sciendo
10.2478/bjdm-2021-0004

BALKAN JOURNAL OF DENTAL MEDICINE
BaSS
ISSN 2335-0245

Evaluation of Stress Distribution on all-on-four Concept and Conventional Implant Designs: 3D Finite Element Analysis

SUMMARY

Background/Aim: *The objective of this study was to evaluate the stress distribution on implants and supporting bone tissue in All-on-Four and conventional designs in edentulous mandible by using 3D finite element analysis.* ***Material and Methods:*** *The different five models were designed according to All-on-Four concept and conventional implant placement designs. While the first two models were involved in All-on-Four concept with two long implants, the remaining models were designed by conventional approaches with three implants in different location and length. After the modelling procedures, a load of masticatory force was applied and the stresses were evaluated.* ***Results:*** *It has been observed that principal stresses in both cortical and spongious bone tissue were concentrated in models of All-on-Four design. Less principal stress levels were found in models of conventional design. Similarly, von Mises stress values on implant surfaces were found to be higher in All-on-Four concept.* ***Conclusions:*** *In severely resorbed mandible, the use of conventional implant placement is recommended. Although All-on-Four design seems to be a reasonable alternative for edentulous mandible, evidence-based results of this approach should be supported by long-term follow-up studies.*

Key Words: All-on-Four, Conventional Implant Design; Finite Element Analysis; Tilted Implants

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ORIGINAL PAPER (OP)
Balk J Dent Med, 2021;46-52

Introduction

Tooth loss causes many problems such as loss of function, decreased masticatory efficacy, impaired aesthetic appearance and speech problems. Therefore, in modern dentistry, restoration and rehabilitation of edentulous cases become a necessity in avoiding mentioned conditions[1]. The treatment options for partially or totally edentulous patients range from removable or fixed partial denture and implant supported dentures[2].

Excessive alveolar ridge resorption and decreases in three dimensional sizes of the supporting bone are the most important problems in providing adequate prosthetic dental rehabilitation. The quality of the alveolar bone tissue, muscle attachments, age and systemic conditions of the patient, as well as duration of edentulousness are causative factors in resorption process of the alveolar bone[3,4]. In such a case, there is insufficient support of the remaining periodontal tissues for proper conventional denture function. Therefore, retention and stability of the dentures reduce due to the loss of alveolar bone support[4,5].

With the development of dental implants, implant supported systems are used in prosthetic rehabilitation of atrophic alveolar bone[6]. Implant supported dentures are effective in providing long-term success in rehabilitation of edentulous mandible. However, the limitations due to the close proximity between anatomical structures and alveolar ridge sometimes lead to difficulties in implant placement in edentulous cases[7]. Therefore, in rehabilitation of atrophic jaw bones, guided bone regeneration, distraction osteogenesis and bone grafts are preferred. The most used graft applications include iliac, tibial and calvaria-derived autogenous grafts. However, the applicability of such advanced techniques is restricted due to requiring an additional surgical intervention and probable complications in the donor site[8,9]. Moreover, the cost of these operations and the duration between the surgical procedures are the undesired conditions[10]. Additionally, although the use of short implants has been recommended, low success rates have led to the need for alternative protocols in such edentulous cases[11-13].

"All-on-Four" concept has been introduced to maximize utilization of alveolar bone left in the atrophic jaws to allow immediate function[14,15]. The protocol includes four implant placements; two of them are located in the anterior region vertically, and the left two implants are placed just anterior proximity of the mental foramens bilaterally with 30 degree distally inclined[14,15]. In the literature, recently, the increased number of long-term clinical trials of "All-on-Four" treatment concept is seen. However, to guide clinical trials, it is necessary to evaluate the stresses on different "All-on-Four" designs and the alternative protocols during mastication.

In dentistry, photoelastic analysis, strain-gauge analysis, brittle-lacquer stress analysis, thermographic stress analysis and finite element analysis (FEA) are used to evaluate the stresses arising around the dental implants and supporting tissues[16-18]. FEA is a non-invasive technique, and it can provide an accurate and reliable results under different loading scenarios. The structures to be examined are modelled to simulate anatomical conditions, and a simulated load is then applied and the results analyzed[16-18].

The objective of this study was to evaluate and compare the stresses in the implant and surrounding tissues under the physiological masticatory forces by using 3D FEA in different implant placement designs of the "All-on-Four" concept and the alternative protocols.

Materials and Methods

In the present study, five mathematical models of atrophic mandible containing different implant placement designs were generated. Two mathematical models were designed in "All-on-Four" concept and three of them were modelled based on conventional implant design. Physiological masticatory forces were applied on all models to evaluate the stress quantity and distribution around the implant structure and periodontal tissues by using 3D FEA.

