Finite Element Stress Analysis of the Influence of Staggered Versus Straight Placement of Dental Implants

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Bending moments resulting from non-axial overloading of dental implants may cause stress concentrations exceeding the physiologic supporting capacity of cortical bone, leading to various kinds of failures. The aim of this study was to evaluate the effect of staggered (offset, tripodization) implant placement configuration and placement of wider-diameter implants in a straight-line configuration in mandibular posterior edentulism. A mandibular Kennedy Class II partially edentulous finite element model was constructed. Seven different partial fixed prostheses supported by 3 implants were designed according to 2 main configurations: straight-line or staggered implant placement. In 5 of the designs, implants with various diameters and length were placed along a straight line. In the other 2 models, offset placement of the middle implant buccally and lingually was simulated. A 400 N static load was applied perpendicular to the buccal inclination of the buccal cusps on each unit. Tensile and compressive stress values on cortical bone in the cervical region of the implants were evaluated. Lower stress values were recorded for the configuration with wider implants placed in a straight line. Other configurations, including staggered implant placement, produced similar stress values. Despite the offset implant placement, the stresses were not decreased; however, straight placement of wider implants may decrease bending moments. (INT J ORAL MAXILLOFAC IMPLANTS 2001;16:722–730)

Key words: *finite element stress analysis, posterior edentulism, staggered implant placement*

The concept of osseointegration, defined as ankylotic anchorage in bone, has revolutionized conventional dental treatment modalities.[1] Although completely edentulous arches received primary emphasis in the early 1960s,[2] during the last 15 years endosseous implants have been used more frequently to restore partially edentulous arches.[3] Especially from the biomechanical point of view, existing natural dentition can complicate treatment planning for partially edentulous arches in comparison with completely edentulous arches.

The major factor leading to late failure of implant-supported restorations is a lack of understanding of biomechanical concepts. In most situations, restoring a posterior segment having 3 missing teeth with a 2-implant–supported fixed partial prosthesis is convenient.[4] However, in situations where risk factors such as parafunctional activities are operative, optimum planning includes replacing each missing tooth with an implant.[5]

Implant overload can emanate primarily from 2 factors: prosthesis design and parafunctional activities. Excessive occlusal force generated in either or both situations presents an opportunity for loosening and/or fracture of the screws through bending overload.[6] Bending overload can be defined as a situation in which occlusal forces on an implant-supported prosthesis exert a bending moment resulting from non-axial loading on the implant cross-section at the crestal bone level.[7]

It has been demonstrated that bending moments increase stresses on the implant and cause negative biologic host responses. Rangert and coworkers[8] have stated that implants placed along a straight line were subject to bending rather than axial forces, thereby elevating stresses. Therefore, in-line implant placement may be considered as a load factor risk. Rangert and Sullivan[9] have emphasized the efficiency of offset implant placement, which brings about considerable stress reduction by converting the bending situation to a more favorable axial loading situation,

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compared with straight-line placement of implants. Additionally, Weinberg and Kruger[10] calculated the torque values mathematically and demonstrated the effectiveness of offset placement with 2-dimensional analysis.

Within 7 years of publication of the Rangert and Sullivan[9] report, offset implant placement has been widely accepted. However, clinical documentation verifying that the usage of offset placement of dental implants would decrease the load on implants has not been published.[11] Furthermore, the amount of implant anchorage, mechanics of the implant-abutment connection, and a preference for cemented restorations are contributing factors governing the outcome of implant-supported posterior fixed partial prostheses.[12] Additionally, Norton[13] has reported that the mechanical advantage of a tapered connection between implant and abutment increased the implant's ability to resist bending overload.

Implant diameter influences the stress concentrations around implants and thus, possibly, the implant success rate. Lekholm and coworkers[14] reported an improved implant success rate when wider-diameter implants were used in partially edentulous arches. Therefore, wider implants are recommended in the posterior regions of an arch, especially where heavy occlusal forces act.[15] Wider implants dissipate occlusal force more effectively and may be an alternative to offset implant placement.[16]

Soltesz and Siegele[17] demonstrated that regions of stress concentration seen in a laboratory model coincided with resorption zones observed in a canine model. Three-dimensional finite element stress analysis provides a means of numeric simulation for determining stress and displacements, via its ability to model geometrically complex structures. Three-dimensional finite element stress analysis is an accepted technique used in the solution of engineering problems. The method has been extensively used to study the biomechanics of dental implants and offers many advantages over other methods.[18–20]

The aim of this study was to evaluate the effect of the placement of wider-diameter and standard-diameter implants along a straight line versus the staggered placement of standard-diameter implants using 3-dimensional finite element stress analysis.

