Evaluation of "All-on-Four" Concept and Alternative Designs with 3D Finite Element Analysis Method

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ABSTRACT

Purpose: The aim of the present study was to evaluate the effect of the forces on the implant and supporting alveolar ridge in "all on four" concept and alternative designs using finite element analysis.

Materials and Methods: Different treatment alternatives with various implant designs were performed in an edentulous mandible. In Design 1, implants were placed according to "All-on-Four" concept; Design 2, two long (13 mm long, 4 mm diameter) and two short (7 mm long, 4 mm diameter) implants; Design 3, four long and two short implants; and Design 4, two long and four short implants were placed vertically. A force of 100 N for each tooth, a total of 300 N load was applied. Finite element analysis was used to evaluate and compare the different designs.

Results: The stress concentration within the cortical bone was significantly higher than the trabecular bone around the neck of the implants. The maximum stress values were located around the cortical bone of the distal implant for all designs. The reduction in the number of implants did not diminish the success of the design.

Conclusions: In the presence of vertically resorbed posterior mandibula, although the "all on four" concept is a feasible approach clinically, short implants had decreased the amount of force transmitted to the supporting bone.

KEY WORDS: "All-on-Four" concept, dental implant-abutment design, finite element analysis, short implant, tilted implant

INTRODUCTION

Edentulous patients have usually excessive bone resorption in the alveolar ridge. This resorption may occur with physiologic or pathologic factors.[1] For these reasons, they are commonly unable to use conventional dentures comfortably. In these patients, implant-supported prostheses are mostly unavoidable. Implant-supported dentures were popular at the end of the 1960s because of its long-term success.[2] Although the same researchers had supposed to use an implant for each missing tooth,[3] it is not possible in every situation especially where the bone height is insufficient.

In edentulous patients, the anatomic limitations (such as mandibular canal and maxillary sinuses) of the residual alveolar bone may cause problems for the insertion of the dental implants.[4,5] There are plenty of materials and techniques in order to get over these problems.[6–8] However, all of these alternative methods and materials cause large quantities of additional financial burden other than the implants and elongate the treatment process.

Malo and colleagues[9] had recently introduced the "All-on-Four" concept (All-on-4™, Nobel Biocare AB, Göteborg, Sweden). According to this concept, four implants are enough for full-mouth fixed restorations. Two of those four implants are placed in the anterior alveolar region, and the other two are placed just in front of the right and left mental foramen regions. Anterior implants

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are placed vertically, but posterior implants are placed approximately 30 degree distally inclined, due to the excessive bone resorption. These distal inclinations of the posterior implants are tolerated with angled abutments.

"All-on-Four" concept is successful according to the short-term clinical study results.[9–13] There are very few long-term study results. Also, there were limited study about the stresses observed in implants, abutments, prostheses, and peri-implant bone according to this concept. On the other hand, short implants are offering alternative treatment options in case of insufficient vertical alveolar ridge.[14] Although the short implants have been associated with low success rates,[15–17] recent studies suggest that the same level of clinical success may be reached for short implants compared with the longer ones.[18–20]

We hypothesized that since the "all-on-four" concept is a clinically feasible approach for severely resorbed mandibula, similarly short implants would be successful alternative treatment design. The aim of the present study was to evaluate the effect of the forces on the implants and the supporting alveolar ridges in the "All-on-Four" concept and in the alternative designs, using finite 3D element analysis (FEA).

MATERIALS AND METHODS

Configuration of the Groups

Different implant designs with different treatment alternatives for the edentulous mandible were performed as study groups. Design 1: implants had been placed according to the "All-on-Four" concept. Brånemark System® MkIII – TiUnite® (Nobel Biocare) implants were used in order to generate the implant models. The short implants were designed as 7 mm, and the long implants were designed as 13 mm in length. All the implants were designed as 4 mm in diameter. In other groups, the long implants were placed in the anterior mandibula, between the mental foramens, and the short implants were placed in the posterior mandible, behind the foramens, and all were placed vertically. Infrastructure was made of titanium and an acrylic denture with 12 acrylic teeth was created for the superstructure for all models. The details of the models were shown in Figure 1.

