

Correlation between abutment angulation and off-axial stresses on biomechanical behavior of titanium and zirconium implants in the anterior maxilla: A three-dimensional finite element analysis study

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Abstract

Aim: The aim of the present study was to evaluate the stress distribution around the titanium and zirconium implant with different abutment angulations in the anterior maxilla to off-axial load.

Setting and Design: *In vitro* – Comparative study.

Materials and Methods: Two models of titanium and zirconium implants (4 mm × 13 mm) and abutment with at 0°, 15°, 25° angulations were modeled to replace missing right central incisor using three-dimensional finite element analysis. A bite force of 178 N was applied on the lingual fossa of crowns at an angle of 120° off-axial to the long axis of implant.

Statistical Analysis Used: Nil.

Results: Von Mises stresses observed are as follows: (1) at the implant–bone interface Ti 0 (8.31 MPa), Zr 0 (8.57 MPa), Ti 15 (83.59 MPa), Zr 15 (98.07 MPa), Ti 25 (197.8 MPa), and Zr 25 (265.77 MPa); (2) at the implant–abutment interface Ti 0 (5.90 MPa), Zr 0 (6.45 MPa), Ti 15 (19.13 MPa), Zr 15 (19.32 MPa), Ti 25 (38.65 MPa), and Zr 25 (38.26 MPa); and (3) within superstructure Ti 0 (3.11 MPa), Zr 0 (5.02 MPa), Ti 15 (6.17 MPa), Zr 15 (5.02 MPa), Ti 25 (8.15 MPa), and Zr 25 (6.131 MPa).

Conclusion: Stress behavior of titanium and zirconium implant with tested abutment angulation at implant–abutment interface and within the superstructure was similar, except at implant–bone interface.

Keywords: Anterior maxilla, dental implant, esthetics, implant abutments, stress, titanium, zirconium

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INTRODUCTION


Dental implants are most commonly used for rehabilitation of the partially or completely edentulous situations.^[1-5] In the esthetically demanding anterior maxillary regions,

restoring missing tooth with an implant-supported crown is a major challenge to a clinician as loss of teeth in this region results in resorption of alveolar bone from the

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labial aspect, leaving a palatally positioned alveolar ridge which compromises positioning of implant and final esthetic outcome of prosthesis.^[6,7] Dental implants made up of commercially pure titanium are commonly used because of its well-documented biocompatibility and mechanical proprieties. Although the various modifications in the fabrication and design of metal abutments were made, there is still disadvantage of metallic components showing through when such abutments are used. To improve the dental and gingival esthetics, various newer ceramic materials were used for fabrication of implants and abutments. Zirconium dioxide has been used recently for implants and abutments because of its mechanical and esthetic properties as zirconia is radiopaque and clearly visible on radiographs and its ivory color is similar to that of natural tooth, rendering it extremely useful in esthetically critical areas of the mouth. Biocompatibility of zirconia as a dental implant has been determined by several investigations, but the behavior upon loading is unclear.^[8-12] Pre or customized angled abutments are often necessary to compensate for such situations, rather than straight abutments with different angulations.^[13] The direction of force and biomechanical factors plays a major role in the success of implant treatment. An off-axial force most common during normal mastication would appear to induce more stress than does axial force. Moreover, the placement of dental implants would be more likely to produce an unfavorable off-axis load in the case of several palatal resorption of the alveolar ridge, following tooth extraction than in the case of a ridge without resorption.^[14] Numerous studies have been conducted about the behavior of implants to the stresses; fewer such studies have been related to the premaxillary region. In cases where esthetics requires tooth overlap in the anterior region, off-axis loading of the implant is usually unavoidable.^[14] The bone quality in the premaxillary region is also typical not as good as that in the mandible. The application of load on crown or implant results in the production of different bending moments; therefore, a more detailed premaxillary finite element analysis (FEA) model with an implant and superstructure is necessary. However, there is a correlation between the abutment angulation and off-axial stresses on biomechanical behavior of titanium and zirconium implants in the anterior maxilla. Earlier studies were attempted to analyze stresses in the cortical bone and cancellous bone surrounding implant site. None of the attempts were made to analyze stresses at implant–bone interface, implant–abutment interface, and within the superstructure. Hence, this study was conducted to analyze the correlation between abutment angulation and off-axial stresses on biomechanical behavior

of titanium and zirconium implants.^[5,9,11-13,15-20] The purpose of the present study is (1) to evaluate the stress distribution around the titanium implant with porcelain fused to titanium superstructure at implant–bone interface, implant–abutment interface, and within superstructure and zirconium implant with zirconia superstructure at implant–bone interface, implant–abutment interface, and within the superstructure and (2) to compare stresses of titanium and zirconium implant at implant–bone interface, within superstructure, and at implant–abutment interface with 0°, 15°, and 25° abutment angulations.