MATERIALS AND METHODS

Finite Element Analysis Model

A mandible taken from a fresh cadaver with a missing left second premolar and first and second molars was digitized using a surface scanner (Mitutoyo, Tokyo, Japan). A 3-D finite element model of

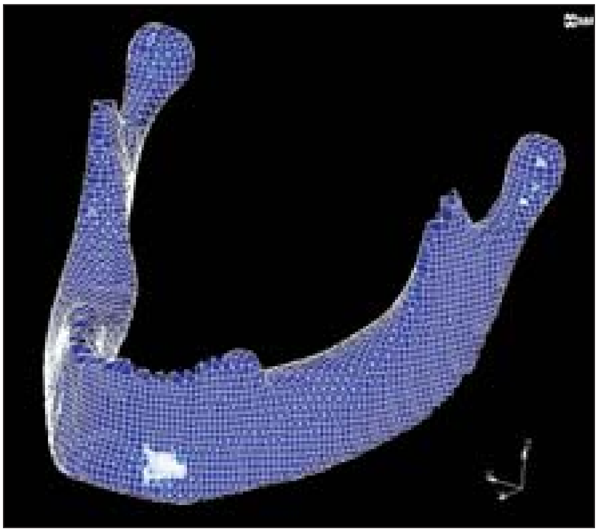

Fig 1 Three-dimensional finite element model derived from a digitized cadaver mandible.

this digitized posterior edentulous mandible was constructed with I-DEAS Artisan Series 3.0 (Structural Dynamics Research Corporation, Milford, OH) and Mentat 3.2 (Marc Analysis Research Corporation, Palo Alto, CA; recently purchased by MSC Software) using 8-node isoparametric, arbitrary hexahedral elements, resulting in 16,027 elements and 20,092 nodes (Fig 1). MARC K 2.7 (Marc Analysis Research Corporation) with direct sparse solver was used for the solutions.

In the absence of information concerning the precise material properties of bone, cortical and cancellous bone was assumed to be isotropic, homogeneous, and linearly elastic,[21] as were the other materials used in the analysis. Cancellous bone was classified as dense because of the anatomic structure of the mandible, and Young's modulus of cancellous bone was assumed to be 1,850 MPa.[22] Cortical bone with a thickness of 1 to 1.5 mm was assumed around a cancellous core. Young's modulus of cortical bone was assumed to be 13,700 MPa.[23] The Poisson's ratio was 0.3 for both.

Prosthetic Designs, Implants, and Dentition

Seven different fixed partial prostheses were designed, each supported by 3 implants. In 5 prosthetic designs, implants were placed along the residual bone in a straight-line arrangement. The buccolingual angulation of the implants was parallel to the angulation of the mandibular corpus and the mesiodistal angulations of the implants were perpendicular to the horizontal plane. In 2 prosthetic

Table 1 Configurations of 3-Implant–Supported Fixed Partial Prostheses

Model	5–6–7*	Configuration	Diameter	Length
1	• • •	Splinted along a straight line	4.1 mm	10 mm
2	• • •	Splinted along a straight line	3.75 mm	10 mm
3	• • •	Splinted along a straight line	4.1 mm	8 mm
4	• • •	Splinted along a straight line	3.75 mm	8 mm
5	• • •	Three single crowns along a straight line	3.75 mm	10 mm
6	• • •	Splinted buccal offset implant placement	3.75 mm	10 mm
7	• • •	Splinted lingual offset implant placement	3.75 mm	10 mm

*Mandibular left second premolar, first molar, second molar.

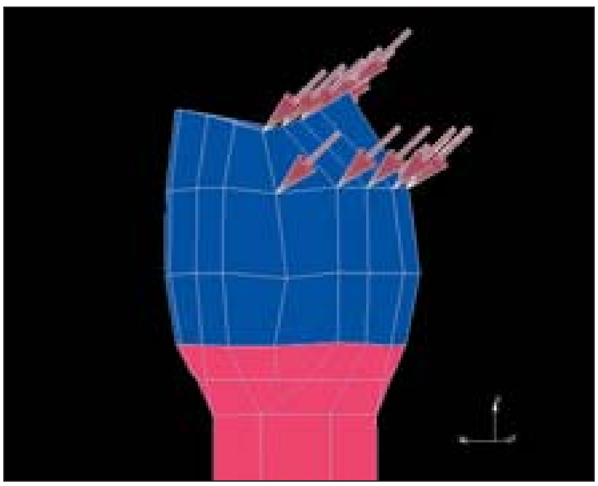

Fig 2 Simulated 400 N oblique load condition.

