A Three-Dimensional Finite Element Analysis of the Osseointegration Progression in the Human Mandible

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ABSTRACT

In this study, three-dimensional (3D) finite element analysis was used to model the effect of the peri-implant bone geometry and thickness on the biomechanical behavior of a dental implant/supporting bone system. The 3D finite element model of the jaw bone, cancellous and cortical, was developed based on computerized tomography (CT) scan technology while the dental implant model was created based on a commercially available implant design. Two models, cylindrical and threaded, representing the peri-implant bone region were simulated. In addition, various thicknesses (0.1 mm, 0.3 mm, 0.5 mm) of the peri-implant bone region were modeled to account for the misalingnment during the drilling process. Different biomechanical properties of the peri-implant bone region were used to simulate the progression of the osseointegration process with time. Four stages of osseointegration were modeled to mimic different phases of tissue healing of the peri- implant region starting with soft connective tissue and ending with complete bone maturation. For the realistic threaded model of the peri-implant bone region, the maximum von Mises stress and displacement in the dental implant and jaw bone were higher than those computed for the simple cylindrical peri-implant bone region model. The average von Mises stress and displacement in the dental implant and the jaw bone decreased as the oseeointegration progressed with time for all thicknesses of the peri-implant bone region. On the other hand, the maximum absolute vertical displacement of the dental implant increased as the drilled thickness of the peri-implant bone region increased.

Keywords: Dental implant, osseointegration, Finite element analysis, human mandible, 3D finite element modeling, Stress distribution, contact element, CT scan, segmentation, volume rendering.

1. INTRODUCTION

The edentulous patient (patient without teeth) presents a treatment challenge that has often been resolved inadequately. Traditionally, edentulous patients have been treated with conventional complete dentures, but it remains difficult for them to eat because their mandibular denture lacks retention and stability. It has been established that implant supported dentures introduced by Branemark[1] is a very feasible treatment option that will aid in the establishment of stability and retention to the mandibular denture.

The success or failure of dental implants depends critically on the osseintegration (ability of the prosthesis to adapt to the surrounding healing bone)[2]. The quality of osseointegration is highly dependent on many factors including the progression of the peri-implant bone tissue with time, the biomechanical stability of the dental implant and the surrounding bone as well as the thickness and geometry of the peri-implant bone region due to the drilling process. An understanding of these factors better enables a decision as to if earlier loading of implants is feasible, and what to consider when loading during healing. So, the realistic and accurate 3D modeling of the dental implant /supporting bone system, taking into account all the key factors that may influence stresses experienced by the jaw bone is of major significance in evaluating the success of the dental implant procedure.

The finite element analysis is the most suitable numerical technique for simulating the peri-implant bone region and for studying the factors behind the osseointegration phenomenon.[3, 4] Many finite element studies initially assumed the full osseointegration case where the dental implant is rigidly anchored in cortical and cancellous bone.[5,6] Other studies were conducted where the osseointegration levels were simulated by changing the insertion depths of the dental implant from

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50%, 75% to 100%. In these analyses three levels of osseointegration were considered. In the first level, the implant body is fully fixed in the jaw bone. In the next two, the degree of implant body embedding decreased to 75 and 50% respectively.[7] In addition, Natali et al. computed the mechanical properties of the transition regions of the bone-implant interfacial layer assuming a progressive corticalization around the implant.[8] The transition regions of osseointegration with constant elastic properties were used in many studies.[3, 4] However, these studies lacked the realistic modeling of different thicknesses and shapes of the peri-implant bone region. Many studies used the internal contact element tools in the finite element software package itself to simulate the different levels of osseointegration. The ‘‘bonded’’ type simulated perfect osseointegration in which the implant and the surrounding cortical bone are fully integrated. The ‘‘no separation’ element type was used to represent an imperfect osseointegration and the poorest osseointegration was modeled by a standard unilateral ‘‘frictionless’’ contact. [9,10] However, these studies did not simulate the realistic shape, thickness and elastic material properties of the peri-implant bone regions during the osseointegration process. Taken as a whole, although many FE studies simulated the osseointegration process [5-9] but, the biomechanical behavior of tissue progression levels and the realistic modeling of the shape and thickness of the peri-implant bone region during surgery is still lacking. The purpose of this study was to develop a realistic 3D finite element model of the dental implant and the supporting bone system to mimic the osseointegration process. Key parameters were varied to investigate their effect on the stability of the dental implant/surrounding bone system as well as their effect on the osseointegration quality. The finite element models are created to simulate the effect of the peri-implant bone thickness with three different values (0.1, 0.3. 0.5mm), the geometry of peri-implant bone with two different shapes (threaded, cylindrical) and the osseointegration progression during healing process using four different mechanical properties of the peri-implant bone on the mechanical behavior of dental implant/surrounding bone system.

2. MATERIALS AND METHODS

2.1. Geometry

2.1.1 Dental implant geometry

A model of a 4 mm x 15 mm square-threaded solid-screw ITI implant (Straumann AG, Waldenburg, Switzerland) having a thread pitch of 0.75 mm and a thread number of 14, a 7 mm long metallic abutment and a 13mm long internal implant-abutment screw connecting the implant and abutment is used in this study [Fig. 1(a) and (b)]. The dental implant system is created in the CAM software Solidworks 2006 (Solidworks® Corporation, USA).