Modeling

Computerized tomography (CT) images of a patient, who is suitable for "All-on-Four" concept and the identifying information was kept confidential, were used as a reference for the modeling of the mandibula. CT images were transferred to the 3D-doctor software (Able Software Corporation, Lexington, MA, USA), and the bone tissues were segmented according to the Hounsfield Values with "interactive segmentation" method. After the segmentation procedure, three-dimensional models were created with three-dimensional complex render method. The implants and abutment components used

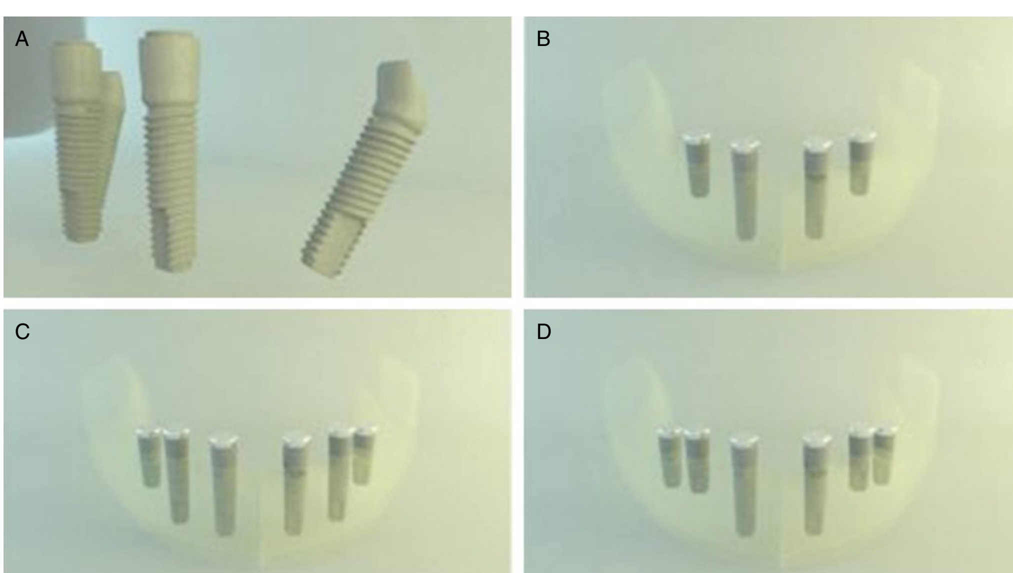

Figure 1 Different implant designs. (A) Design 1: "All-on-Four" concept. (B) Design 2: anterior two straight-long, posterior two straight-short implant. (C) Design 3: four straight-long, two straight-short implant. (D) Design 4: two straight-long, four straight-short implant.

TABLE 1 Element and Node Numbers According to Groups

	Design 1	Design 2	Design 3	Design 4
Nodes	103,914	161,797	206,344	186,341
Elements	1,040,032	903,454	1,166,472	1,047,902

in the study were scanned three-dimensional with Activity 880 digital scanner (Smart Optics Sensortechnik GmbH, Bochum, Germany). Rhinoceros 4.0 program (McNeel, Seattle, WA, USA) was used as a three-dimensional modeling software. An acrylic denture was modeled via the Rhinoceros, and the same denture was used for each group in order to ensure the standardization of the loading process. All models were situated to the three-dimensional space with correct coordinates and the model merging procedure had been completed.

Meshing Procedure

Models were transferred to Algor Fempro (ALGOR, Pittsburgh, PA, USA) software in stl format in order to analyze after they were geometrically created by VRMesh Studio (VirtualGrid Inc, Bellevue City, WA, USA) software program. Material values, (elastic modulus and Poisson's ratio) which define the physical properties of the structures used to form the models, were entered to the software program. Solid body properties were regarded as linear elastic, homogeneous, and isotropic in the software program. The elastic modulus and Poisson's ratio values of the materials were given in Table 1 according to the literatures.[21–23] Meshes were formed with 10 noded (brick type) elements as much as possible. In this way, it was attempted to form the highest quality mesh structure (Table 2).

