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Comparison of stress distribution on the prosthetic screws in standard All-on-4, M4, and V4 techniques in maxilla - A 3D Finite Element Analysis

[1]Dr.Malik Aneeqa Hassan, MDS final year, Dept of Prosthodontics, VSDC Dental College and Hospital, Visvesvarapuram, Bengaluru, Karnataka 560004

[2]Dr Bharat Raj R, Reader, Dept of Prosthodontics, VSDC Dental College and Hospital, Visvesvarapuram, Bengaluru, Karnataka 560004

[3]Dr Surendra Kumar GP, HOD of Dept of prosthodontics, VSDC Dental College and Hospital, Visvesvarapuram, Bengaluru, Karnataka 560004

[4]Dr Anupama Gautam, Professor, Dept of Prosthodontics, VSDC Dental College and Hospital, Visvesvarapuram, Bengaluru, Karnataka 560004

Corresponding Author: Dr. Malik Aneeqa Hassan, MDS final year, Dept of Prosthodontics, VSDC Dental College and Hospital, Visvesvarapuram, Bengaluru, Karnataka 560004

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Abstract

Background: Complete edentulism is one of the challenges in prosthetic dentistry. There are several prosthetic options available among which All-on-4 is one of the treatment modality. It is a revolutionary approach which allows the rehabilitation of totally edentulous patients with placement of only 4 implants in each jaw. It also presents with other modifications as M4 and V4.

Method: A 3D CAD model of fully edentulous maxilla was created using DICOM files. Tetrahedral elements were used for mesh generation. Two mesial implants of 4-mm diameter and 11.5-mm length and two distal implants of 4-mm diameter and 13-mm length were placed. Three different configurations were modeled by changing the tilt angle of the anterior implants with V4 and M4 concept. Abutments were connected to the fixtures and the metal framework was connected to the abutment. Stress distribution over the prosthetic screws was evaluated by applying a cantilever load of 200N in the Ist molar region of the metal framework.

Result: Peak stress values observed on the posterior prosthetic screw and anterior prosthetic screw was highest in V4 group when compared to All-on-4 and M4 groups.

Conclusion: All-on-4 and M4 offers advantages in stress distribution when compared to V4 design.

Keywords: 3D CAD, DICOM files, 3D Finite Element

Clinical implication: All-on-4 with all other configurations can be used in the rehabilitation of patients with severely atrophic maxilla's and mandibles.

Introduction

Many treatment options such as complete dentures, implant supported removable, and implant supported fixed prostheses are available for the rehabilitation of completely edentulous patients.[1] However, the Implant-supported treatment options have been used successfully to replace either a single tooth or multiple teeth, as well as a completely edentulous jaw.[2] But the implant supported fixed prosthesis may not be feasible in many conditions due to which the use of conventional dentures becomes a question especially when the bone height is insufficient.[3] But the anatomic limitations such as a pneumatized maxillary sinus, proximity of the inferior alveolar canal, and resorption of the alveolar bone results in additional treatments such as bone augmentation and maxillary sinus elevation to get over these problems. However, all of these alternative methods cause large quantities of additional financial burden other than the implants and elongates the treatment process.[1,3] In completely edentulous patients, these anatomical limitations can be overcome with the use of all-on-4 treatment concept by avoiding these additional treatments.[1] This treatment protocol involves the placement of four implants in either maxilla or mandible in the anterior part of complete edentulous jaws to support a provisional, fixed and immediately loaded prosthesis. The two most anterior implants are placed axially, whereas the two posterior implants are placed distally up to 45 degrees and angled to minimize the cantilever length, and to allow the application of prostheses with up to 12 teeth, thereby enhancing masticatory efficiency.[4,5] In addition, the inclination of the distal implants enables placement of longer implants with improved cortical anchorage, achieving increased inter-implant distance, and the fabrication of prostheses with reduced cantilever length.[6] From a biomechanical perspective, a bone height of at least 10 mm in the anterior maxilla is required for the immediate loading of a fixed implant-supported prosthesis.[5] However, this is not always possible since bone height augmentation is a challenging advanced surgical procedure in severely atrophic anterior maxillae. These clinical conditions may result in an insufficient alveolar height of the anterior maxilla, preventing the axial placement of implants of at least 10 mm. Therefore, tilting the anterior implants enables the placement of longer implants as distal implants in accordance with the All-on-4 concept. Jensen et al. presented an M-shaped configuration, called M-4, in which the anterior implants are angled distally up to 30 degrees in the axial plane and extend into the lateral nasal rim. Another configuration, called V-4, consists of four implants that are inclined toward the midline in a V-shaped pattern, with the two anterior implants apically engaged in the maxillary midline.[5] However many clinical studies have proven that the mechanical complications such as prosthetic fracture and abutment or prosthetic screw loosening are most commonly encountered.[1] Therefore, this study compared the stress distribution on the prosthetic screw of standard All-on-4 treatment concept with the M-4 and V-4 techniques.

