3-DIMENSIONAL ANALYSIS OF THE STRESS-STRAIN RELATION DURING ORTHODONTIC ANCHORAGE ON DENTAL IMPLANTS

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ABSTRACT

This study uses the Finite Element Analysis (FEA) to investigate the stress-strain relation in peri-implant bone, caused by orthodontic anchorage. **Materials and method**. A tridimensional (3D) mathematical model was created to simulate the frontal teeth distalisation during anchorage on three dental implants. Using FEA was calculated the distribution of equivalent von-Mises stress when orthodontic forces of 2, 3 and 4 N were applied. ANSYS v11 software was properly configured for strain analysis in the model using FEA. **Results and discussion**. Periradicular maximum equivalent von-Mises stress values were 4,54 MPa for 2 N force, 6,82 MPa for 3 N force and 9 MPa when 4 N force was applied. **Conclusions**. FEA is a calculation method widely used in structural analysis that proved successfully in medical research. The forces caused by implant anchorage caused peri-implant bone stress in the model. The values of this stress correlated with the criterion of bone remodeling caused by mechanical load, and relative to study conditions, did not revealed biomechanical overload of peri-implant bone structure.

Keywords: finite element model, orthodontic anchorage, dental implant

INTRODUCTION

The orthodontic treatment of certain malocclusions can be challenging in the conditions of insufficient anchorage. Such conditions can include multiple edentations or anodontia, dental ingression and non-compliance patients [1]. A role in choosing the inticated type of implant has also the dento-maxilary devolpement pattern [2], [3], [4] and type of installed malocclusion [5].

In certain cases of multidisciplinary orthodontic and implantology approach, it represents a solution to increase dental anchorage by using prosthetic implants [6], [7], [8]. Using this technique, orthodontic movements were reported to be relized in a shorter period of time and without side effects like egressions and tilting [9], [10]. Besides Temporary Anchorage Devices (TAD's) like mini-implants, miniplates and palatal implants, prosthetic implants have also been used in orthodontic treatments to increase anchorage [1]. For predictable multidisciplinary treatment using implants, the planning and exactely pursuing the planned steps are required to ensure fix anchorage and meanwhile perform orthodontic mechanics (like space closing) without interfering with the implanted sites [6].

Although recently the use of implants for anchorage became more frequent, the remodeling processes that take place in bone are not considered fully underdstood [11]. The strength and distribution of stresses and strains in peri-implant bone are considered to influence the dinamics of biologic proceses in bone remodeling [12] and consequently have a rol in obtaining and maintain implant stability. Several factors are considered, in order to understand this complex process that can cause loss of stability and implant failure: bone structure (volume and density), implant properties (design and dimensions), surgical technique, orthodontic mechanics [13] and patient factors.

Frost [14] described the biomechanic effects of different load values on bone remodeling. These processes are characterized by stresses that produce strains in bone, called thresholds. A number of four thresholds are defined: MESr is bone's genetically determined disuse-mode threshold strain range, MESm is the modeling threshold strain range, MESp is bone's genetically determined operational microscopic fatigue damage threshold strain range and Fx is bone's fracture strength or ultimate strength, Table 1.

Table 1.

Set Point values for bone thresholds and maximum limit of fracture strenght
Frost [14]

Biomechanical threshold name	Strain threshold	Stress and unit-load terms
MESr	50 – 100 με	~1-2 MPa, ~0,1 kgf/mm^2
MESm	1000 – 1500 με	~20 MPa, ~2 kgf/mm^2
MESp	~3000 με	~60 MPa, ~6 kgf/mm^2
Fx	~25000 με	~120 MPa, ~12 kgf/mm^2

1 MPa = 10^6 N/m^2 = 0.1 kgf/mm^2.

Thresholds are represented on inferior horizontal line (Fig. 1). Mentioning that cortical strain values are extremely small, about ε ~ 10 – 6, when comapared to other materials and biomaterials, it is a reason for using the term microstrain to describe strain equal to 10-6. Subsequently in this study will be used as measure unit for strain:

1 microstrain (με) = 10 – 6

Biomechanical thresholds separate the intervals with biologic activity correlated to stress values. These intervals are: Disuse Window (DW), the Adapted Window (AW), Mild Overload Window (MOW), Pathological Overload (POW) and Fracture strain (Fx), (Fig. 1). These biomechanical correlations are used in many studies analysing the biologic effect of loads in peri-implant bone [15], [16].

