Original Article:

Comparative Evaluation of Stress Distribution Around The Supporting Bone, Abutment, Prosthesis, Using Zirconia And Titanium Implants In The Anterior Maxilla: A Three Dimensional Finite Element Analysis

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Abstract:

Objective: The study was designed to evaluate and compare stress distribution intrans cortical section of bone with titanium implant and zirconia implant model under vertical and oblique forces in anterior maxillary region. ***Materials and Methods:*** A three-dimensional finite element model was designed using ANSYS 13.0 software. Around the prepared implant, bone was constructed with definitive differentiation of outer cortical and inner cancellous. Two straight abutment was constructed, crowns of 9mm mesiodistal width and 11mm cervicoincisal length were created and they were cemented with 50 micron meter cemental layer. The bone-implant interface for both the models was bonded, simulating complete osseointegration and the dental implant, abutment and crown were assumed to be connected as a single unit. Force application was performed in both oblique and vertical conditions using 100 N as a representative masticatory force. For oblique loading, a force of 100 N was applied at 45° from the vertical axis. Von Mises stress analysis was evaluated. ***Results:*** The results of the study showed cortical stress in the Titanium and Zirconia model under oblique forces were 81.317 MPa and 78.405 MPa, respectively. Cortical stress in the titanium and zirconia implant model under vertical forces was 46.161 MPa and 46.097 MPa, respectively. ***Conclusion:*** Results from this study showed the zirconia implant model led to relative decrease in von Mises stress in trans cortical section of bone compared to titanium under vertical and oblique forces in anterior maxillary region.

Keywords- FEA; Implant Titanium; Von mises stress; Zirconia,

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Introduction:

Osseointegrated implants have been used successfully for the rehabilitation of fully and partially edentulous patients. Despite the high success rate of such dental implants, the literature shows a significant incidence of technical complications, mainly related to excessive occlusal force and implant design. [1]

The most common technical failures include loosening and fracture of abutment and prosthetic screw, micro displacement of the abutment-implant connection, and restoration of a single-crown implant. Although these failures generally do not result in the loss of the implant, they pose a significant problem for both the patient and the practitioner and involve additional costs. [2]

In natural teeth, the periodontal ligament serves as an intermediate cushioning element. However,

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osseointegrated dental implants transfer the occlusal load directly to the surrounding bone. This can cause micro bone-implant interface fracture, implant fracture, implant, loosening of implant system components and undesirable bone resorption. Therefore, it is necessary to understand the stress concentration on the bone which is affected by the implant type, implant material, thread end shape, screw pitch, width of thread end, and the height of thread, the diameter of the implant and the angle of inclination of the implant. To understand the stress concentration phenomenon, various stresses and strain distributions for commercial implants were studied.[3]

Bone usually undergoes cyclic loading with consequences other than static loading. Microstress fractures can occur in bones when a sufficient number of repeated load cycles are applied. After the appearance of bone micro-fractures, the micro-damage caused by excessive stress can stimulate osteoclast activity to eliminate the damaged bone. Bone is a relatively fragile material that breaks if it exceeds its elastic limit. If the chewing forces on the implants can create stresses at the implant's bony interface beyond the elastic limit of the bone, fractures can occur. Although theoretical analyzes of the stress distribution around the implants have been performed, stress analysis studies (photoelasticity analyzes and/or finite element FEA analyzes) have mainly focused on the implant material itself. [4] The aim of this three-dimensional (3D) FEA study was to investigate a clinical simulation with a single implant that can cause extreme stress. For the comparative evaluation of von Mises stresses, the stresses caused by titanium and zirconium implants were applied by applying 100 N vertically and obliquely to the anterior maxilla region of bone, implants, abutments and prostheses.

