J Indian Prosthodont Soc (July-Sept 2013) 13(3):196–204
DOI 10.1007/s13191-013-0257-7

ORIGINAL ARTICLE

Predicting Peri-implant Stresses Around Titanium and Zirconium Dental Implants—A Finite Element Analysis

Manmohan Choudary Gujjarlapudi · Narayana Venkata Nunna · Sanjay Dutt Manne · Varalakshmi Reddy Sarikonda · Praveen Kumar Madineni · Reddi Narasimha Rao Meruva

Received: 9 January 2012 / Accepted: 13 January 2013 / Published online: 13 March 2013

Abstract Due to anatomical and surgical constrains the implant placement may not be parallel to each other always. Non-parallel implants are subjected to detrimental stresses at implant bone interface. Also depending on type of implant material i.e. titanium or zirconium, stresses tend to vary due to change in physical and mechanical properties. Hence stress analysis at implant bone interface between different parallel and non-parallel implants becomes significant. Evaluation and comparison of stress distribution in the bone around two parallel and non-parallel titanium and zirconium dental implants on axial and non-axial loading supporting three unit fixed prosthesis. Three dimensional finite element models (M1, M2, M3) were made of three differently angulated implants in ANSYS (11.0 Version) software and P4 processor with a speed of 3 GHz and 3 Gb RAM hardware, common for titanium and zirconium implants. Stress around the implants was analyzed on an axial load of 200 N and a non-axial load of 50 N. In both titanium and zirconium implants on axial loading in cortical bone, higher stresses were observed in M3 followed by M2 and M1. On non-axial loading higher stresses were observed in M2, followed by M3 and M1. In both titanium and zirconium implants on axial and non-axial loading in cancellous bone stresses were higher in M3 followed by M2 and M1. Zirconium implants showed lower stresses in cortical bone and higher stresses in cancellous bone compared to titanium implants. Over all Stresses in the bone were more due to titanium implants than zirconium implants. Zirconium implants led to lower peri-implant stresses than titanium implants.

Keywords Finite element analysis · Stress around implants · Implant bone interface · von Mises stress

M. C. Gujjarlapudi (✉) · V. R. Sarikonda · P. K. Madineni
Department of Prosthodontics, MNR Dental College, Sangareddy, India
e-mail: drmanumds@yahoo.com

V. R. Sarikonda
e-mail: varalakshmi.reddy67@gmail.com

P. K. Madineni
e-mail: praveenis@yahoo.com

N. V. Nunna
Department of Prosthodontics, Lenora Institute of Dental Sciences, Rajahmundry, India
e-mail: drnvnmds@gmail.com

S. D. Manne
Department of Prosthodontics, Dr. NTRUHS, Vijayawada, India
e-mail: ms0203ss@gmail.com

R. N. R. Meruva
Department of Prosthodontics, CKS Theja Institute of Dental Sciences and Research, Tirupathi, India
e-mail: drrnrprostho@yahoo.co.in

Introduction

Osseointegrated dental implant revolutionized contemporary clinical dentistry [1]. The material of choice for dental implants is commercially pure titanium due to its well-documented biocompatibility and suitability for loading. This material has been in use since almost about 40 years as implant substrate with good success rate. One possible alternative to titanium is tooth-colored material such as ceramics. Recently, zirconium ceramic material with potential as a dental implant material was introduced. Zirconium possesses good physical properties, such as flexural strength, hardness for determining long-term success [1]. Furthermore, its biocompatibility has been demonstrated in several animal investigations. Hence zirconium may be considered as an alternative to titanium [2].

Biomechanical factors play an important role to prevent undue bone resorption, to which the implants are anchored. They deal with the stresses within and as well around an implant. Bone, a plastic tissue is known to remodel its structure in response to mechanical stress. A minimum amount of positive stress has rewarding effect in physiological bone remodeling. But, excess of stress could lead to osseous micro damage and induce resorptive modeling and structural failure when it exceeds the tolerance limits of bone [3, 4].