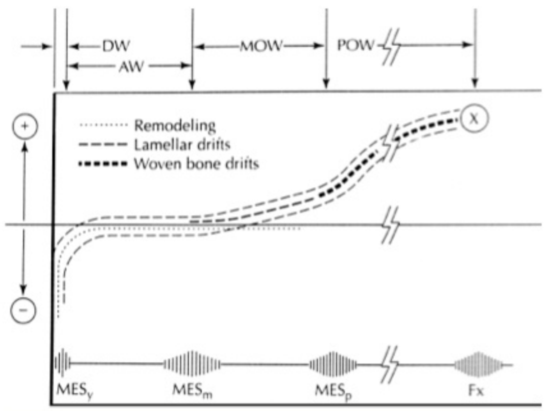


Figure 1. In this graphic can be observed drifts of remodeling bone, triggered by diferent stress values. This biomechanical behavior is estimated for healthy bones. Thresholds MESr, MESm, MESm, Fx and intervals DW, AW, MOW, POW are explained in text [14]

Studies that analyse bone stress-strain

distributions become more frequent in dentistry [17], [18] because bones supporting mechanical loads are also submitted to same continuous environment mechanical laws, subsequently bones structures have the same parameters. However, the same type of bone structure can have different limit values of mechanical parameters, but they maintain in a narrow margin.

These mechanical characteristic properties of materials, organic or inorganic, including bones, are *elastic modulus Young* E (kPa) that characterizes *linear-elastic behaviour* and *transversal contraction coefficient Poisson* ν characterising transversal contraction. These biomechanical parameters become often used in FEA studies, in Romania [19], [20], [21], [22] and abroad [23], [24], [25], [26], in order to calculate stress-strain relation in peri-implant bone.

The universal behaviour law is the stress-strain relation, known as *Hooke law* in study of materials, emphasises strain increase in a material when it is subjected to increasing stress values. This law expresses the proportionality between *stress* σ (force per surface unit, kPa) and *strain* resulted ε (adimensional), Stematiu D. [27].

$$\sigma = E\varepsilon$$

To simulate a tridimensional stress-strain relation, Hooke's law became matrix form known as *generalized Hooke law* [27]:

$$\{\sigma\} = [E]\{\varepsilon\},$$

where {σ} is the vector of stress and [E] is a symmetric matrix of elastic constants.

Wolff J. cited by Panait Gh. et al [28] formulated one of the principal biomechanical laws that explain how bone volume variation relates to specific loads. Bone homeostasis, described in Frost's Mechanostat [14], is the property of a system where variables are maintained or adjusted to normal values through feedback mechanism. In this system, threshold strains produce, depending on value, biomechanical effects that will vary, from atrophy to overload and ultimately fracture. It is relevant mentioning that the notions used in biology: threshold, homeostasis and feedback relates to *set point* and *control theory* notions used in cybernetics and other technical areas [29].

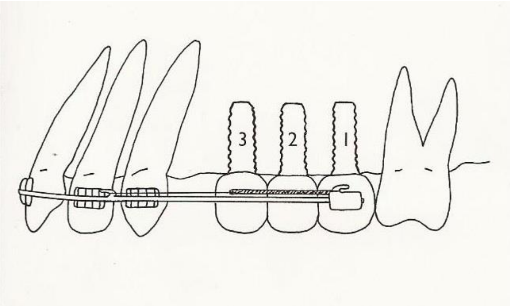
OBJECTIVE

Both TAD's and dental implants became used more often to increase orthodontic anchorage. Because of the different success rate, several factors influencing the bone stress-strain relation are studied [30], [31], [32]. The study reveals through mathematical modelling, using finite elements, the values and distribution of stresses in peri-implant bone during anchorage.

MATERIAL AND METHODS

A finite element model was created using ATOS 3D scanner, to scan an acrylic dento-alveolar maxilla (Spofa Dental) (Fig. 3). The volume of the obtained model was reduced to the left hemimaxila. The model mesh is composed of 89723 elements through 157440 nodes that represent four teeth (21, 22, 23, 27), three dental implants and the alveolar maxilla (Fig. 4) [33]. The values of stress-strain parameters for biologic components and titanium used in this study, according to Gedrange et al [34], Table 2.