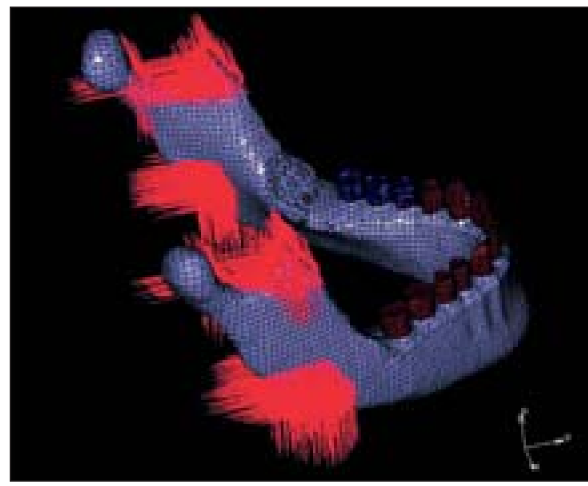

Fig 3 The nodes at the attachments of the masticatory muscles are constrained.

designs, staggered placement of implants was simulated, one with a 1.9 mm buccal offset of the middle implant (radius of 3.75-mm-diameter implant) and the other with a 1.9 mm lingual offset of the middle implant. In straight-alignment simulations, 3.75-mm- and 4.1-mm-diameter and 8-mm- and 10-mm-long implants were used, while 3.75×10-mm implants were used in the offset alignment simulations (Table 1).

Implants were modeled as a solid structure with abutments that were 4 mm high and had a 4-degree convergence angle. Comprehensive structural modeling of the implant collar and surface was not included. Three-unit cement-retained prosthesis was also fabricated with dimensions 6 mm high, 8 mm long mesiodistally, and 7 mm wide buccolingually.

Titanium-aluminum-vanadium (Ti-6Al-4V) was used as the implant material, and Young's modulus and Poisson's ratio were assumed to be 117,000 MPa and 0.35, respectively.[24] Type III dental gold alloy was selected for the prostheses; Young's modulus and Poisson's ratio were assumed to be 100,000 MPa and 0.33, respectively.[24]

All anterior teeth, the right premolar and molar teeth, and the left first premolar tooth were oriented into the models without periodontal membrane simulation. The anterior teeth were included for improved positioning of implants in the posterior region. The following values were assumed for Young's modulus and Poisson's ratio: enamel 130,000 MPa and 0.33, and dentin 14,700 MPa and 0.31.[25]

The Load Case and Constraints

The ratio between a horizontal (F_h), a vertical (F_v), and an oblique (F_o) bite force was established previously as $F_h : F_v : F_o = 1 : 3, 5 : 7$.[26] Thus, the rationale for use of an oblique loading condition was based on the finding that vertical (axial) forces directed to the implant system are relatively low and well tolerated in comparison to oblique forces, which generate bending moments. To simulate an oblique loading condition, a static load of 400 N was applied perpendicular to an area consisting of 20 nodal points on the 30-degree inclined buccal cusps of each prosthetic unit (Fig 2). The selected region for loading was assumed to simulate the contact area

Table 2 Highest Tensile and Compressive Stress Values Recorded at Cortical Bone in the Cervical Region of the Implants

Model	Configuration	Implant diameter	Implant length	Maximum tensile stress (MPa)	Maximum compressive stress (MPa)
1	Splinted along a straight line	4.1 mm	10 mm	53.12	132.2
2	Splinted along a straight line	3.75 mm	10 mm	58.65	138.9
3	Splinted along a straight line	4.1 mm	8 mm	54.55	134.8
4	Splinted along a straight line	3.75 mm	8 mm	58.93	145.4
5	Three single crowns along a straight line	3.75 mm	10 mm	77.39	139.7
6	Splinted buccal offset implant placement	3.75 mm	10 mm	59.76	142.3
7	Splinted lingual offset implant placement	3.75 mm	10 mm	59.24	139.1

with the adjacent teeth. Prevention of rotation of the model around the condyles was promoted by constraining the nodes at the attachments of the masticatory muscles (Fig 3).[27]

RESULTS

The highest values for tensile stress and compressive stress recorded on cortical bone in the cervical region of the implants are presented in Table 2.