The angulation of the implant is one of the most important factors in the management of the stress around the implants. The behavior of bone in peri-implant region is closely related to the direction, magnitude and concentration of stresses transmitted to the implant [5]. Due to the anatomic and surgical constrains the implants may not be parallel to each other [5, 6]. The ultimate removal torques, which depend on healing time, are described by a time-dependent healing function [7]. Application of oblique loading resulted in increase of stiffness in the peri-implant bone [8]. So mode of application of torque, time dependent healing function and implant angulation all effect the stress on implants. Unparallel implants would change direction of stress at the bone implant interface. Therefore the stress analysis at the bone implant interface becomes significant.

The finite element analysis (FEA) offers several advantages, including accurate representation of the complex geometries, easy model modification and representation of the internal state of stress and mechanical quantities [1, 3, 4].

This FEA was being conducted to evaluate and compare stress distribution around parallel and non-parallel dental implants (titanium and zirconium) on axial and non-axial loading, supporting three unit fixed prosthesis.

Materials and Methods

The axial and non-axial loading of parallel and non parallel plain textured and tapered dental implants (titanium and zirconium) supporting three unit fixed prosthesis were studied using three dimensional finite element models created on a workstation computer with configuration of hardware P4 processor with a speed of 3 GHz and 3 Gb RAM. The software used is ANSYS (11.0 Version), ANSYS corporation, USA. Titanium and zirconium implant materials were standardized and medical grade or grade 4 titanium was considered for study. The dimensions of titanium and zirconium implants correspond to implant length 10 mm and diameter 4 mm. Implant design used for the study was as per requirement for application of FEA [1, 3, 9].

Application of Finite Element Analysis

Mandible

It has been observed in numerous investigations that to assess stress distribution around dental implants, it is not necessary to build a finite element model of the entire jaw. Because of its complicated and individually different geometry, the jaw bone was not completely modeled, but idealized by the way of cylindrical section around the implant [9–11]. The mandible was modeled with a height of 24 mm, length of 40 mm and width of 11 mm.

Using this model, it is not possible to determine actual stresses in the bone quantitatively; however, it provides the basis for relative evaluation of the particular implant design.

The bone was modeled as a cancellous core surrounded by a 2 mm thick cortical layer, except in the upper part, where the cortical layer was flattened to obtained 1 mm thickness [3]. For implant longevity it is important to maintain at least 1 mm of bone buccally and lingually at the implant neck [3].

Creation of Finite Element Model

Three models each for titanium and zirconium were created. All the three models represented different situations.

Model-1 (Fig. 1) two parallel implants supporting a fixed prosthesis (M_1).

Model-2 (Fig. 2) two implants bucco-lingually angulated supporting a fixed prosthesis(M_2).

Model-3 (Fig. 3) two implants mesio-distally angulated supporting a fixed prosthesis(M_3).

Angulations

- In model 2 and 3 the implants were angulated by 5 degree to the long axis
- In model -2 the mesial implant was angulated 5 degrees lingually and the distal implant was angulated 5 degrees buccally.