Materials and method

The 3Dimensional- CAD Model of (CATIAV 5) 2018 software were exported to (ABAQUS) 2018 software for mesh generation, definition of material properties, boundary, and loading conditions. Because of the complexity of the given model tetrahedral elements (C3D4, a 4- node linear tetrahedron) were used for mesh generation. Meshes of 165862 – 173288 nodes and 941078 – 980013 elements were generated for the models.

A Scanner (INEOS X5, Dentsply Sirona, USA) was used to scan (with an accuracy of 0.4 um) the implants and abutments to obtain the exact geometry of the components and the data were modeled with ABAQUS software. Three different configurations were modeled by changing the tilt angle of the anterior implants (Table 1)

Models	Anterior implants				Posterior implants				No. of Elements	No. of Nodes
	Implant length(mm)	Tilt angle (deg)	Abutment angle (deg)	Abutment gingival height (mm)	Implant length (mm)	Tilt angle (deg)	Abutment angle (deg)	Abutment gingival height (mm)		
All-on-4	11.5	0	0	2,5	13	30	30	3,5	941078	165862
M-4	11.5	30	30	2,5	13	30	30	3,5	991905	176572
V-4	11.5	30	30	2,5	13	30	30	3,5	980013	173288

Table 1 : Description of the implant and abutment characteristics used in study.

The posterior implants were angled exactly the same in each model, in accordance with the all-on-4 concept (Fig. 1)

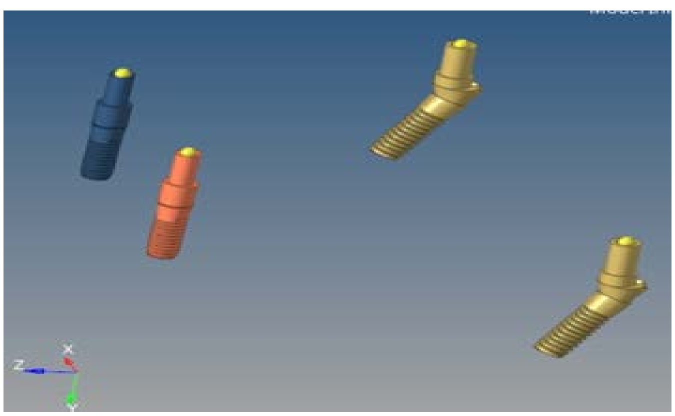


Fig. 1: Showing posterior implants which were same in all the groups.

In the first model (All-on-4), two anterior implants were placed parallel to the vertical axis at the lateral incisor site (Fig. 2a).

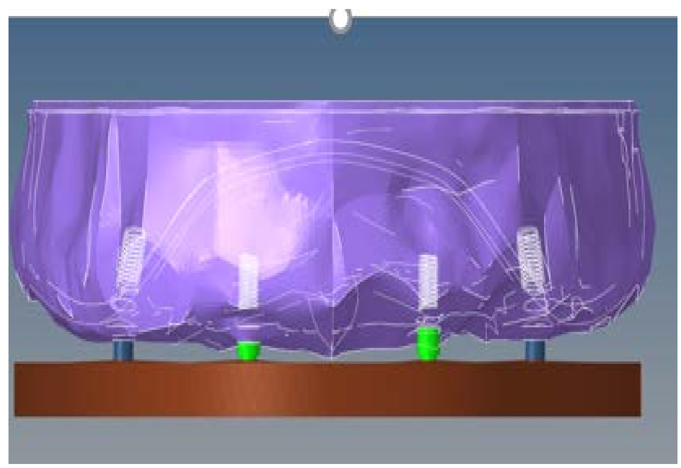


Fig. 2a" Showing anterior implants which were same in all-on-4 group.

