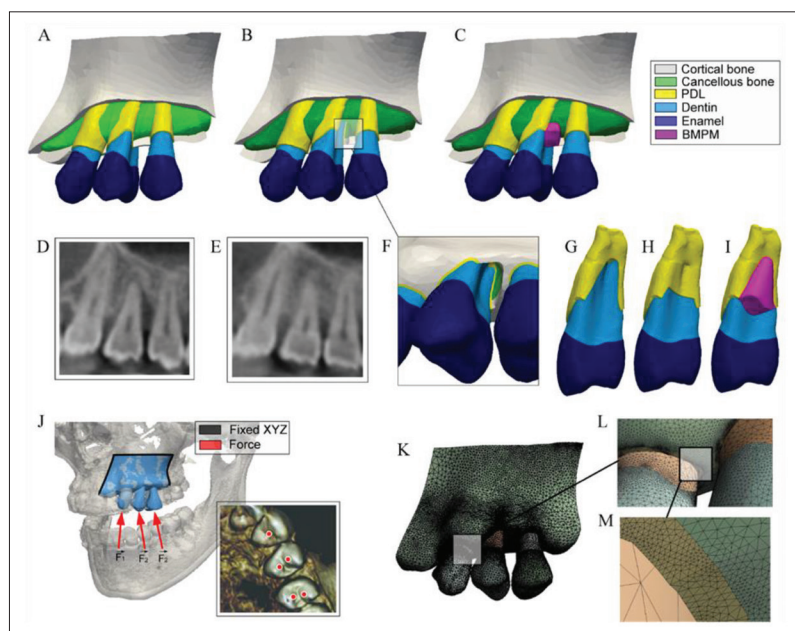


Figure 1. Overall procedure: a – model 1; b – model 2; c – model 3; d – before surgery; e – six months after surgery; f – intrabony defect; g – tooth #24 periodontal ligament (model 2); h – tooth #24 periodontal ligament (model 3); i – bovine porous bone mineral granules; j – boundary conditions and application of masticatory forces; k, l, m – tetrahedron volume mesh

situation achieved six months following the regenerative periodontal surgery (Model 3). Hence, bone level adjacent to tooth #24 was the same in Model 1 and Model 3.

Model 2 represents a patient-specific FE model, generated by using preoperative CBCT scans (Figure 1d), representing an identical situation in the region of interest before regenerative periodontal surgery (intrabony defect along the distal aspect of tooth #24 (Figure 1b, f)). PDL was not modeled on the tooth #24, at the root's site adjacent to the intrabony defect (Figure 1g).

Model 3 represents a patient-specific FE model created from CBCT scans acquired six months following the surgical procedure (Figure 1e). Reconstructed intrabony defect along the distal aspect of tooth #24 was modeled, whereas the material properties of bovine porous bone mineral granules six months following the surgical therapy was applied [5] (Figure 1c and i). Bone level adjacent to teeth #23 and #25 did not differ in all three 3D FE models.

In the region of reconstructed intrabony defect 80% of PDL was created, starting from the bottom of the defect towards the alveolar crest, based on previous histological findings when this treatment protocol was applied (Figure 1h) [14].

Meshing and material properties of the tissues

The STL files of the developed models were imported into the CATIA V5 software (Dassault Systèmes, Velizy-Villacoublay, France) version R20, and converted into the NURBS surfaces using the Digitized Shape Editor and Quick Surface Reconstruction modules. The solid models were further exported to ANSYS software (SASI, Canonsburg, PA, USA), version 14.5.7, for producing the FE mesh and structural analysis. By using the ANSYS

Table 1. Mechanical properties of the modeled tissues and material

| Material | Elastic Modulus (MPa) | Poisson ratio |
|----------------------|-----------------------|---------------|
| Pulp [9] | 6.8 | 0.45 |
| Dentin [6] | 18.6×10^3 | 0.31 |
| Enamel [6] | 84.10×10^3 | 0.3 |
| PDL [6, 23] | 0.68 | 0.45 |
| BMPB [5] | 1.69×10^3 | 0.3 |
| Cortical bone [15] | 13.7×10^3 | 0.3 |
| Cancellous bone [15] | 1.37×10^3 | 0.3 |

