Original Research Article

Finite Element Stress Analysis of Overdentures Supported by Angled Implants

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Abstract

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The aim of this study was to evaluate the stress distribution in the supporting bone of splinted inclined implants by 3D finite element stress analysis. A three dimensional edentulous mandibula was constructed. Four dental implants were placed in the inter-foraminal area; 4 different models were created by inclining the mesial two implants with 0, 5, 10, and 15 degrees. 90 N vertical and 180 N oblique loads were applied unilaterally to right canine. Also, 150 N oblique loads were applied to the incisors to simulate biting force. Maximum and minimum principle stresses in the cortical bone around implants were evaluated. For the first and the second loading conditions, the highest maximum principle stress was observed in the highest inclined models and the lowest stresses were observed in the control models. For the third loading condition the highest maximum principle were observed in the vertically placed model, whereas the maximum inclined implants had shown the lowest maximum principle stress values. In all loading conditions, the highest maximum stress values were observed at the cortical bone around the neck of the implant. The principle stress in the supporting bone, were affected by loading conditions and the direction of the loading.

Keywords: Bar attachments, inclined implants, overdentures, three dimensional finite element analyses

INTRODUCTION

Edentulous patients' major problem has been the lack of satisfaction with their complete dentures, especially the instability of the lower dentures. Osseointegrated dental implants are ideal treatment alternatives to enhance the retention and stability of the complete dentures (Dario, 2002; Misch, 2005; Narhi et al., 2001). The implant overdenture obtains support and retention from an attachment assembly affixed to the denture base. It is well known that implant-retained/supported overdentures provide improved retention, support, stability, function, and comfort for the patients (Bidra et al., 2012; Naert et al., 1999; Jemt et al., 1996). Multiple prosthetic designs, materials, and techniques have been extensively described in the literature (Bidra et al., 2012; Sadowsky,

2001). No single method or technique has been proven to be superior and there is inconclusive evidence about the clinical superiority of using splinted (bars) versus unsplinted overdenture abutments (Bidra et al., 2012; Sadowsky, 2001; Sadowsky, 2007).

Fully implant-supported overdenture is an attachment assembly that usually includes four or more implant supporting the prosthesis. This type of prosthesis receives support directly from the bar superstructure connected to the implants, and the design provides resistance to rotational and lateral forces in a way similar to a conventional hybrid prosthesis (Galindo, 2001). During mastication, the attachment assembly transfers all of the masticatory forces to the supporting implants. The

use of a milled bar for a purely implant-supported mandibular overdenture may be considered for clinical advantages similar to those of a fixed prosthesis (Eliasson et al., 2000; Kreisler et al., 2003), and possibly, the prosthetic advantages of the removable denture (Sadowsky, 2001; Krennmair et al., 2007; Engstrand et al., 2003; Meijer et al., 2004). The designs of the implant supported prostheses were determined according to the position and inclination of the implants. There are many possibilities to correct the disinclined implants. There are angled abutments for the fixed prostheses and ball, bar or locator abutments are used for the removable prostheses in order to compensate the wrong inclination. Merickse-Stern stated in a recent article that more information is needed regarding the effect of multiple implant (3 or 4) splinted with a bar in terms of force distribution (Mericske-Stern, 1998).

Appropriate alignment and position of implants are important for its long-term success. It has been suggested that implants be positioned parallel to the path of insertion of planned prostheses and as perpendicular to the occlusal plane as possible so that they are loaded axially, minimizing the production of bending moments (Gulizio et al., 2005; Mericske-Stern, 1993). Most implant overdenture abutments and related components require parallelism within approximately 10 degrees to function properly (Dario, 2002). In order to provide long term implant success, optimal biomechanics should be achieved. Disturbance of sensitivity can be caused by a minor mesiodistal deviation of the drilling axis in areas close to neural structures, such as the mental nerve (Payer et al., 2008). Despite the use of drilling supports and precise preparation techniques, aberration from the planned ideal mesiodistal implant axis can frequently be seen in postoperative radiographic evaluation (Payer et al., 2008). Reports have documented that excessive occlusal load is generated when the implant is inclined (Watanabe et al., 2003).

Non-parallel implant placement may preclude the use of conventional implant overdenture abutments, requiring the use of costly custom abutments or bar prostheses (Dario, 2002; English, 1994). Bars are advantageous when the implants are misaligned (Bidra et al., 2012).

Factors that affect the load transfer at the bone-implant interface include the type of loading, material properties of the implant and prosthesis, implant geometry, surface structure, quality and quantity of the surrounding bone, and nature of the bone-implant interface (Bozkaya et al., 2004).