MATERIALS AND METHODS

The study was approved by institutional review board, ref no.: MDC_T_D128805001. A model of a maxillary anterior segment to replace missing right central incisor region featuring an implant and its superstructure was constructed using computer-aided design software (Catia Version 5, Dassault System, France) [Figure 1]. Anterior maxillary D3 bone (Type III) was modeled using computed tomographic images of the human maxilla. A simulated two models of titanium and zirconium implant (4 mm × 13 mm) with 0°, 15°, and 25° abutment angulations were used for this study. Titanium and zirconium implants with their superstructure were placed into the right central incisor region with 0°, 15°, and 25° abutment angulations. Thus, the maxillary bone was assumed to be isotropic, homogenous, and linearly elastic Type III bone, i.e., 2 mm cortical bone surrounding the cancellous bone. The section of bone was traced on a graph paper, and X and Y coordinates of the contouring points were joined to form partial volumes of both cortical and cancellous bones. Later, these sections were extended mesially and distally in Z plane to construct geometric model of bone at every node [Figure 2]. These planes

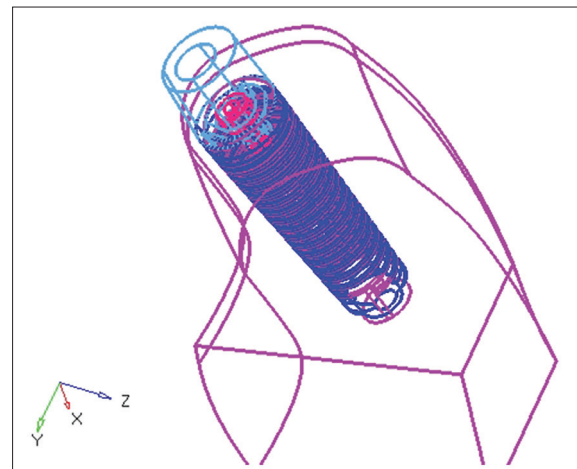


Figure 1: Graphic representation of model with fixture

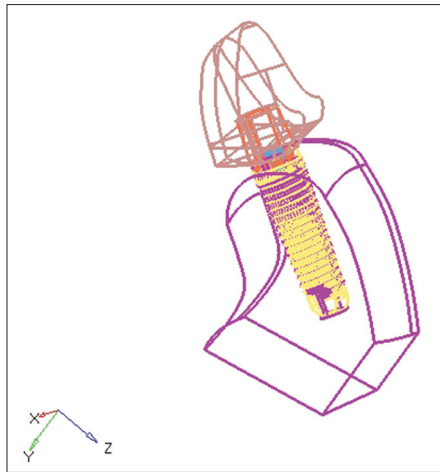


Figure 2: Graphic representation of model with superstructure

Table 1: Material properties of bone, titanium, and zirconium implant along with abutments, superstructures and luting agent (glass ionomer cement)

Material	Young's modulus (Mpa)	Poisson's ratio
Cortical bone	13,700	0.3
Cancellous bone	1,370	0.3
Titanium implant	110,000	0.35
Titanium abutment	110,000	0.35
Zirconium implant	200,000	0.31
Zirconium abutment	200,000	0.31
Titanium core	110,000	0.3
Porcelain veneer	67,700	0.28
Zirconia core	200,000	0.31
Zirconia veneer	80,000	0.265
GIC	54,000	0.30

GIC: Glass ionomer cement

Table 2: Total number of elements and nodes present at the 0°, 15°, and 25° angulated models of titanium and zirconium implants

Model	Elements	Nodes
0	367,777	82,601
15	382,456	85,542
25	391,232	88,341

acted as supports to the model. The supporting planes had to be located far from the areas where stress was to be analyzed to avoid influencing the analysis.