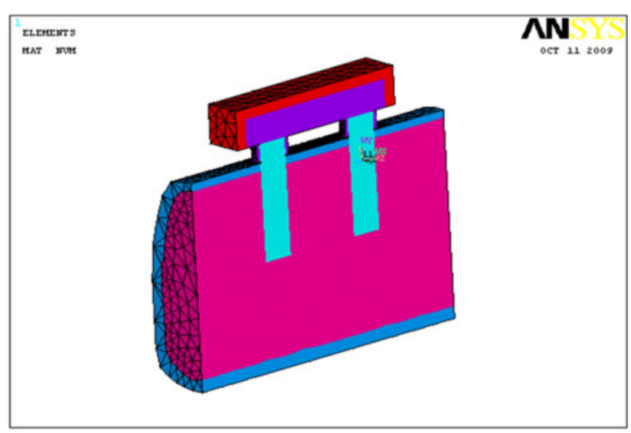

Fig. 1 Sectional plots of model geometries—model-1-buccal view

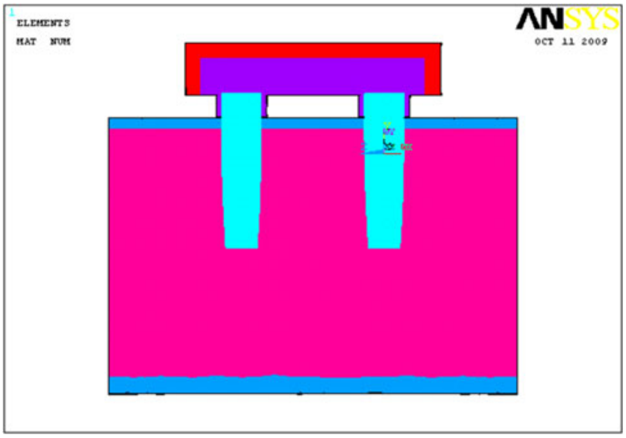

Fig. 2 Sectional plots of model geometries—model-2-buccal view

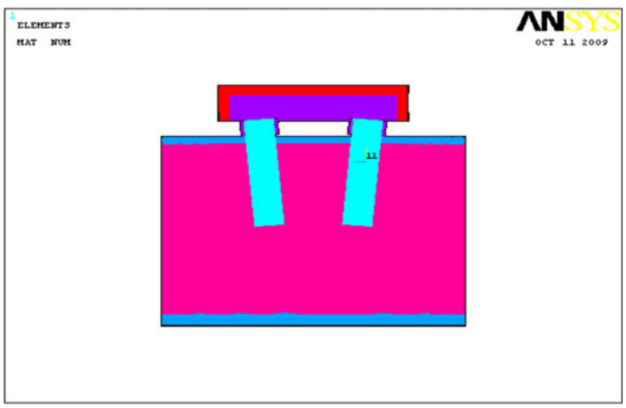

Fig. 3 Sectional plots of model geometries—model-3-buccal view

- In model -3 the mesial implant was angulated 5 degrees mesially and the distal implant was angulated 5 degrees distally.

The angulation of the implant is one of the most important factors in the management of the stress around the implants. The behavior of bone in peri-implant region is closely related to direction, magnitude and concentration of stresses transmitted to the implant [5]. Due to anatomical and surgical constrains the implants may not be parallel to each other [5, 6]. Unparallel implants would change direction of stress at the bone implant interface. Therefore the stress analysis at the bone implant interface becomes significant.

Sectional Plots of Model Geometries

Simulation of Material Properties

All materials used in the models were considered to be isotropic, homogenous and linearly elastic and hence bone-implant interface is evenly defined. The contact between the components was assumed to be uniform and use of a linear solution is applicable.

Along with all the remaining material properties the titanium and zirconium elastic properties were simulated in three similar models each.

The elastic properties were taken from the literature available [4–6]. (Table 1)

Table 1 Elastic properties of materials used

Material	Modules of elasticity (GPa)	Poisson's ratio
Cortical bone	13.7	0.3
Cancellous bone	1.37	0.3
Titanium	117	0.3
Zirconium	210	0.28

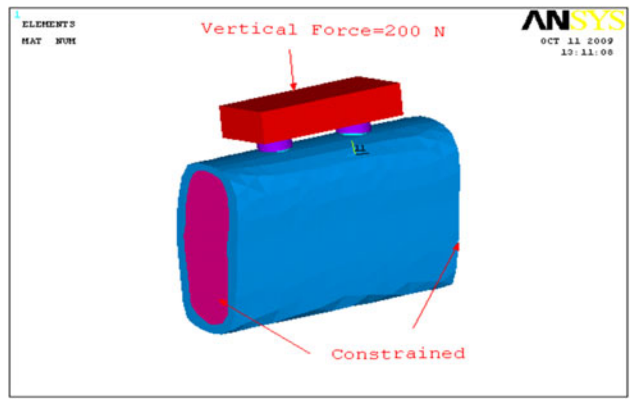

Fig. 4 Assembly after application of boundary conditions—axial loading

Interface Conditions: Figures 4 and 5

To simulate ideal osseointegration the implants along their entire interface were rigidly anchored in the bone model. The same type of contact was provided at all material boundary interface [11].

Constraints and Loads

In this study an axial load of 200 N was applied and a non-axial load of 50 N was applied which is assumed to be 2–4 times less than the axial force [3, 12]. The non-axial loading was applied at an angle of 10° to the line perpendicular to the prosthesis [3, 12]. The load applied is a body load to analyze the concentration of von Mises stresses.