Tensile Stress Results

Principal stresses in bone surrounding the implants were recorded in all configurations. Tensile stresses were found to be dominant on the buccal side of cortical bone in the cervical region of dental implants within all prosthetic designs. The highest tensile stress value (77.39 MPa) was found for the free-standing, 3-single-crown configuration; this was significantly higher than the values obtained for the other designs. Lower values were recorded with the wider-diameter straight implant placement configurations (53.12 MPa and 54.55 MPa for 10-mm-long and 8-mm-long implants, respectively). None of the recorded highest tensile stress values approached the ultimate tensile strength of cortical bone. Distributions of tensile stresses were found to be very similar for all prosthetic designs. The highest tensile stress values were observed at the mesiobuccal surface of cortical bone surrounding the cervical region of the most mesial implant, in all designs (Figs 4a to 4d).

Compressive Stress Results

Compressive stresses were found to be dominant on the lingual surface of cortical bone in the cervical region of the implants in all 7 prosthetic designs. The highest compressive stress value (145.4 MPa) was recorded for the straight-line placement design with 3.75×8-mm implants. The lowest compressive stress value (132.2 MPa) was recorded in the straight-line placement design, but with 4.1×10-mm implants. Compressive stress values recorded for the other designs were similar. None of the maximum compressive stress values exceeded the ultimate compressive strength of the cortical bone. Distributions of compressive stresses were found to be very similar for all prosthetic designs. Maximum compressive stress values were observed on the distolingual surface of the cortical bone surrounding the cervical region of the most distal implant (Figs 5a to 5d).

DISCUSSION

An increasing number of studies have investigated the causes of implant failure in clinical practice using various stress analysis methods.[28–30] The major expectation from these studies is to extrapolate findings relevant to the risk factors, rather than learning them by clinical experience. Three-dimensional finite element stress analysis seems to be advantageous compared to other stress analysis methods.

Although outcomes of some studies[17–31] revealed that areas of bone resorption coincided with stress

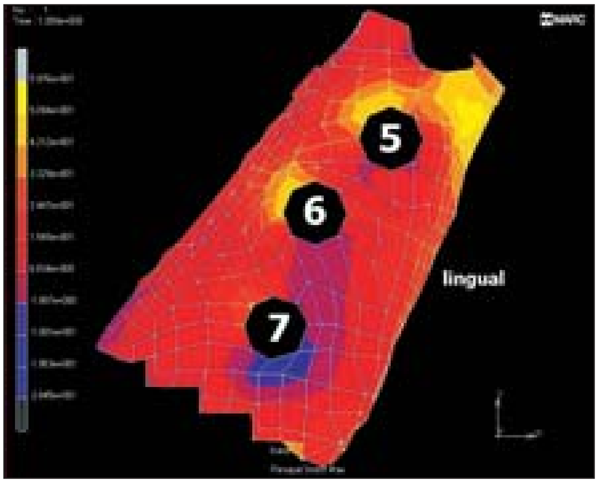

Fig 4a Distribution and highest tensile stress values in buccal offset implant placement (3.75×10-mm implants).

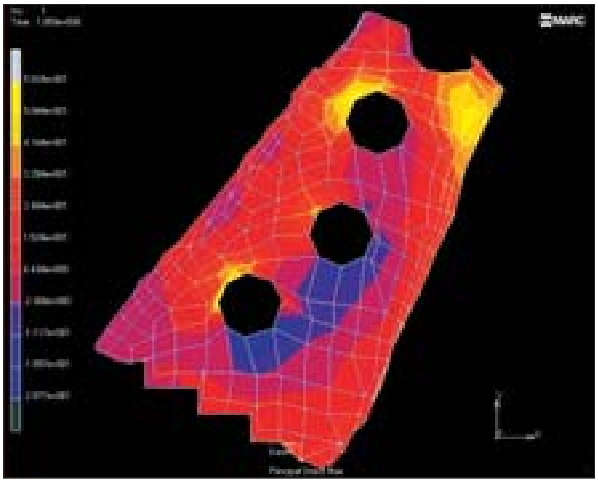

Fig 4b Distribution and highest tensile stress values in lingual offset implant placement (3.75×10-mm implants).