Mathematical Models

In All-on-Four models presented in this study 4 implants were used, and 6 implants were used in other three models of conventional designs. In all models, all the implants were designed to be 4 mm in diameter.

Model A: Four implants were bilaterally placed in canine region vertically and anterior of the mental foramen with a 30-degree angle (All-on-Four concept). All the implants was designed as 13 mm in Model A.

Model B: Four implants were bilaterally placed in canine region vertically and anterior of the mental foramen with a 30-degree angle (All-on-Four concept). The length of anterior and posterior implants was designed 13 and 15 mm, respectively.

Model C: Six implants were bilaterally placed vertically in first premolar, second premolar and first molar regions. The length of implants was designed as 13 mm in first premolar region, 6 mm in second premolar and first molar regions.

Model D: Six implants were bilaterally placed vertically in lateral incisor, first premolar, and first molar regions. The length of implants was designed as 6 mm in first molar region, 13 mm in lateral incisor and first premolar regions.

Model E: Six implants were bilaterally placed vertically in canine, first premolar, and first molar regions. The length of implants was designed as 6 mm in first molar region, 13 mm in canine and first premolar regions.

Modelling Procedures

Cone Beam Computerized Tomography (CBCT) images of a patient with atrophic mandible, which is appropriate for "All-on-Four" implant placement were used for the modelling of the study models. Tomography images were transferred to 3D-Doctor Software (Able Software Corp., Lexington, MA, USA). Compact and spongious bone tissues were segmented based on the Hounsfield units by interactive segmentation method. 3D bone tissue modelling was completed by using 3D Complex Render Method. All the implant and abutment parts used in the presented study were scanned by the Activity 880 digital scanner (Smart Optics Sensortechnik GmbH, Bochum, Germany). After these procedures, 3D digital modelling software (Rhinoceros 4.0 software, McNeel, Seattle, WA, USA) was used for completion of the mathematical modelling. A partial acrylic denture was modelled for loading process of the masticatory force for all models.

Finite Element Analysis

Mathematical finite element models were transferred to Algor Fempro Software (ALGOR, Inc. 150 Beta Drive Pittsburgh, PA 15238-2932 USA) in .stl format to analyse stress distribution. All structures used in this study were considered to be homogenous, linearly elastic and isotropic. Young's modulus and Poisson ratios for the dental tissues and implant materials are shown in Table 1[19].

Table 1. Mechanical properties of dental tissues and materials

Material	Young Modulus (GPa)	Poisson Ratio (ν)
Cortical Bone	13.7	0.30
Spongious Bone (D2 and D3)	1.37	0.30
Titanium Implant and Abutment	110	0.35
Polymethyl methacrylate	3	0.35

Meshes were mostly formed by 8 nodded (brick type) elements. The number of nodes and elements for all models were shown in Table 2. All the models used in the study, degrees of freedom in the inferior and posterior border of the cortical bone were constrained.

Table 2. The number of nodes and elements

	Model A	Model B	Model C	Model D	Model E
Nodes	216323	217043	243539	250774	251495
Elements	1036907	1036638	1173133	1213583	1217692

The force vectors applied to the constrained models were generated by considering the attachment points of all muscles connected to the lower jaw. The value of the masticatory force was calculated by the average contractile forces of all muscles (approximately 100 N). Thus, a more realistic force values and distribution were obtained on the implants and prosthesis.

Assessment of Analysis Results

For all models, minimum principle stresses (compressive stresses) and maximum principle stresses (tensile stresses) were calculated and evaluated numerically on cortical and spongious bone surfaces. However, von Mises stress values were preferred for implant and abutment surfaces. Additionally, to assess the stresses more accurately, a colour scale was used to visualize the stress pattern and distribution for each model.

Results

Stress Distribution on Alveolar Bone Structures

In cortical bone, minimum principal stresses indicating compressive loading, were most commonly observed in Model A and B, where the All-on-Four concept was designed, followed by Model C (Figure 1, Table 3). The maximum principal stresses providing information about tensile stress were mostly concentrated in Model A and B (Figure 2, Table 3). In spongious bone tissue, both minimum and maximum principal stress values were mostly observed in the models of All-on-Four concept compared to the conventional designs (Figure 3 and 4, Table 3). The well-balanced force and stress distribution in bone tissue were observed in Model E. Additionally, in conventional designs, Model C had the more unbalanced force distribution.