Material properties, elements, and nodes

Table 1 depicts the elastic modulus and Poisson's ratio of the bone (Type III cortical and cancellous bone) titanium and zirconium implants with their superstructures, and Table 2 depicts the number of nodes and elements [Figure 3] used in this study.

Interface conditions

The bone–implant interface was assumed to be perfect, simulating complete osseointegration, and the implant, screw-retained abutment with 0°, 15°, and 25° angulations,

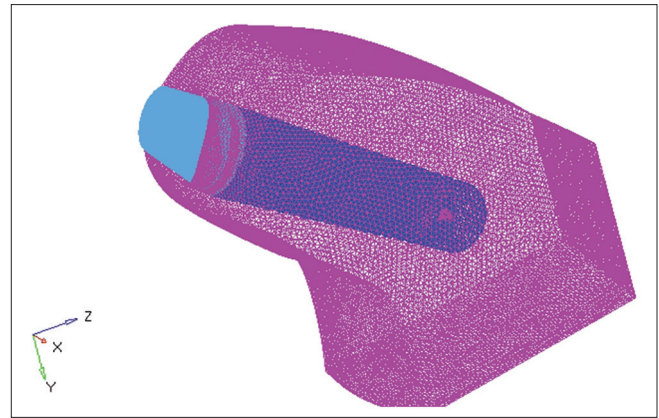


Figure 3: Three-dimensional model denotes elements and nodes

and crowns were assumed to be connected as a single unit [Figure 4].

Loading and boundary conditions

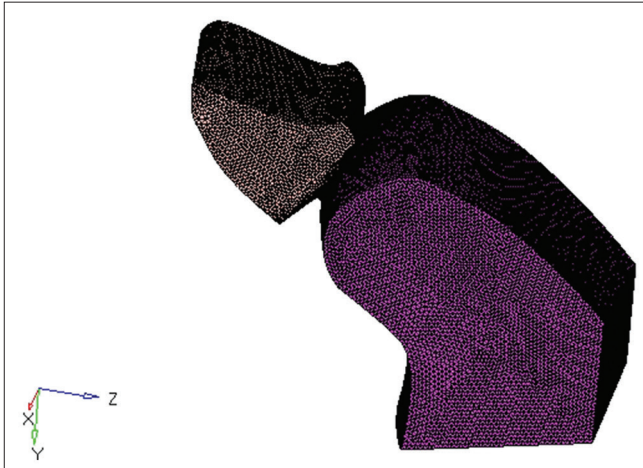
The three-dimensional (3-D) mesh structure was accomplished with the creation of a solid 3-D model using ANSYS software 14.5 (computer software, Canonsburg, Pennsylvania, United States). To create the solid models, tetrahedral solid elements were prepared. A 178 N of load was applied on the lingual fossa of crowns with 0°, 15°, and 25° abutment angulation which was 120° angle to the long axis of the implant. The present study was conducted to evaluate the stress distribution around the titanium and zirconium implant at the implant–bone interface, at the implant–abutment interface, and within the superstructure with 0°, 15°, and 25° abutment angulations.

RESULTS

Angulations had influenced stress behavior of titanium and zirconium implants to off-axial load. In the present study, Von Mises stresses observed were as follows: (1) at the implant–bone interface of titanium and zirconium implant models with 0°, 15°, and 25° abutment angulation Ti 0° (8.31 MPa) [Figure 5], Zr 0° (8.57 MPa) [Figure 5], Ti 15° (83.59 MPa) [Figure 6], Zr 15° (98.07 MPa) [Figure 6], Ti 25° (197.8 MPa) [Figure 7], and Zr 25° (265.77 MPa) [Figure 7]; (2) at the implant–abutment interface Ti 0° (5.90 MPa) [Figure 5], Zr 0° (6.45 MPa) [Figure 5], Ti 15° (19.13 MPa) [Figure 6], Zr 15° (19.32 MPa) [Figure 6], Ti 25° (38.65 MPa) [Figure 7], and Zr 25° (38.26 MPa) [Figure 7]; and (3) within superstructure Ti 0° (3.11 MPa), Zr 0° (5.02 MPa) [Figure 5], Ti 15° (6.17 MPa), Zr 15° (5.02 MPa) [Figure 6], Ti 25° (8.15 MPa), and Zr 25° (6.131 MPa) [Figure 7]. Upon comparison, observed stress values of titanium and zirconium implants with 0°

