The influence of cantilever length and implant inclination on stress distribution in maxillary implant-supported fixed dentures

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Statement of problem. The benefits and limitations of jaw treatments with tilted versus vertical implants, as well as prosthesis design with and without posterior cantilevers, have been extensively discussed. However, biomechanical advantages associated with cantilevers in fixed dentures (FDs) and tilted implants in the maxillae are less well documented.

Purpose. The purpose of this study was to compare and analyze, via 3-dimensional (3-D) finite element analysis, stresses transmitted to tilted versus vertical implants and the surrounding periimplant bone in the maxillae.

Material and methods. A 3-D edentulous maxillary model was created using customized computer software (FEMAP 8.3). Four implants were virtually placed in the premaxilla and splinted with an FD. Keeping the prosthesis length constant, 4 different configurations were evaluated with the distal implants inclined 0, 15, 30, and 45 degrees; cantilever extensions were 13, 9, 5, and 0 mm, respectively. A vertical load (150 N) was applied to the distal portion of the posterior cantilevers. Von Mises' stress values transmitted to periimplant bone and at the metal framework of FDs on implants were evaluated in cancellous and cortical bone.

Results. The maximum stresses recorded in periimplant bone for the vertical implants were 75.0 MPa (distal implants), 35.0 MPa (mesial implants), and 95.0 MPa for the metal frameworks. Tilted distal implants, with consequent reduction of the posterior cantilevers, resulted in decreased stress values for all of the variables: -12.9%, -18.3%, and -11.5% for the 15-degree configuration; -47.5%, -52.6%, and -31.3% for the 30-degree configuration; and -73.5%, -77.7%, and -85.6% for the 45-degree configuration.

Conclusions. Finite element analysis data regarding rehabilitation of atrophic maxillae revealed that tilted distal implants, rigidly splinted with an FD, decrease stress in the periimplant bone and frameworks. This treatment modality seems to be a valid therapeutic alternative to conventional maxillary fixed complete prostheses supported by vertical dental implants with posterior cantilevers. (J Prosthet Dent 2010;105: 5-13)

Clinical Implications

On the basis of this 3-D finite element analysis, distal tilted implants, splinted with rigid FDs, with short or no posterior cantilevers, provided favorable results in the treatment of atrophic maxillae with fixed prostheses supported by dental implants when compared to shorter vertical distal implants restored with cantilevered prostheses.

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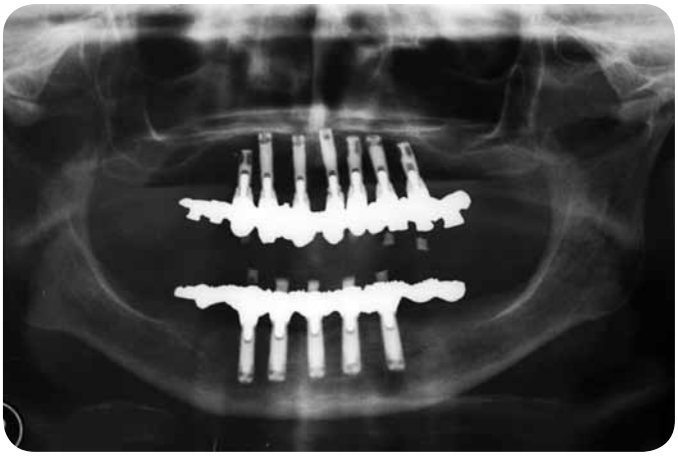
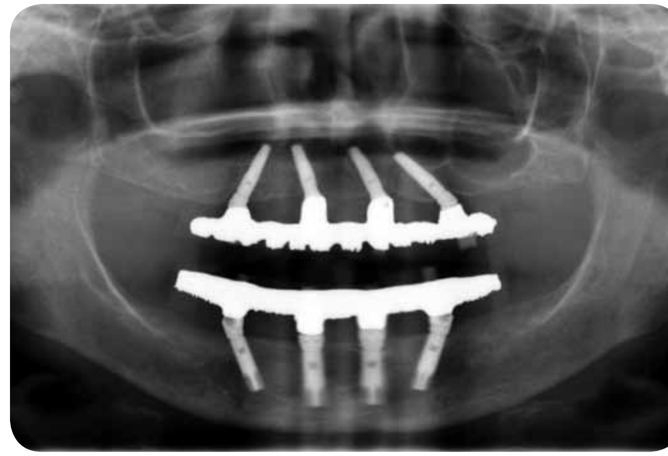