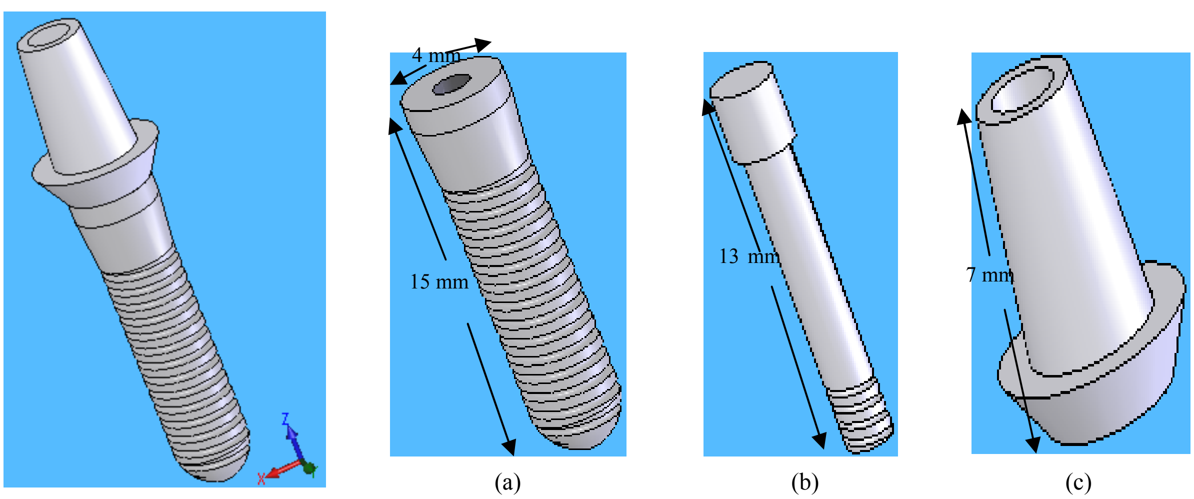


Fig. 1. The dental implant system. (a) The dental implant. (b) The dental implant- abutment screw. (c) The abutment.

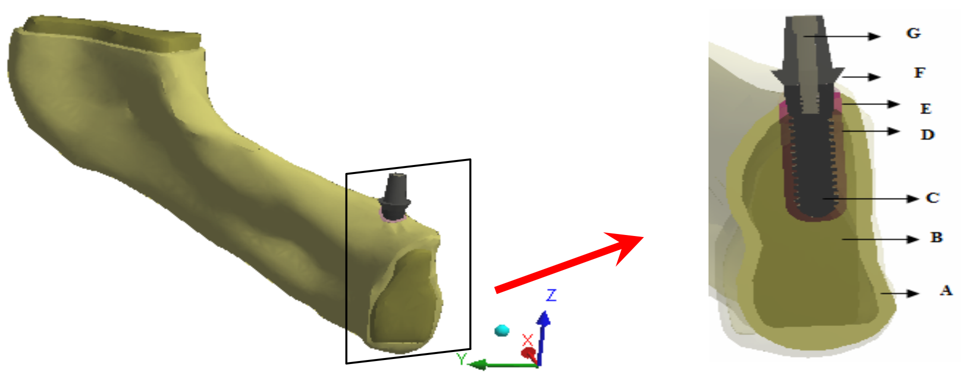
1.2 Geometry of the mandible

The three dimensional geometrical model of the human mandible was constructed from 48 DICOM format Computed Tomography (CT) slices of 0.5 mm thickness through image segmentation and 3D reconstruction using the

CAD software Mimics (Materialise Corporation, USA). Different regions (cortical and cancellous) of mandible bone were distinguished in order to assign different mechanical properties to them in the subsequent finite element model. Two peri-implant bone regions at cancellous and cortical jaw bone that were particularly important from the biomechanical point of view were defined. Specific mechanical properties where the bone tissue shows the most significant change during the healing phases that follows the insertion of the implants were assigned to these regions.
The complete mandible and dental implant system inserted in the first premolar region (Fig. 2) is assembled in CAM software Solidworks 2006 (Solidworks® Corporation, USA) in order to export into the finite element (FE) package.

2. Material properties

The Young's moduli, the Poisson's ratios and the density of the dental implant system and the surrounding bone are listed in Table 1. [9] Osseointegration region (peri-implant bone regions surrounding the implant) material properties for each level of osseointegration progression from 4 weeks after surgery to full osseointegration after 16 weeks are listed in Table 2. [11] All materials used in the models were assumed to be isotropic, homogeneous, and linearly elastic.



(a) (b)

Fig.2: Geometry of jaw bone with dental implant system. (a) The jaw bone region with dental implant system. (b) The axial section of the geometry containing cortical bone A, cancellous bone B, dental implant C, peri-implant region at cancellous bone D, peri-implant region at cortical bone E, the abutment F and the implant-abutment screw G.

Table 1. Material properties used in numerical analysis [9]

Material	Young's Modulus *E*(Mpa)	Poisson's ratio υ	Density ρ (Kg/m^3)
Titanium alloy (TI-6AL-4V)	110 000	0.35	4500
Abutment	110 000	0.35	4500
Screw	110 000	0.35	4500
Cortical bone	14 000	0.3	1700
Cancellous bone	3 000	0.3	270

Table 2. Tissue histology and Young's moduli of the two peri implant bone regions of osseointegration at 4, 8, 12 and 16 weeks full osseointegration.