Materials and method:

Implants with abutment were modelled using a computer with specifications. A finite element program, ANSYS version 13 (South of Pittsburgh, USA) was used for the study. ANSYS software offers an unparalleled breadth of solutions across a broad range of disciplines that can accurately address the fluid, structural, electromagnetic and thermal modelling of any product or process. These solutions are built within the ANSYS Workbench user environment – a single framework enabling us to undertake FEA simulations quickly and efficiently at both concept and validation stages of design. The implant was assumed to be placed in the region of anterior part of maxilla. The models were provided in close approximation to the in vivo geometry. The steps involved in this study are as follows:

I. *Finite element modeling*

1. Construction of geometric model
2. Mesh generation
3. Specifying material properties
4. Applying boundary conditions
5. Application of loads

II. *Finite element analysis*

I. Finite element modelling

1. Construction of geometric model

Bone Design

Initially, computerized tomography (CT scan) of a normal human maxilla with no history of an implant placement or any associated pathologies of the maxilla was obtained using a SIEMENS CT Scanner (emotion 6 series). [5] The maxilla was modelled as a sagittal cut of the palatine process of the maxilla, including the residual alveolar process and the palatine bone from the CT scan. The section of bone was traced on the graph paper, x and y coordinates of the contouring points were extracted and joined to form partial volumes of both cortical and cancellous bone that together defined the final geometry. Then the section was extended medially and distally in the z plane. Through this process the CT scan data was converted into a three dimensional solid model of the anterior maxilla region for analysis purpose using Ansys mixed approach.

Implant design

A three-dimensional finite element model of endossoeus implant simulating BIOMET 3iImplant System was generated using Catia V19 (Palm Beach Gardens, Florida). The dimension of the implant designed was 4mm in diameter and 13mm in length. Around the prepared implant, bone was constructed with definitive differentiation of outer cortical and inner cancellous. Thus, constructed model of implant and bone was duplicated to one more model. Two straight abutment was constructed, and a cemental layer of 50 micron meter was constructed for both the models and crown of 9mm mesiodistal width and 11 mm cervicoincisal length for both the models were created. The bone-implant interface for both the models was bonded, simulating complete osseointegration and the dental implant, abutment and crown were assumed to be connected as a single unit.(Figure.1)