Table 3: Comparison between model Ti-0 (titanium implant) “0°”, 15°, 25° and model Zr-0 (zirconium implant) “0°”, 15°, and 25° abutment angulations

Stress evaluation sites	0° (178 N force) angulated abutment		15° (178 N force) angulated abutment		25° (178 N force) angulated abutment	
	Titanium implant	Zirconium implant	Titanium implant	Zirconium implant	Titanium implant	Zirconium implant
Implant-bone interface	8.31 MPa	8.57 MPa	83.59 MPa	98.07 MPa	197.8 MPa	265.77 MPa
Implant-abutment interface	5.90 MPa	6.45 MPa	19.13 MPa	19.32 MPa	38.65 MPa	38.26 MPa
Within superstructure	3.11 MPa	5.02 MPa	6.17 MPa	5.02 MPa	8.15 MPa	6.131 MPa

**Figure 4:** Graphic representation completed three-dimensional model

abutment angulation at [Table 3] implant–bone interface, implant–abutment interface, and within the superstructure were identical. In case of 15° and 25° [Table 3], similar stresses were found at implant–abutment interface and within the superstructure, but the highest stress was noted at the neck of the zirconium implant (98.073 MPa) when compared to the titanium implant (83.59 MPa) with 15° abutment angulation while the peak stress was noted near to the neck region of the zirconium implant (265.77 MPa) when compared to the titanium implant (197.811 MPa).

As this is a single-sample study, no statistical analysis can be performed; further study with increase in the sample size is required to establish its hypothesis.

DISCUSSION

Osseointegration is a well-documented phenomenon, and dental implants have proved to be predictable treatment option. The success or failure of a dental implant determined by the influence of stress distribution around the implant and surrounding bone.^[21-23] However, the implant-supported restoration in the anterior segment must feature a natural appearance and a high degree of customization required. For this study, zirconia implants and abutments are used because of its mechanical and esthetic properties. More so, zirconia is preferred over titanium for its shade-matching ability in esthetic zones.

Many studies were conducted in the past comparing these two materials for their property of stress distribution to axial loads in the various regions of maxilla and mandible.^[12,15] Biomechanical behaviour of implant restorations in the completely edentulous situation found to be more favorable when compared to restoration in the partially edentulous situation as implants can be placed at ease, wherein with partially edentulous situations implant positioning is to be straighter especially in the anterior region affecting the functional and esthetic outcomes.^[23-28] In the esthetically demanding maxillary anterior regions, restoring a single missing tooth with an implant-supported crown is a major challenge to the clinician, as loss of teeth in the anterior maxilla results in resorption of alveolar bone from labial aspect, leaving a palatally positioned alveolar ridge.^[29] This can adversely affect implant positioning and compromise the final esthetic result of the restoration; McCarthy *et al.* have suggested bone augmentation as a viable alternative, yet its main disadvantage is that extensive surgical procedures are involved.^[29]

Above said problems with implant supported restoration in the anterior maxillary region can be nullified by usage of angulated abutments as suggested by Clelland *et al.*^[13] and zirconium as a choice of material for implant and abutment from studies of Caglar *et al.*^[12]

Occlusal force applied on implant-supported prosthesis in areas of compromised bone may result in the development of an unfavorable off-axis load. An off-axis force could induce a bending moment and thus exert stress gradients within the implant as well as the adjacent bone than the axial.^[14] So far, axial as well as off-axial forces on zirconium implant have been investigated, and not many studies were performed on zirconium implant with varying abutment angulation supporting zirconium superstructure. Different methods have been used to study the stress/strains in bone and dental implants. For example, photoelasticity provides good qualitative information pertaining to the overall location of stresses but only at the specific location of stresses but only limited quantitative information. Strain gauge measurements provide accurate data regarding strains only at the specific location of the gauge. FEA is capable of