PDL – periodontal ligament; BMPB – bovine porous bone mineral (values after six months of healing period)

Meshing module, the models were discretized into the very dense and quality tetrahedron volume mesh (Figure 1k-m). Number of nodes for Model 1, Model 2 and Model 3 was 1176135, 1179101, and 1228269 respectively; while the number of finite elements for the models was 5684279, 5702597, and 5952010 respectively. All the tissues

were assumed to be homogeneous and linearly elastic. The values of the Young's moduli and the Poisson's ratios for dental tissues, PDL, cortical and cancellous bone, and BMPB were taken from the literature (Table 1).

Boundary conditions and calculations

In order to assess the stress distribution (Von Mises, compressive, tensile) and effective displacements, the same boundary conditions were applied on each model using the ANSYS Static Structural Analysis module (Figure 1j). The sides of models that represent cut-off planes from the overall maxilla were fixated in all degrees of freedom following Figure 1j, black color. Masticatory forces were applied on the buccal and lingual cups of premolars simultaneously (Figure 1j – red arrows, red color), to gain the resulting force of 200 N parallel to the long axis of these teeth (vertical load) [15]. Load of 150 N was applied at an angle of 45° to the center of the canine's palatal surface within the physiological limitations reported for a canine [15].

RESULTS

The results for the displacement, Von Mises and principal stresses for all three models are presented on Figures 2–5.

Results in this study showed that alveolar bone loss patterns may cause differences in the tooth displacement. Although displacement of tooth without bone resorption was not tested, it may be notice that the greatest influence had vertical bone loss before regenerative therapy and the greatest displacement of all evaluated teeth was detected in this case (Figure 2). Since the characteristics and the height of tooth supporting tissues differed only in region

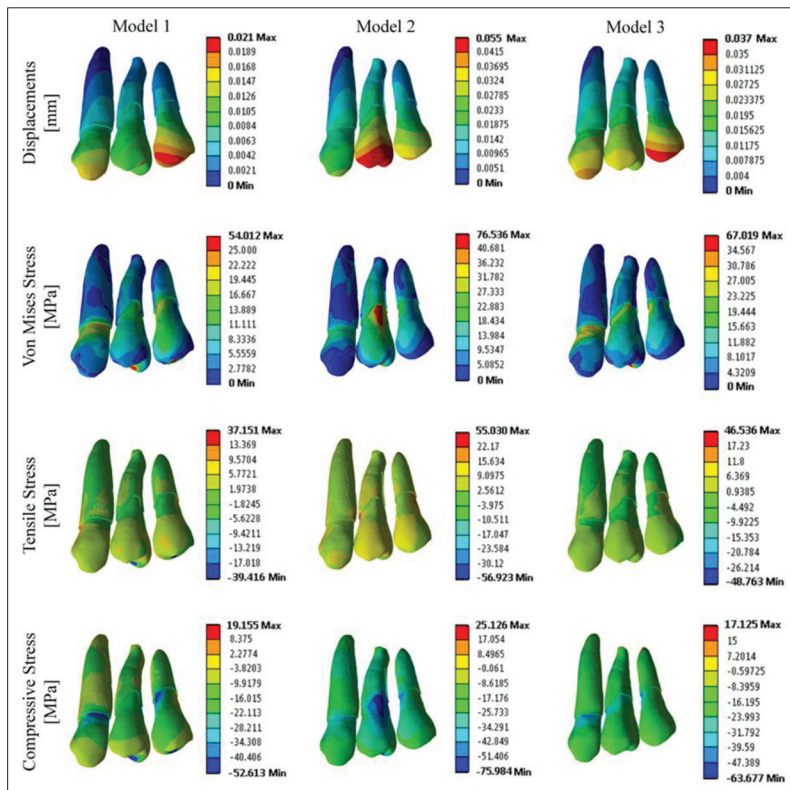


Figure 2. Displacement, Von Mises, tensile and compressive stress in the teeth and periodontal ligament in all three three-dimensional finite element models