Stage (weeks)	Peri-implant bone region at cancellous bone (inner) [tissue type]	Modulus (Mpa)	Peri-implant bone region at cortical bone (outer) [tissue type]	Modulus (Mpa)
4	Soft connective tissue with invading vasculature	3.8	Soft fibrocartilage tissue	76
8	Woven bone, 25% maturation	700	Dense fibrous tissue, 45% maturation	2860

12	Woven bone, 25% maturation	765	Dense fibrous tissue, 45% maturation	3060
16	Woven bone, 60% maturation	5000	Bone, 100% maturation	20000
Poisson' ratio (υ) = 0.3.[11]				

3. Finite Element Analysis

The finite element (FE) model and computations were performed in ANSYS Workbench 10.0 (ANSYS Workbench™ 10.0, ANSYS®, Inc, USA). The whole system is discretized with 143,153 nodes and 113,334 elements, including 89,902 10-node quadratic tetrahedron solid elements and 23,432 quadratic triangular contact/target elements. A refined mesh is used in the threaded areas and the surrounding bone and dental implant interface surface. The bonded contact conditions were considered for all jaw bone and dental implant system interfaces. All nodes at the inferior surface of the mandible are treated as fixed boundaries. Occlusal forces of 100N were applied axially (AX) to the top surface of dental implant-abutment screw.

In this study, nine finite element models are created to simulate the effect of:

1. The peri-implant bone thickness with three different values (0.1, 0.3. 0.5mm).
2. The geometry of peri-implant bone with two different shapes (threaded, cylindrical).
3. The osseointegration progression during the healing process using four different mechanical properties of the peri-implant bone region.

on the mechanical behavior of dental implant/surrounding bone system. The maximum von Mises stresses in the bone and dental implant system and the maximum vertical absolute displacement in the dental implant in micrometer were computed and compared.

3. RESULTS

3.1The effect of the geometry of the peri-implant bone region:

The Maximum von Mises stress in the dental implant/surrounding bone system as well as the maximum absolute vertical displacements in the dental implant are listed in Table 3. Computations were performed at a peri-implant bone region thickness of 0.5 mm and for an osseointegration level = 4. As listed in Table 3, the micromovement (the maximum absolute vertical displacement) of the dental implant increases as the geometry of the peri-implant bone region changes from a cylindrical shape to a threaded shape.

The von Mises stress contour plots for two different geometrical shapes (cylindrical and threaded) of the peri-implant bone region are illustrated in Fig. 3 (a) and (b).

Table 3. Computed displacements and stresses for two different peri-implant region geometries.

Peri-implant region geometry	Maximum von Mises stress in the implant (MPa)	Maximum von Mises stress in lower peri-implant region (MPa)	Maximum von Mises stress in upper peri-implant region (MPa)	Maximum von Mises stress in bone (cortical/trabecular) (MPa/MPa)	Maximum Absolute Vertical displacements in the dental implant (μm)
Cylindrical shape	21.095	2.058	12.179	3.0568 / 1.0088	2.5238
Threaded shape	26.685	4.664	14.429	4.3265 / 1.5195	2.9759

It is observed that the stress distribution on the cortical bone, the cancellous bone and the dental implant increases as the geometry of the peri-implant bone region changes from a cylindrical shape to a threaded shape**.**

3.2 The effect of the osseointegration progression of the peri-implant bone region at different thicknesses:

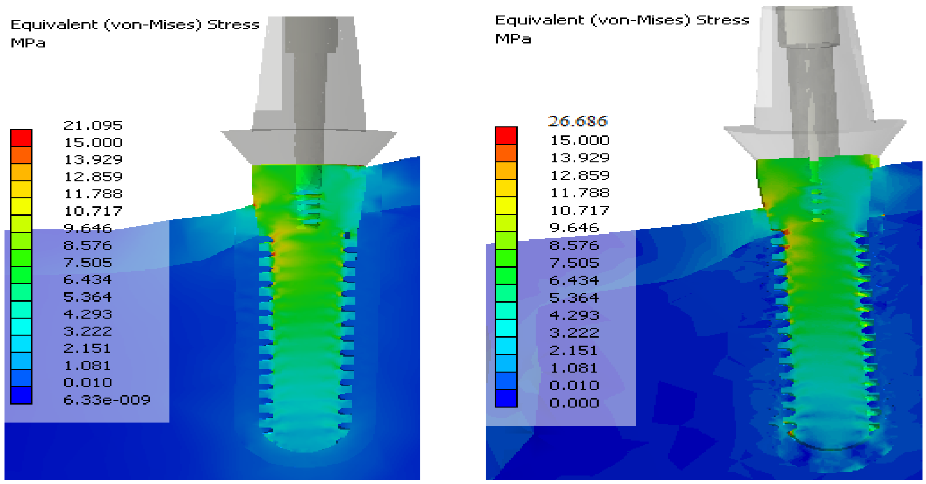


Fig. 3. The mesial-distal section of von Mises stress distribution on the dental implant/surrounding bone system in MPa for two different geometrical shapes of the peri-implant bone regions. (a) Cylindrical shape. (b) Threaded shape.

The average von Mises stress distribution on the dental implant, the cortical jaw bone and the cancellous jaw bone for different osseointegration levels at various peri-implant bone region thicknesses of 0.1, 0.3 and 0.5mm are listed in Table 4. The dental implant has the largest average von Mises stress compared to the jaw bone. On the other hand, the average von Mises stress values on the cortical jaw bone are observed to be higher than those computed on the cancellous jaw bone.

Table 4. The von Mises stresses and vertical displacement for different osseointegration levels and at the peri-implant bone region thicknesses of 0.1, 0.3 and 0.5mm.