The components of the model were adapted to the case of patient J.S. (Fig. 2 A and B) from Brunski and Slack [6], in order to simulate a treatment situation close to clinic situations. The 3D modelling of the three dental implants was adapted from Branemark implant dimensions of 11,5 mm length and 5 mm diameter. Corresponding to the clinical case, the implants were placed in lateral region of second quadrant in order to allow the distalisation of frontal teeth. All the crown replacements (three) were solidarised. The contact between cortical and the surface of each implant was continuous, on the entire surface of embedded portion of implants (similar to osseointegration situation).

a)


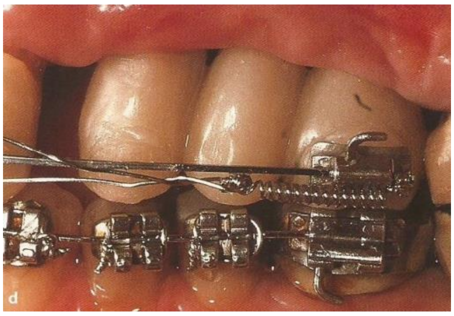
b)


Figure 2. a) The scheme of orthodontic anchorage on dental implants to ensure frontal distalisation [6]; b) Intraoral view of the orthodontic anchorage using dental implants [6]

Table 2.

Model components	Young's modulus of elasticity E (MPa)	Poisson's transversal contraction coefficient ν
Dentin	18600	0,31
Cortical bone	15000	0,33
Titanium	110000	0,3

The forces of 2, 3 and 4 N value were used to simulate orthodontic retrusiv forces applied on each frontal tooth (21, 22 and 23). Each force was applied on tooth crown in the geometrical center (bracket position) (fig. 4), (fig. 5) and (fig. 6). These forces, in horizontal plane, had a distal sense when were applied on teeth, and a mesial sense when applied on the implants (action and reaction effect).

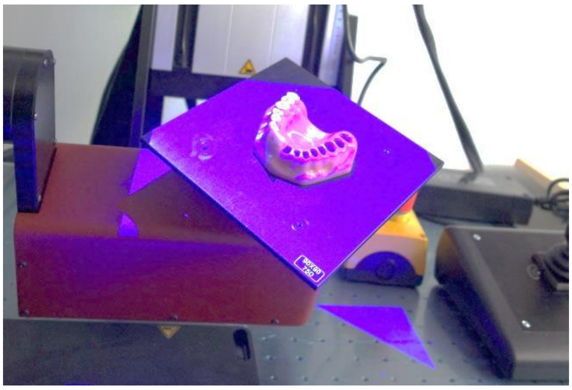


Figure 3. 3D scanning of the acrylic model [33]

ANSYS v11 program was used to evaluate the stress distribution in the model. The hardware system used in the study was a desktop computer, Intel Core i5 processor, 3,2 GHz frequency, 4 GB DDR3 and graphics accelerator.

RESULTS AND DISCUSSIONS

The maximum values of equivalent von-Mises stress, localized in periradicular bone of the central incisor, were: 4,54 MPa for a force of 2 N; 6,82 MPa for 3 N force and 9 MPa for 4 N force. Smaller values of equivalent stress were localized periradicular of 22 and 23. The calculated peri-implant bone stress values, localized mesial of first implant, had much smaller values compared to periradicular values.

Correlating maximum equivalent stress values, obtained using the estimated biologic effects of loads, criterion described by Frost [14], the biomechanical effect is situated in AW interval (Fig. 1), (Fig. 6). The peri-implant biomechanical effect, caused by much lower equivalent stress values, is localized differently, respectively in DW (Fig. 1), (Fig. 5). In real conditions, to this periradicular and peri-implant stress values caused by orthodontic forces, masticatory forces are added increasing the total bone stress value. In the FEA study of Ventura et al [25], the bone stress distribution is analysed when axial forces (comparable to masticatory forces) are exerted on a dental implant. The results of stress values obtained are 10 and 20 MPa, values that are considered in physiological interval of bone loading.