1 Panoramic radiograph of edentulous jaws restored with 2 fixed complete dentures supported by vertical dental implants placed into mandibular interforaminal regions (5 implants) and maxillary premolar regions (7 implants). Note lengths of posterior cantilevers. Photograph reprinted with permission from *Columbus Bridge Protocol*, Quintessence, 2009.[27]



2 Panoramic radiograph of edentulous jaws restored with 2 fixed complete dentures supported by tilted distal dental implants: 4 maxillary, 4 mandibular. Note reduced length of posterior cantilevers without significant reduction in prostheses occlusal surface. Photograph reprinted with permission from *Columbus Bridge Protocol*, Quintessence, 2009.[27]

Edentulous maxillae have certain anatomic characteristics that are not present in edentulous mandibles. These differences need to be analyzed during treatment planning for maxillary prostheses supported by dental implants. The nasal cavities and maxillary sinuses, in combination with the soft, trabecular bone common in the maxillae, tend to make maxillary implant placement and prosthetic protocols critical.[1,2] Loss of alveolar bone secondary to periodontal disease, tooth loss, or periapical disease further reduces the amount of available bone for implant placement.

For edentulous jaws, implants should be placed relative to the positions of the largest teeth and volumes of alveolar bone, for instance, relative to the canines and first molars. This implant arrangement allows clinicians to obtain favorable biomechanical, cross-arch stabilization for prostheses. This arrangement cannot always be achieved with the placement of vertical implants, greater than 10 mm in length, in the distal areas of the resorbed maxillae. If the purpose of a specific maxillary prosthetic treatment is to fabricate a fixed complete denture with 10 to 12 masticatory units, clinicians generally have to consider 1 of 2 implant placement strategies in the anterior maxillae.

The first, traditional option calls for vertical implants, splinted together with a fixed prosthesis placed with a conventional implant protocol.[3] This type of prosthesis is generally made with posterior cantilevers to provide the patient with molar teeth. The most distal implants typically are placed in the premolar regions (Fig. 1). Because of the maxillary sinuses, the distal implants usually are relatively short (<10 mm). Biomechanically, short implants and distal cantilevered segments are associated with increased problems such as screw loosening, as well as screw, denture teeth, denture base, and framework fractures.[4,5]

Subsequent to published reports of complications with such prostheses, several authors have studied and reported on the use of distal tilted implants.[6-10] Oblique implant placement (up to 45 degrees), parallel to the anterior wall of the maxillary sinus, optimizes the anterior-posterior spread of implants, minimizes cantilever lengths, and provides satisfactory molar support for an FD. Tilted implant placement reduces cantilever length compared to vertical implants with an equivalent number of masticatory units (Fig. 2). Tilted implants permit the use of significantly longer implants, negating the need for maxillary sinus grafting.[11]

Tilted implants may be especially useful for providing stability for immediate loading in maxillary bone that is more trabecular and therefore less dense when compared to interforaminal mandibular bone.[9,10] Implant macrodesign and osteotomy preparation are critical to control stresses associated with the bone-implant interface to obtain osseointegration. Short implants have been reported to have lower survival rates and higher marginal periimplant bone loss than longer implants.[4,5] Short implants often require the use of 6 or more implants in edentulous jaws to provide satisfactory support for implant-supported prostheses. Many authors have reported that stresses tend to be concentrated in the cortical bone around the occlusal aspects of the implants closest to the load.[12-14] This may be because the elastic modulus of cortical bone is higher than that of cancellous bone, resulting in greater resistance to deformation.[15,16] Stress distribution in the bone allows for a potentially safe use of short, orthogonal distal implants in the mandible, where a greater amount of cortical bone is present compared to the maxilla.[17]