Biomechanical factors play an important role in the implant loss. For instance, if occlusal overloads causing extra stress in the bone were transmitted to the implants, bone resorption with the loss of osseointegration and implant failure would occur. A deterministic factor for the loss or success of the implant is the type of transferred stresses to the bone during function (Satoh et al., 2005).

Bone resorption and higher stress concentrations have been reported in the cortical bone around excessively inclined implants (Watanabe et al., 2003; Meijer et al., 1992); conversely, other studies have reported lower stress concentrations at the crestal region of tilted implants (Naini et al., 2011). Clinical studies have demonstrated similar survival rates for straight and tilted implants (Naini et al., 2011; Capelli et al., 2007; Sethi et al., 2002; Sethi et al., 2000).

There is a consensus that, the location and magnitude of occlusal forces affect the quality and quantity of induced strains and stresses in all components of the bone-implant-prosthesis complex (Sahin et al., 2002). Complex forces are present in the mouth. According to Holmgrem et al.,(Holmgren et al., 1998) the study of stress on implants must include not only vertical and horizontal forces, but also combined or oblique forces, since these represent realistic bite directions and may produce greater forces that cause greater damage to the cortical bone. Theoretically, the production of torque is dependent on the position and direction of the force relative to the position of the implant (Watanabe et al., 2003).

A key factor for success or failure of dental implants is the manner in which stresses are transferred to peri-implant bone (Bevilacqua et al., 2010). Finite element analysis (FEA) is a useful tool to investigate the effect of the biomechanical properties of prostheses on dental implants (Bevilacqua et al., 2010).

The purpose of the study was to evaluate the load transmission to the mandibular peri-implant bone, using different implant inclinations with three dimensional finite element analyses (3D FEA), simulating the implant placement into inter-foraminal area of the edentulous mandibula.

MATERIALS AND METHODS

This study was carried out in Gazi University, Faculty of Dentistry, Department of Prosthodontics and Ay Tasarım Ltd. Şti.

Four inter-foraminal implants were connected to each other by Dolder bar and loaded upon an acrylic overdenture with three different forces. The aim of the study was to investigate the stress transmitted to the peri-implant bone around the tilted versus vertical implants via 3D FEA. For that purpose, maximum and minimum principle stresses in the cortical bone around the implants were evaluated.

A mandibular bone model -with moderate alveolar ridge resorption and as symmetric as possible- was selected, simulating D2 type bone, according to the classification system of Lekholm and Zarb (Lekholm and Zarb, 1985). Gingival soft tissues were not modeled, while the bone segment was modeled with two volumes: an outer shell with a thickness of 1.5 mm representing
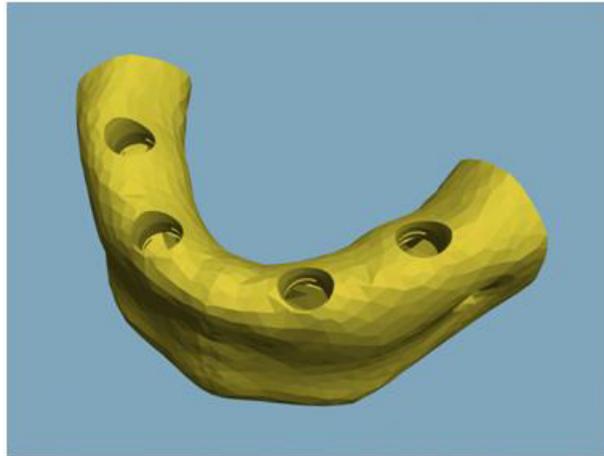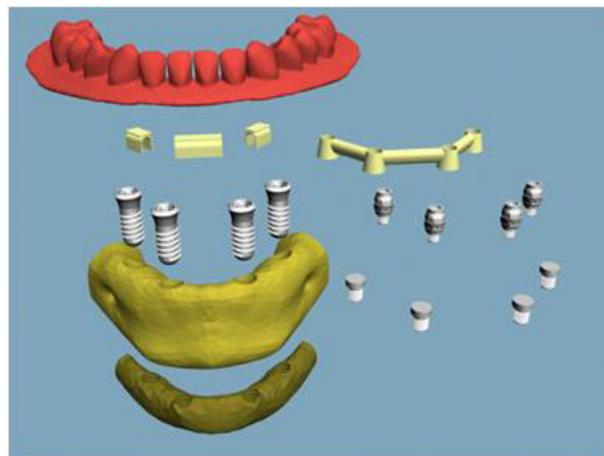
Figure 1. Mandibular model

Figure 2. Sectioned model

the cortical bone layer; and an inner volume, representing the cancellous bone tissue. The latter was assumed to be perfectly connected with the cortical shell. Cortical and trabecular bone were assumed to be isotropic, homogeneous, and linearly elastic. Posterior parts of the mandibula which would not affect the analyze results were extracted from the model (Figure 1).