Boundary Conditions

Boundary constraints for the mandibular model were applied, with no degree of freedom (DOF), to the posterior and inferior regions.

A force of 100 N for each, a total of 300 N load was applied with a 75-degree angle to the occlusal plane from the lingual side, on the buccal cusps of the two premolars and the first molar teeth. It was assumed that there was a tight bond between the modeled structures.

Evaluation of the FEA Results

Data were evaluated according to the materials' mechanical properties (Table 1). Principal stress values were important for the bone tissue. The interpretations were done according to the minimum principal stress values. The stresses in the implants and the abutments were reported according to the von Mises stress values. The results were evaluated by the range scales. All the stress values were shown by the color and magnitude scales. The software had automatically calculated the values of the stress patterns on the any desired location in megapascal unit.

RESULTS

Von Mises Stress Assessments

Von Mises stress values on implants were shown in Table 3. According to this table, the highest stress values were found in the most posterior second short-straight implant in Design 2. The stresses on the short-straight implant in the posterior were greater than the long-inclined implants. The lowest von Mises stress values were established in the third and fourth designs. Stresses formed on implants were shown in Figures 2 and 3.

Principal Stress Assessments

Minimum principal stress values for different designs were shown in Figures 4–6. Highest stress values were measured in Design 4 among all groups, and for this design, short-straight implant in the posterior had caused the highest stress value in the surrounding bone.

TABLE 2 Elastic Modulus and Poisson's Ratio Values of the Materials

Materials	Young Modulus (GPa)	Poisson's Ratio (ν)	References
Titanium	110	0.35	19
Cortical bone	14	0.30	19
Spongious bone (D2)	1.4	0.30	20
Acrylic resin	2.4	0.40	21

TABLE 3 Von Mises Stress Values for Each Design on Loading Side Implants (MPa)

Implant Location	1st Implant	2nd Implant			3rd Implant	
Type of Implant	Straight-Long	Straight-Long	Straight-Short	30° Inclined-Long	Straight-Long	Straight-Short
Design 1	252.96400	–	–	454.60000	–	–
Design 2	139.95800	–	694.787	–	–	–
Design 3	76.77960	283.38700	–	–	296.69300	–
Design 4	75.8213	–	426.67300	–	–	293.29800

As the Design 3 and 4 were compared, usage of a short implant rather than a long one in the middle implant area had caused higher stress values on the supporting tissues, as being higher in the trabecular bone. Lowest stress values were measured in Design 3 among all groups. As the Design 1 and 2 were compared, long-inclined implant had caused higher stress values in the supporting bone than short-straight implants. These results of the finite element analyses do not have a variance; therefore, there was no need to perform statistical analysis (Table 4).

DISCUSSION

In implant-retained restorations, functional and parafunctional forces generated during chewing are transmitted to the implants and peri-implant