For the second model (M-4), anterior implants were placed at the lateral incisor site and apically angled posteriorly to the lateral pyriform rim (Fig. 2b).

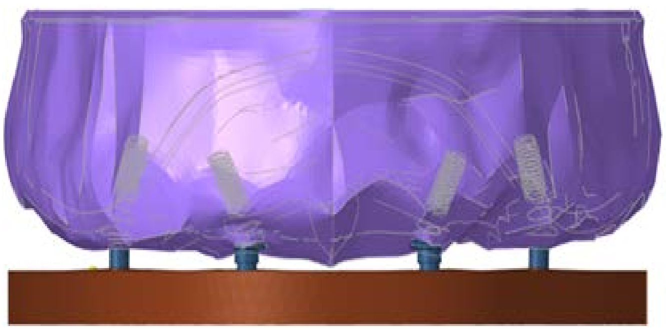


Fig. 2b: Showing position of anterior implants in M4.

For the third model (V-4), two anterior implants were placed in the lateral incisor area and apically angled anteriorly to the midline of the nasal crest (Fig. 2c). stress

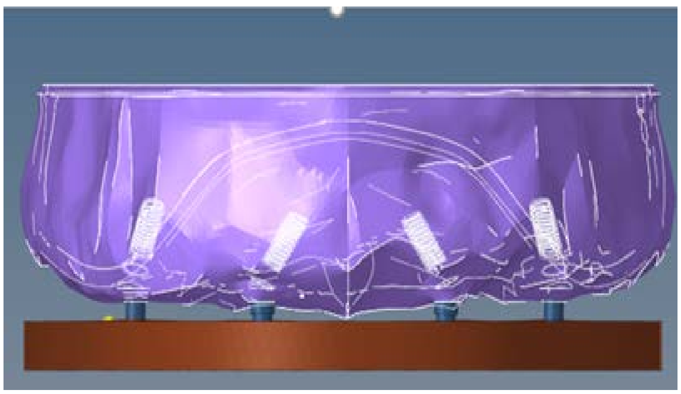


Fig. 2c: Showing position of anterior implants in V4.

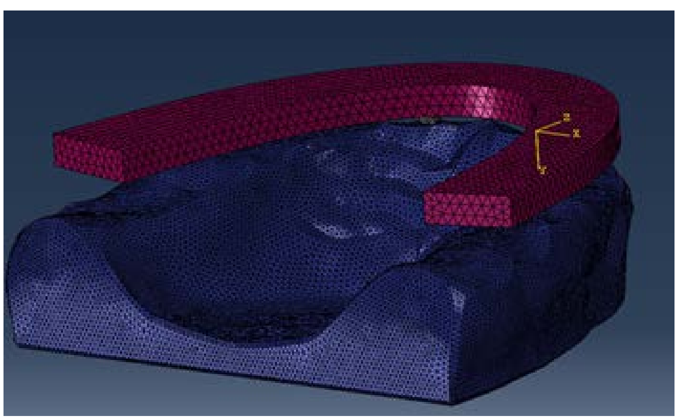
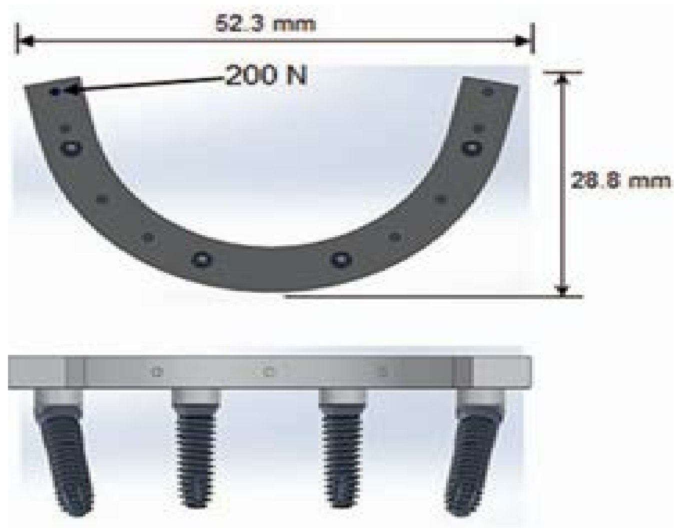