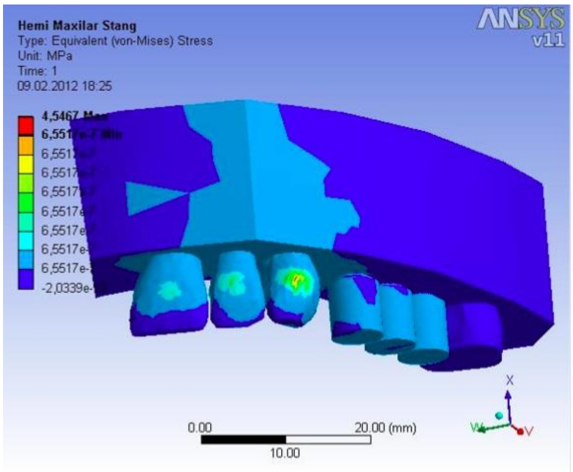


Figure 4. The 3D finite element model used in simulation to calculate peri-implant and periradicular equivalent stress distribution, caused by 2 N orthodontic forces applied on frontal teeth and on implants [33]

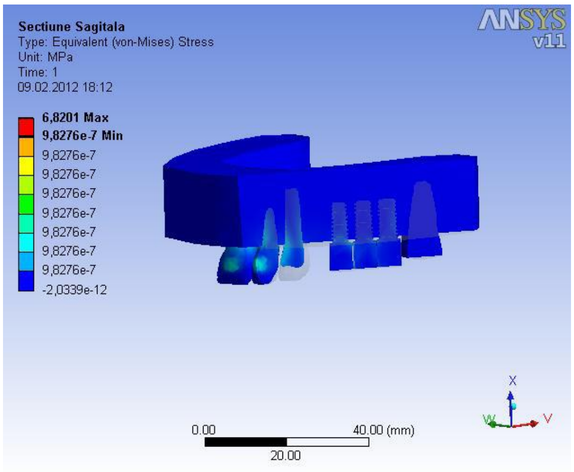


Figure 5. Section through the study model, to observe the distribution of peri-implant and periradicular equivalent stress, caused by 3 N orthodontic forces applied on frontal teeth and on implants [33]

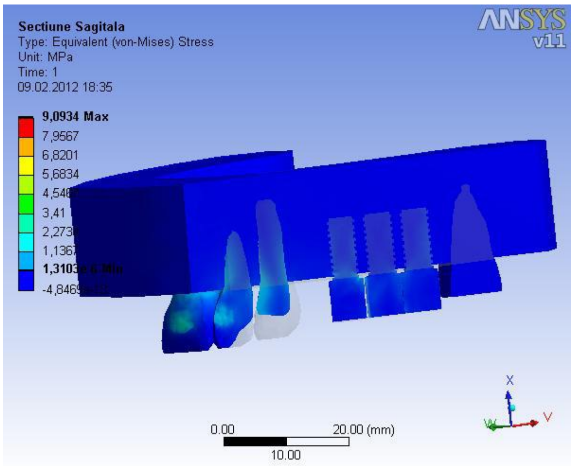


Figure 6. Section through the study model, to observe the distribution of peri-implant and periradicular equivalent stress, caused by 4 N orthodontic forces applied on frontal teeth and on implants [33]

A moment of force resulted, localized in cervical region of the mesial implant, periapical on distal edges of the implants and distaly of the third implant (in mesio-distal direction). Periradicular moments of force caused mesial cervical and distal periapical stress distributions. Thus, the axial rotation (of all three implants) had the cervical region of first implant as tipping point, while the axial rotation of each frontal tooth had the tipping point in the cervical region.

The values and relative uniform distribution of bone stresses, in the conditions of this study, confirms the significant potential of osseointegrated dental implants as orthodontic anchorage.

The stress distribution in peri-implant bone is subjected to several factors, some of them controlled by surgeon (technique of implant insertion), orthodontist (orthodontic treatment mechanics) and patient. These factors can affect the stability of implants [35], [36], [37], [38]. Some of these factors as: implant design, dimensions and moment of force are studied using FEA.

The limits of this in silico model consist in the representation of bone component completely as cortical, and the entire force applied on each tooth because of the absence of an orthodontic wire representation, in the study model. In order to obtain results closer to clinic situation it is necessary to increase the complexity of the model by using study models constructed on micro-computed tomography investigation, more divers implant designs and by adding new components like periodontal ligaments.

CONCLUSIONS

FEA is a calculation method widely used in structural analysis that proved successfully in medical research. The forces caused by implant anchorage caused peri-implant bone stress in the model. The values of this stress correlated with the criterion of bone remodelling caused by mechanical load, and relative to study conditions, did not revealed biomechanical overload of peri-implant bone structure. It is clear that this method will be implemented in day-to-day orthodontic activity as technology progresses and will set a benchmark in practitioners' guides.

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