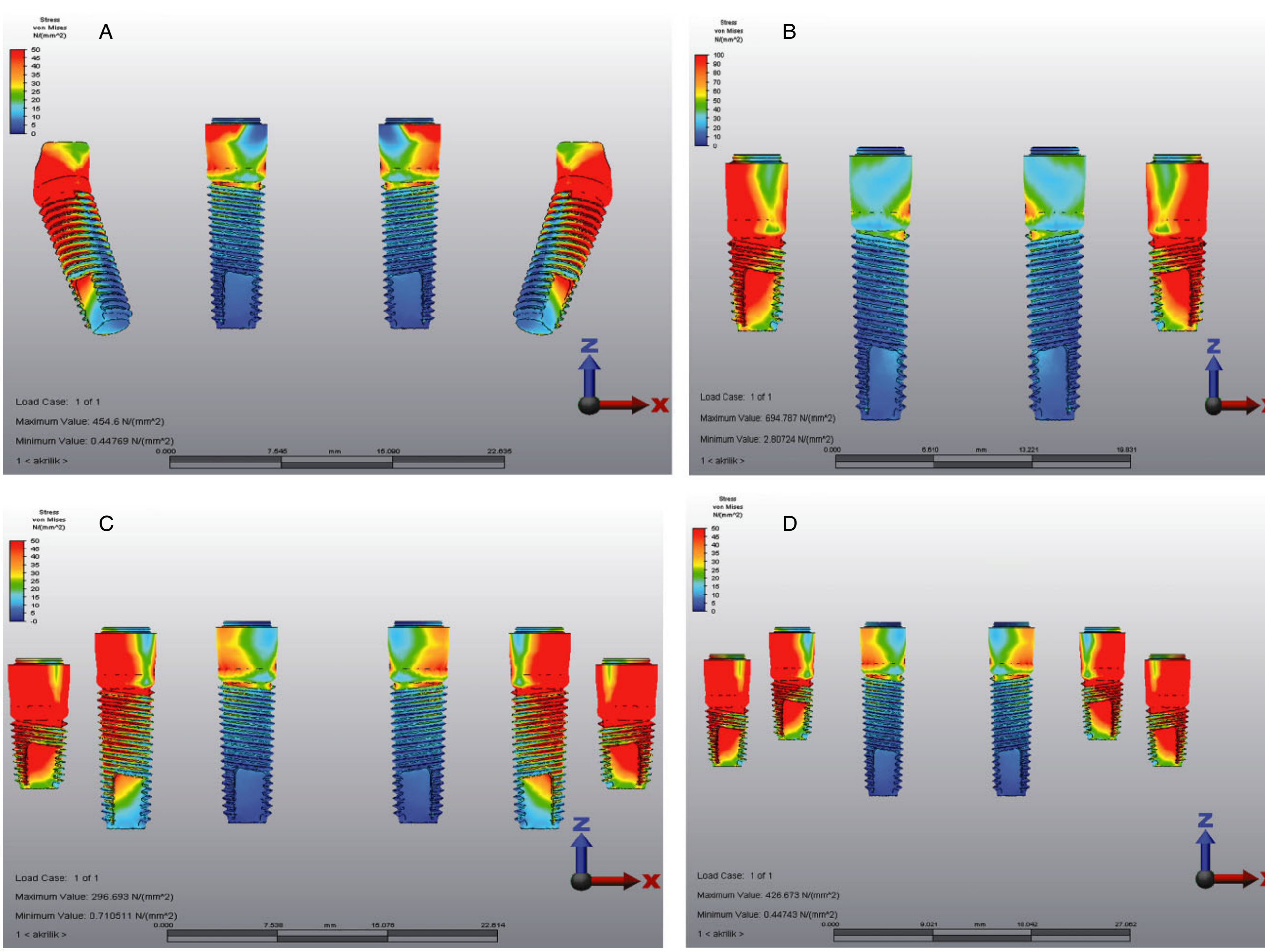

Figure 2 Von Mises stresses on implants for different designs: (A) Design 1; (B) Design 2; (C) Design 3; (D) Design 4.

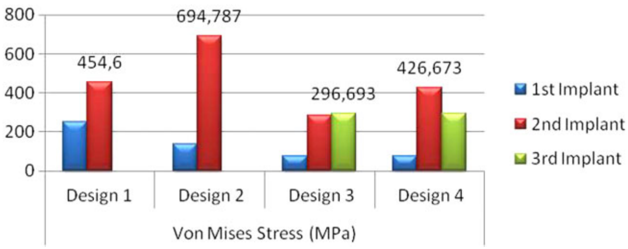

Figure 3 Von Mises stress value graphics of each design on implant.