2. Mesh generation

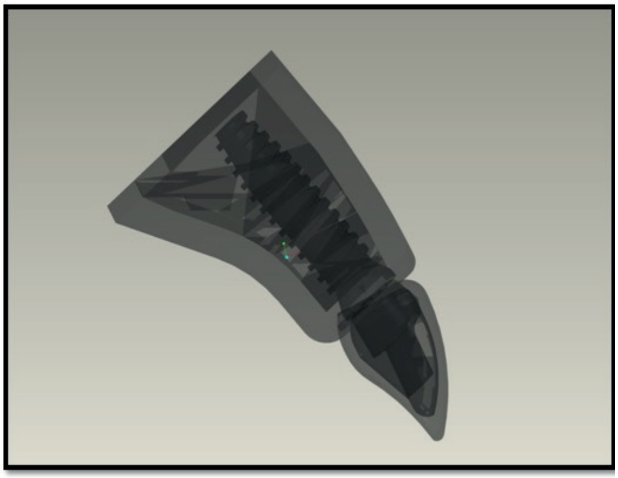

FIGURE 1: SHOWING MODEL OF BONE, IMPLANT, ABUTMENT, CEMENT, COPING AND CROWN

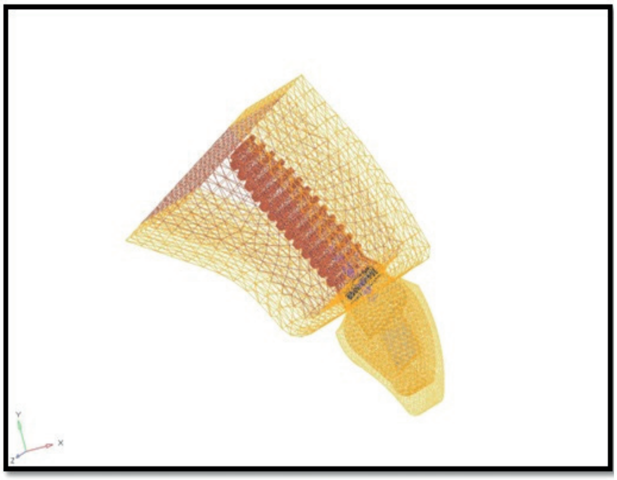

FIGURE 2: SHOWING MESH MODELLING OF BONE, IMPLANT, ABUTMENT, CEMENT COPING, AND CROWN

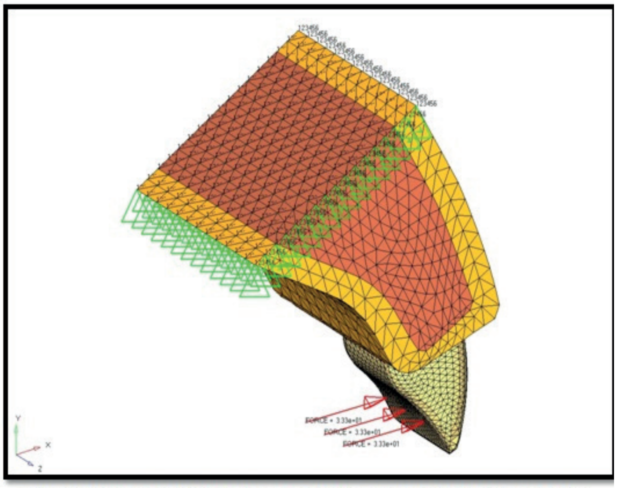

FIGURE 3: SHOWING MESH MODELING OF THE MODEL UNDER HORIZONTAL FORCE

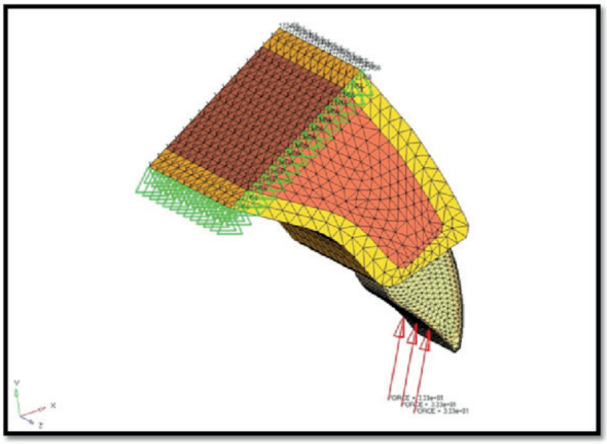

Figure 4: meshing of model of under vertical forces

When the geometry of model was complete, a specialized mesh generation procedure was used to discretize the model.(Figure.2) The three-dimensional finite element model corresponding to the geometric model was meshed using hypermesh software (ANSYS version 14.5 software). The type of meshing is free meshing because the model is not geometrically symmetric. The element size (SOLID 185) was selected according to default settings. The type of element suitable for this particular study was noded tetrahedron element which was assigned four degrees of freedom per node, namely translation in the x, y and z directions. The elements were constructed so that their size aspect ratio would yield reasonable solution accuracy. The coordinates were finally imported into the ANSYS software as key points of the definitive image. (figure 3 to figure 4)

3. Specifying material properties

For the execution and accurate analysis of the program and interpretation of the results, two material properties were utilized i.e. Young’s modulus and Poisson’s ratio. All the materials used in this study were isotropic, homogenous and linearly elastic. The physical properties

of different components used in this study were illustrated (Table 1)

Material	Elastic Modulus (M Pa)	Poisson’s ratio
Cortical Bone	10000	0.30
Cancellous Bone	250	0.30
Titanium Implant	103194	0.35
YPSZ Implant	200000	0.35
Ceramic (Empress)	100000	0.28
Cement (GIC)	7560	0.35

4. Applying boundary conditions

Zero displacement constraints must be placed on boundaries of the model to ensure an equilibrium solution. In this study, a zero displacement constraint was placed on all nodes lying along the external lines of the cortical bone. The final models (Table 2) had a total number of nodes 2,00,000 and elements 1.68,000 for both the models

Table 1: the physical properties of different components used in study

MODEL	NO OF ELEMENTS	NO OF NODES
Titanium	1.68,000	2,00,000
Zirconia	1,68,000	2,00,000

5. Application of loads

The magnitude of the force of 100 N was also within the range of mean values reported in the literature. After applying the static loads on each model, the stress generated in the bone and in the implant was recorded.

II. Finite Element Analysis

These different models were analyzed by Processor i.e. solver and the results were displayed by Post-Processor of the Finite Element Software (Ansys version 13) in the form of colour-coded maps using Von misses Stress Analysis. Von misses stress values are defined as the beginning of deformation for ductile materials. Metallic implant failure occurs when Von misses stress values exceed the yield strength of an implant material. Von misses stresses are most commonly reported in FEA studies to summarize the overall stress state at a point.