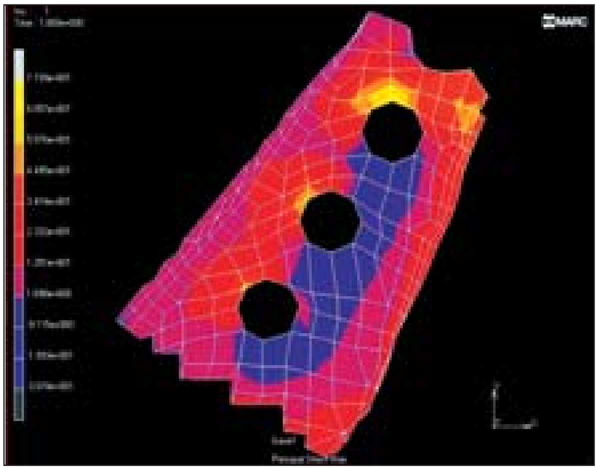

Fig 4c Distribution and highest tensile stress values in 3 single crowns placed in a straight line (3.75×10-mm implants).

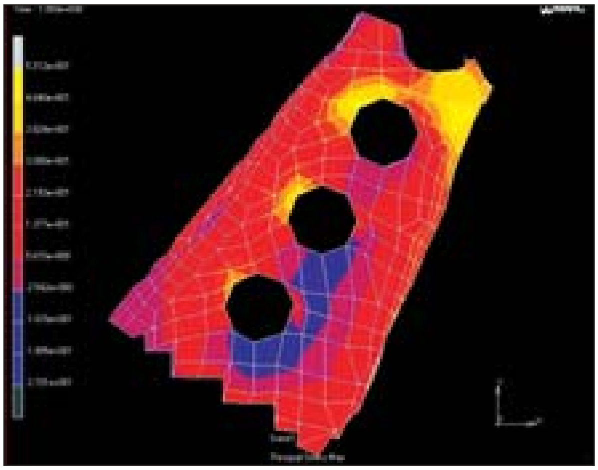

Fig 4d Distribution and highest tensile stress values in wider-diameter implants (4.1×10 mm) placed in a straight line.

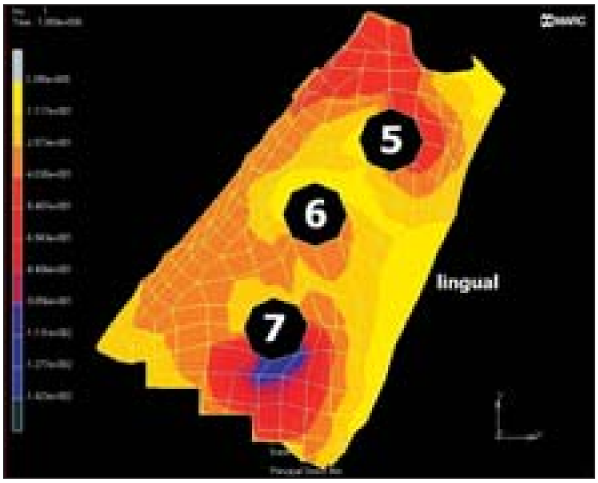

Fig 5a Distribution and highest compressive stress values in buccal offset implant placement (3.75×10-mm implants).

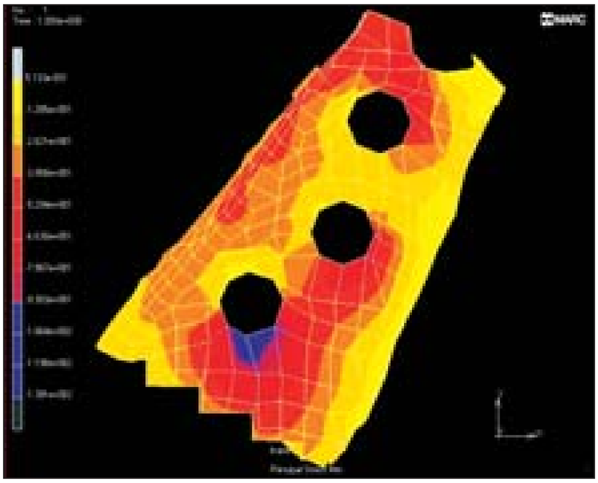

Fig 5b Distribution and highest compressive stress values in lingual offset implant placement (3.75×10-mm implants).