Thickness	**Osseo-integration level**	**Average von Mises on dental implant**	**Average von Mises Stress on jaw bone**		**Vertical displacement in the dental implant**
			Cortical	**Cancellous**	
mm		**MPa**	**MPa**	**MPa**	**μm**
0.1	1	15.134	10.199	5.83	29.58
	2	12.99	2.1536	1.039	3.23
	3	12.86	2.1237	0.99	3.18
	4	10.301	1.3602	0.547	2.67
0.3	1	39.99	9.62	2.63	53.85
	2	15.71	2.05	0.819	3.48
	3	15.59	2.02	0.817	3.41
	4	14.83	1.982	0.757	2.77
0.5	1	15.42	5.908	4.145	74.52
	2	14.27	1.668	0.898	3.56
	3	14.21	1.626	0.867	3.47
	4	10.675	1.529	0.5045	2.52

3.2.1 The average von Mises stress distributions on the jaw bone:

a) Cortical jaw bone:

The variation of the von Mises stress in the cortical bone with the progression of time and at different thicknesses of the peri-implant bone region is illustrated in Fig. 4. The average von Mises stress values on the cortical jaw bone decrease as the osseointegration progression changes from soft tissues in level 1 to mature bone in level 4.

In addition, the average von Mises stress in the cortical jaw bone decreases as the thickness of the peri-implant bone region increases for the first three levels of the osseointegration process. However, at full osseointegration (level 4), the von Mises stress in the cortical jaw bone increases with the peri-implant bone region thickness (0.1 mm to 0.3 mm) and decreases again as the thickness of this region becomes 0.5 mm.

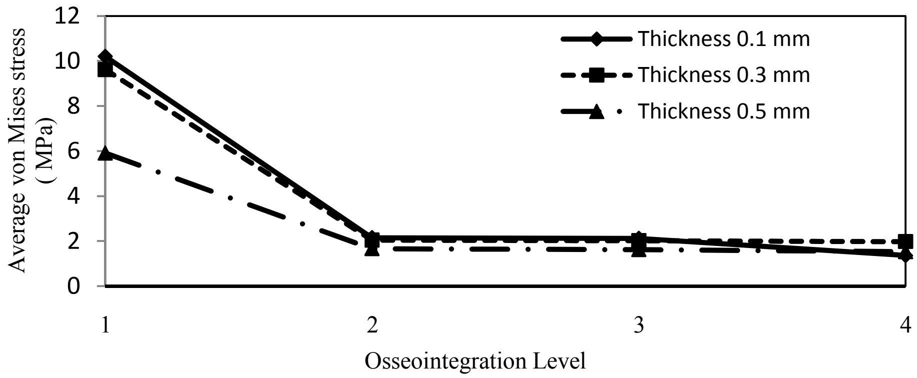


Fig. 4. Average von Mises stress in the cortical bone at different osseointegration levels for various thicknesses of the peri-implant bone region.

Fig. 5. shows the spatial distribution of von Mises stress in the cortical jaw bone at full bone maturation (level 4). The maximum von Mises stress in the cortical jaw bone is concentrated in the area surrounding the dental implant neck for all osseointegration progression levels.

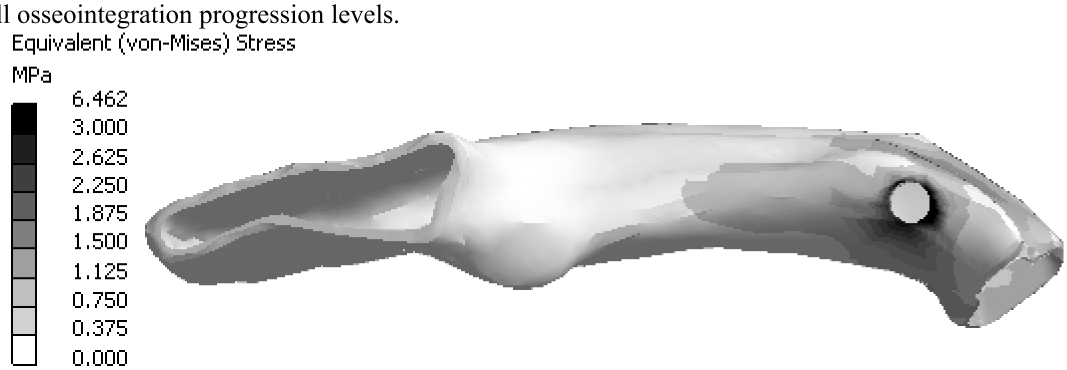


Fig. 5. The von Mises stress distribution in the cortical jaw bone at level 4 of the osseointegration.

b) Cancellous jaw bone:

Fig. 6 shows the variation of the von Mises stress in the cancellous bone with the progression of time and at different thicknesses of the peri-implant bone region. During the osseointegration process, the average von Mises stress in the cancellous jaw bone decreases as the bone becomes mature at all thicknesses of the peri implant bone region.

On the other hand, the von Mises stress in the cancellous jaw bone decreases with the peri-implant bone region thickness (0.1 mm to 0.3 mm) and increases again as the thickness of this region becomes 0.5 mm in level 1 and level 2 of the osseointegration process. The von Mises stress in the cancellous jaw bone decreases with increasing of the peri-implant bone region thickness in level 3 of the osseintegration. In addition, The von Mises stress in the cancellous jaw bone increases with the peri-implant bone region thickness (0.1 mm to 0.3 mm) and decreases again as the thickness of this region becomes 0.5 mm in the full osseointegration level (level 4) . Fig. 7 shows the spatial distribution of the von Mises stress in the cancellous jaw bone at full bone maturation (level 4).

The maximum von Mises stress in the cancellous jaw bone is located in the contact surface with the bottom of the dental implant.