The von misses’ stresses were generated in cortical, trabecular and implant regions after application of loads. Therefore, they are important for interpreting the stresses occurring within the implant.

Ethical clearence: Not required. **IN VITRO STUDY FEA STUDY**

Results:

Stress distribution pattern generated in the FE models comes in numerical values and in colour coding. Maximum values of von misses stress is denoted by red colour and minimum value by blue colour. In between the values are represented by bluish green, green, greenish yellow and yellowish red in the ascending order of stress distribution. The two models of different implant materials were studied under a load of 100 N. The colour plots obtained were studied and the maximum von misses stresses were noted and tabulated for each condition. Table 3 & 4 shows the values of Von misses stress in implant, cortical and cancellous bone in a model of TITANIUM Implant and Zirconia implant model, after application of loads of 100N.

Table.2- number of nodes and elements used in study

MODEL	IMPLANT STRESS(M pa)	OVERALL STRESS(M pa)	CORTICAL STRESS(M pa)	CANCELLOUS STRESS(M pa)
TITANIUM IMPLANT MODEL	102.942	320.708	81.317	76.888
ZIRCONIA IMPLANT MODEL	120.968	320.707	78.405	65.607

Table 3: Under oblique forces of 100 *N*

MODELS	IMPLANT STRESS(M pa)	OVERALL STRESS (Mpa)	CORTICAL STRESS (Mpa)	CANCELLOUS STRESS (Mpa)
TITANIUM IMPLANT MODEL	64.08	295.663	46.161	46.161
ZIRCONIA IMPLANT MODEL	51.451	295.662	46.097	46.097

Table 4: Under vertical forces of 100 *N*

Figures 5 and 6 show the stress distribution after application of load in titanium model and Zirconia model under the oblique force of 100 N. Cortical von Mises stresses were found to be maximum in the cervical region of bone measuring 81.317 MPa and 78.405MPa, respectively.

Figures 7 and 8 show the stress distribution after application of load in titanium model and Zirconia model under the vertical force of 100 N. Cortical von Mises stresses were found to be maximum in the cervical region of bone measuring, 46.161 MPa and 46.097 MPa respectively.

