BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 63, No. 2, 2015
DOI: 10.1515/bpasts-2015-0060

Safe rebuilding of the periodontal loss an experimental study

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Abstract. This study aimed at the simulation of bone tissue remodeling within a bone defect with the utilization of the finite element method (FEM), enabling – via elaborated application – objective evaluation of orthodontic forces which positively influence periodontium in vivo. The initial position of each bracket on the passive archwire was registered, and then a geometrical and discretemodel of the appliance was created automatically. Assessment of the dental scans obtained using cone beam computed tomography (CBCT) allowed evaluation of the range of bracket displacement: from the initial position to the final one achieved on the active archwire. Those displacements established terminal conditions in the finite element analysis, enabling calculation of orthodontic force levels. An individual design of a tooth with periodontal ligaments and the periodontal defect subsequently loaded with the determined forces allowed simulation of bone remodeling according to Carters adaptation process. Mainly, the bone apposition processes took place in the central part of the periodontal defect, in proximity of the alveolar ridge. However, FEM application in the analysis of bone tissue regeneration within bone defects enables precise evaluation of the achieved changes, therefore allows determination of orthodontic forces positively influencing periodontium in vivo.

Key words: FEM, bone remodeling, orthodontics, periodontally compromised patients, bone defects.

1. Introduction

The periodontal disease is one of the main causes of a permanent tooth lossof adult patients. It is assumed that this problem affects from 16.7% to 98.9% of the adult population [1–3]. The development of periodontal disease contributes to the creation of bone defects and loss of attachment. Consequentially, efficiency of the periodontal support is reduced and the ability to resist occlusal forces and those forces generated by the tongue, lips and buccal muscles is diminished. In 30% to 50% of periodontally compromised patients this leads to pathologic teeth migration [4, 5]. In such cases interdisciplinary periodontal - orthodontic treatment is necessary [6]. It is however important not to forget that periodontal tissues under the influence of inflammatory processes react to orthodontic forces differently than the tissues of healthy patients [7, 8]. Despite the current knowledge of this fact, there is still a lack of an unequivocal therapeutic management algorithm. Furthermore, data from literature which shows changes in the periodontium influenced by orthodontic forces can sometimes even be contradictory [9, 10]. As a result, the strategy of orthodontic treatment for periodontally compromised patients is still predominantly dependant on doctors experience instead of scientific evidence. The lack of objective records has prompted the authors to undertake proper studies. Their aim was the simulation of bone tissue remodeling within a bone defect with the utilization of the finite element method (FEM), and thus the elaboration of an application which enables the evaluation of orthodontic forces which positively influence periodontium in vivo.

2. Materials and methods

All analyses in the present study were carried out numerically, using FEM with ANSYS 11 software. The study used a mandibular bone model and a lower incisor model developed and based upon real tomographic measurements of a jaw bone taken from a cadaver – Fig. 1.

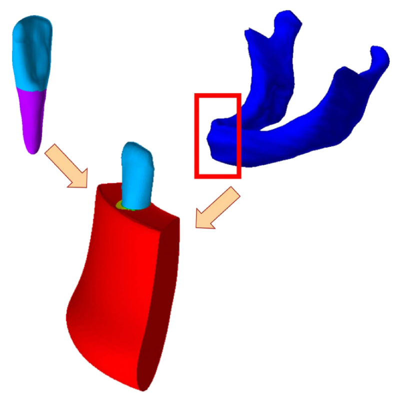

Fig. 1. Geometric model of central lower incisor and mandibles segment

A fully integrated model of the tooth and mandible segment was made by developing a model of the periodontal

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ligament (PDL). The PDL model was introduced to the existing model of the incisor and mandible through the surround of the tooth root with the additional volume. The last stage was the geometric model elaboration of the periodontal bone defect. In the mandible model the additional volume reproducing the periodontal hard tissue defect was elaborated. The shape and dimensions of the defect were determined on the basis of measurements of real defects in patients from a study group examined during the project – Fig. 2. The prepared model was meshed using a solid 10-nodal tetrahedron element with three degrees of freedom at each node. 10-node tetrahedral element is a higher order 3D element which is well suited to modelling irregular biological objects. The next work phase was the determination of the external forces, created by an orthodontic fixed appliance, which load teeth. A library of geometric models for the orthodontic brackets was created. The dimensions of the brackets were measured with a stereoscopic microscope. Subsequently, the geometrical models of all the brackets were stored in the library, which was connected to the procedure to develop a geometric model of the entire orthodontic fixed appliance.