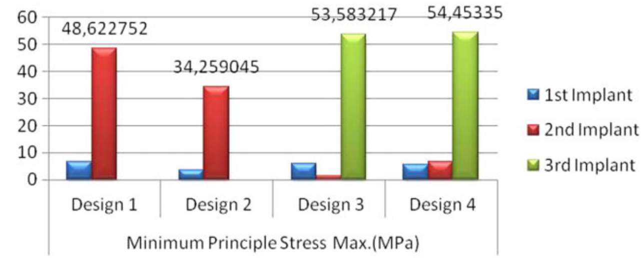

Figure 4 Minimum principal stress maximum values graphics of each design on cortical bone.

supporting tissues by prosthetic restorations. These forces cause deformations in the surrounding bone and various stresses in the contact zone of implant and supporting tissues.[24]

Stress analyses are utilized in dentistry in order to examine the biomechanical behavior of the restorations and the surrounding tissues under functional forces. FEA, one of these methods, is mostly preferred in medical studies because of its advantages, such as the implementation to the complex structures showing irregular geometry, with the variability of dimensions and shapes of the elements, it could precisely mimic the geometry of the object to be examined.[25,26] Besides, the most important disadvantage that limits the finite element studies is that the necessity of taking some factors that vary in nature as constant to simulate the living tissues.[27] Indeed, as in all FEA studies, all the simulated living tissues and synthetic materials were