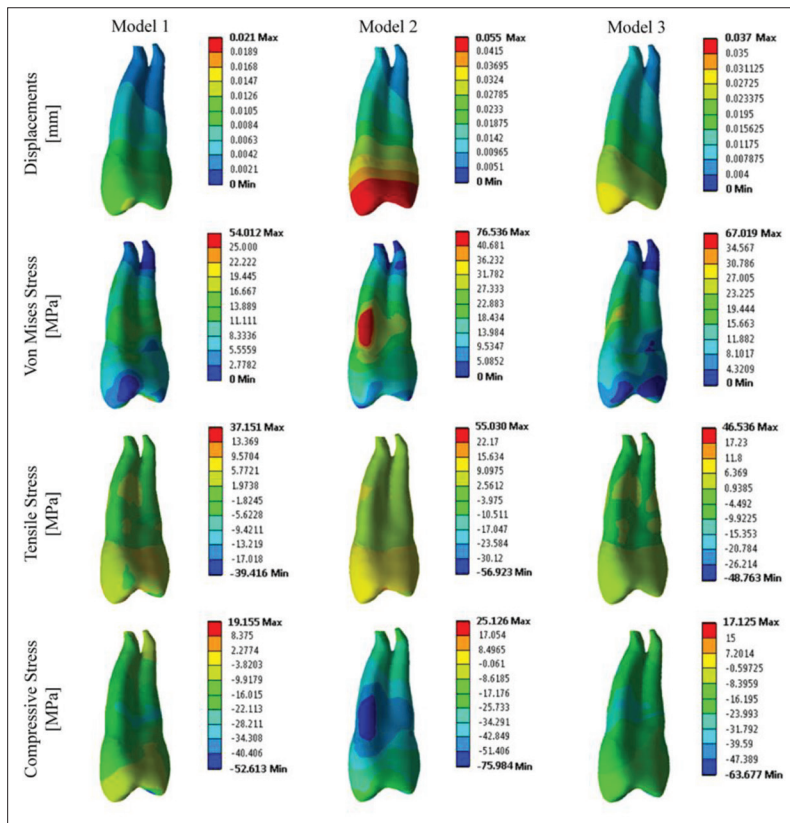


Figure 3. Displacement, Von Mises, tensile and compressive stress in the tooth #24 in all three three-dimensional finite element models

of tooth #24 in all three models, this tooth exhibited the biggest differences in displacement (Figure 3). Under occlusal force, the tooth inclined toward bone defect. Displacement of tooth #24 was five times greater in case of vertical bone loss compared to horizontal bone loss. Moreover, it was noticed that tooth #25 in Model 2 also exhibited displacement towards the defect adjacent to tooth #24 (Figure 2). On the other hand, six months following the surgical treatment and bone defect reconstruction, displacement of these teeth significantly diminished, but was greater than the values which were present in case of horizontal bone loss (Model 1).

Analysis of stresses distribution in teeth showed significant differences between Model 1 and Model 2 (Figure 2). Higher values of Von Mises were seen especially in tooth #24 (Figure 3). However, six months after the surgery, the level of stresses was noticeably lower. These findings are in agreement with the results of the teeth displacement.

Assessing alveolar bone in all three 3D FE models showed that Von Mises stresses had greater magnitudes in cortical bone when compared to cancellous bone (Figures 4 and 5). In all three models, maximum stress values were present in narrow zones of alveolar crest (Figure 4). Only in the case of the vertical bone loss Von Mises stresses reached maximum values of 76.54 MPa in alveolar crest at distopalatal aspect of tooth #24. Evaluation of the buccal and palatal aspects of maxilla, demonstrated that buccal plate was affected at a higher level, and the widest stressed zone was observed in the case of vertical bone loss (Figure 4). Six months following the surgery, both buccal and palatal plates exhibited lower stresses values, and stress distribution was similar to that detected in the case of horizontal bone loss. Figure 5 displays uniform Von Mises stresses distribution in cancellous bone for all three models. Concerning the pattern of bone destruction, the highest stresses values in cancellous bone were revealed in the case of vertical bone loss. The stress was obviously reduced six months following the surgery, but did not achieve values exhibited in the case of horizontal bone loss. Analysis of the principal stresses revealed that the in Model 2 (vertical