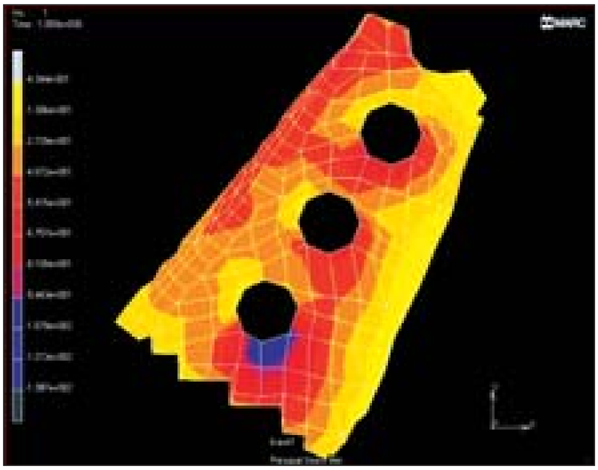

Fig 5c Distribution and highest compressive stress values in 3 single crowns placed in a straight line (3.75×10-mm implants).

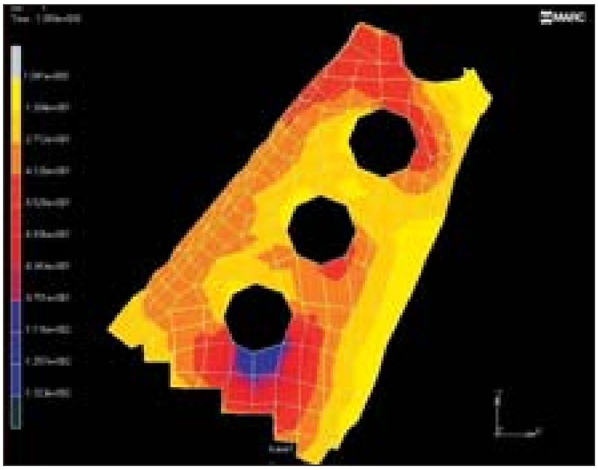

Fig 5d Distribution and highest compressive stress values in wider-diameter implants (4.1×10 mm) placed in a straight line.

analysis predictions, the stress values that actually cause biologic changes, such as resorption and bone remodeling, are not presently known.[32] Glantz and Nilner[33] stated that precise calculations cannot be made because of the great variation in and unknown magnitudes of the important mechanical background factors for bone and chewing mechanics of individual patients.

In addition to these observations, several assumptions are made in finite element stress analysis. The structures in the present study were all assumed to be homogeneous and isotropic and to possess linear elasticity. However, the mandible is in fact transversely isotropic and inhomogeneous[34] and is especially subjected to functional elastic deformations originating from masticatory forces, as bone is a living tissue.[35] Additionally, in the present study, implants were simulated as 100% osseointegrated, as in previous studies.[27,28] However, histomorphometric data have indicated that there is never 100% bone-to-implant contact. It was also assumed that a homogeneous external layer of 1 to 1.5 mm of cortical bone existed around the cancellous bone. However, an actual mandible has more compact bone at the inferior border and less compact bone on the superior aspect. Therefore, the inherent limitations of finite element stress analysis must be acknowledged.

There are no explicit guidelines in the literature for interpreting the results of stress analysis, nor are there any suggestions regarding the kind of stresses that must be used in the explanations. Principal stresses and Von Mises stress have been used equally. The present study focused on the stresses formed in the cortical bone around the cervical region of the implants. Principal stress (tensile stress and compressive stress) values are important for brittle materials such as bone, because failure occurs when tensile stress is greater than or equal to the ultimate tensile strength of bone, or when compressive stress is greater than or equal to the ultimate compressive strength of bone. Therefore, principal stresses that offer the possibility of making a distinction between tensile and compressive stresses were presented in this study. The highest tensile and compressive stress values at cortical bone around the cervical regions of implants were recorded and compared with the ultimate tensile and compressive strength of cortical bone (121 MPa and 167 MPa, respectively).

Von Mises stress values are defined as the beginning of deformation for ductile materials such as metallic implants. Since failure occurs when Von Mises stress values exceed the yield strength of an implant material, Von Mises stress criteria are important for interpreting the stresses occurring within the implant material.