Fig. 2d: Meshed (Discretized) model.

Straight and angled multiunit abutments (Nobel Biocare, Sweden) were placed on both the posterior and anterior implants (Table 1, Fig. 1).

Two mesial implants of 4-mm diameter and 11.5-mm length were placed bilaterally and vertically in the lateral incisor area, and 2 distal implants of 4-mm diameter and 13-mm length were placed bilaterally in the second premolar region with a 30^0 distal tilt as shown in (Fig.1). To follow a path parallel to the straight multiunit abutment of the mesial implant, a 30^0 angled multiunit abutment was used for the distally tilted implant.

The abutments were connected to the fixtures and the metal framework with 6-mm width and height extended up to the 1st molar and had the form of an ideal arch made using an orthodontic arch wire that overlapped the margin of the abutment by 2mm (Fig.3).



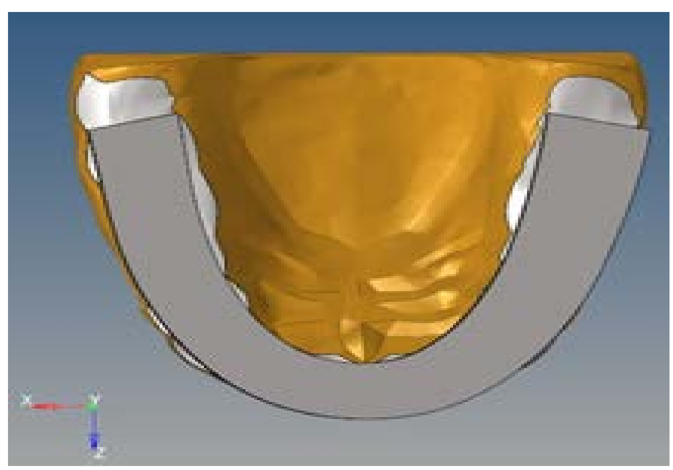


Fig. 3: Design of the components of the finite element analysis, Three-dimensional model in Abaqus software.

The finite element analysis was performed in 3 groups, of same screw design, using the smeared simulation method. Stress distribution over the prosthetic screws on the loaded side was evaluated by applying a cantilever loading of 200N in the ist molar region of the metal framework, because with implant supported fixed prosthesis the average maximum occlusal force exerted by the first premolar and molars is approximately 200N (Fig.3). In Figure 3, a spot labelled 200 N indicates the cantilever area where the cantilever loading was applied. The cantilever area is farther posterior to the position of the connection between the distal implant and the metal framework. Its area was 0.79 mm^2. The loading was applied directly onto the metal framework. (Table 2) shows the mechanical properties such as type, young's moduli, and Poisson ratios of the materials used in this study.

Table 2: Material properties used in this finite element analysis

Component	Material	Youngs Modulus, MPa	Poisson Ratio
Fixture	Ti-Grade4	105 000	0.37
Screw	Ti-6AL-4V	110 000	0.33
Abutment	Ti-6AL-4V	110 000	0.33
Metal framework	Co-Cr alloy	218 000	0.33

A boundary condition for the prosthetic and abutment screws was set to rotate around the axis of the screw so that no translational movement was possible (Fig.4).