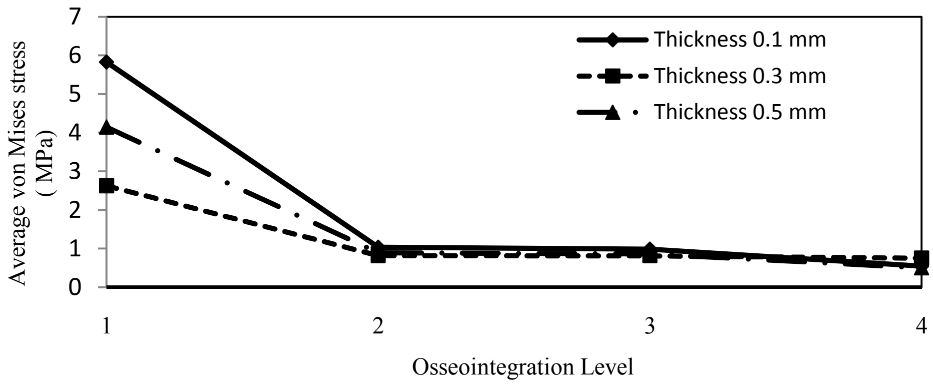


Fig. 6. Average von Mises stress in the cancellous jaw bone at different osseointegration levels and at various thicknesses of the peri-implant bone region.

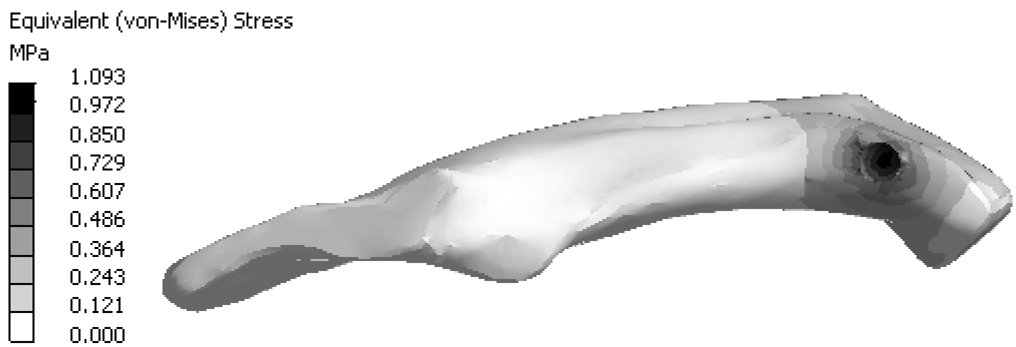


Fig.7. The von Mises stress distribution on the cancellous jaw bone at level 4 of the osseointegration process.

c) The dental implant:

Fig.8 shows the average von Mises stress computed in the dental implant with the progression of time and at different thicknesses of the peri-implant bone region. The average von Mises stress on the dental implant decreases as the osseointegration progresses with time and the surrounding jaw bone becomes more mature.

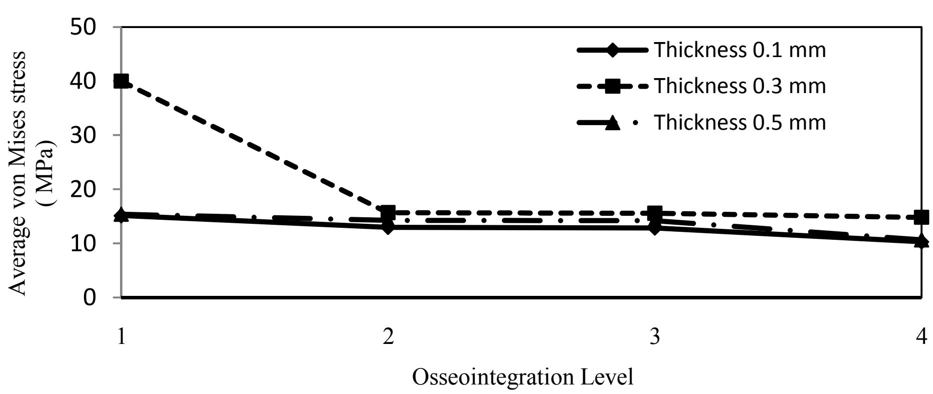


Fig. 8. Average von Mises stress in the dental implant at different osseointegration levels for various thicknesses of the peri-implant bone region.

Fig. 9 illustrates the contour plot of the average von Mises stress in the dental implant. The maximum stress values are concentrated around the first thread of the dental implant.

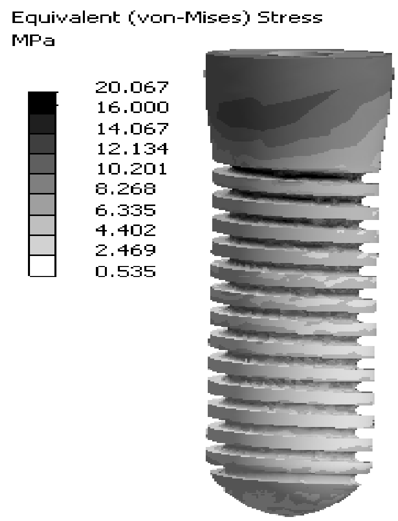


Fig.9. The von Mises stress distribution on the dental implant at level 4 of the osseointegration process.

3.2.2 The vertical displacement of the dental implant:

Fig. 10 shows the vertical displacement in the dental implant at different osseointegration levels and for various thicknesses of the peri-implant bone region. The maximum absolute vertical displacement of the dental implant decreases with the progression of time for all thicknesses of the peri-implant bone region. In other words, the micromovement of the dental implant decreased with the progression of peri-implant bone region's tissues from soft tissue to mature bone (level 4 of osseointegration).