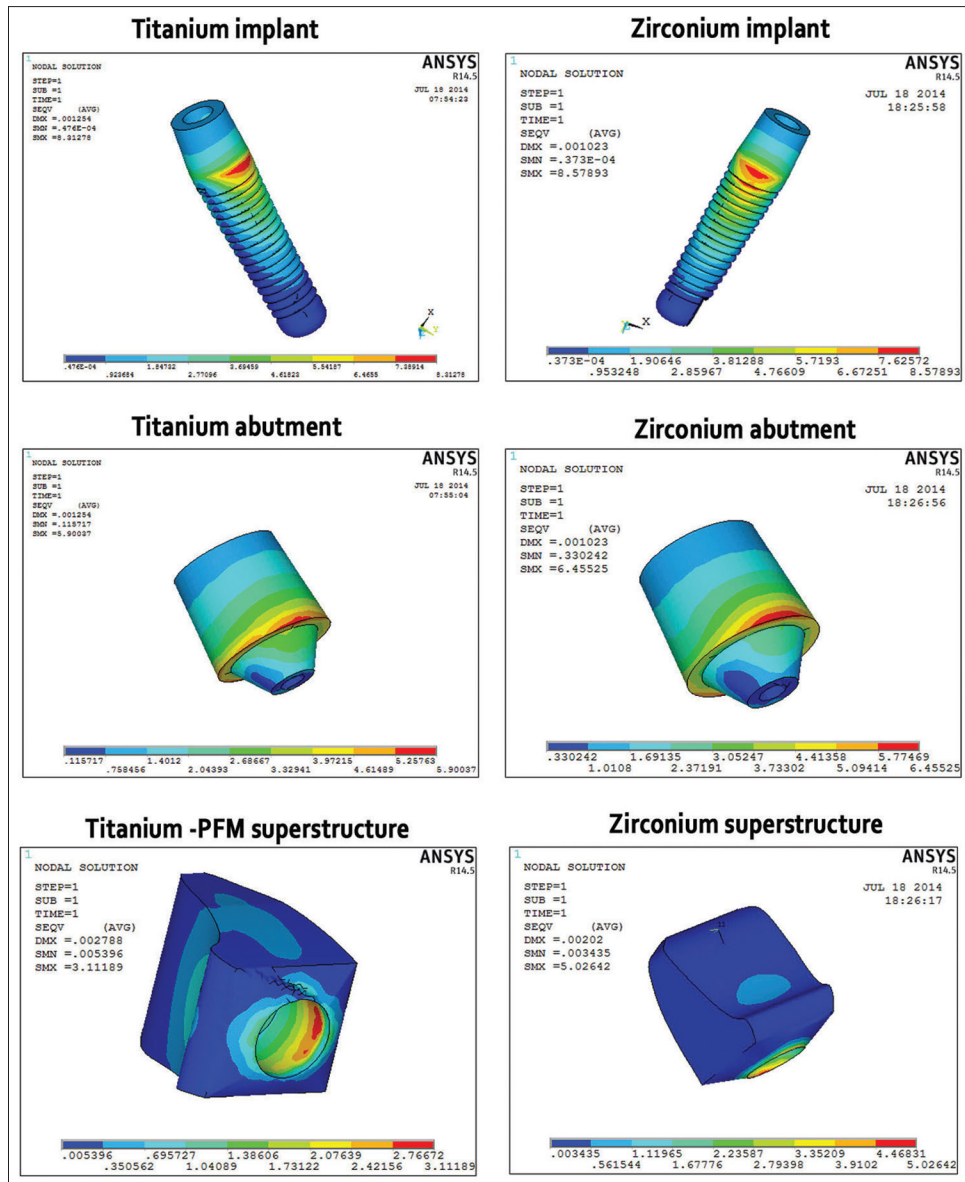


Figure 5: Stress behaviour of titanium and zirconium implants with zero degree abutment angulation at implant bone interface, implant abutment interface and within the superstructure

providing detailed quantitative data at any location within a mathematical model. Assumptions imposed on the FEA models (e.g., regarding model geometry, load magnitude, load direction, and material properties) influence the relative accuracy of the FEA. The use of a fine mesh is also a major factor in the achievement of an accurate model in FEA.^[14]

The ideal method of testing the stress distribution is 3-D FEA. 3-D models were created using 3-D FEA, and it simulates the behavior of 3-D structures as realistically as 3-D models.^[30,31]

This study used 3-D FEA to evaluate the influence of off-axial stresses on biomechanical behaviors of

titanium and zirconium implants with varying abutment angulation (0° , 15° , 25°) in the anterior maxilla to replace the maxillary right central incisor.