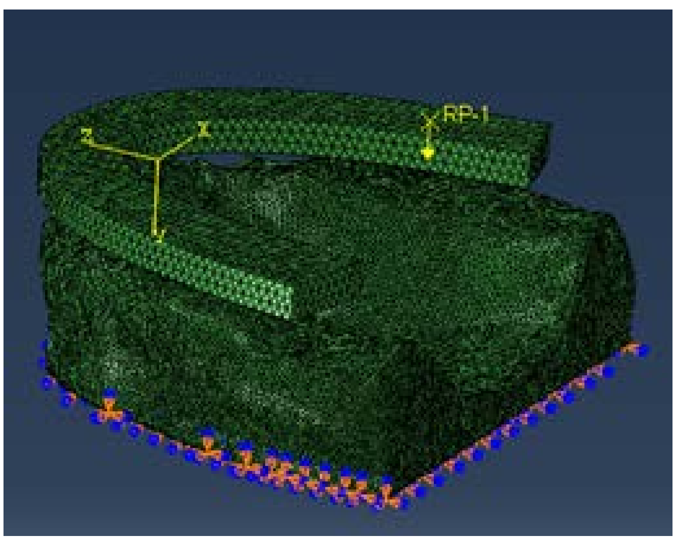


Fig. 4: Application of Load and Boundary conditions in Abaqus software.

The whole model was set to have the same contact conditions, except the thread portion of the screw; the thread portion was made to have the bolt conditions of the half-thread angle, pitch, and diameter. The contact property was 0.5 of the friction coefficient in tangential behavior and 1 of the stiffness scale factor as penalty method in normal behavior. The bone implant fixture interface was assumed to be completely fixed as if it were osseointegrated. The results were visually transformed using colors ranging from blue to red, where red represented the highest stress value. The stress analysis was conducted using the von Mises stress value.

Results

The peak stress values observed on the anterior and posterior prosthetic screws of the loaded side in each group are described in (Table 3). The results suggested that the posterior prosthetic screw on the loaded side in V4 showed highest stress values compared to standard All-on-4 and M4 configurations. The results also suggested that the anterior prosthetic screw on the loaded side in V4 showed highest stress values compared to standard All-on-4 and M4 configurations. Least stress was seen on the prosthetic screw in case of standard All-on-4 when compared to V4 and M4. The anterior prosthetic screws showed lower stress values than the posterior prosthetic screws (Table 3).

	Posterior Implant 1		Anterior Implant 1		Anterior Implant 2 (Loaded side)		Posterior Implant 2 (loaded side)	
	Displacement (mm)	von_ Mises Stress (MPa)	Displacement (mm)	von_ Mises Stress (MPa)	Displacement (mm)	von_ Mises Stress (MPa)	Displacement (mm)	von_ Mises Stress (MPa)
ALL-ON-4	0.001	22.351	0.003	23.598	0.006	463.847	0.012	221.947
M4	0.031	21.37	0.031	56.932	0.031	138.494	0.031	185.194
V4	0.0012	20.0392	0.0022	36.4704	0.0048	527.1163	0.0116	1163.9099

Table 3. Stress distribution on prosthetic screws on the loaded and unloaded implants.