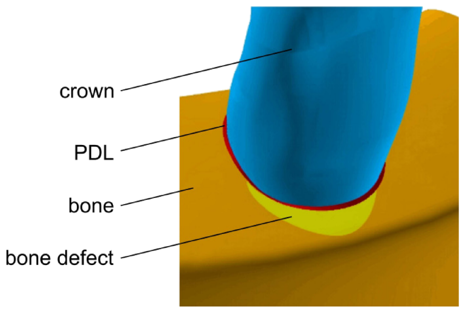


Fig. 2. The final geometric model

A similar process was used regarding the orthodontic wire. The main procedure to develop a geometric model of the orthodontic appliance was coded in the internal Ansys programming language (APDL). As part of the survey, the operator can choose the shape of the wire and then select one of a set of previously developed bracket models from the library to determine their position on the wire – Fig. 3.

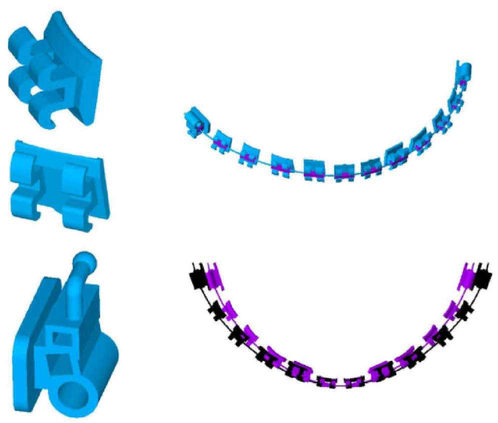
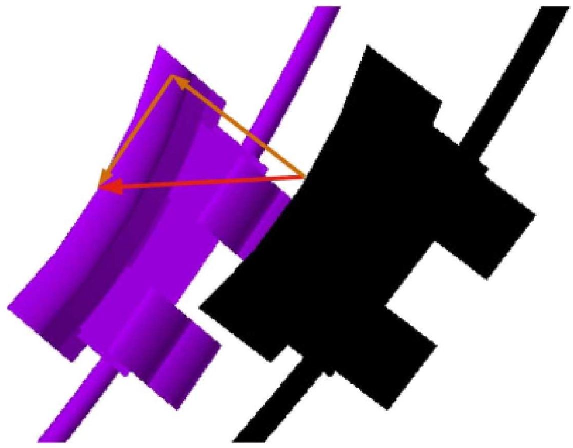


Fig. 3. Orthodontic appliance model

The combination of brackets and wires was implemented with additional volume to simulate vulnerable fixation elements. The attained geometric model was divided in two halves. It should be emphasized that the developed model of wire was present with the initial, un-deformed shape. By moving the brackets to the position occupied by them in the real clinical case it was possible to determine the clinical value of displacements which were then introduced into the model as a mechanical load. For this purpose, based on tomographic studies, the coordinates of the tooth labial surfaces, where the brackets should be placed, were determined. The difference between the coordinates for initial and correct positions of the patient's teeth was the value of the displacement of the brackets, which should be added to the appliance to achieve the correct position. It is possible to determine the forces acting on the individual teeth based on an FEM calculation for a model loaded with displacements. A sample of the force – displacement relationship for the lower incisor is presented in Fig. 4. Having been obtained via this method, the force values were utilized in the simulation of bone remodeling within the periodontal defect, as the load acting on the tooth.

a)



b)