In the present study, a maxillary model with missing right central incisor was developed as suggested by Kao *et al.*^[16] Titanium implant, titanium abutment, porcelain fused to metal (PFM) as a superstructure and zirconium implant, zirconium abutment, and zirconia as a superstructure were luted with glass ionomer cement with 0° , 15° and 25° , respectively. Stress distribution between the titanium implant and zirconium implant with various abutment angulations was compared, by applying a bite force of 178 N on the lingual fossa of crown, with 120° angle

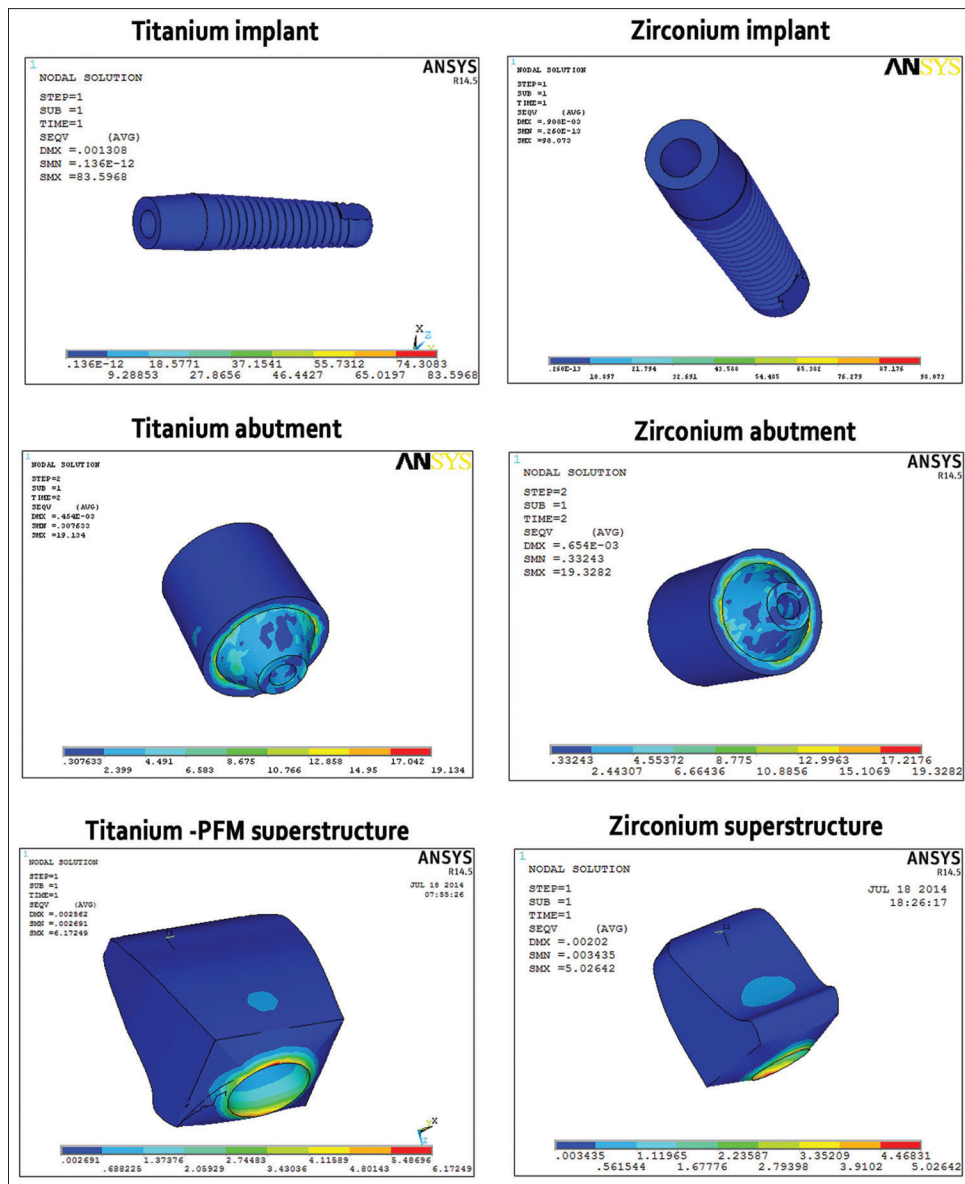


Figure 6: Stress behaviour of titanium and zirconium implants with 15 degree abutment angulation at implant bone interface, implant abutment interface and within the superstructure

to the long axis of the implant using 3-D FEA, and the finite element modeled was created using ANSYS 14.5 software.