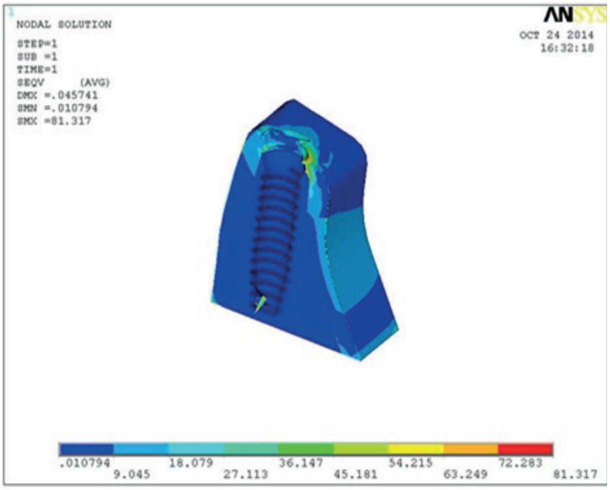

FIGURE 5: STRESS DISTRIBUTION ON CORTICAL BONE HAVING TITANIUM IMPLANT UNDER HORIZONTAL LOADING OF 100Ncm

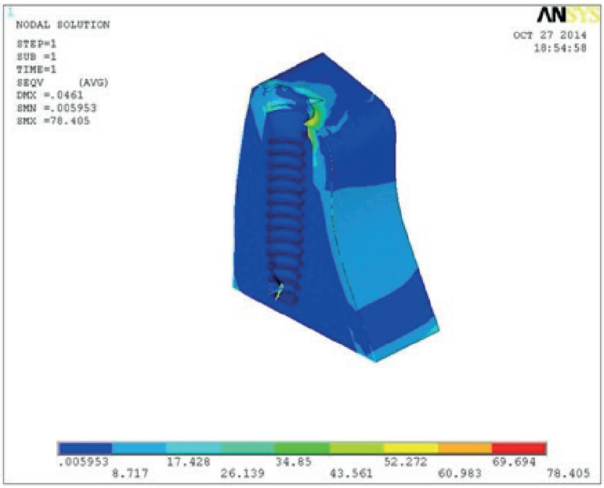

FIGURE 6: STRESS DISTRIBUTION ON CORTICAL BONE IN A MODEL OF ZIRCONIUM UNDER HORIZONTAL FORCE OF 100Ncm

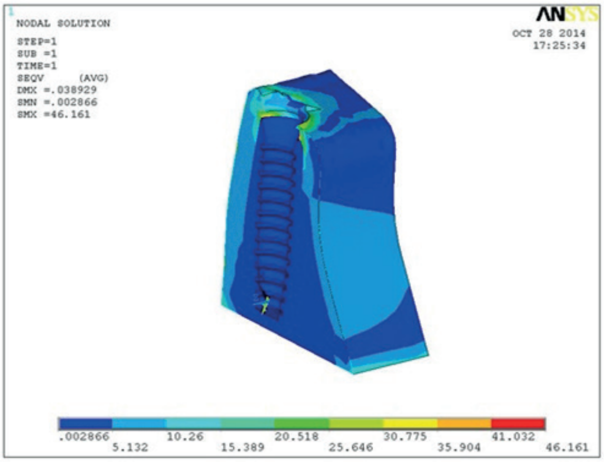

FIGURE 7: STRESS DISTRIBUTION ON CORTICAL BONE IN A MODEL OF TITANIUM UNDER VERTICAL FORCE OF 100Ncm

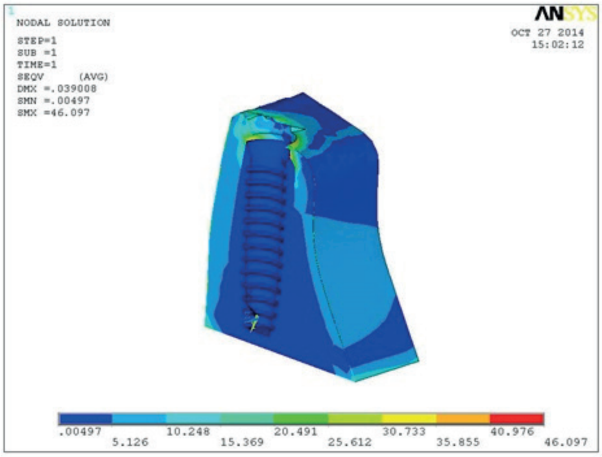

FIGURE 8 : STRESS DISTRIBUTION ON CORTICAL BONE IN A MODEL OF ZIRCONIA IMPLANT UNDER VERICAL FORCE OF 100N

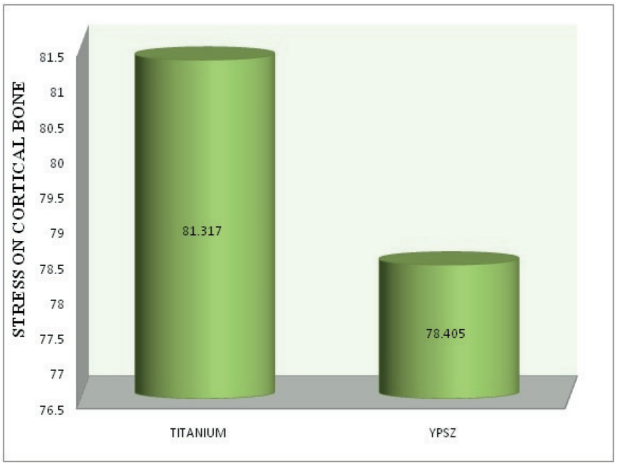

FIGURE.9:comparision of titanium and zirconia implant model with cortical stress on under oblique load of 100n

Figure 9: comparisionof titanium and zirconia implant model with cortical stress on under oblique load of 100 N