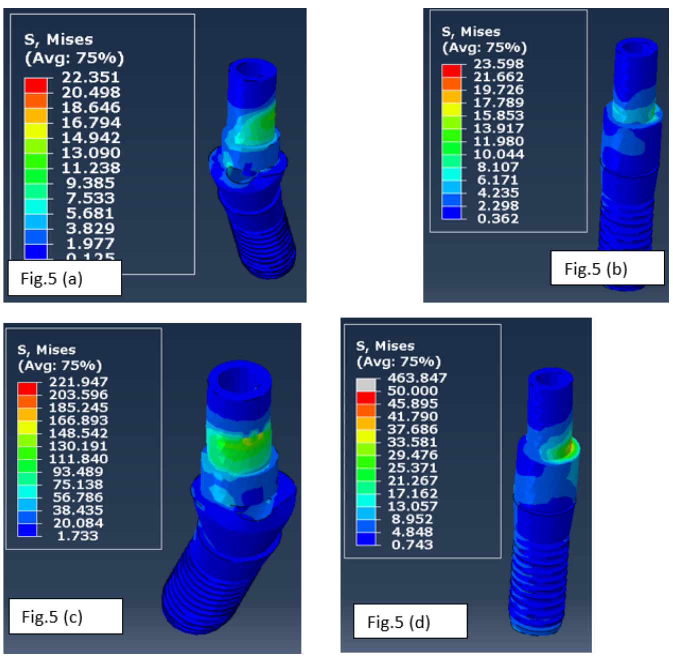


Figure 5: Schematic designs of stress distribution on prosthetic screws of the anterior and posterior loaded and unloaded implants in All-on-4.

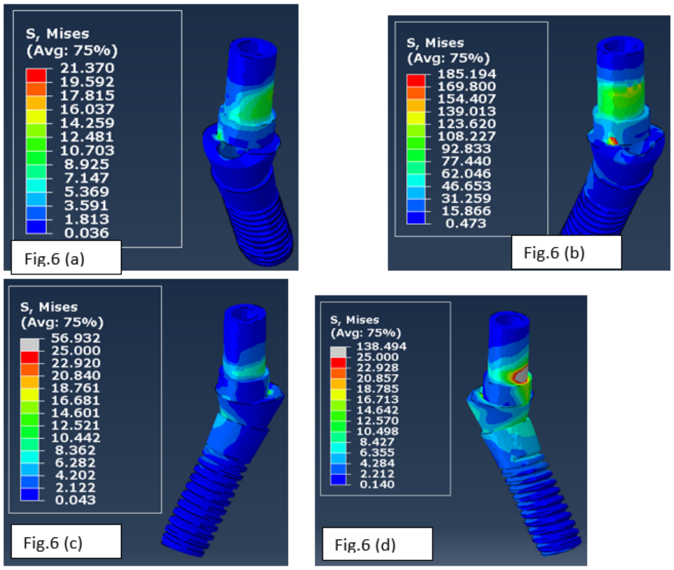


Figure 6: Schematic designs of stress distribution on prosthetic screws of the anterior and posterior loaded and unloaded implants in M4.

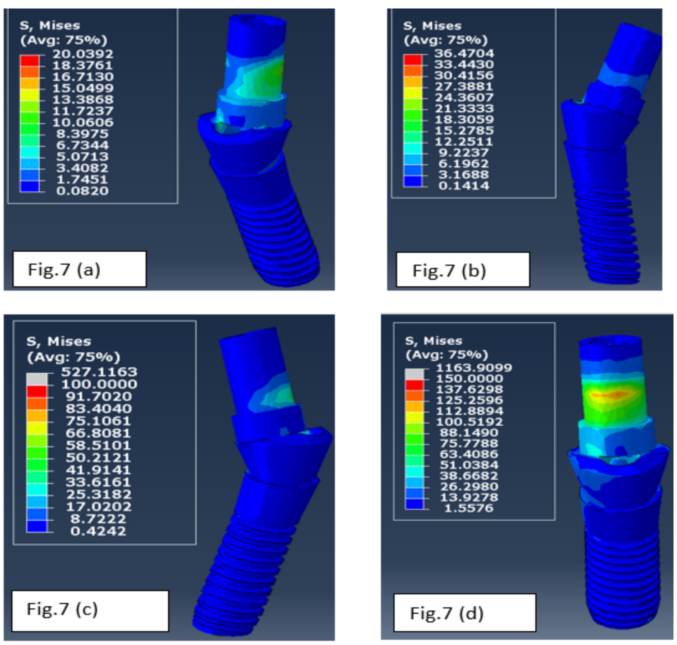


Figure 7: Schematic designs of stress distribution on prosthetic screws of the anterior and posterior loaded and unloaded implants in V4.