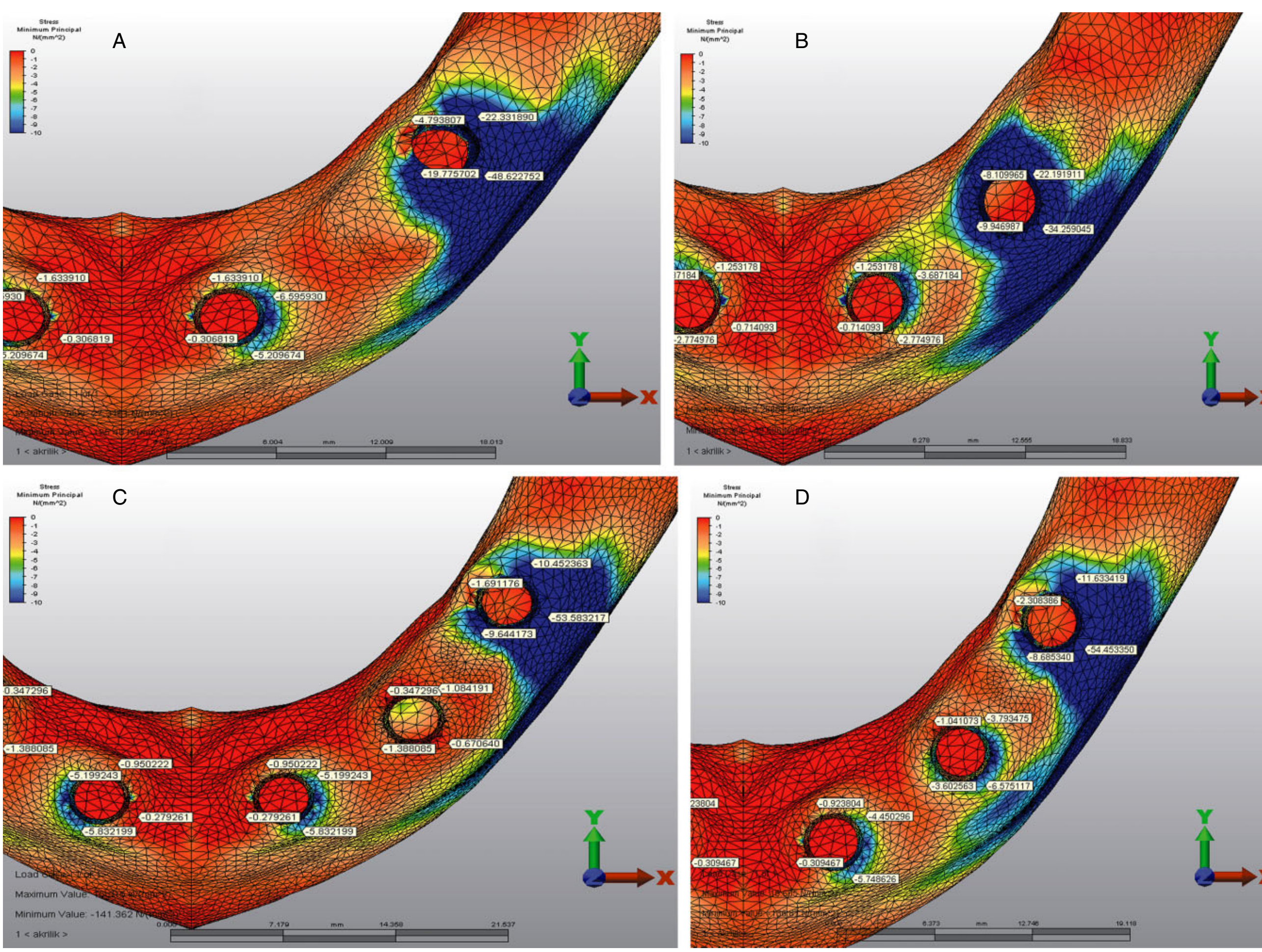

Figure 5 Minimum principal stresses on cortical bone for different designs: (A) Design 1; (B) Design 2; (C) Design 3; (D) Design 4.