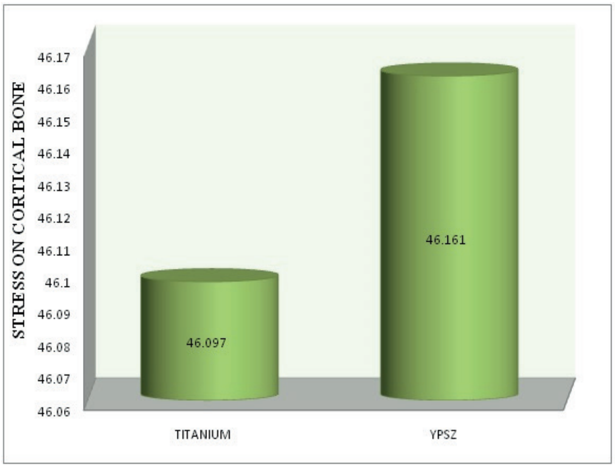

Figure 10: comparision of titanium and zirconia implant model with cortical stress on under vertical load of 100n

The comparison values of von Mises stress on the bone and implant were summarized in Figures 9 and 10 when a load of 100 N was applied to the titanium implant model and Zirconia implant model. This study states that the von Mises stress changed considerably with implant materials. The stress was minimal in zirconia model and increased progressively in titanium models. Furthermore, the stress was highest in the palatal aspect of implant-abutment junction.

Discussion:

Clinical results to date provide encouraging and promising results regarding the use of zirconia as a potential dental implant material. Research has shown that this material integrates into bone and soft tissue, so histologically, titanium peri-implant tissue does not respond differently to the two materials when evaluated under a light microscope. Zirconia has been relatively used as a coating material for oral implants in animal studies. Animal studies have shown that zirconia's osteointegrative ability appears to be comparable to that of titanium. Zirconia ceramics are biocompatible and less likely to form plaque than reduced metals. To date, there is minimal information regarding the biomechanical behavior and wire and body design of zirconia implants [6].

The purpose of this computer model is to compare and evaluate von Mises stresses from titanium and zirconium implants by applying a load of 100 N vertically and indirectly to the bone, implant, abutment and prosthesis in the anterior maxilla. These stresses were analyzed using the FEA technique. The results show the transmission of the simulated chewing forces through the abutment to the implant and its surrounding bone structures in the three-dimensional section of the anterior maxilla. The data of this study showed that with oblique loading, 100 N resulted in 81.317 MPa of von Mises stress in a titanium implant model, while a zirconia implant model resulted in a 2.9% reduction in von Mises shear stress. The effect with vertical loading was smaller than with oblique loading. A crestal von Mises shear stress of 46.161 MPa was observed with the titanium implant model, compared to a 0.064% reduction in von Mises shear stress when using the zirconia implant model.

In a study of 3D FEM s of maxillary incisor with implant made of zirconia and restored with ceramic crown and titanium restored with porcelain fused to metal crown were made. Zirconia implants provided low -distributed stress with a fully bone bonding interface and the contour of stress distribution, similar to the titanium implants. The knowledge and clinical experience of Zirconia implants is very limited and has not been reported to a year. Description According to Chang et al., success rates of 100 consecutive zirconia implants in humans have been published.[7]

According to the literature, the variation in the stress distribution will be small until the Young's modulus is tripled. Zirconia has an elastic modulus of 200000 while titanium has an elastic modulus of 103194, so there is very little difference in stress distribution between zirconia and titanium implants. Zirconia can be used as a viable substitute for titanium because zirconia distributes stress distributions similar to titanium.8

A comparative 3D finite element analysis was done to compare titanium implant and titanium abutment, yattrium-stabilized zirconium dioxide implant and yattrium-stabilized zirconium dioxide abutment, titanium abutment and zirconia implant and one piece zirconia implant by loading forces horizontally and obliquely to calculate von mises and compressive forces. The results showed that the stress transmitted to the cortical bone was lower and well distributed stresses in zirconia implant and even in zirconia abutment delivered stress in cortical bone than in titanium abutment .[9]

Animal studies have shown osseointegration success with zirconia implants, with an average bone-to implant contact greater than 66% 10,11and demonstrated osseointegration properties similar to titanium implants.12