Clinical studies have reported high survival rates for tilted implants supporting maxillary FDs with immediate occlusal loading protocols.[9,10] However, questions remain with respect to the amount of stress generated at the periimplant bone surrounding tilted implants and to the biomechanical advantages, if any, of using tilted implants.[18]

In vitro (computer based and real time) and clinical studies are indicated to quantitatively address these issues. The authors of a previous article reported on the stresses transmitted to mandibular periimplant bone by altering implant inclinations and cantilever lengths with 3-dimensional finite element analysis (3-D-FEA).[19]

A key factor for success or failure of dental implants is the manner in which stresses are transferred to periimplant bone.[20] Finite element analysis (FEA) is a useful tool to investigate the effect of the biomechanical properties of prostheses on dental implants. Clinically, it is impossible to assess stresses and strains transmitted to periimplant bone, although strain gauges may be used to measure strains at the abutment level.[21,22] FEA allows investigators to predict stress distribution in the contact area of the implants with bone using a mathematical model of the structures.[20] Using various FEA models, numerous investigators have reported decreased periimplant bone stress around tilted implants.[23,24]

The purpose of the present study was to evaluate load transmission to maxillary periimplant bone, using different implant inclinations and cantilever lengths with 3-D-FEA, simulating implant placement into edentulous maxillae.

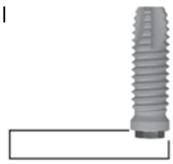
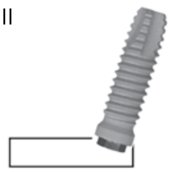
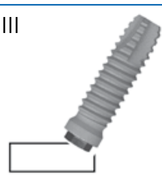
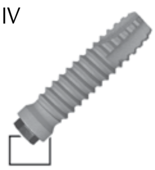
3 Configuration I designed with 4 cylindrical dental implants placed into premaxillae, simulating clinical treatment of edentulous patient with fixed complete denture. Prosthesis was supported by bilateral, vertical distal implants; posterior cantilevers were 13 mm in length. Photograph reprinted with permission from *Columbus Bridge Protocol*, Quintessence, 2009.[27]

MATERIAL AND METHODS

A 3-D finite element model reproducing an edentulous maxilla was created with customized computer software (FEMAP 8.3; Siemens PLM Software, Plano, Tex). The mesh value, which indicates the number of tetrahedral elements forming the investigated model, was 140,000 units. The elastic modulus was equivalent to 103,400 MPa for the titanium implants, 13,700 MPa for cortical bone, 1370 MPa for cancellous bone, and 210,000 MPa for the metal frameworks of the FD.[25] Poisson's ratio of titanium and bone was considered to be 0.3. Boundary conditions for the model were defined according to the union of the maxilla to the base of the skull, by which the movement of the maxilla was restrained. Boundary constraints were applied to the top of the bone in the shape of a "W" (Fig. 3). The movements of the nodes in this area were completely constrained. Four, 4-mm-diameter, cylindrical screw-type implants with smooth apices (Biomet 3i, Palm Beach Gardens, Fla) were virtually placed into the premaxilla, simulating clinical treatment of an edentulous patient with an FD. The FD's virtual metal framework (cross-section equal to 10 mm^2) was designed with first molar occlusion and connected to the implants. The connections between the superstructure and the implants were designed as rigid connections.

A vertical load (150 N) was applied to the right-side posterior cantilever of the prosthesis framework. This value represents the mean vertical component of occlusal force in adults with dentures supported by implants.[26] Data were analyzed in compact and cancellous bone. Von Mises stress values transmitted at the periimplant bone and framework were evaluated according to 4 configurations. Framework length was constant (Table I). In the first configuration, four 13-mm-long implants were placed vertically, according to the protocol described by Zarb et al[3] (Fig. 3). This technique calls for vertical implants to be perpendicular to the occlusal plane with no grafting procedures in the molar areas. Conventionally, the prostheses have distal cantilevers for molar support. In the first configuration, distal cantilevers were modeled to be 13 mm in length. In the second, third, and fourth configurations, posterior implants were tilted 15, 30, and 45 degrees distally; cantilever extensions were 9, 5, and 0 mm in length, respectively. Distal implant lengths were also modified: 15 mm in the 15- and 30-degree configurations; 18 mm in the 45-degree configuration (Fig. 4).