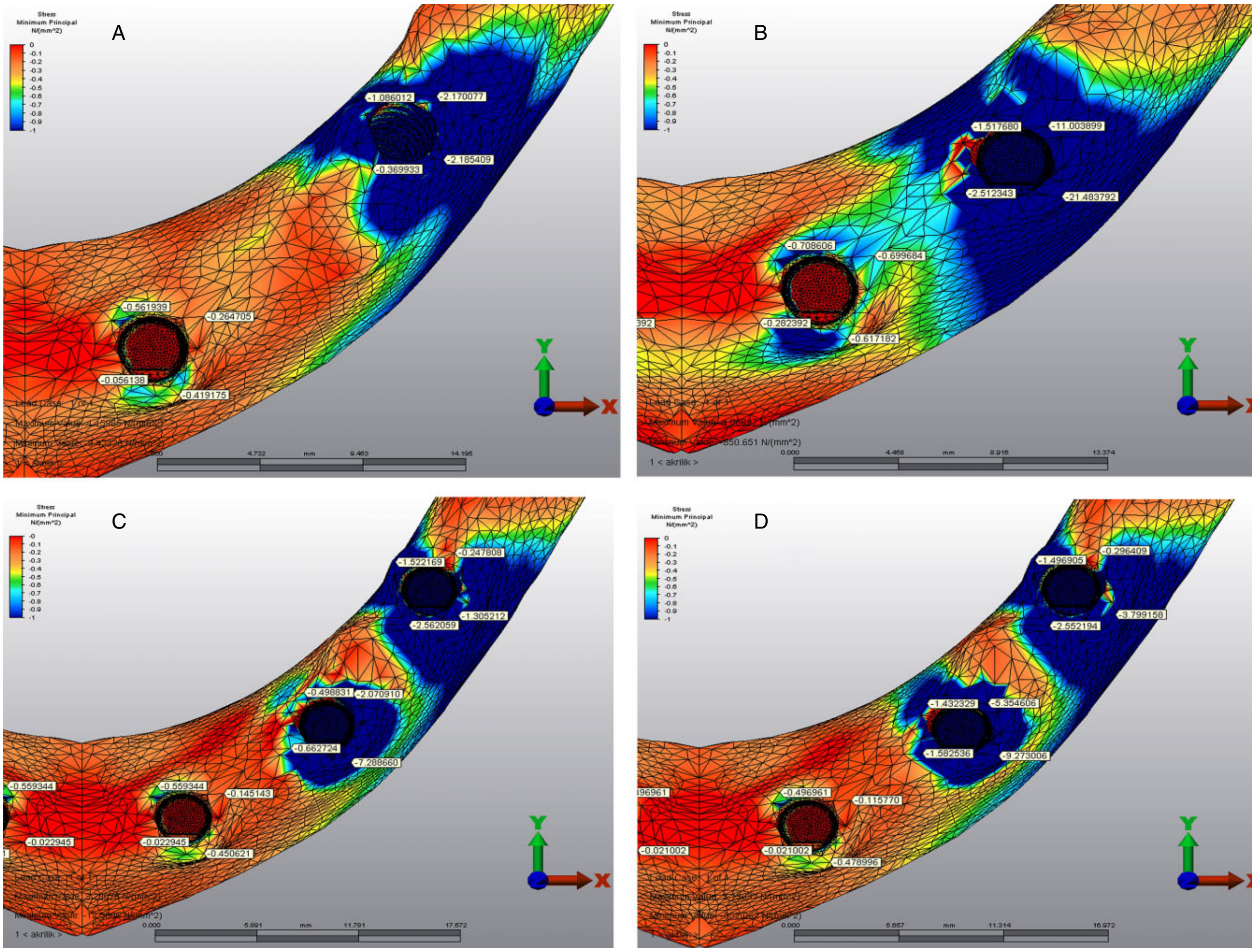

Figure 6 Minimum principal stresses on trabecular bone for different designs: (A) Design 1; (B) Design 2; (C) Design 3; (D) Design 4.

described as 100% homogeneous, isotropic, and linear elastic in this study. Even though the histological studies showed that osseointegration between the bone-implant interfaces has not been fully achieved;[28] in this study, the implants were assumed to be 100% osseointegrated to the bone as well as in other studies.[29,30]

A case of appropriate quality from the clinical CT records were selected and used as reference for the

TABLE 4 Minimum Principal Stress Max. Values for Each Design on Loading Side Bone Tissues (MPa)

Implant Location		1st Implant	2nd Implant			3rd Implant	
Type of Implant		Straight-Long	Straight-Long	Straight-Short	30° Inclined-Long	Straight-Long	Straight-Short
Design 1	Cortical	6.595930	–	–	48.622752	–	–
	Trabecular	0.561939	–	–	2.185409	–	–
Design 2	Cortical	3.687184	–	34.259045	–	–	–
	Trabecular	0.708606	–	21.483792	–	–	–
Design 3	Cortical	5.832199	1.388085	–	–	53.583217	–
	Trabecular	0.450621	7.288660	–	–	2.562059	–
Design 4	Cortical	5.748626	–	6.575117	–	–	54.453350
	Trabecular	0.496961	–	9.273006	–	–	3.799158

modeling. The exact reflection of the current clinical case is the superior advantage of this method compared with others. In addition, implants and abutments used in this study were obtained from the distributor, digitally scanned and actual sized models were formed. It was reported that the success of the three-dimensional stress analysis techniques were associated with the ratio of the elements and nodes in the prepared mathematical models.[31] In this study, 206,344 nodes and 1,166,472 elements were used for single design. When compared with similar studies, the nodes and the element numbers are enough to maximize the sensitivity of the analysis.[32–35]

In a study of Demenko and colleagues,[36] they had determined the ultimate oblique masticatory forces for different cylindrical implants. They had simulated the resulting masticatory force of 118.2 N at an angle of approximately 75 degrees to the occlusal plane. Some studies have shown that oblique forces reflect the occlusal loads better.[37,38] Therefore, to simulate the masticatory forces better, 100 N oblique forces were applied to the premolar and the first molar regions as 75 degree inclination with the occlusal plane.

Although the usage of the short implants are the first treatment alternative that comes to mind in the presence of inadequate vertical bone, there are recent studies in the literature that mention the low success rates of the short implants.[15–17] High occlusal stresses causing resorption in the crestal region, especially the concentrated chewing forces in the posterior regions, are shown to be the causes of the most failures.

Many studies about the effect of the length of the implant on stress transmission have shown that when implant diameter kept constant, the increase in length is advantageous in the primary stabilization and enhance the bone-implant contact area. However, it has a little effect in reducing the stresses occurring in the crest hills and supportive tissues around the implants against the occlusal loads.[39–43] The results of this study are in harmony with these studies.