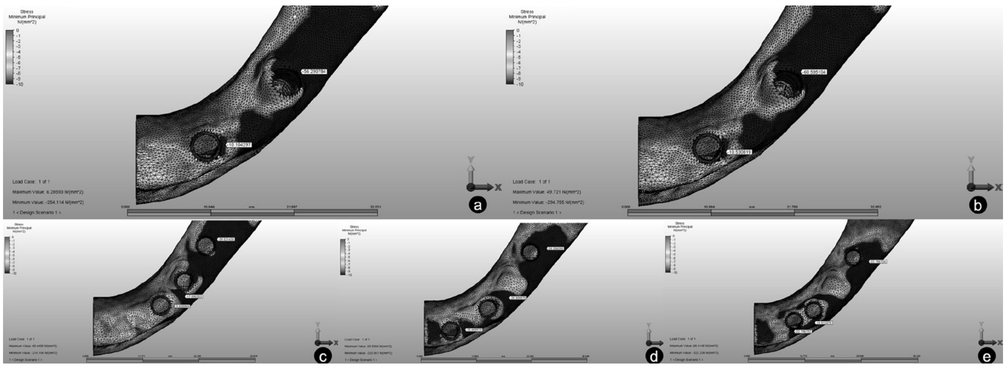

Figure 1. Minimum principal stresses on cortical bone tissue for All-on-four (a: Model A and b: Model B) and conventional designs (c: Model C, d: Model D and e: Model E).

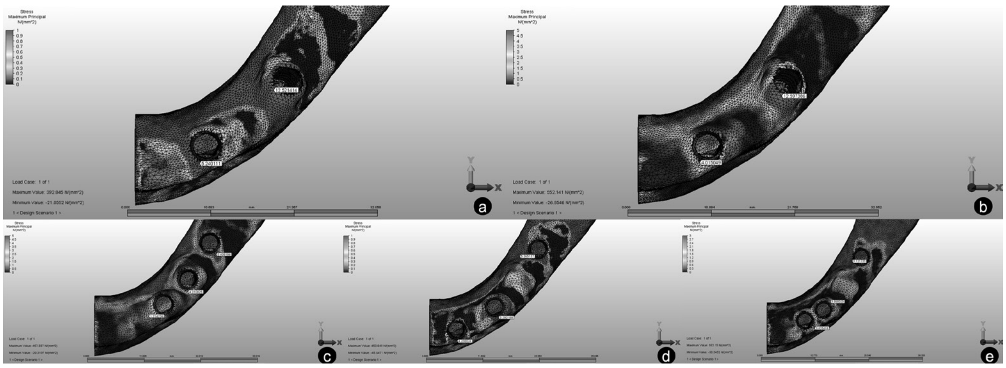

Figure 2. Maximum principal stresses on cortical bone tissue for All-on-four (a: Model A and b: Model B) and conventional designs (c: Model C, d: Model D and e: Model E).

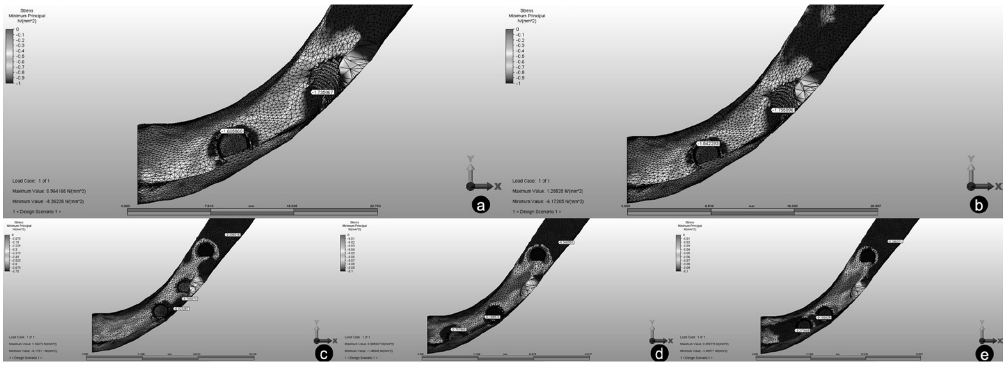

Figure 3. Minimum principal stresses on spongious bone tissue for All-on-four (a: Model A and b: Model B) and conventional designs (c: Model C, d: Model D and e: Model E).