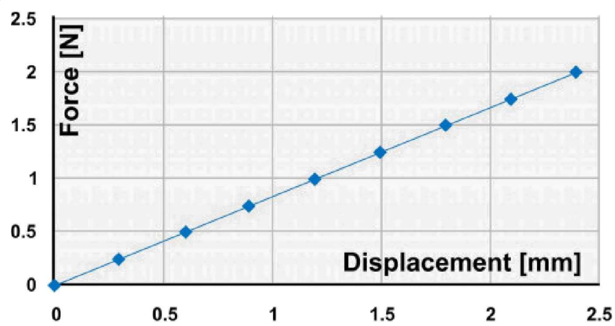


Fig. 4. Change of the position of the brackets as a result of addition of displacement (a), force-displacement relationship (b)

Models of tissue material used in the simulation models were isotropic, linear-elastic stress-strain. The literature review, as well as the personal experience, enabled the authors to select mechanical properties of particular tissues personally considered as the most adequate [11–16]. The values of the mechanical properties of these tissues are shown in Table 1.

Table 1
The mechanical properties of tissues

Material	E [MPa]	ν [–]
Enamel	85000	0.3
Dentin	20000	0.3
Cortical bone	20000	0.3
Spongeous bone	450	0.42

The only exceptions were the material properties of the PDL, which were defined as isotropic material, elastic, but with a strongly non-linear stress-strain relationship based on the model of Cattaneo [15]. In the completed analysis, the stress-strain characteristics of PDL were mapped using a multi-linear model – Fig. 5.

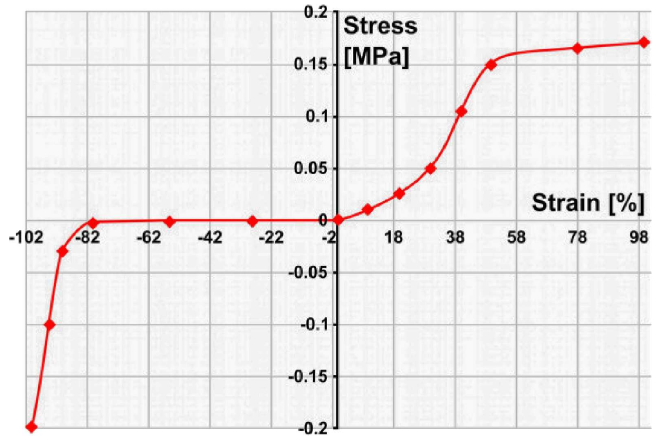


Fig. 5. Characteristics of stress – deformation of the PDL material

The simulation of bone remodeling was carried out based on the model of Carter [17]. For each finite element model the value of strain energy density was determined. The value of effective stress was determined according to the formula:

$$\sigma_i = \sqrt{2\text{EU}}, \tag{1}$$

where E stands for Youngs modulus, U stands for strain energy density. The value of the remodeling stimulus was determined by the ratio taking into account the number of load cycles in a given period of time:

$$\psi = \left[\sum_{i=1}^{N} n_i \sigma_i^m\right]^{\frac{1}{m}}, \tag{2}$$

where Ψ stands for a daily stress stimulus, N stands for the number of analyzed load type, n_i stands for the number and type of load cycles, m stands for a constant determined experimentally, σ_i stands for the value of effective stress caused by load type i. Determination of the mechanical stimulus values for each finite element in the model allowed the determination of a growth/bone loss factor according to the formula presented in Fig. 6. In the presented three zones of influence of mechanical stimulus on bone remodeling can be distinguished. Stimulus values slightly differing from the average value of the stimulus, occurring physiologically, are located in the "lazy zone", in which there are no changes in bone density. When the stimulus is significantly larger, the average bone density increases, while for smaller values of the stimulus bone tissue undergoes atrophy.