Models were made up of implant, abutment, screw, gold bar and clips, mandibula with cortical and cancellous bone and acrylic resin overdenture (Figure 2). Four, 4.1-mm-diameter, 10-mm-length cylindrical screw type standard plus implants (ITI; Institut Straumann AG, Waldenburg, Switzerland) were virtually placed between the mandibular foramens and splinted with a golden bar substructure. Titanium abutments with 4.8 mm diameter and 1.5 mm length, gold copings with 6 mm height, gold Dolder bar with 3 mm height and 50 mm length and golden clips with 4.5 mm height and 50 mm long were also modeled. Infra-structures and the prosthesis were scanned with Nextengine Laser Scanner (NextEngine,

Santa Monica, USA) with macro resolution. It was assumed that there was a tight bond between them. Implant-supported overdenture was tightly bonded to the superstructure by gold clips.

All these models were created using customized computer software (Fempro, ALGOR, USA). The mesh values (node and element numbers), which indicates the number of tetrahedral elements forming the investigated models were listed in Table 1. All materials were presumed to be linear elastic, homogenous, and isotropic. The corresponding elastic properties such as Young's modulus and Poisson ratio were determined from values obtained from the literature, and are summarized in Table 2. The posterior sections of the mandibula segment were constrained in x, y and z directions as the boundary condition (Figure 3).

Four implants were placed between the mandibular foramens, to the mandibular lateral and first premolar regions according to Misch criterions (Misch, 2005). In Model 1, the implants were vertically oriented,

Table 1. Number of nodes and elements for each model

	Nodes	Elements
Model 1 (0-0-0-0)	67206	318957
Model 2 (0-5-5-0)	67077	319225
Model 3 (0-10-10-0)	67257	323656
Model 4 (0-15-15-0)	67799	323337

Table 2. Elastic modulus and Poisson's ratio for the used materials

Materials	Young's Modulus (E)	Poisson Ratio (v)	References
Trabecular bone	1370 N/mm^2	0.30	(40, 44, 54-56)
Cortical bone	13700 N/mm^2	0.30	(21, 33, 44, 54, 57)
Titanyum (implants, abutments, screws)	103400 N/mm^2	0.35	(33, 44)
Type III gold (bar, clips)	100000 N/mm^2	0.30	(44)
Polymethyl methacrylate	3000 N/mm^2	0.35	(44, 58)
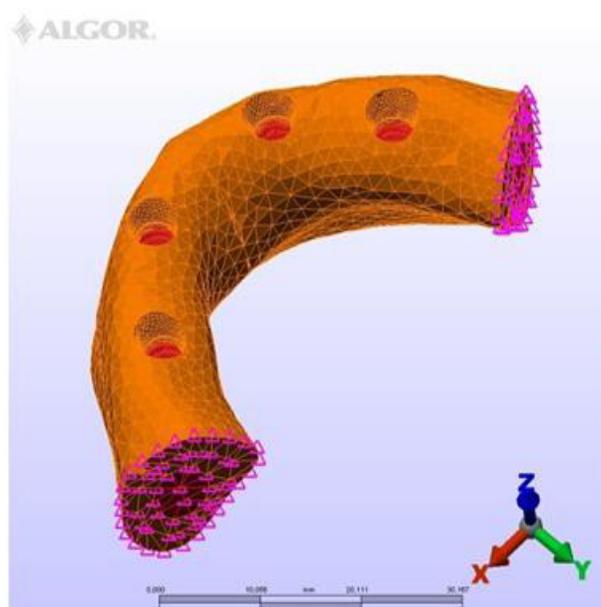
Figure 3. Boundary conditions of the model

perpendicular to the occlusal plane and parallel to each other. Keeping the distal implants vertical and the substructure length constant, three different configurations were constituted by inclining both anterior implants mesially as 5, 10 and 15 degrees, respectively. Four different models were created (Figure 4). Finite element method was used to evaluate the biomechanical performance of the whole implant-prostheses system in the surrounding bone. The four implants were splinted by means of a gold bar.

The connections between the superstructure and the implants were designed as rigid connections. A tight bond between bone and whole implant interface was accepted (Figure 5).