It has been suggested that the general features of mastication in patients with normal and implant-restored dentitions are approximately the same.[36] Mericske-Stern and associates[37] explored occlusal forces in a group of partially edentulous patients restored with ITI implants supporting fixed partial prosthesis. They found the range of occlusal forces on the second premolar and molar teeth to be 210 to 400 N and 130 to 395 N, respectively. Thus, the magnitude of the load in the present study was set at 400 N.

When partially edentulous arches are restored with dental implants, a widely accepted treatment of choice is the fabrication of free-standing implant-supported fixed partial prostheses.[38] Generally, either 2 or 3 implants are placed to support a fixed partial prosthesis in situations involving 3 missing posterior teeth. Whenever 2 implants are used to support a 3-unit fixed partial prosthesis, it is preferable to place them as terminal implant abutments, rather than placing them immediately adjacent to one another to support either distal or mesial cantilever 3-unit fixed partial prostheses.[4] However, Rangert and coworkers[39] have suggested that implant-supported, 3-unit fixed partial prosthesis represent a geometric risk factor when 3 implants are placed along a straight line, which causes a risk of potential bending of the implants. The stated philosophy is to place 3 implants to support 3-unit restorations, and the straighter the implant placement alignment, the greater the potential for bending of the implants. According to the theoretical studies, bending moments lead to higher stress levels in the implant components than compressive and tensile forces. Thus, it has been suggested that in the case of a 3-unit posterior implant-supported fixed partial prosthesis, staggered implant placement allows the load response to bending forces to be mostly axial, reducing the stress level by approximately 50%.[40] On the other hand, Taylor and associates[11] stated that it is rare to find the required buccolingual ridge width to allow a bodily offset of 1 implant, and a slight change in the angulation of 1 implant gives only the appearance of tripodization, not the expected effect. In addition, animal studies have shown that non-axial loading is not detrimental to the osseointegration of the implant, even when nonaxial occlusal forces are greatly exaggerated.[41–43]

Small-diameter implants have less mechanical yield strength than large-diameter implants, and short implants have less bone support than long implants. If the implant dimension selected is considerably smaller than the ideal, this adds to the risk of failure. However, partial posterior implant restorations have shown an increased susceptibility to implant bending, and based on the same rationale, use of 4.0-mm-diameter or wider implants may now be recommended to further improve the strength between components within the implant for this modality.[8] Sato and associates[44] have demonstrated that the use of wider implants might be considered to prevent loosening or fracture of screws instead of offset placement, since offset configuration did not always decrease the tensile forces at screws.

The above-mentioned studies addressed the mechanical advantages of the placement of wider-diameter implants to reduce the stresses transferred to the implant-abutment connection. In addition to these findings, outcomes from the present study revealed that placing wider implants in a straight-line configuration when compared with staggered implant placement reduces tensile and compressive stress values on cortical bone in the cervical region of the implants.

There are 2 main factors that reduce stresses around wide-diameter implants: increased diameter and, hence, increased surface area and mass. When the area increases while the amount of applied force remains constant, the amount of stress decreases. This basic rule affects the magnitude of stresses in bone around wide-diameter implants and neighboring implants. The increased diameter and mass of the implant counteracts transverse forces that cause bending moments on neighboring implants.

When the stress patterns of the present study were evaluated, it was seen that the areas of highest stress concentration were identical in all prosthetic designs. However, staggered implant alignment and 3 single crowns in a straight alignment demonstrated a significant increase in the magnitude of stress distribution pattern over 3 splinted crowns placed in a straight-line configuration.

According to the highest recorded tensile and compressive stress values, wider implant placement in a straight alignment significantly reduced the numeric values of stresses transferred to cortical bone. Similar numeric stress values were observed for the use of standard-diameter implants, regardless of the implant placement configuration. When ridge width sufficient to allow bodily offset of 1 implant placement is available, placement of wide implants seems to be more effective as a means of reducing stress levels. Therefore, a new debate could arise as to whether to place wider implants along a straight line versus offset implant placement whenever the available bone permits.

CONCLUSIONS

The conclusions derived from this 3-D finite element stress study are limited to the assumptions made for the composition of the computer model and its boundary conditions. Within the limits of this study, lower stresses were observed in cortical bone at the cervical region of implants when wider implants were placed along a straight line rather than in offset placement. Therefore, it could be proposed for further consideration that whenever the buccolingual width of the residual bony ridge is sufficient for staggered implant placement, placement of wider implants along a straight line may be much easier and more functional for stress distribution.

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