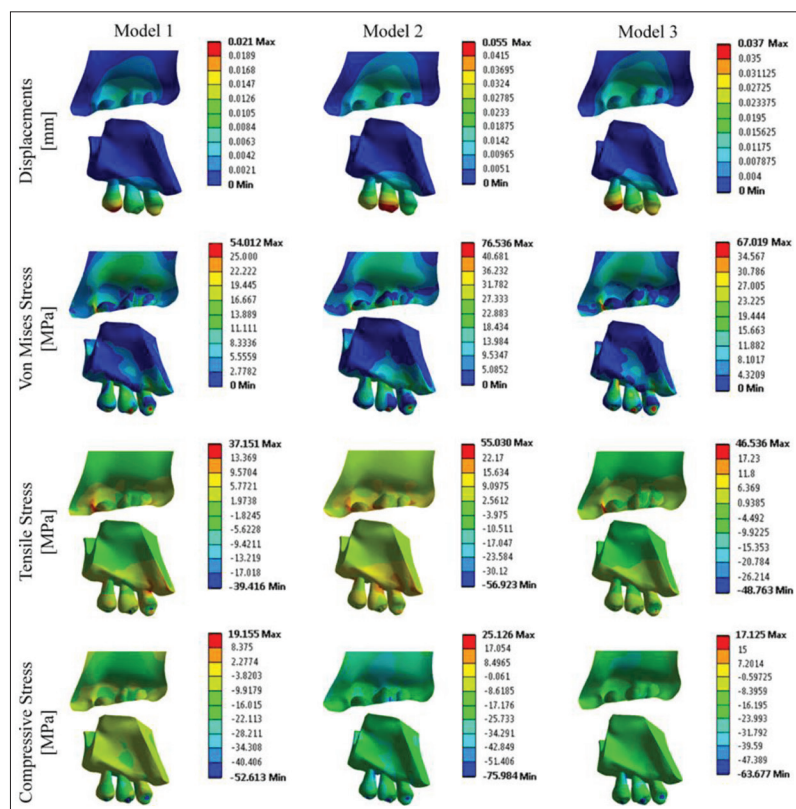


Figure 4. Displacement, Von Mises, tensile and compressive stress in cortical bone in all three three-dimensional finite element

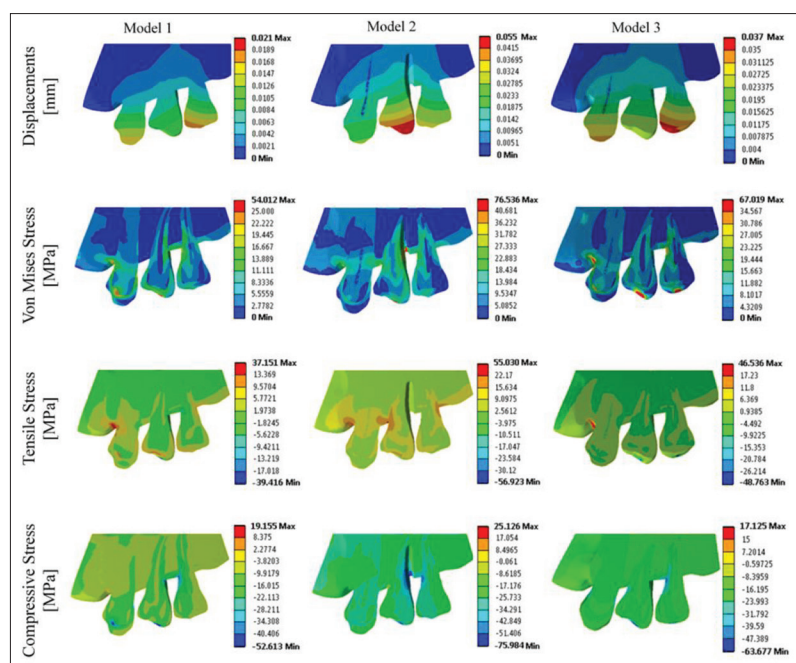


Figure 5. Displacement, Von Mises, tensile and compressive stress in cancellous bone in all three three-dimensional finite element

bone loss) tensile stresses were generated in alveolar crest at mesial aspect of the tooth #24, while the compressive stresses were noticed on the opposite (distal) aspect of the tooth. Six months after the surgery, the levels of principal stresses decreased but remained higher than in Model 1 (horizontal bone loss) (Figure 4).