Loading Conditions

In the present study, two types of loads (vertical and oblique) were applied to the abutment to simulate different loading conditions seen during mastication or occlusion on implants that support overdentures. The ratio between the vertical and oblique loads was similar to the ratio reported in the investigation by Koolstra and colleagues (Koolstra et al., 1988). This ratio has also been used by other authors in various studies on this subject (Meijer et al., 1993; Caglar et al., 2006; Meijer et al., 1994). The applied forces were static.

Overdentures were connected to the implants by gold clips. These gold clips were situated approximately under
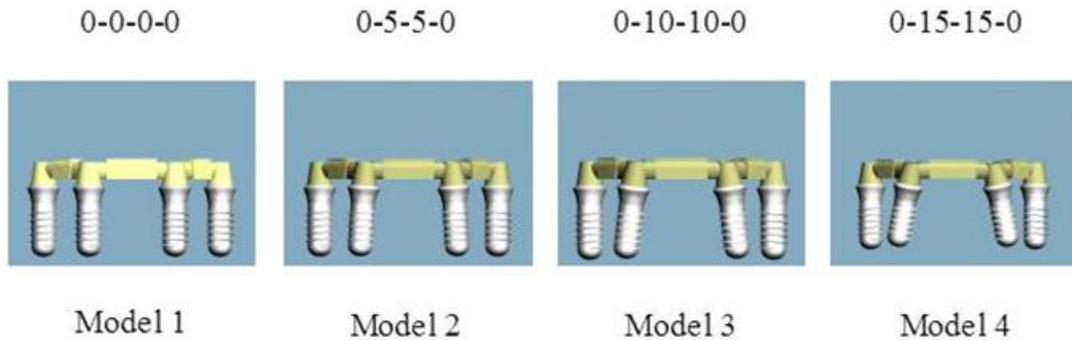
Figure 4. Models created with inclining the anterior implants
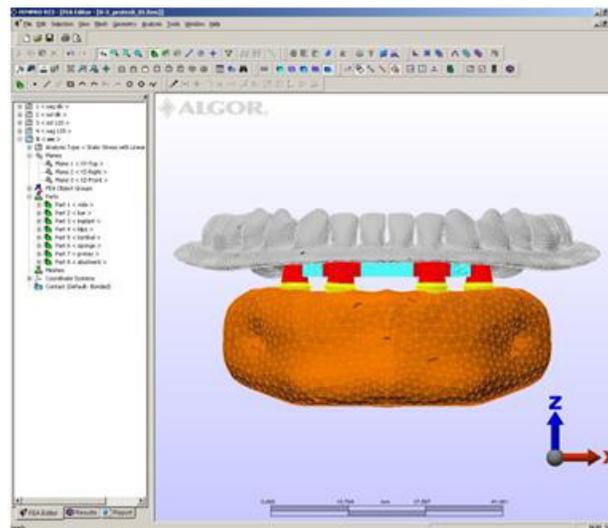

Figure 5. Connected model in Algor

the canine teeth of the overdenture. Therefore, in order to simulate the maximum biting force, a unilateral vertical load (90N) was applied to the right side canine crown apex of the denture. The oblique component of the same load (180 N) was also applied. In order to evaluate the consisted stresses during biting, 150 N oblique load from the mandibular incisors (each 75 N) was applied (Figures 6-8). These load amounts were selected according to the maximal bite forces for implant overdenture patients, depending on the dentition of the opposing arch (Fontiin-Tekamp et al., 2000). The canine and incisors were selected for the loading because the prosthesis is only implant-supported and the mucosa was not modeled. Since the aim was to evaluate only the implants' inclination affect, cantilever arms were not modeled either. Thus, the resilience of the posterior part of the overdenture was eliminated.

Loading Condition 1

90 N load was applied vertically from the right canine

crown apex of the overdenture, parallel to the long axis of the denture teeth.

Loading Condition 2

180 N oblique load, 120 degree angled to the long axis of the denture teeth from the horizontal plane was applied from the right canine crown apex of the overdenture.

Loading Condition 3

150 N oblique load, 120 degree angled to the long axis of the denture teeth from the horizontal plane was applied from the labial side of the mandibular central incisors of the overdenture. Load was split to each of the incisors equally.