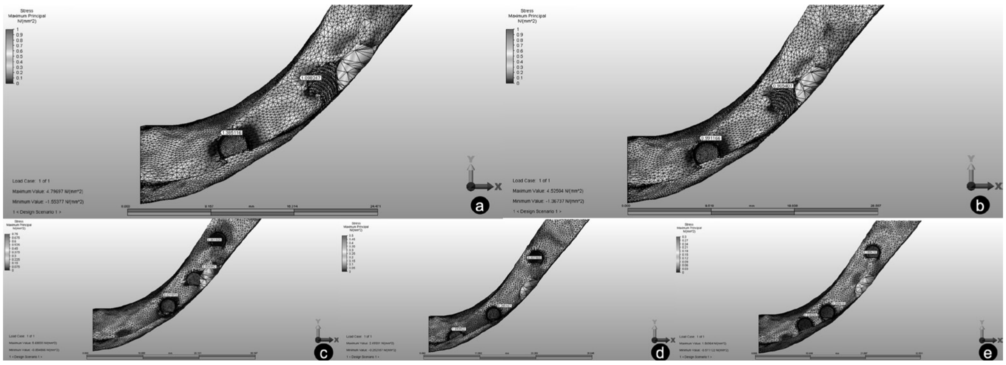

Figure 4. Maximum principal stresses on spongious bone tissue for All-on-four (a: Model A and b: Model B) and conventional designs (c: Model C, d: Model D and e: Model E).

Table 3: The stress distribution on all groups

	Cortical Bone (P_{min})(N/mm^2=MPa)	Cortical Bone (P_{max})(N/mm^2=MPa)	Spongious Bone (P_{min})(N/mm^2=MPa)	Spongious Bone (P_{max})(N/mm^2=MPa)
Model A	-56.29	12.52	-1.73	1.09
Model B	-60.58	12.59	-1.75	0.90
Model C	-39.52	5.4	-2.23	2.85
Model D	-28.33	5.3	-0.34	0.55
Model E	-22.15	9.12	-0.26	0.18

(P_{min}: Minimum Principal Stresses; P_{max}: Maximum Principle Stresses

Stress Distribution on Implants

Von Mises stress values measured on the implant surfaces were concentrated in the cervical area of all implants regardless of designs. In intergroup comparison, it was found that the implants in the models of All-on-Four concept were most exposed to the stresses. In distal implant surfaces, All-on-Four concept had 9 times more stress values than conventional designs. Similarly, stress concentrations were observed to a greater extent in distal implants, regardless of the all groups (Figure 5).

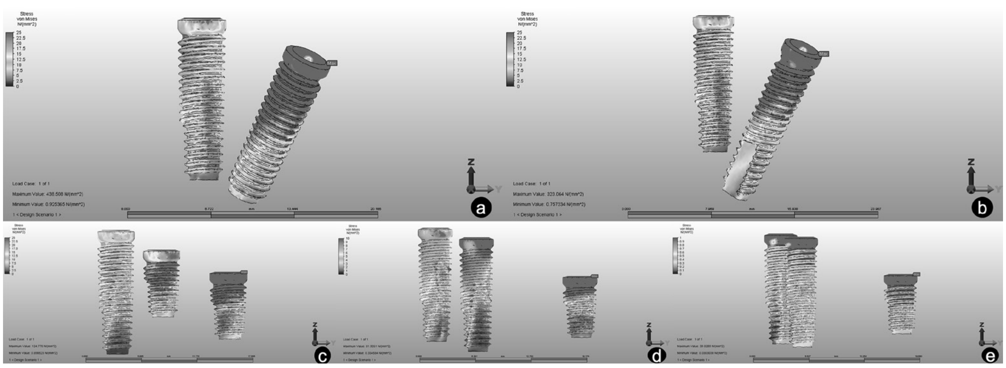

Figure 5. Von Mises stresses on implant surfaces for All-on-four (a: Model A and b: Model B) and conventional designs (c: Model C, d: Model D and e: Model E).

Discussion

The long-term success and survival of implant-supported dentures especially depends on a balanced biomechanical force distribution[20]. In implant dentistry, the stress concentration around the implant can cause bone resorption[21]. Therefore, accurate assessment of the amount of stresses and distribution on the implant and surrounding bone tissue is important for designing implant placement and treatment planning[22].

The limited distance between the mandibular canal and the upper outer border of the alveolar bone in atrophic mandible restrains the long implant placement. All-on-Four technique allows the use of long implants with distal-inclined implant placement[14,15]. It has been reported that tilted single implants may cause increased stress in the marginal bone in functional loadings. However, if these types of implants belong to an implant supported prosthesis, this failure is reduced due to balanced force distribution[23]. It is necessary to examine the stress distributions in "All-on-Four" technique as this approach is more recent than conventional implant designs. Therefore, the aim of this study was to evaluate the stress distribution on the implant and surrounding bone in "All-on-Four" and alternative conventional designs by using 3D FEA.