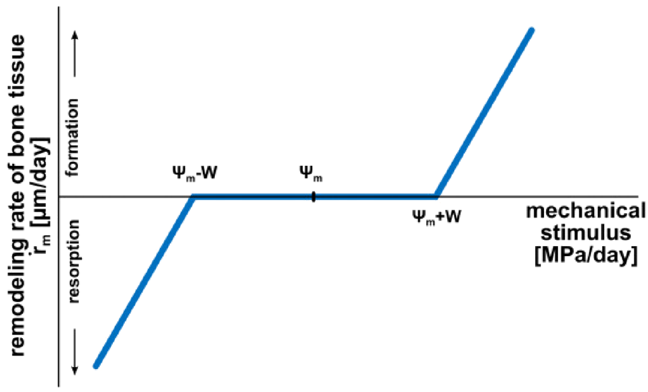


Fig. 6. Change in bone mineral density determined by the dependence of a growth/bone loss factor – a daily mechanical stimulus

The correct determination of changes in value of bone density is only possible by taking into account the relationship between the current density of bone tissue and the size of the active surface, which can develop cellular processes that occur during remodeling – Fig. 7 [18].

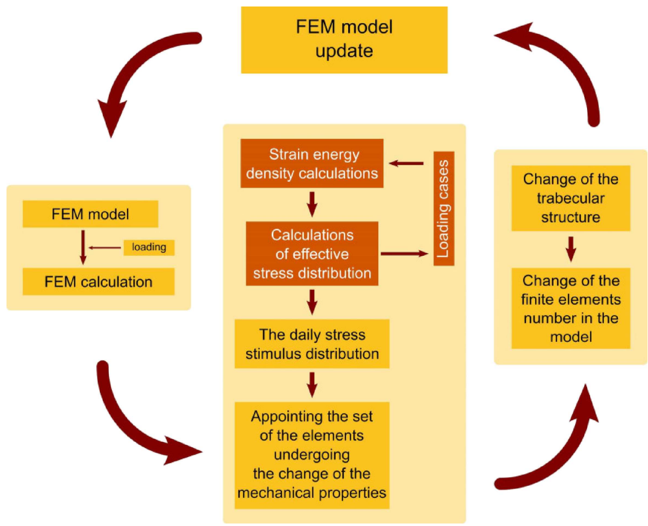


Fig. 7. The relationship between bone density and the active surface of bone tissue

In such a case, the change of bone density for each finite element is determined by the relationship:

$$\frac{\Delta\rho}{\Delta t} = k\,(BS/TV)\,\rho r, \tag{3}$$

where ρ stands for the current bone density, k stands for the part of the active surface which is currently being rebuilt, BS/TV stands for the active area of bone tissue, r stands for the coefficient of growth/loss of bone tissue. A change in density for an element in the model also means changing the mechanical properties of the element. The new values of the mechanical properties are inputted into the next step of the remodeling procedure. In summary, simulations of the remodeling process are carried out as an iterative procedure according to the diagram in Fig. 8.

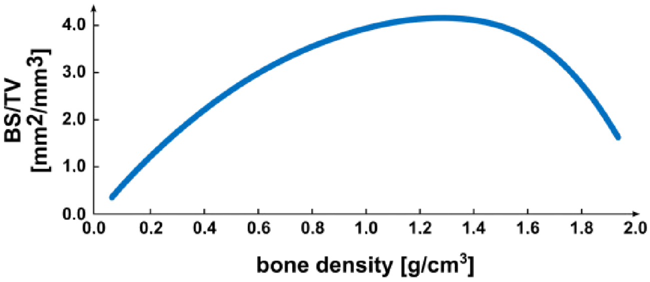


Fig. 8. Algorithm of the simulation of bone remodelling

3. Results

The obtained data clearly show that the mechanical load created by orthodontic fixed appliances influences the remodeling process of the alveolar bone within the bone defect. The process of bone tissue remodeling (changes of bone density) within the periodontal defect is shown in Fig. 9.