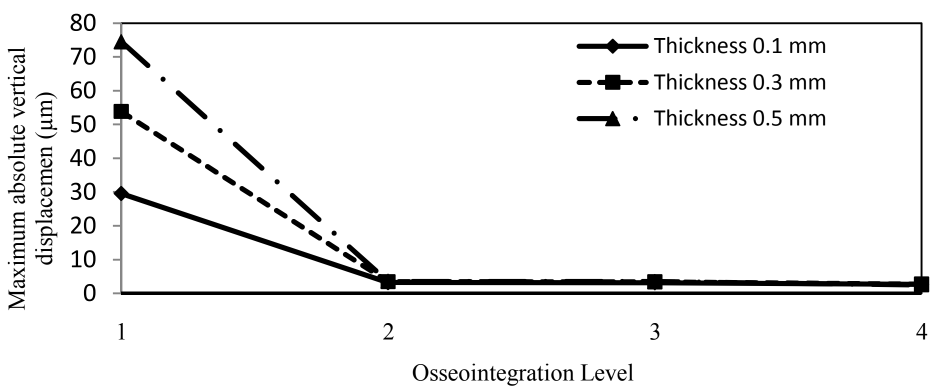


Fig. 10. Vertical displacement in the dental implant at different osseointegration levels and for various thicknesses of the peri-implant bone region.

3.2.3 The effect of the thickness of the peri implant bone region at the beginning of osseointegration:

Fig. 11 shows the maximum absolute vertical displacement of the dental implant for three different thicknesses of the peri implant bone region (0.1, 0.3, 0.5 mm) at the beginning of the osseointegration process (level 1).The vertical displacement of the dental implant increases as the drilled thickness of the peri-implant bone region increases. This is due to the fact that the wound region between the implant and jaw bone increases as the thickness of the drilled area increases. The implant moves freely in the wound region under mechanical stress and its micromovement increases.

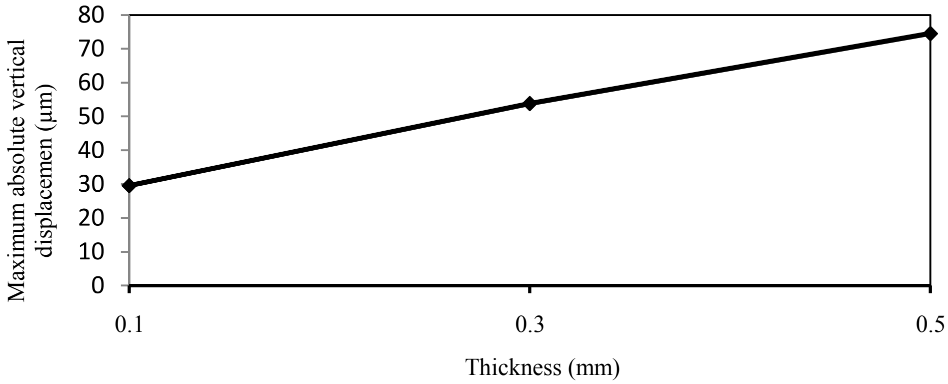


Fig.11. Micromovement of the dental implant for three different thicknesses of the peri implant bone region (0.1, 0.3, 0.5 mm) at the beginning of the osseointegration process (level 1).

4. DISCUSSION

The focus of this paper was to develop a realistic 3D finite element model of a commercially available dental implant and the supporting bone system mimicking the osseointegration process in the human mandible. Studies on osseointegration have brought to attention some key factors. Some of these factors which are critical for determining the success of osseointegration are micromotion, primary stability, implant design and implant surface characteristics. An understanding of these factors better enables a decision as to if earlier loading of implants is feasible, and what to consider when loading during healing. Therefore, key parameters were varied in our study to investigate their effect on the stability of the dental implant/surrounding bone system as well as their effect on the osseointegration quality. The quality of the drilling process is of major significance in the determination of the primary stability of the dental implant and the acceleration of the osseointegration process. The primary stability is the tight anchorage of the implant to the bone as a result of implant insertion. The primary stability and consequently the success of the implant osseointegration depend on the material used, the technique of host site preparation and the design of the implant.[12] The thickness of the peri-implant bone region during the healing process, which consequently affects the magnitude of the potential micromovement is affected by the technique of host site preparation regarding osteotomy size.[13]

The micromovement of the dental implant (the maximum absolute vertical displacement) increases as the drilled thickness of the peri-implant bone regions increases for all osseointegration levels [see Figs. 10 and 11]. This is due to the fact that the wound area between the implant and jaw bone increases as the thickness of drilling increases. The implant moves freely in the wound area under mechanical stress and its micromovement increases. In addition, the micromovement of the dental implant decreases as osseointegration progresses with time since the stiffness of the peri-implant bone tissue gradually increases and the ability of jaw bone to absorb stress increases during different levels of the healing process.