Negligible diminishing of the stresses transmitted to the bone through the apices shows that the biomechanical advantage was low in the implants longer than 7 to 8 mm.[41,44,45]

In some completely edentulous patients, implant-supported prosthetic treatment is almost impossible without complex techniques, such as nerve transposition and bone grafting in the posterior mandible.[39] Recently, a concept was developed to restore the completely edentulous arches with immediately loaded, tilted distal implants with the use of an "All-on-Four" guide.

The method of tilting the distal implants in the edentulous arches represents an alternative technique that leads the placement of longer implants, improved prosthetic support with a shorter cantilever arm, improved interimplant distance, and improved anchorage in the bone. However, in vitro studies and theoretical calculations on single implants have shown that tilted implants may increase the stress to the bone.[46,47]

Tilted single implants may also be subjected to bending during function, which may lead to increased stress in the marginal bone. However, if such implants are part of a multiple implant-supported prosthesis, the spread of the implants and rigidity of the prosthesis will reduce or change the nature of the bending forces.[39] In this study, greater stresses were formed around the inclined implants than the short-straight implants.

The highest values of the compressive stresses were also evaluated in the crestal cortical bone layer in the study, like most of the other studies.[29,48,49] Stress absorption capability of a material is directly proportional to the hardness of that material. The cause of these high stress values are thought to be the high elastic modulus of the cortical bone, being a supporting tissue closest to the occlusal loading area and surrounding the weakest part – neck – of the implant.[49] Although most of the stress would be borne by the cortical bone, in this study, the values of the trabecular bone is greater than expected. As the forces were transferred to the bone by the threads of the implants, in this study model, the threads of the implants were starting from the trabecular bone due to the morphology of the mandibula, and the forces are higher in this area. Although there have been short-term clinical studies about the applicability of the "All-on-Four" concept,[50–52] there are no sufficient in vitro studies about this subject.[53–58]

In a retrospective clinical study of tilted, immediately loaded implants of 245 patients with a total of 980 immediate function implants, Malo and colleagues reported a total of 21 implants failed in 13 patients, giving cumulative patient-related and implant-related success rates of 94.8% and 98.1%, respectively, at 5 years, and 93.8% and 94.8%, respectively, with up to 10 years of follow-up. The prostheses survival rate was 99.2% with up to 10 years of follow-up.[50]

Some studies have shown that the large amount of force applied to the distal extensions of the prostheses is absorbed by the distal implant, and the total load absorbed by this implant is not related to the number of fixtures.[59]

In this study, increasing the number of the implants have not increased the success, and the highest stresses were formed on the most posterior implant and its surrounding bone for all designs. Although the "All-on-Four" concept was found to be a successful and viable design, in case of limited bone volume due to the vertical resorption in the posterior region of the mandibula or the presence of mandibular foramen, instead of placing a distally inclined long implant, it would be a more reasonable approach to place a short-straight implant. In this case, it could be stated that short-straight implants absorb the occlusal loads better by reducing the compressive stresses that is destructive in the cortical bone and extend the clinical life of implants and prosthesis. Furthermore, in many situations, the 2 to 3 mm most coronal part of the implant transfers major load to the bone tissue;[45] these findings may be interpreted as a rationale for selecting short implants provided that they are well anchored in the residual bone.

Mechanical properties of the tissues and the prosthetic materials used were determined and limited as described in the literature. However, anatomic variations and the variety of materials used may change the shape and the findings of this study. Differences in the macrostructure and microstructure of the implants and implant designs would play a decisive role on the results, so the findings of this study would present differences with different implant systems. Therefore, similar studies should be done with different implant systems and investigate the biomechanical properties of other implant systems.

CONCLUSIONS

According to the results obtained in this study, in the presence of vertically resorbed bone in the mandibular molar region, instead of placing a long-inclined implant, shorter implant with the same diameter would decrease the amount of force transmitted to the supporting tissues. It is believed that with an optimized implant design and insertion protocol, short implants may play a more important role in the rehabilitation of the severely resorbed mandibula.

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