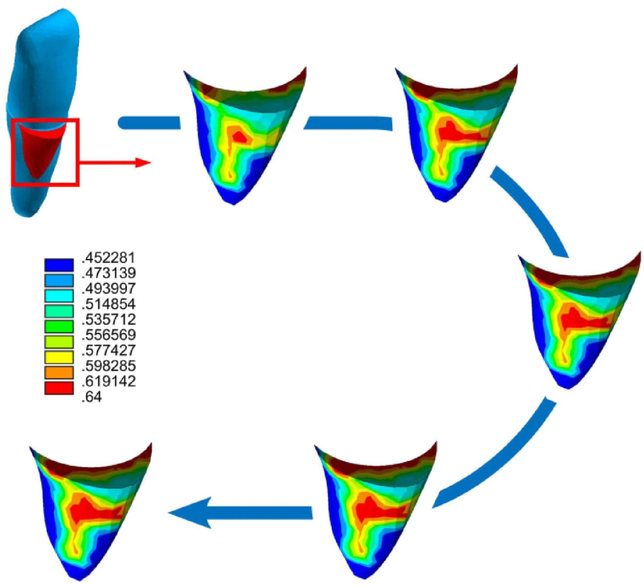


Fig. 9. The exemplary results of the bone remodeling process occurring inside of the bone defect (loading force 1.3N)

Changes in the distribution of bone density demonstrate the increase in the amount of bone tissue within the bone defect with the following iterations. In the initial simulation phase it is possible to observe three different foci of osseointegration. Two of them are located within the upper part of the defect, close to both defect margins adjacent to the defect surface. It is probably related to a small cross-section surface of the defect in this region. The third focus of osseointegration is located in the centre of the defect. The surface of the focus of osseointegration is irregular. It has two visibly distinguishable branches a horizontal branch that runs almost across the entire width of the defect and a vertical branch that runs from the focus of osseointegration to the bottom of the defect. In the areas between the foci of osseointegration the values of bone density are relatively low but not minimal, which provide the bone structures formation, though they are not fully formed. The minimal values of bone density have been observed only close to the bottom of the defect and on one of the side margins. In the following interpretations of the remodeling process, an increase of bone tissue density is observed, particularly in the upper volume of the defect. Two hitherto separate osseointegration foci are seeking a connection in one layer, which is situated directly at the tooth surface. The third of the osseointegration foci develops explicitly; the areas which show the biggest values of bone density are growing. This effect is particularly pronounced on the horizontal branch, on the vertical branch there are practically no changes. The changes within the bottom of the defect are minimal. In summary, an increase of the volume of newly-created bone within the bone defect has been observed. The volume occupied by bone tissue with high density have been defined as the fulfilment of the defect and have been determined for each iteration of the simulation process by calculation of the sum of the volume of all finite elements in which the value of density is greater than established. Afterwards, the simulation has been performed for different loading force values. The results are shown in Fig. 10.

The fulfilment growth with following iterations of simulation follows a nonlinear pattern but, for the loading force of value 2N and 1N, until the moment of the termination of the simulation, the magnitude of fulfilment of the defect was still growing. In the case of the force 0.5N after minimal growth of the fulfilment value in the initial phase of the simulation, a gradual decrease of this value follows through to the termination of the simulation. It is therefore possible to state that the significant influence of load created by an orthodontic fixed appliance on the treatment process of the periodontal bone defects exists and depends on the value of the force loaded.