The design of commercially available dental implants is characterized by shape, type of implant-abutment mating, presence (or absence) of threads, thread design, surface topography, and chemical composition.[14] Previous studies modeled the peri-implant bone region shape as a cylindrical geometry.[8,15] However, screw-shaped implants were observed to provide the greatest retention, to enhance initial stability and to increase surface contact after insertion and during the initial healing phase.[16-19] In addition, the internal jaw bone surface was observed to conform to the threaded shape of the dental implant during the drilling process.[3]

Therefore, we investigated the biomechanical behavior of the jaw bone and the inserted dental implant due to the change of the geometry of the peri-implant bone region from the conventional cylindrical shape to the more realisitic threaded shape. Our results (see Table 3) demonstrated that the stress distribution on the cortical bone, the cancellous bone and the dental implant as well as the micromovement of the dental implant increases as the geometry of the peri-implant bone region changes from a cylindrical shape to a threaded shape**.** Thus, indicating the importance of realistically modeling the peri implant bone region.

The selection between the von Mises stress and the principal stress values when calculating stress in the bone is controversial. Researchers who adopted the use of the principal stress suggest that bone is a brittle material and should be described with stress patterns utilized for brittle materials which are the maximum and minimal principal stresses. Other researchers suggested that the von Mises stress can be also used because wet bone does not show a brittle behavior.[20] Furthermore, most of the stress values that occur during occlusal loading are below the yield strength of the material which makes the description brittle or ductile irrelevant. Wang et al. [21] calculated both von Mises and principal stresses for their models and found that the tendency and percentage of changes were similar for both stress types. Therefore, we investigated the biomechanical behavior (von Mises stress and displacement) of the dental implant/surrounding bone system with the progression of time throughout the healing process. Four levels of osseointegration are modeled by changing the material properties (Young's moduli and Poisson's ratio) of the peri-implant bone region to mimic different phases of tissue healing starting with soft connective tissue and ending with complete bone maturation. The average von Mises stress values on the dental implant were observed to be higher than those on the jaw bone for different thicknesses of the peri-implant bone region and at all osseointegration levels (Table 4). This is due to the fact that the stress distribution through the dental implant/surrounding bone system seems to decrease in magnitude consistently as it propagates from the working to the non-working side. This is in agreement with the findings of Sadowsky et al. [22]

In addition, the stress distribution had maximum values on the cortical bone side and the lowest values were observed on the cancellous bone side during all levels of the healing period. This was due to the fact that the cortical bone has more stiffness than the cancellous bone.[23] Moreover, the average von Mises stresses on the cortical, cancellous bone and dental implant decreases as the tissues in the peri-implant bone regions grow from soft tissues to mature bone during osseointegration process (Figs. 4, 6 and 8). This is due to the increase in the elastic modulus of the peri-implant bone region during the healing period which aided in homogeneity spread of stress and the decrease in the subsequent deformation in the jaw bone with dental implant. The maximum von Mises stress values were observed surrounding the implant neck like a ring on the cortical bone side (see Fig. 5), at the implant bottom on the cancellous bone side (Fig. 7) and at the first thread of the dental implant as shown in Fig. 9 for all the osseointegration levels. Sun et al. reported similar stress distributions in the cortical and cancellous bone. [6] Our findings provide information about the effect of the increase of the density and quality of the peri-implant bone -at cortical and cancellous jaw bone- on stress values in jaw bone, and also show the ability of cortical bone to absorb stress and the ability of cancellous bone to transfer stress as the osseointegration progresses with time.

The dental implant is inserted in the jaw bone during the surgery and drilled into jaw bone. This process depends on the quality and experience of the implantologist who performs the surgery and on the surgery circumstances. Therefore, we investigated the effect of the peri-implant bone thickness on the stress distribution in the jaw bone and on the stability of the dental implant. Different thicknesses were simulated (0.1, 0.3, 0.5 mm) using the same shape of the peri-implant bone region and at the same osseointegration level. The biomechanical behavior of the jaw bone varies as the thickness of the peri-implant bone region changes. At the beginning of osseointegration, the average von Mises stress in the jaw bone decreases for realistic thicknesses of the peri implant bone region (0.1 to 0.3 mm) (see Figs. 4 and 6). However, the average von Mises stress in the dental implant increases for realistic thicknesses of the peri implant bone region (0.1 to 0.3 mm) (see Fig. 8). These results indicate that the dental implant withstands more stress compared to the jaw bone as the drilling thickness increases at the beginning of the osseointegration process.

Experimental validation of our numerical results should be the goal in future studies. However, the higher number of parameters (models of different peri-implant bone region geometry, thicknesses, and osseointegration levels) made it very complicated to validate all the models using the finite element method. Our study could be expanded to model the osseointegration process based on CT scans of each level of osseointegration and clinical experiments performed on human subjects during each period of the healing process.

5. CONCLUSIONS

The biomechanical behavior of a dental implant/supporting bone system model mimicking the osseointegration process is investigated using a 3D finite element model. Our study demonstrated that the success rate and the quality of osseointegration is highly dependent on many factors including the progression of the peri-implant bone tissue with time throughout the healing process, the biomechanical stability of the dental implant and the surrounding bone as well as the thickness of peri-implant bone due to the misalignment during the drilling process. The von Mises stress distribution in the jaw bone (cortical and cancellous) decreases as the osseointegration of the peri implant bone region changes from soft connective tissue to complete bone maturation. The micromovement of the dental implants was shown to increase with the progression of osseointegration. On the other hand, the primary stability of the dental implant increases as the peri-implant bone region thickness increases during the drilling process. The Accurate modeling of the geometry of the peri-implant bone tissue region is shown to be of vital importance since our results indicate that the cylindrical model underestimates stress experienced by the dental implant /supporting bone system. Thus, the realistic and accurate 3D modeling of the above dental implant /supporting bone system, taking into account all the key factors that may influence stresses experienced by the jaw bone is of major significance in evaluating the success of the dental implant procedure.