The cortical with interposed trabecular bone is considered isotropic, homogenous, linearly elastic body; the cortical layer is taken as 2 mm thick surrounding the cancellous bone and assumed as Type III of bone. The maxilla was approximately 11 mm in width buccoligually, 16 mm in height inferosuperiorly, and 6.5 mm in width mesiodistally for each implant under study. While Young's modulus of cortical and cancellous bone is taken as 1.37×10^4 and 1.37×10^3 , respectively, Poisson's ratio for both is considered 0.3 according to Çağlar *et al.*^[15]

Geometric information of tapered implants of 4 mm diameter, 13 mm length, and 0.75 mm smooth coronal margin with V-shaped thread design^[32,33] and trichannel is the input for Catia software for modeling of implants. Young's modulus of 110,000 MPa and 200,000 MPa is considered for titanium and zirconia implants, respectively. Poisson's ratio of 0.35 for titanium and 0.31 for zirconium is given according to Çağlar *et al.*^[15]

The implants are enclosed by cortical bone in the crestal region and the cancellous bone for the remainder of bone-implant interface. The abutments for the implants are of 3.5 mm height and 4 mm diameter. While the Young's modulus remained the same, Poisson's ratio was

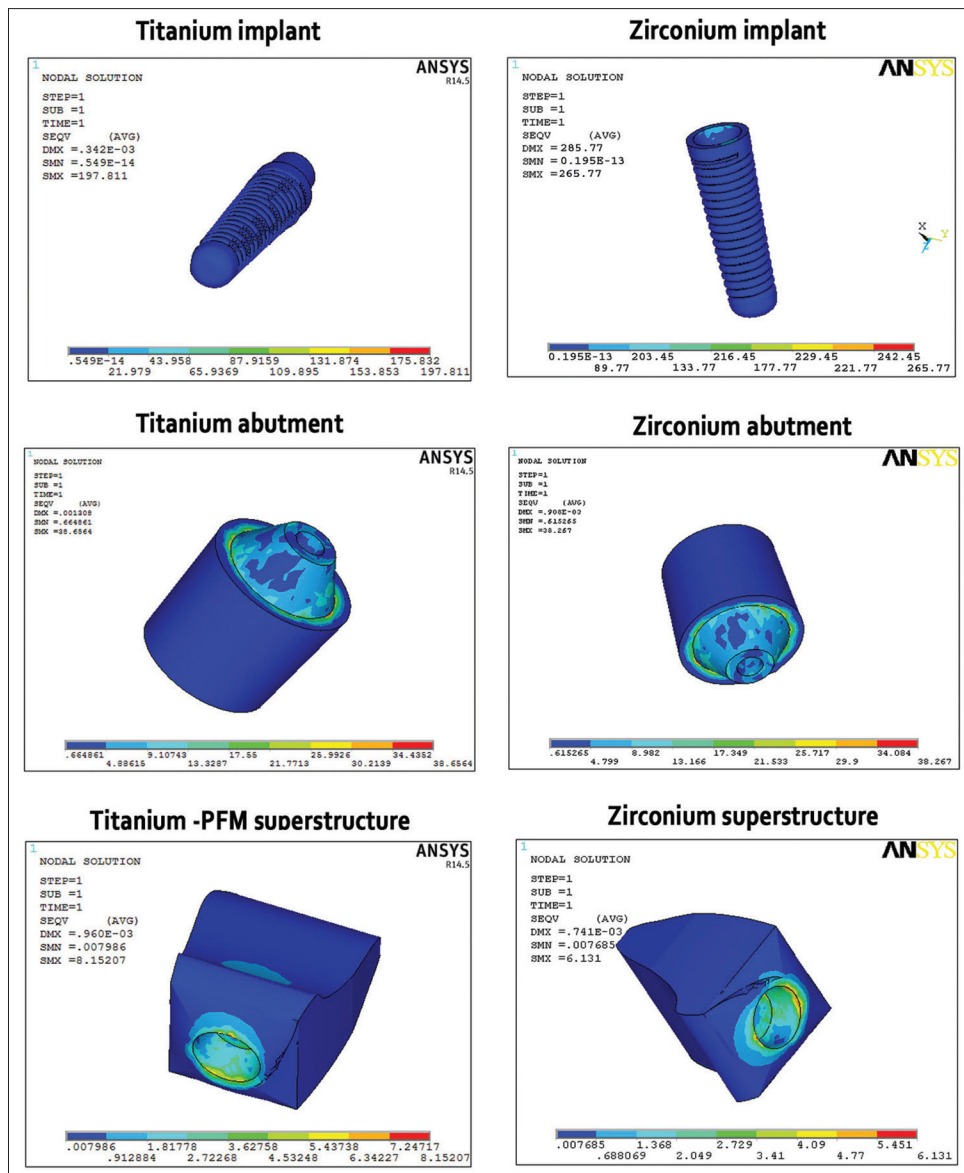


Figure 7: Stress behaviour of titanium and zirconium implants with 25 degree abutment angulation at implant bone interface, implant abutment interface and within the superstructure

0.35 for titanium abutment and 0.31 for zirconia abutment according to Çağlar *et al.*^[15]

In the present study, it was found that similar stresses in titanium and zirconium implants at implant–bone interface, implant–abutment interface, and within the superstructure with 0° abutment angulation.

With respect to implant–bone interface in relation to zirconium implant, stresses were more concentrated more near to neck region than the titanium implants. Stress concentration in neck region with respect to be zirconium implants may be attributed to disparity between elastic modulus of bone and elastic modulus of zirconium, and it is in concurrence with studies conducted by Clelland *et al.*^[13]

The behavior of titanium and zirconium implants with increase in angulation (15° and 25°) of abutments has produced the higher stresses at implant–bone interface, at implant–abutment interface, and within superstructure (PFM and zirconium) to off-axial loads, and in fact, they are well within the physiological limit as maximum tolerable stress values of titanium and zirconium implants are 680 MPa and 953 MPa.^[34]

Incorporating properties of bone (D3) and it remain as one of the drawback of study as mere type 3 bone may not occur in all individuals. Earlier studies were attempted to analyse the stresses at cortical and cancellous bony natures of type 3 density bone (most commonly in the anterior maxillary region). However the observed stress