4. Discussion

From mechanical point of view, alteration in the strain-stress distribution within the periodontal ligaments (PDL) and the surrounding alveolar bone is the first reaction to an orthodontic load [19, 20]. Analysis of the impact of forces resulting from orthodontic appliances on PDL regeneration in periodontally compromised patients is relatively new. Single published case reports [21–23], or studies conducted on animals [24], show that properorthodontic therapy with the application of light forces may stimulate regeneration of both soft and hard periodontal tissues. However, the attempt to evaluate either the exact value of the light efficient forces, as well as the stress and strain distribution in the compromised periodontium, is a completely new problem. Since non-destructive estimation of those parameters in vivo is impossible, laboratory in vitro studies or digital techniques have become essential. The finite element method (FEM) – the best example in times when computational power is progressing rapidly – is selected more and more often to simulate dental movements induced by orthodontic forces. Analysis by Wood of stress and strain distribution in the facial cranium arising under physiological forces such as mastication shows that the characteristics of PDL can be ignored if values of stress and strain within the alveolar process are not the factor which facilitates PDL modelling [25]. Nevertheless, selective studies on the behaviour of PDL after loading prove that modelling of PDL is a critical element which cannot be ignored [12]. Such a thesis is supported by the studies of Cattaneo et al. [15], showing that the distribution of stress and strain is different after the application of a model with isotropic and linear characteristics than those with anisotropic and non-linear characteristics. There are articles in literature proving that the material properties of the PDL are linear, elastic and isotropic [11, 13, 16, 26, 27]. On the other hand the most current publications [12, 15, 28] indicate that PDL is not a homogenous material and its properties are non-linear. In terms of this recent concept, the methodology of the presented work, that is defining PDL as isotropic or elastic but with strong non-linear stress and strain characteristics, is fully justified. Information about changes of homeostasis of periodontal structures following physical stimulus is already present in literature. As proved by Katona et al. in animal experiments, stress and subsequent strain induced in PDL do indeed cause bone resorption on the pressure aspect, enabling orthodontic movement but following a period of increased activity of osteoblasts in PDL [29]. This study significantly influences the treatmentconcept of periodontally compromised patients, since one may assume that increased activity of osteoblasts, triggered by orthodontic forces, may lead to regeneration of the bone defect. Clinical evidence supporting such a thesis is already present in literature. Case reports of periodontally compromised patients [21–23] clearly prove that orthodontic treatment stimulates PDL in terms of the regeneration of bone defects. There are no original studies yet referring to either loci of the highest osteoblast concentration within the bone defect or the force values stimulating activity of the osteoblasts thus positively influencing bone defect regeneration. We attempted to estimate those parameters precisely for the first time, using the described application. The tooth loaded in our study was being tipped towards the bone defect with a gradually increasing level of force with each iteration. The highest stress and strain, which clinically corresponds to the highest concentration of osteoblasts [29], was found in the proximity of the alveolar process and in the central part of the periodontal defect but not at its bottom. Such characteristics resemble the model of osteoblast concentration along the root-length of the tooth being displaced under orthodontic forces [30–32]. It may lead one to the conclusion that a properly established force level increases osteoblastic activity in a significantly enlarged PDL space. The question of force values defined in our laboratory studies are, however, more controversial. The results of the experiment show that the stimulation of bone defect repair is directly proportional to an increasing (with each iteration) force level. It could contribute to the false conclusion that 2N force – achieved in this laboratory experiment – is the most suitable one for periodontally compromised patients. Such force levels causes considerable, non-physiologic strain high enough to break the tissue continuity. However, translation of the tooth centre of resistance towards the root apex in those patients, a phenomena disregarded in an in vitro experiment, is the crucial factor preventing the use of such heavy forces. This is an obvious limitation and requires alteration of the biomechanics: a decrease of force values and their moments of rotation at the clinical level [33]. Therefore, establishing optimal force values seems impossible without simultaneously conducted in vivo studies. Thus, our further research – enabling comparison of the laboratory and clinical results – will definitively and precisely establish the desired force levels: low enough to avoid harmful iatrogenic effects on periodontal structures and the teeth themselves and high enough to stimulate regeneration of bone defects. Although final conclusions are not yet possible, the hitherto presented results show, for the first time, behaviour of the periodontal defects at the molecular level.

5. Conclusions

The developed procedure enables analysis of the regeneration of bone tissue within bone defects. This tissue, responding to loading with fixed orthodontic mechanics and transferred by dental tissues, creates new internal structures and changes both its density and mechanical properties. Orthodontic forces acting on the bone cause either its resorption or apposition.

The presented procedure allows optimal appliance design, which is the selection and distribution of its elements providing full control of resorptive and developing processes. From the clinical point of view it means an entirely new chapter in the treatment of malocclusion in patients with a compromised periodontium: the possibility of its regeneration with a surgery-free method.

The results of FEM simulation studies, consistent with proceeding clinical trials, prove that both periodontal remodeling and structure are under the influence of either the orthodontic appliance design as well as the severity of periodontitis and destruction of masticatory system. In such cases the authors recommend FEM application for evaluation the predictable orthodontic treatment effects.

Acknowledgements. The project has been funded by the National Science Center. Grant number NN518 382537. Ethical Approval was given by the Medical University (KB-224/2008).

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