In dentistry, FEA analysis is used to evaluate the stress and strains occurring around the biological tissues and dental materials. In the analysis, various types of stresses (minimum and maximum principal and von Mises stresses) demonstrate stress amount and distribution[22]. While minimum and maximum principle stresses provide detailed data about compressive and tensile strains respectively[16,24,25], von Mises stresses are mostly used for dental materials or implant surfaces[22]. In the present study, while minimum and maximum principal stresses were preferred for the stress evaluation of the cortical and spongious bone, von Mises stress values were used for implant surfaces. Additionally, the data that were obtained in the study were interpreted using visual, quantitative and qualitative comparisons instead of statistical analysis, which is not applicable to FEM analysis[26]. In a previous study[27] researchers applied a 100 N force at a 75 degree inclined from the occlusal surface in the premolar-molar region to form the chewing stresses. In our study, instead of applying linear force in order to provide more realistic results, all masticatory muscles attached to the mandible were simulated. The contractile forces of the muscles as the force vector and the average contractile forces in the literature are taken as reference. Thus, it is thought that stresses can be evaluated as more appropriate to reality.

Although short implants are the first option in patients with inadequate alveolar bone in the mandible, different results have been reported in the literature between the success rates of short implants[28-30]. Naert *et al.*[31] reported that the rate of success in implants shorter than 10 mm was 81.5%, whereas it was 97.2% in implants longer than 10 mm. There are also opinions that short implants function as successfully as long implants in proper clinical conditions. Arlin[32] also observed the success of implant groups with 6-8 mm and 10-16 mm for 2 years and reported success rates were 94.3% for 6 mm implants, 99.3% for 8 mm and 97.4% for 10 mm.

In the literature, many studies showed that the cortical bone surrounding the implant may be subjected to compressive stress[33,34]. In our study, regardless of the study designs, the minimum and maximum principal stresses in the cortical bone were mostly concentrated in the cervical parts of the implants. However, in the spongious bone, both stress types were found to be extremely low compared to the cortical bone tissue.

In a retrospective clinical study about the "All-on-Four" concept[35] 13 implants were lost in 21 of 245 patients. The 10-year success rate was reported as 94.8% while the 5-year success rate was 98.1%. However, in biomechanical studies related tilted implants, it has been reported that stresses may especially increase in cortical bone[36,37]. Similarly in our study; in "All-on-Four" designs, cortical bone stress values were found to be more excessive compared to the short implant designs. However, in the present study, although it is known that the minimum principal stresses are well tolerated by the cortical bone; the spongious bone tissue was exposed to stresses especially in "All-on-Four" designs - the spongious bone was exposed to approximately 7 times more stress than the conventional implant placements.

In implant-supported restorations performed on edentulous cases, masticatory forces most often cause excessive stress on the distal implant and its surrounding bone tissue[27]. In our study, although the number of implants increased, stresses in all models (von Mises stress in implants, minimum and maximum stresses in bone tissue) were concentrated in the distal implant and bone tissue. Horita *et al.*[20] reported that the minimum principal stresses in cortical bone in the conventional implant designs were generally less compared to "All-on-Four" design. In our study, similar results were obtained. In conventional designs, the minimum and maximum principal stresses in both cortical and spongious bone were found to be less than in "All-on-Four" design. It was observed that the most well-balanced force distribution belongs to Model E presented in the conventional implant placement design. Similarly, Özdemir Doğan *et al.*[27] reported that the use of short implant would be more reasonable, although the "All-on-Four" design was found to be a successful and viable.

Conclusions

Within limitations of this study, it was concluded that "All-on-Four" design caused extra destructive stresses in cortical bone, spongious bone and inclined implant surfaces; instead of this approach, the placement of short implants would be more appropriate in severely resorbed mandible. According to the results obtained in this study, the placement of a short implant on the resorbed posterior region and two long implants on the anterior mandible would provide better favourable biomechanical behaviour. However, there is a need for additional long-term clinical studies about "All-on-Four" concept.

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Conflict of Interests: Nothing to declare.

Financial Disclosure Statement: Nothing to declare.

Human Rights Statement: All the procedures on humans were conducted in accordance with the Helsinki Declaration of 1975, as revised 2000. Consent was obtained from the patient/s and approved for the current study by national ethical committee.

Animal Rights Statement: None required.

Received on July 7, 2020.
Revised on July 28, 2020.
Accepted on September 20, 2020.

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