Overall, the Zirconium implant model had the lowest results in both loads. The FEA was performed on the anterior part of the maxilla and concluded that single-piece zirconia implants had lower stresses than titanium implants with titanium or zirconia abutments, except for tensile stresses under oblique loading. The final disagreement is due to differences in study designs. 13 The 1-piece zirconia group (G4) showed lower stress values than the one-piece titanium group (G3). Another FEA study evaluated the stress in the peri-implant bone and implants used to support maxillary overdentures, concluding that 1- piece zirconia may be a potential alternative to conventional titanium implants for this prosthesis. 14 They found that groups with zirconia implants (G2 and G4) showed low stress values, in agreement with another FEA study

Talmazov G, et al concluded in their study that, in general, Zir implants perform better than Ti implants with respect to peri-implant stress distribution. Three different FEA models, healed edentulous site (HS), vertical periodontal defect under compression (RB), and immediate tooth extraction with bone grafting site (EG), mimic common clinical scenarios, suggeste the following conclusion: Due to the stiffness of the material and the inherently higher modulus of elasticity, Zir implants transmit less von Mises stress and induce lower equivalent strain to the peri-implant bone compared to Ti implants. Therefore, the peri-implant bone surrounding Zir implants may be less prone to mechanically induced biologic peri-implant bone resorption. Zir implants may be considered not only for their aesthetic features, but also for the stress modulation properties of the material. 15

The use of 3D modeling in this study for analysis with isotropic properties will increase the clinical relevance, when compared to the 2D modeling and analysis allows infinite thickness to increase clinical relevance and its contact with the bone around it. Therefore, the axial forces that would have been absorbed by the bone around the implant are not taken into account and the maximum strains is greater than in the 3D model. 16

The FE model was used to calculate the von Mises stress. However, since the bone sometimes can be classified as a brittle material,17 the primary load is also used to assess the condition of the dense bone surrounding the implant. Furthermore, the stress distribution of the FE model was presented to compare the biomechanical effects between the titanium implant model and the zirconia model. 16

The analytical part of this study specified that both vertical and oblique loading models should be tested. An angle of 45° and a loading force of 100 N were chosen as it has been shown in other studies to be superior comparative to in vivo mastication.15 To reinforce the oblique condition, an additional model with the vertical loading of 100 N was done. While these forces and angles represent potential forces applied to dental implants, the actual force vector may vary from person to person.16

Limitations

Although FEM is an accurate and precise numerical method for structural analysis, this study has certain limitations such as the dissimilarity of FEM to oral conditions. The implant is assumed to be 100% osseointegrated, which is never found in clinical situation. The cortical bone, trabecular bone and the implant were considered to be isotropic and the applied static load differs from the dynamic load experienced during function. As this is an in vitro study several limitations such as tissue resiliency and bone remodelling patterns should be considered and evaluated. Limitations of modeling assumptions also should be considered because certain parameters vary clinically.

Conclusion:

Within the limitations of this study and on the basis of results obtained, it can be concluded that:

- The cortical von Mises stresses in titanium implant model were found to be maximum as compared to zirconia implant model. The stress was concentrated in the cervical region of bone
- The overall stresses in zirconia implant model were found to be maximum as compared to titanium implant model
- The magnitude of stresses decreased as the implant material is changed
- Maximum von Mises stress, compressive, and tensile stresses in cortical bone were lower in

zirconia implant model than in the titanium implant model

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Ethical clearence: Not required. IN VITRO STUDY FEA STUDY

Authors's contribution:

Data gathering and idea owner of this study: Dr. Jayashankar. Dr.Anupama Ardaya, Dr.Ramesh Chowdhary

Study design: ... Dr. Ramesh Chowdhary, Dr. Jayshankar.

Data gathering: .... Dr.Jayashankar

Writing and submitting manuscript: Dr. Ramesh Chowdhary, Dr.Anupama Ardaya

Editing and approval of final draft: . Dr.Anupama Ardaya, Dr. Jayashankar

Conflict of interest- Nil

References:

1. Quaresma SE, Cury PR, Sendyk WR, Sendyk CA finite element analysis of two different dental implants: stress distribution in the prosthesis, abutment, implant, and supporting bone. J Oral Implantol. 2008;34(1):1-6. doi: 10.1563/1548-1336(2008)34[1:AFEAOT]2.0.CO;2
2. Kohal RJ, Papavasiliou G, Kamposiora P, Tripodakis A, StrubJR.Three-dimensionalcomputerizedstressanalysis of commerciallypuretitanium and yttrium-partiallystabilized zirconiaimplants. Int J Prosthodont. 2002;15(2):189-94
3. Chang CL, Chen CS, Yeung TC, Hsu MLBiomechanicaleffect of a zirconia dental implant-crown system: a three-dimensionalfinite element analysis. Int J Oral Maxillofac Implants. 2012 J;27(4):e49-57
4. Papavasiliou G, Kamposiora P, Bayne SC, Felton DA Three dimensionalfiniteelementanalysis of stress-distributionaroundsingletoothimplants as a function of bony support, prosthesistype, and loading during function. J Prosthet Dent. 1996 Dec;76(6):633-40.
5. Sujon, M. K. ., Alam, M. K. ., Rahman, S. A. ., & Mohd Noor, S. N. F. . Third Molar Impactions Prevalence and Pattern Among Adults Using 5923 Digital Orthopantomogram. Bangladesh Journal of Medical Science. 2022; 21(3):717–729. https://doi.org/10.3329/bjms.v21i3.59590V
6. Fernanda HS, Ricardo M, Márcio F, Filipe S , Júlio CMS, Zhang et al,Zirconia surface modifications for implant dentistry. Mater SciEng C Mater Biol Appl. 2019 May; 98: 1294–1305
7. Chang CL, Chen CS, Yeung TC, Hsu ML. Biomechanicaleffect of a zirconia dental implant-crown system: a three-dimensionalfinite element analysis. Int J Oral Maxillofac Implants. 2012 J;27(4):e49-57
8. AritzaB, Mariano HC, Elisa RC, co Jose VRS, Roman AP, Jose MM et al., Influence of the Elastic Modulus on the Osseointegration of Dental Implants. Materials (Basel). 2019 Mar; 12(6): 980.
9. Çaglar A, Bal BT, Karakoca S, Aydın C, Yılmaz H, SarısoyS.Three-dimensionalfiniteelementanalysis of titanium and yttrium-stabilizedzirconiumdioxideabutments and implants. Int J Oral MaxillofacImplants. 2011 Sep-Oct;26(5):961-9.
10. Akagawa Y, Ichikawa Y, Nikai H, Tsuru H. Interface histology of unloaded and early loaded partially stabilized zirconia endosseous implant in initial bone healing. J Prosthet Dent. 1993;69:599–604.
11. Akagawa Y, Hosokawa R, Sato Y, Kamayama K. Comparison between freestanding and tooth-connected partially stabilized zirconia implants after two years' function in monkeys: a clinical and histologic study. J Prosthet Dent. 1998;80:551–558.
12. Gahlert M, Roehling S, Sprecher CM, Kniha H, Milz S, Bormann K. In vivo performance of zirconia and titanium implants: a histomorphometric study in mini pig maxillae. Clin Oral Implants Res. 2012;23:281–286.
13. aglar A, Bal BT, Karakoca S, Aydın C, Yılmaz H, Sarısoy S. Three dimensional finite element analysis of titanium and yttrium-stabilized zirconium dioxide abutments and implants. Int J Oral Maxillofac Implants. 2011;26:961–969
14. Osman RB, Elkhadem AH, Ma S, Swain MV. Titanium versus zirconia implants supporting maxillary overdentures: three-dimensional finite element analysis. Int J Oral Maxillofac Implants. 2013;28:e198–e208.)
15. Talmazov G, Veilleux N, Abdulmajeed A, Bencharit S. Finite element analysis of a one-piece zirconia implant in anterior single tooth implant applications. PLoS One. 2020 Feb 24;15(2):e0229360. doi: 10.1371/journal.pone.0229360. PMID: 32092128; PMCID: PMC7039452.
16. Aradya A, Kumar UK, Chowdhary R. Influence of different abutment diameter of implants on the peri-implant stress in the crestal bone: A Three-dimensional finite element analysis - In vitro study. Indian J Dent Res 2016;27:78-85
17. Shunmugavelu, K. Unilateral zygomaticomaxillary complex fracture. Bangladesh Journal of Medical Science 2018; 17(4), 674. https://doi.org/10.3329/bjms.v17i4.38335