All these data were transferred to the computer and analyzed via 3D FEA. Data were analyzed in cortical and trabecular bone.
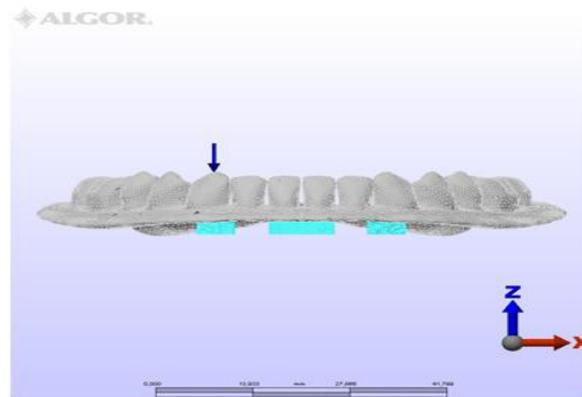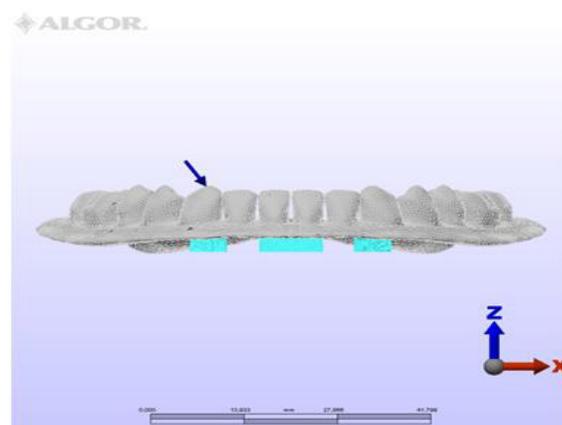
Figure 6. First loading condition

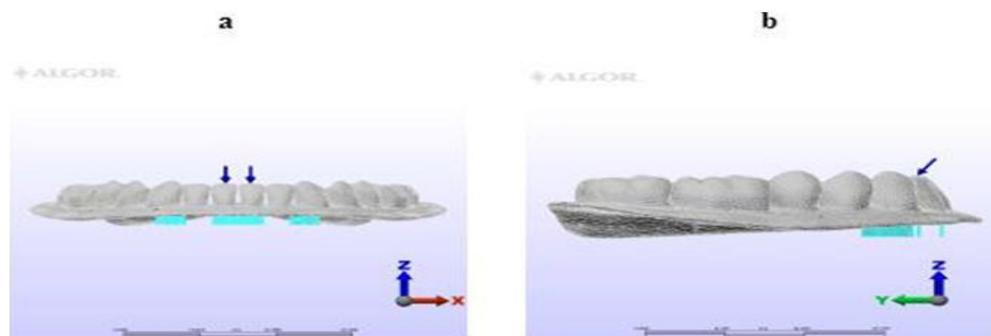**Figure 7.** Second loading condition

Figure 8. Third loading condition; a. Frontal view b. Sagittal view

RESULTS

Stresses were concentrated at the neck of the implant. Maximum stresses were located within the cortical bone surrounding the implant and within the labial/buccal contour of the mandible. There was no stress within the trabecular bone, so it is not mentioned in the results. Maximum stress values within the cortical bone surrounding the implant were summarized in Figure 9.

Minimum principle stress values were not mentioned in the results because they're mostly in harmony with the maximum principle stresses. For all loading conditions, lowest maximum principle stress values were seen in the third model (10-10 degree inclination).