values of Titanium and Zirconium implants with 0,15, 25 degree abutment angulation of the present study reveals an increase in the stress values at crestal (neck) portion of the implant, when compared to body (middle) and apex of the implant embedded in the bone which were not been evaluated earlier.

Even though the present study has certain limitations to rehabilitate missing teeth using implants, the present study was performed utilizing FEA by incorporating properties of bone (Type III), material properties of implants (titanium and zirconium), and their superstructures (PFM and zirconia) along with luting agent (glass ionomer cement), assuming that implants are 100% osseointegrated which is never found in clinical situation, cortical bone and cancellous bone were considered to be isotropic, linearly elastic, and homogenous and finally the static loads that were applied differed from the dynamic loading encountered during function with different clinical situations. In most of the cases, for dental implants in the anterior maxilla, the use of angled abutments has become an increasing common practice as per patient expectations and clinical conditions. It is widely accepted that increased stress on implants and bone has been associated with the use of angulated abutments. Moreover, axial stresses on implants can be well tolerated as usually they occur with straight abutments; as the angulation abutment increases, there is a strong evidence that forces subjected will become non/off-axial in nature rather than axial. Although positioning of implant and provision of over jet may decrease stresses, they will affect the esthetics and functional outcome of implant restorations in the anterior maxilla.^[17] Cone beam computed tomography-guided implant placement in the anterior maxilla will overcome the possibility of an angulated abutments, yet expensive; hence, its use can be restricted to place multiple implants in the same region.^[35-38] Therefore, further studies can be carried out with improvements made to finite element models with respect to geometry of implants with regard to thread pitch, thread shape, and thread depth, applying dynamic loading conditions depending on the clinical situation.

CONCLUSION

Within the limitations of the study, titanium (Ti-0°) and zirconium (Zr-0°) implants showed similar values of stresses, zirconium (Zr-15°) implant showed higher stresses than titanium (Ti-15°) at the implant–bone interface, at the implant–abutment interface, and within the superstructure, while zirconium (Zr-25°) implant showed peak stresses at implant–bone interface than titanium (Ti-25°) implant and similar stresses were found at the implant–abutment

interface and within superstructure with the application of load of 178 N on the lingual fossa of crown at 120° angle to the long axis of implant (off-axial load).

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Nil.

Conflicts of interest

There are no conflicts of interest.

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