TABLE I. Features of fixed complete dentures (FD) used in this 3-D FEA

FD Configuration	Implants Length (mm)		Implant Angulation		Posterior Cantilever Length (mm)
	Distal	Mesial	Distal	Mesial	
I 	13	13	0	0	13
II 	15	13	15	0	9
III 	15	13	30	0	5
IV 	18	13	45	0	0

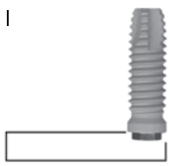
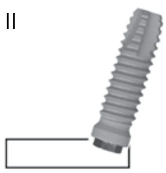
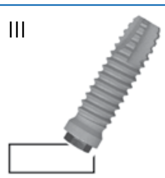
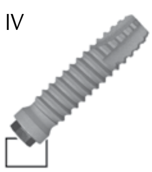
4 Configurations II, III, and IV were designed with bilateral, tilted distal dental implants; posterior cantilevers were shortened in length (configuration IV represented). Photograph reprinted with permission from *Columbus Bridge Protocol*, Quintessence, 2009.[27]

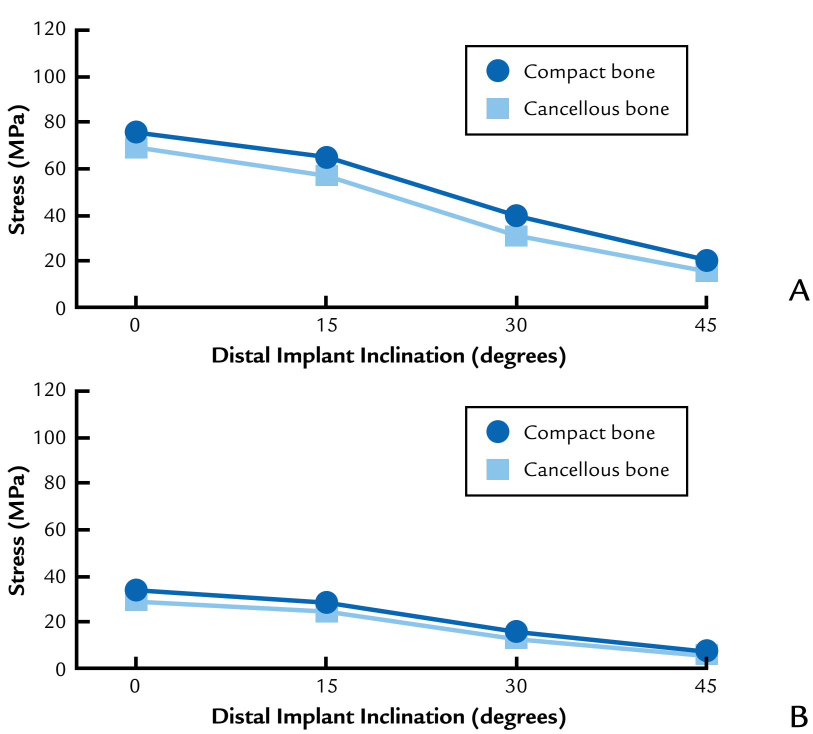
RESULTS

In each test, the highest von Mises stress values in periimplant bone and metal frameworks were recorded after the 150-N load was applied. The stress values were always recorded on the same side (right). Values (MPa) are reported in Table II.