Regarding the PDL, the highest Von Mises stresses was also present in the case of vertical bone loss, mostly located on the buccal and mesial aspect of the tooth #24 root (Figure 2). Six months following the surgery, the stress magnitude in PDL was obviously reduced and uniformly distributed, not only in the case of tooth #24 but in all evaluated teeth, and reached the values detected in the case of horizontal bone loss.

DISCUSSION

The present concept and use of computer modeling followed by FEA allows the insight into the stress transition of occlusal forces into the alveolar bone. In this study we were able to visualize the undetectable values of tooth displacement and to analyze its influence on stress distribution.

Results of this study supported the hypothesis that higher stresses are generated during occlusal load in teeth affected with vertical than in horizontal bone loss. Also, as it was hypothesized, regenerative periodontal therapy decreased displacement and stress values in the affected teeth and supporting periodontal structures. However, it was demonstrated that six months following the surgery the magnitude of these values were still higher than the values detected in case of horizontal bone loss, although the coronal level of bone was the same.

Jang et al. [16] using the FEA method showed that the diverse extent of periodontal bone loss had a greater impact on biomechanical response. In the present study we analyzed tooth displacement which was not clinically detected. It was demonstrated that, although being small, tooth displacement affects the level of principal stresses. Namely, tooth #24 was “bending” distally towards the intrabony defect (Model 2) (Figure 3). Subsequently, tensile stress was generated on the mesial aspect of adjacent alveolar crest, while compressive stress was developed on the distopalatal edge

(Figure 4). In the case of horizontal bone loss (Model 1) our results showed much lower values of tooth displacement and principal stresses in the bone.

Even though the maximal vertical biting forces in humans can approach 700 N [17, 18], the moderate physiological occlusal forces in this study (150 N and 200 N) can cause localized stress concentrations in alveolar bone

affected by vertical resorption. It was revealed in the study of Jeon et al. [8] that localized stress concentrations are closely related with bone resorption. Knowing that yield stress of 60 MPa may cause harmful effects on cortical bone in humans [19], detected value of 75.98 MPa would have detrimental effects on cortical bone and most likely would lead to further bone resorption. Furthermore, fatigue loadings that are continuous and repetitive can potentially “accumulate” the stress, triggering bone degeneration or resorption [20]. In the study, the highest values of localized compressive stress were detected at palatal alveolar crest adjacent to intrabony defect (Figure 4), which might be an area of further bone resorption, supported by bacterial stimulation [21].

In this study, BPBM and EMD were used to promote periodontal regeneration in the treatment of periodontal disease. Histological examination in humans showed that bone defects treated with the combination EMD–BPBM healed with a new connective tissue attachment and new bone [22]. These findings were used (and applied) in this study to create PDL in the Model 3 (Figure 1h). We applied the values for mechanical properties of BPBM following the six months healing period, described in the work of Kwon et al. [5]. They demonstrated that stiffness of BPBM six months following the surgery (1.69×10^3) was slightly greater than cancellous bone (1.37×10^3). Even though the new-formed bone (six months following the surgery) was stiffer than the natural cancellous bone, FEA results showed that the displacement of the tooth #24 was still greater than in the Model 1. This is probably the consequence of the lack of cortical bone in this area, which is much stiffer. However, stress levels were significantly diminished, especially the high tensile stress in alveolar crest at the mesial aspect of this tooth. Thus, we can conclude that even though the therapy could regenerate bone to approximate level of the alveolar crest in the case of intrabony defects with favorable osseous architecture [4], this study showed that there is still the weak point at the previously affected site which is jeopardized in terms of further bone loss (Figure 4).