REFERENCES

[1] Brånemark, P. I., Adell, R., Breine, U., Hansson, B. O., Lindström, J., and Ohlsson, A.,"Intra-osseous anchorage of dental prostheses, I. Experimental studies," Scand J Plast Reconstr Surg, vol.3, pp.81-100, (1969).

[2] Turner, C. H., Anne, V., and Pidaparti, R. M. V., "A uniform strain criterion for trabecular bone adaptation: Do continuum level strain gradients drive adaptation?," J. Biomechanics vol.30, no.6, pp. 555-563, (1997).

[3] de Cos Juez, F., Lasheras, F. , Nieto, P. and Àlvarez-Arenal, A., "Non-linear numerical analysis of a double-threaded titanium alloy dental implant by FEM," J. Applied Mathematics and Computation, vol.206, pp. 952–967, (2008).

[4] Veziroglu, F. and Yilmaz, D., "Biomechanical evaluation of the consolidation period of alveolar distraction osteogenesis with three-dimensional finite element analysis," Int. J. Oral Maxillofac. Surg., vol. 37, pp.448–452, (2008).

[5] Huang, S., and Tsai, C. F., " Finite Element Analysis of a Dental Implant, " J.Biomed Eng Appl Basis Comm, vol.15, no.2, pp.82-85, (2003).

[6] Sun, Y., Kong, L., Liu, B., Song, L., Yang, S. and Wei T., "Comparative study of single-thread, double-thread, and triple-thread dental implant: a three-dimensional finite element analysis," J. Modelling and Simulation, vol.3, no.4, pp. 310-314, (2007).

[7] Wierszycki, Kąkol, W., and Łodygowski, T., "The Screw Loosening and Fatigue Analyses of Three Dimensional Dental Implant Model," ABAQUS Users' Conference (2006).

[8] Natali, A., Pavan, P., and Ruggero, A., "Evaluation of stress induced in peri-implant bone tissue by misfit in multi-implant prosthesis, " J. Dent. Materials, vol. 22, pp. 388–395, (2006).

[9] Yang, J., and Xiang, H., "A three-dimensional finite element study on the biomechanical behavior of an FGBM dental implant in surrounding bone," J. Biomechanics, vol.40, pp.2377–2385, (2007).

[10] Ihde, S., Goldmann, T., Himmlova, L., and Aleksic, Z., "The use of finite element analysis to model bone-implant contact with basal implants," J.Oral Surg Oral Med Oral Pathol Oral Radiol Endod, vol.106, pp.39-48, (2008).

[11] Gardner, T., and Mishra, S., "The biomechanical environment of a bone fracture and its influence upon the morphology of healing," J. Medical Engineering & Physics, vol.25, pp.455–464, (2003).

[12] Meyer, U., Wiesmann, H. P., Runte, C., Fillies, T., Meier, N., Lueth, T., and Joos, U., "Evaluation of accuracy of insertion of dental implants and prosthetic treatment by computer-aided navigation in minipigs," Journal of Oral and Maxillofacial Surgery vol. 41, pp.102–108, (2003).

[13] Malo, P., Rangert, B., and Dvarsater, L., "Immediate function of Branemark implants in the esthetic zone: A retrospective clinical study with 6 months to 4 years of follow-up," Clin Oral Implants Res., vol.2, pp.137-145, (2000).

[14] Sykaras, N., Iacopino A. M., Marker, V. A., Triplett, R. G., and Woody, R. D., "Implant materials, designs and surface topographies: their effect on osseointegration A literature review," Int. J. Oral and Maxillofacial Implants, vol.15, pp.675—690, (2000).

[15] Natali, A.., Carniel, E., and Pavan, P ., "Investigation of bone inelastic response in interaction phenomena with dental implants," J. dental materials, vol.24, pp. 561–569, (2008).

[16] Lee, J. H., Frias, V., Lee, K. W., Wright, R. F., "Effect of implant size and shape on implant success rates: A literature review," J. Prosthetic Dentistry, vol.94, no.4, pp.377-381, (2005).

[17] Tada, S., Stegaroiu, R., Kitamura, E., Miyakawa, O., and Kusakari, H., "Influence of Implant Design and Bone Quality on Stress/Strain Distribution in Bone Around Implants: A 3-dimensional Finite Element Analysis," Int. J. Oral Maxillofacial Implants, vol.18, pp.357–368, (2003).

[18] Hansson, S., and Werke, M., "The implant thread as a retention element in cortical bone: the effect of thread size and thread profile: a finite element study," J Biomech, vol.36, pp.1247-58, (2003).

[19] Ivanoff , C., and Grondahl, K.., "Influence of variations in implant diameters: a 3- to 5-year retrospective clinical report," The International Journal of Oral & Maxillofacial Implants, vol. 14, pp. 173-180, (1999).

[20] Fung, Y. C., [Biomechanics: Mechanical properties of living tissues], Springer, 2nd ed., New York, (1993).

[21] Wang, T., Leu, L., Wang, J., and Lin, L., “Effects of prosthesis materials and prosthesis splinting on peri-implant bone stress around implants in poor-quality bone: A numeric analysis,” Int. J. Oral Maxillofacial Implants, vol.17, pp.231-7, (2002).
[22] Sadowsky, S. J., and Caputo, A. A., “ Effect of anchorage systems and extension base contact on load transfer with mandibular implant-retained overdentures, ” J. Prosthetic Dentology, vol.84, pp.327-34, (2000).
[23] Davies, J., “Understanding Peri-Implant Endosseous Healing,” J. Dental Education vol. 67, no. 8, pp. 932-949, (2003).