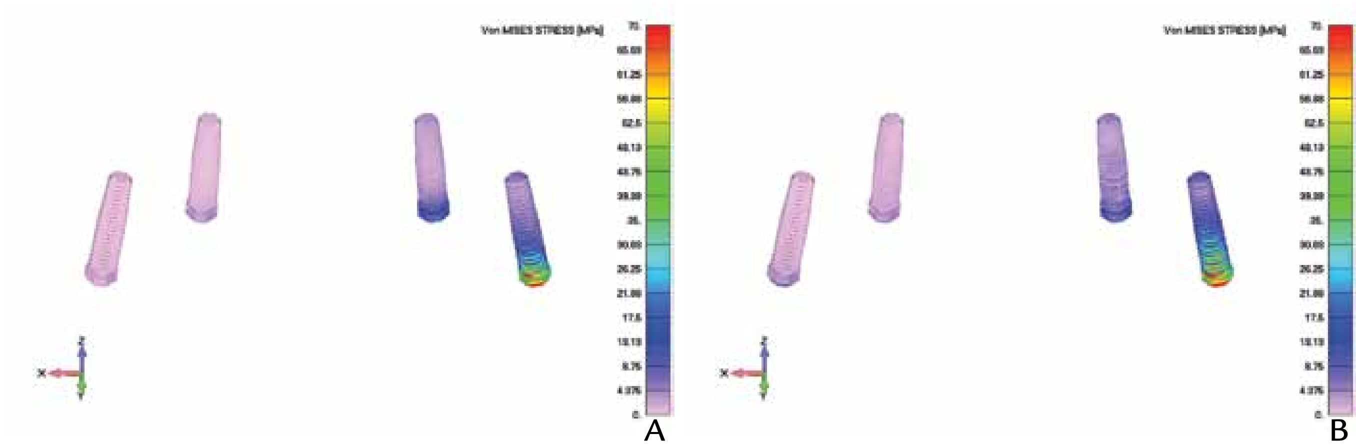
Generally, when the 4 implants were splinted with a rigid FD, stresses at the periimplant bone decreased at both distal and mesial implants as the inclinations of the distal implants increased and the lengths of the cantilever segments were reduced. The maximum stress values recorded in compact bone for the vertical implants were 75.0 MPa for the distal implants and 35.0 MPa for the mesial implants (Fig. 5). The maximum stresses for the 45-degree tilted distal implants were reduced to 19.9 MPa for the distal implants and 7.8 MPa for the mesial implants. Maximum stress values for vertical implants in cancellous bone were 68.6 MPa for distal

Table II. Maximum stress values (MPa) recorded during finite element analysis with 4 splinted maxillary implants. Percentage of stress variation with respect to configuration I with 4 vertical implants noted below MPa value

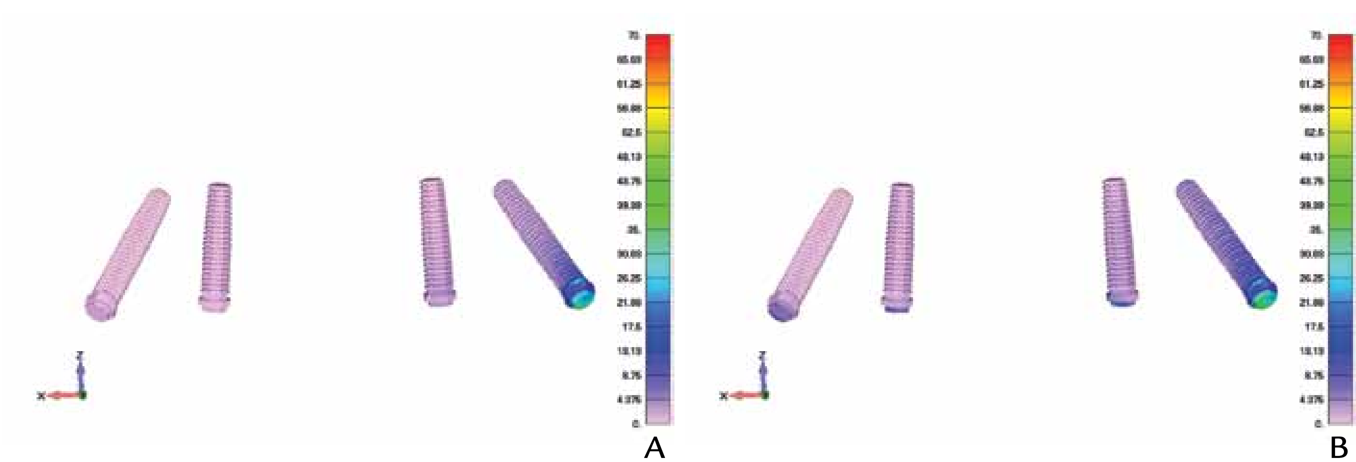
FD Configuration	Compact Bone			Cancellous Bone		
	Distal Implant (MPa)	Anterior Implant (MPa)	Metal Framework (MPa)	Distal Implant (MPa)	Anterior Implant (MPa)	Metal Framework (Mpa)
I 	75.0	35.0	95.0	68.6	30.0	103.9
II 	65.3 − 12.9%	28.6 − 18.3%	84.1 − 11.5%	56.8 − 17.2%	24.5 − 18.3%	93.2 − 10.3%
III 	39.4 − 47.5%	16.6 − 52.6%	65.3 − 31.3%	31.0 − 54.8%	13.7 − 54.3%	73.1 − 29.6%
IV 	19.9 − 73.5%	7.8 − 77.7%	13.7 − 85.6%	15.5 − 77.4%	5.7 − 81.0%	16.3 − 84.3%