Stress in loading 1 (anterior oblique): Stress was highly concentrated in the mesio-labial side of the cervical area of the implants for all models. Stress was decreased as the inclination of the implants increases.
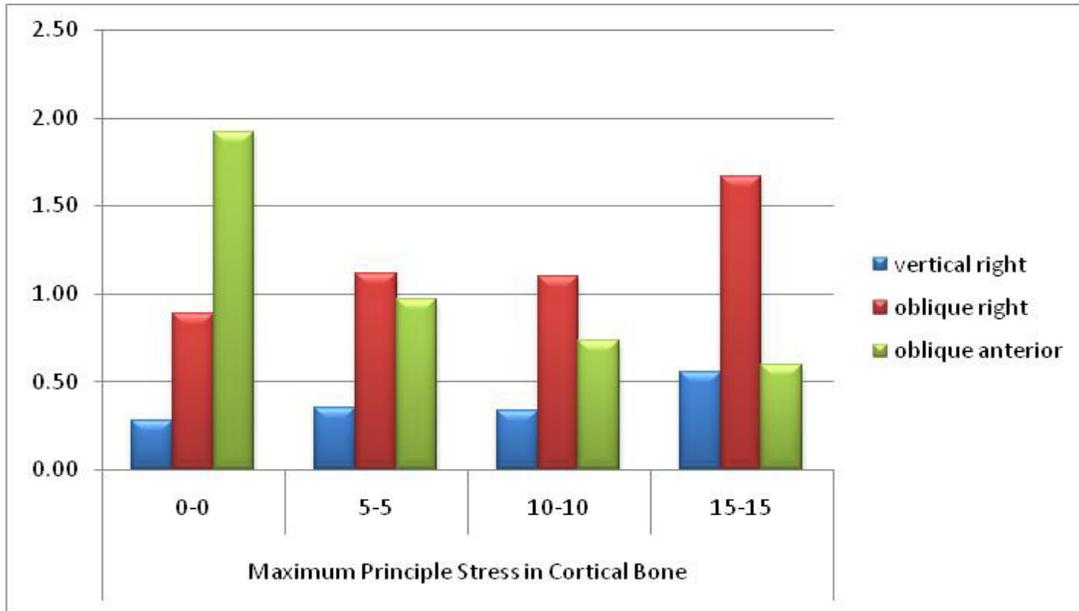
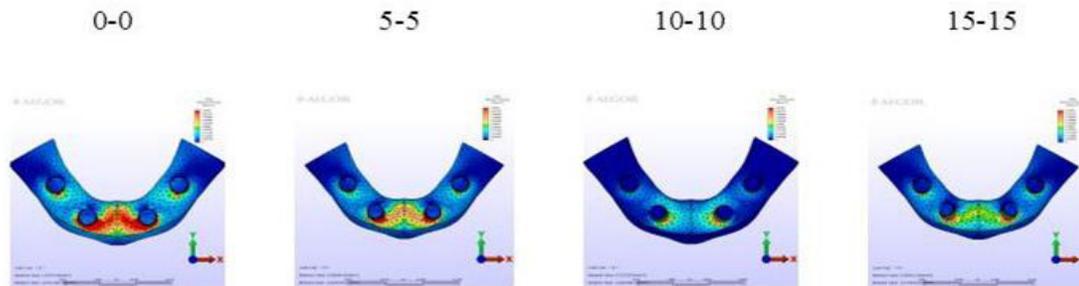**Figure 9.** Maximum Principle Stress values according to the loading condition

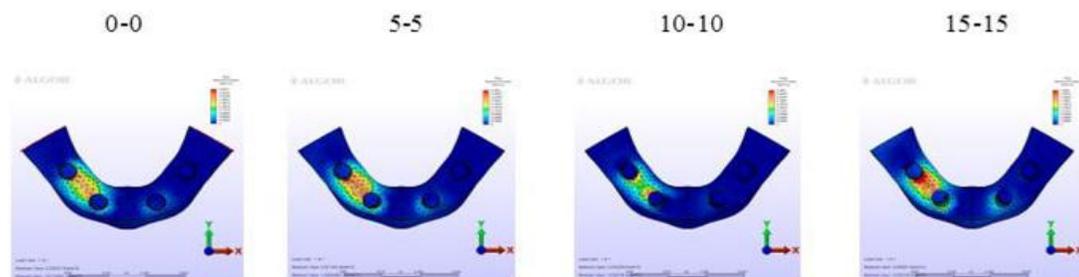**Figure 10.** Stresses occurred in anterior oblique loading

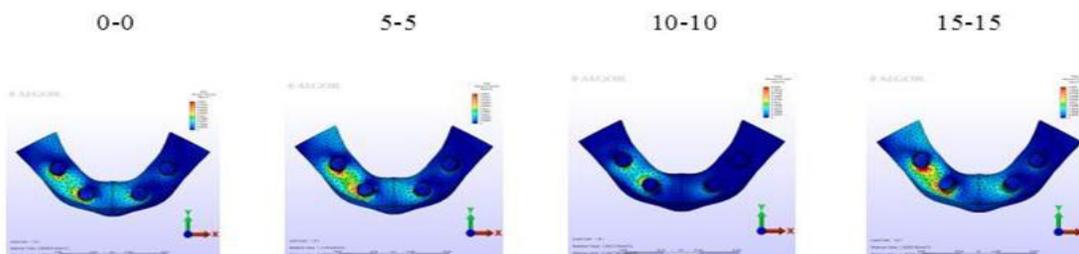**Figure 11.** Stresses occurred in right vertical loading

Figure 12. Stresses occurred in right oblique loading

Lowest maximum principle stress and the best stress distribution were seen in the third model. Highest stress values were in the control model, where all the implants were vertically placed. As the inclination increases, the stress distribution gets better (Figure 10). Wider stress distribution was not only around the cervical area of the anterior implant, but also around the cervical area of the posterior implants in all models.

Stress in loading 2 (right vertical): The lowest maximum principle stress value was in the third model. The stress was concentrated between the implants on the loading side. As the inclination of the anterior implants increased, the load distributions to all implants got better. Maximum principle stress value was detected on the mesial side of the posterior implant of the fourth model on the loading side.