FE studies showed that in an area with periodontal disease bone support and PDL area are reduced, and the same magnitude of occlusal load will cause higher stress in the PDL [8, 10]. This should be bear in mind, because even the physiological occlusal loads may result in high stress values which may contribute to further bone loss. Ona et al. [3] described in their FE study that bone resorption will reduce the root area available for support, which may cause an increase of the maximum stress within the PDL. Results of our study are in agreement with this finding, as the highest value of overall stress was detected in PDL of tooth #24 in the case of vertical bone loss (Figure 2). However, this value was evidently reduced six months following the surgery since the root area available for support has been expanded.

In the present study, using CBCT scans before and after regenerative therapy was an advantage. Experimental study with the same study design would be impossible, since horizontal bone loss, vertical bone loss (intrabony defect), and reconstructed intrabony defect were simulated in the same region allowing comparison of the gained results.

It is important to emphasize that the results should be interpreted with caution due to the study's limitation. Namely, as this study is based on computer simulations, some simplifications were made. Only a nondestructive static occlusal loading was applied, and the dynamic loading behavior which is present in the oral cavity was not simulated. Furthermore, aiming to avoid the influences of load directions only the vertical occlusal forces were evaluated, while horizontal and oblique forces were neglected.

To the best of authors' knowledge, this is the first study which provided the basic information of biomechanical aspects in periodontal tissues regarding the diverse pattern of bone loss, and may serve as a basic template which could be useful for calculating the effectiveness of different approaches in regenerative periodontal treatment.

CONCLUSION

This study demonstrated that computer modeling and FEA can give new information regarding the biomechanical behavior of periodontal structures when diverse patterns of bone loss are present. Followed by CBCT, in a patient specific model, this method revealed significant displacement of periodontally compromised tooth, whereas tooth mobility was not clinically evident. The tooth displacement caused high stresses which could be potentially dangerous in promoting further bone resorption. Resolution of vertical bone defect resulted in reduction of tooth displacement and significantly lower level of principal stresses in the bone. However, the magnitude of these values was higher than the values detected in case of horizontal bone loss, showing that there is still a weak point at the previously affected site which is in jeopardy for further bone loss.

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Биомеханичко понашање структура денто-алвеоларног комплекса пре и после регенеративне терапије пародонтопатије

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САЖЕТАК

Увод/Циљ Метод коначних елемената је математички метод који се може користити у циљу испитивања биомеханичког понашања структура денто-алвеоларног комплекса.

Циљ овог рада је био испитати биомеханичко понашање зуба, периодонцијума и околне алвеоларне кости под дејством оклузалних сила у случају присуства различитих типова ресорпције алвеоларне кости пре и после регенеративне терапије пародонтопатије.

Метод На основу радиолошких слика добијених компјутеризованом томографијом конусног зрака креирана су три тродимензионална математичка модела која су се састојала од горњег левог очњака, првог и другог премолара и околне алвеоларне кости. На моделу 1 је представљен хоризонтални губитак алвеоларне кости. Модел 2 је садржао инфракоштани дефект дуж дисталне површине зуба #24. Модел 3 је представљао ситуацију шест месеци после ре-

генеративне терапије пародонтопатије. Применом метода коначних елемената израчунати су степен померања зуба, интезитет и дистрибуција *Von Mises* и главних напона под дејством умерених оклузалних сила.

Резултати Метод коначних елемената је показао да у моделу са вертикалним губитком кости постоје значајна померања зуба услед дејства оклузалних сила, а самим тим и већи интезитет напона у периодонцијуму и околној алвеоларној кости у односу на хоризонтални губитак кости. Шест месеци после регенеративне терапије пародонтопатије степен померања и интезитети напона су били знатно смањени.

Закључак Регенеративна терапија пародонтопатије утиче на побољшање биомеханичких карактеристика зуба, периодонцијума и околне алвеоларне кости.

Кључне речи: пародонтопатија; ресорпција алвеоларне кости; усмерена регенерација ткива; метод коначних елемената