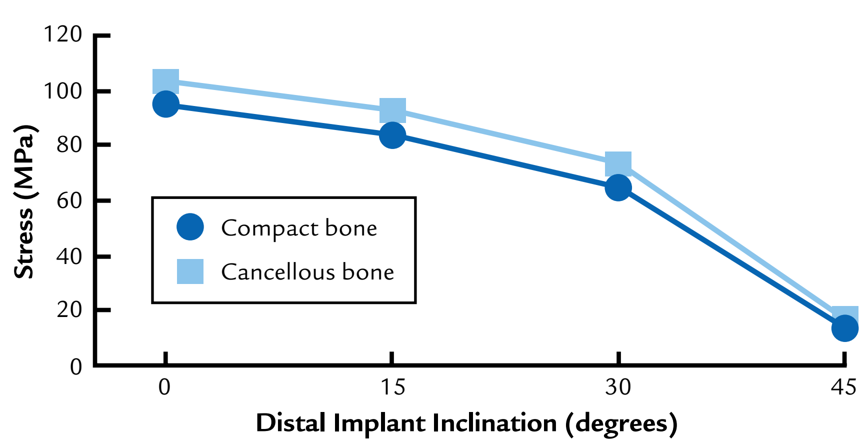
5 Graphs identified maximum stress values in periimplant bone around distal implant (A) and mesial implant (B) relative to the inclination of posterior implants. Black line: compact bone; gray line: cancellous bone.



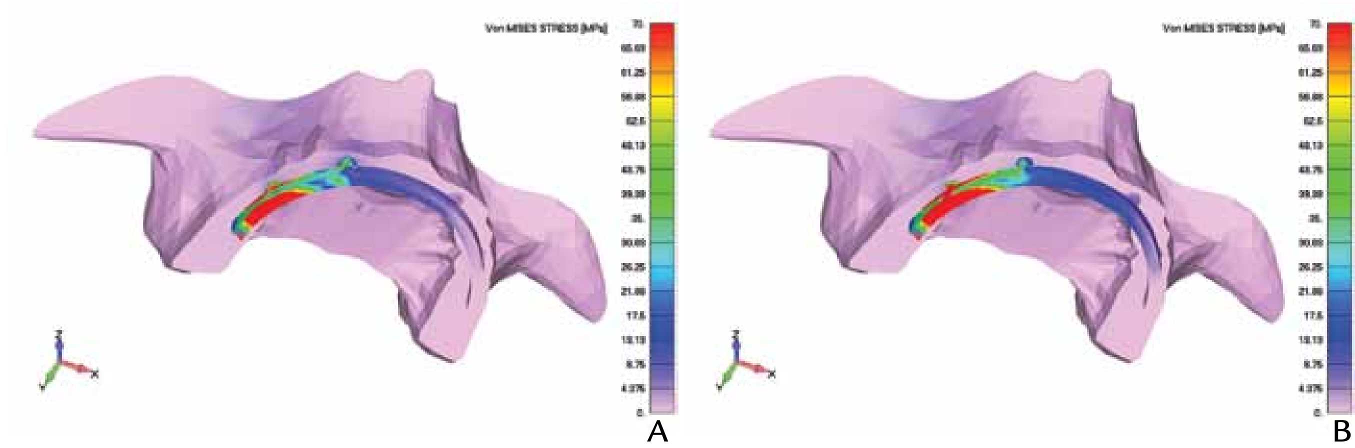
6 Simulations of stress transmission to periimplant bone in configuration I. Vertical load of 150 N applied on right distal portion of cantilevered segment (not represented in figure). Color scale reflects von Mises' values. A, Posterior view in compact bone. B, Posterior view in cancellous bone. Photograph reprinted with permission from *Columbus Bridge Protocol*, Quintessence, 2009.[27]