Stress in loading 3 (right oblique): Again the best distribution and the lowest maximum principle stress values were measured in the third model. Although the highest principle values were determined in the fourth model, the load was distributed to the non-loaded side also. The same distribution was also monitored in the second model.

DISCUSSION

The inclination or placement angle of the implant has a significant role in biomechanics (Satoh et al., 2005; Weinberg, 1998). For ensuring a successful long-term implant prognosis, clinicians are advised to place implants parallel to each other and perpendicular to the occlusal plane (Krennmair et al., 2005). In the study of Payer et al.(Payer et al., 2008), the deviation of the longitudinal axis of the implant drilling (performed manually) from the longitudinal axis of the pilot drilling (performed with the parallelometer) was measured. The evaluation of the surgeon's influence on the deviation of the implant drillings showed clear tendency for drillings performed by experienced surgeons to have less mesiodistal deviation than those of a beginners group.

Walton and Peck had also studied the implant inclinations during implementation. The long axis was measured using digital photography, and measurements showed that implant deviations were less marked when implant placement was done by experienced surgeons than when it was done by inexperienced surgeons (Walton et al., 2001).

Precise mesiodistal positioning of an implant is important for a number of clinical and functional reasons; such as loading conditions or maintenance of the interproximal bone and soft tissue. Payer et al., (Payer et al., 2008) noted that for precise angular implant angulation, using a low drilling velocity and all bur diameters available should be used. In a study by Walton et al (Walton et al., 2001), angular deviations up to 6 degree were considered to be 'precisely' placed.

Therefore, this study had aimed to evaluate how the stress distribution occurs in the surrounding bone with different mesio-distal inclined implants.

The biomechanical analysis of an implant-supported prosthesis could be done with various methods. While computer modeling offers many advantages over other methods in considering the complexities that characterize clinical situations, it should be noted that these studies are extremely sensitive to the assumptions made regarding model parameters such as; loading conditions, boundary conditions, and material properties (Sevimay et al., 2005). FEA allows investigators to predict stress distribution in the contact area of the implants with bone using a mathematical model of the structures (Bevilacqua et al., 2010).

Three dimensional finite element models were used in the present study, to analyze the effect of implant inclination on stress distribution in the surrounding bone of the implants. The structures in the model were all assumed to be homogenous and isotropic and linearly elastic. However, the properties of the materials are different. For instance, it is well documented that the cortical bone of the mandible is transversely isotropic and non-homogenous (Sevimay et al., 2005). It is also assumed that implant-bone interface was completely osseointegrated, which may not realistically simulate the actual contact conditions.

In the present study, the stress in the bone-implant interface changes according to the implant inclination and the loading conditions. Using various FEA models, numerous investigators have reported decreased peri-implant bone stress around tilted implants (Bevilacqua et al., 2010; Zampelis et al., 2007; Rubo and Souza, 2010). When considering the loading conditions in the present study, although the stress values increase as the inclination of the implants increase, the load distribution gets better. In the third loading condition which represents the biting position, the stress values decreases and the load distribution is more fluent as the inclination of the implants increase.

Satoh et al. (Satoh et al., 2005), had studied inclined implants in the posterior mandible and stated that, stress levels in the cervical area of the mesial and distal implants and the surrounding bone were higher with 0M than 5M, 10M and 20M. These results suggest the biomechanical advantage of mesially inclined distal implants when loads act perpendicularly to the occlusal surface. It is reasonable to suppose that the occlusal force transmits most efficiently in the direction of the tooth axis (Satoh et al., 2005). The results of the present study were in harmony with these results.

In Çağlar et al study, inclinations of 0, 15 and 30 degrees were used in the maxillary posterior region with implant-supported fixed prosthesis (Caglar et al., 2006). They concluded that the inclination of the implant in the molar region was found to result in increased stress.

According to the load transfer study of Tokuhisa et al, the bar attachment produced higher stress on the non-loading side implant compared with the ball and magnet attachments because of primary splinting effect, even at low pressure (Tokuhisa et al., 2003). In the present study, non-loaded side implant stress values were much lower than the loaded side. It's thought that the distribution gets better because of the splinting effect of the bar.

In vitro and in vivo studies by Menucicci et al.(Menicucci et al., 1998) compared the stresses on the bone surrounding 2 implants with either a bar clip or ball attachments for overdentures. They found greater stresses on the peri-implant bone with a bar-clip attachment. This was consistent with a photoelastic analysis by Kenney et al (Kenney et al., 1998). In Takahashi et al study, the use of four implants or inclined implants induces an increase in stress on peri-implant cortical bones (Takahashi et al., 2010). However, other authors, in an in vivo study on force transmission onto implants supporting overdentures, found that rigid bars contributed to load sharing (Mericske-Stern et al., 1996), which is consistent with the current study.