Discussion

Abutment and prosthetic screw loosening is one of the most common complications related to implant prosthesis. Hence, dentists should have an understanding of implant screw mechanics rather than solely depending on an implant manufacturer to fulfill the basic requirements. Most common causes of screw fracture are a partially unretained restoration or fatigue related to the amount of force or number of cycles. Prosthetic screw fracture occurs approximately 4% of the time and abutment screw fracture 2% of the time.[7] The functional and parafunctional forces during chewing in implant retained restorations are directly transmitted to the implants and peri-implant tissues by prosthetic restorations. These forces may be the major factors that can cause deformations in the surrounding bone and various stresses in the contact zone of implant and supporting tissues.[7]

In dentistry stress analyses is used to examine the biomechanical behavior of the restorations and surrounding tissues which are induced to functional forces. The methods mostly preferred in medical studies is Finite element analysis, because of various 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 that has to be examined.[8,9] Therefore, the current study compared the stress distribution on the prosthetic screws of all-on-4, m4 and v4 techniques using a 3D finite element analysis method. Clinical studies have proved that the number of implants needed to rehabilitate edentulous jaws using four implants resulted in similar success rates when compared to rehabilitating with more implants.[10,11] Jensen et al. stated that tilting anterior implants applies same number as tilting posterior implants and allows placement of 50% longer implants. These configurations include M-4 and V-4. In M-4 configuration two anterior implants are angled posteriorly up to 30^0 in the axial plane, extending into the lateral nasal rim.[12] Whereas V-4 consists of four implants in a V-shaped pattern that are tilted towards the midline, with the two anterior implants apically engaged in the maxillary midline.[13] Studies have not been done to evaluate the effect of different configurations of All-on-4 on the success rate of prosthetic components.

In this study, implants and abutments 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. In this study, 165,862 nodes and 941,078 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.[14] Studies have proved the effect of the length of the implant on stress transmission which have shown that when implant diameter is kept constant, the increase in length is beneficial in the primary stabilization and enhance the bone-implant contact area. However, it has a little effect in minimizing the stresses that are seen in the crest hills and supportive tissues around the implants against the occlusal loads.[3] The results of this study are in harmony with these studies.

Kanneganti et al reported that, as the length of the abutment screw increased, the stress decreased.[15] In addition, Himmlova et al reported that an increase in the implant length and diameter led to a decrease in the maximum von Mises equivalent stress values on the implant, and an increase in the implant diameter decreased the maximum von Mises equivalent stress values more than an increase in the implant length.[16] In this study longer and wider screw with long abutments were used because as the length and diameter of the screw increases, the stress on the posterior prosthetic screw tends to decrease because the contact area of the screw increases.[17] As the diameter of the screw increases, the preload increases, and may increase the clamping force at the screw joint, which reduces screw loosening. In many studies it was found that the longer and wider the screw was, the greater the contact area with the abutment, and the lesser the stress concentrated on the screw. This may suggest that the short and narrow screw was likely to loosen more frequently than the long and wide screw.[1] And some studies suggest that increase in the abutment height has the benefit of decreasing the loss of marginal bone.[18] Therefore it can be considered clinically.

In this study, all stress values of the posterior prosthetic screws were higher when compared to those of the anterior prosthetic screws. These values indicate that posterior screw loosening may occur more frequently than anterior screw loosening. Stress on the posterior prosthetic screw tended to be concentrated on the lower part of the screw, as previously reported,[1] whereas stress on the anterior prosthetic screw tended to be distributed on the neck and lower part of the screw.

The current study simulated clinical conditions as accurately as possible; however, 3D finite element studies have some limitations to simplify the analysis, regarding the bone type, boundary conditions, osseointegration level, and amount and direction of forces. Within the limitation of the study longitudinal clinical follow up and clinical trials are needed to confirm the results of this study. Study on severely atrophied maxilla or mandible are needed to analyze the stress distribution on different configurations. Long term clinical studies that analyze the effect of different configurations on the success rate of prosthetic components and implants would be beneficial.

Conclusion

According to the present study's findings posterior prosthetic screw on the loaded side in V4 showed highest stress values compared to standard All-on-4 and M4 configurations. Anterior prosthetic screw on the loaded side in V4 showed highest stress values compared to standard All-on-4 and M4 configurations. Least stress was seen on the prosthetic screw in case of standard All-on-4 when compared to V4 and M4.

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