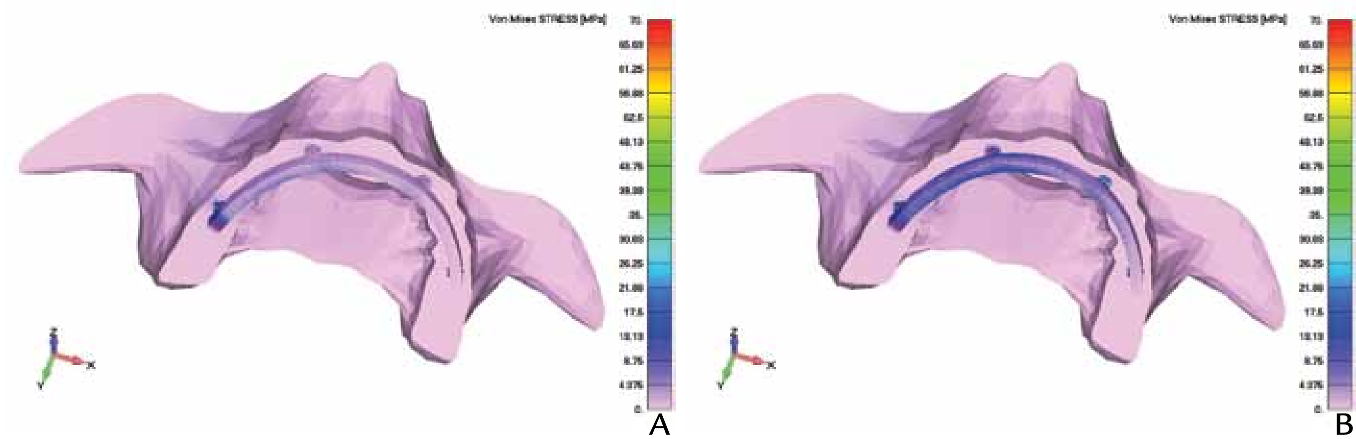
7 Simulations of stress transmission to periimplant bone in configuration IV. Distal implants were inclined 45 degrees relative to occlusal plane. Vertical load of 150 N applied on right distal portion of cantilevered segment (not represented in figure). Color scale reflects von Mises' values. A, Posterior view in compact bone. B, Posterior view in cancellous bone. Photograph reprinted with permission from *Columbus Bridge Protocol*, Quintessence, 2009.[27]



8 Maximum stress values on metal framework relative to increase in implant inclination. Blue line: compact bone; light blue line: cancellous bone.



9 Simulation of stress recorded at metal framework level in configuration I. Vertical load of 150 N applied on right posterior cantilever. A, Compact bone, occlusal view. B, Cancellous bone, occlusal view. Photograph reprinted with permission from *Columbus Bridge Protocol*, Quintessence, 2009.[27]



10 Simulation of stress recorded at metal framework level. Distal implants were inclined 45 degrees relative to occlusal plane (configuration IV). Distal cantilevers were absent, with corresponding reduction of lever arm that was present in Figure 9. Vertical load of 150 N applied on right posterior cantilever. A, Compact bone, occlusal view. B, Cancellous bone, occlusal view. Photograph reprinted with permission from *Columbus Bridge Protocol*, Quintessence, 2009.[27]

implants and 30.0 MPa for mesial implants. Maximum stresses for the 45-degree tilted distal implants were reduced to 15.5 MPa for distal implants and 5.7 MPa for mesial implants (Figs. 6 and 7).