Celik et al., (Celik et al., 2007) had studied the photoelastic stress analysis of three implant-retained mandibular overdentures. They stated that, for the inclined implant, moderate stresses were noted for unsplinted designs and low stresses were observed for splinted designs on the loaded side implant. For the inclined implant arrangement, when comparing the stud attachments to bar and bar-ball designs, the loaded side implants with stud attachments were subjected to greater stresses. The effect of load sharing between three splinted implants may be the reason for this result.

Mericske-Stern et al.(Mericske-Stern et al., 1996) had compared single telescoping attachments and a splinted bar design on mandibular overdentures retained by two implants by using piezoelectric transducers. The authors found a tendency for higher forces with solitary anchors and a positive effect of rigid bars for load distribution. With connected implants, there was a reduction in the magnitude of the extreme principle stresses compared with solitary implants (Meijer et al., 1996; Geng et al., 2001). In this study, in order to distribute the load appropriately, and to decrease the stress values, bar-retained mandibular overdentures were modeled, so the results were compatible with before mentioned studies.

Vertical and transverse loads from mastication induce axial forces and bending moments and result in stress gradients in the implants, as well as in the bone. A key factor for the success or failure of a dental implant is the manner in which stresses are transferred to the surrounding bone. FEA allows investigators to predict stress distribution in the contact area of implants with cortical bone and around the apex of the implants in trabecular bone (Geng et al., 2001). When applying FEA to dental implants, it is important to consider not only the axial loads and horizontal forces, but also a combined load (oblique occlusal load), because the latter represents more realistic occlusal directions and, for a given force, will result in localized stress in the cortical bone (Holmgren et al., 1998). Siegele and Soltesz (Siegele and Soltesz, 1989) showed that lateral loading caused maximum stress concentration in the region of direct-implant bone contact and soft tissue layer for the cylindrical implants and below the uppermost thread for the screw-type of implant. Holmgren et al (Holmgren et al., 1998) had suggested considering application of oblique load to FE analysis, indicating that these were more realistic occlusion directions capable of causing the highest localized stress in the cortical bone. Oblique and vertical loads were applied to the models in order to simulate realistic biting forces.

Bone quality types 1 and 4 are found much less frequent than types 2 and 3 (Sahin et al., 2002). Although the variations in density exist in each region, quality 2 bone dominates the mandible, and quality 3 bone is more prevalent in the maxilla (Sahin et al., 2002). From a biomechanical point of view, although 70% of the bones appear to withstand functional forces, it is believed that the implant survival rate is directly proportional to the bone density (Sahin et al., 2002).

The bone density influences the amount of bone in contact with the implant surface, not only at first-stage surgery but also at second-stage surgery and early prosthetic loading. Cortical bone having a higher modulus of elasticity than the trabecular bone is stronger and more resistant to deformation. For this reason, cortical bone will bear more load than trabecular bone in clinical situations (Misch, 1990).

Many authors have reported that stresses tend to be concentrated in the cortical bone around the occlusal aspect of the implant closest to the load (Bevilacqua et al., 2010). This may be because the elastic modulus of cortical bone is higher than that of cancellous bone, resulting in greater resistance to deformation (Bevilacqua et al., 2010; Stegaroiu et al., 1998). A consistent observation from the current study was the concentration of maximum stress at the bone-implant interface and at the level of cortical bone.

The mechanical distribution of stress occurs primarily where bone is in contact with the implant. When all factors are equal, the smaller the area of bone contacting the implant body, the greater the overall stress will be (Misch, 1990). This could be the reason for the lower stress values around inclined implants in various loading condition. As the implants had been inclined, the implant-bone contact area increases.

The numeric values reported in this study must be considered as biomechanical indications within the limitations of the model presented, since the 3D finite element models represent a simplification of the investigated structures. It should also be emphasized that the aim of the study was not to report the absolute values

of stress but to compare the stress levels in different implant inclinations. Despite these limitations, the method used in the current investigation can be useful for further in vivo studies on the use of tilted implants for improving prosthodontic supports in specific clinical situations.

CONCLUSIONS

Within the limitations of this 3D FEA study, the connected tilted implants had better stress distribution than vertical implants. Stress occurring in the implant and surrounding bone decreases when the angle increases. These results also suggest that a mesial inclination similar to the direction of the occlusal force is desirable. Therefore departure from the planned perpendicular placement relative to the occlusal plane should be considered when placing interforaminal implants.

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