Decreased von Mises values were noted in the FD frameworks when tilted implants were compared to vertical implants. In cortical bone, the maximum stress value was 95.0 MPa for vertical implants; the maximum stress for 45-degree tilted distal implants decreased to 13.7 MPa. In cancellous bone, the maximum stress was 103.9 MPa for vertical implants, and the maximum stress for the 45-degree tilted distal implants decreased to 16.3 MPa (Figs. 8-10).

DISCUSSION

FEA is used for the determination of stresses and displacements in mechanical objects and systems, but is also frequently used in biological systems, for example, in orthopedics and dentistry. For dental implants, FEA studies have reported that tilting single implants increases periimplant bone stress compared to stresses observed around vertical implants.[18,19] Bevilacqua et al[19] reported that stress at the bone-implant interface increased with increasing implant inclinations. The authors reported maximum stress values in compact bone were 10.6 MPa for a single vertical implant submitted to a vertical load of 150 N; 18.9 MPa for 15-degree angulation (+78.3% in comparison to a vertical implant); 20.2 MPa for 30-degree angulation (+90.6%); and 25.0 MPa for 45-degree inclination (+135.8%). Bevilacqua et al[19] demonstrated that vertical implants remain the first choice for single implants, given that stress transmitted to the bone-titanium interface increases with increasing implant inclinations.

Different results are reported in the present 3-D FEA study, in which tilted implants were used in FD designs. In this study, tilted distal implants, rigidly splinted with an FD, decreased periimplant bone stresses as compared to a vertical implant model with cantilevered segments. The maximum reduction of stress values, in simulated compact bone, at the level of the distal implants were -12.9% for 15-degree angulation, -47.5% for 30-degree angulation, and -73.5% for 45-degree angulation. Similarly, stress was reduced in cancellous bone: -17.2% for 15-degree angulation, -54.8% for 30-degree angulation, and -77.4% for 45-degree angulation. In compact bone, higher stresses were limited to the bone around the first 3 or 4 threads of the implant; in trabecular bone, the stresses were distributed along a greater number of threads until the apical portion of the periimplant bone was reached (Figs. 6 and 7).

Zampelis et al[23] drew similar conclusions in a 2-dimensional study, reporting that periimplant bone stresses at the most coronal bone-implant contact point were reduced when cantilever segments were eliminated and the distal implants were inclined distally to support the distal end of the cantilevers. The cantilever length reduction associated with the FD design involving tilted implants probably had a key role in decreasing periimplant stresses around the implants. A 3D-FEA by Rubo et al[24] demonstrated that the increase in stress on implants was proportional to increased cantilever lengths. Krekmanov et al[7,8] reported that distal implants tilted 45 degrees distally (distalization of the implant/restorative platform) resulted in reductions of distal cantilevers up to 10 mm, when compared with the use of vertical implants.

In the present study, stress reduction at the level of the metal substructure in compact bone was -11.5% for 15-degree implant angulation, -31.3% for 30-degree angulation, and -85.6% for 45-degree angulation. Stresses were also reduced with respect to tilted implants and metal substructures in cancellous bone: -10.3% for 15-degree, -29.6% for 30-degree, and -84.3% for 45-degree angulations. The point of maximum stress of the metal framework was at the level of the junction of the framework and the distal implant where the bar, at a point of resistance that acted as a fulcrum, tended to bend (Fig. 9). In the authors' opinion, shorter cantilevers associated with distal tilted implants protected the prosthetic components from overloads.

The numeric values reported in this study must be interpreted as biomechanical indications within the limitations of the model presented, since finite element 3-D models represent a simplification of the investigated structures. It should also be emphasized that the aim of the study was not to report absolute values of stress but to compare stress levels in different prosthetic solutions. In this study, the compact and cancellous bone were regarded as isotropic, as anisotropic properties of the maxilla are not yet available in the literature. In addition, the connecting screws at the abutment-implant and prosthesis-abutment interfaces were not modeled, and the connections were designed to be rigid. 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 3-D FEA study, the use of distal tilted implants results in a reduction in stresses in the periimplant bone and in metal frameworks secondary to cantilever length reduction and implant length increase. This treatment modality seems to be a valid therapeutic alternative to conventional maxillary fixed complete prostheses supported by vertical dental implants with posterior cantilevers.

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