Results

Stress distribution in the cortical bone is exhibited using axial and non-axial loading, enabling comprehensive

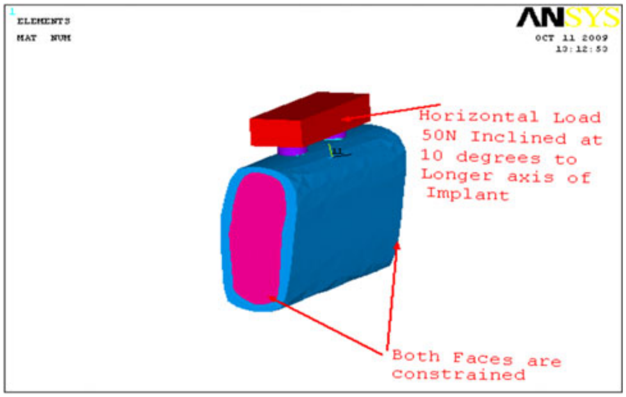

Fig. 5 Assembly after application of boundary conditions—non-axial loading

Table 2 Stress values in different conditions on Ti and Zr implants on axial loading

Stress values in different conditions	Titanium (MPa)		Zirconium (MPa)	
	Cortical	Cancellous	Cortical	Cancellous
M_1	9.887	0.942	8.814	1.037
M_2	12.097	0.992	12.006	1.071
M_3	23.903	1.273	22.444	1.380

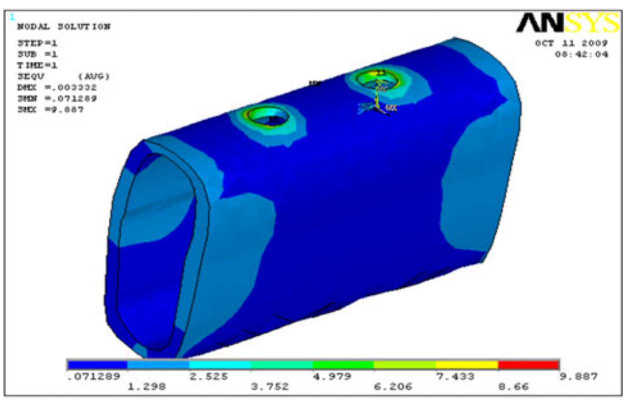

Fig. 6 Stresses on cortical bone-titanium–axial loading-model-1

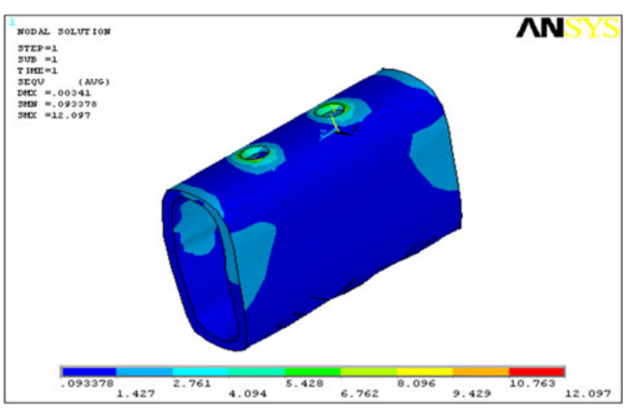

Fig. 7 Stresses on cortical bone-titanium–axial loading-model-2

display of stress concentration in each case. Highest stress was concentrated around the neck both in titanium, zirconium implants. Comparatively little bit less stresses were noted in zirconium implants.

On axial loading in cortical bone more stresses were observed in M_3 followed by M_2 and least in M_1. On non-axial loading more stresses were observed in M_2, followed by M_3 and least in M_1 in both titanium and zirconium models.

In general the stresses in cancellous bone were less when compare to cortical bone both in Ti and Zr implants. But in relative comparison titanium implants shows less stresses in cancellous bone compare to zirconium implants.

On axial and non-axial loading in cancellous bone stresses were more in model-3 followed by model-2 and least in model-1 in both titanium and zirconium models

Table 2 represents the maximum von Mises stress values in MPa under a unit Axial load of 200 N on titanium and zirconium implants in three models on Cortical Bone and Cancellous Bone. (Figs. 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29)

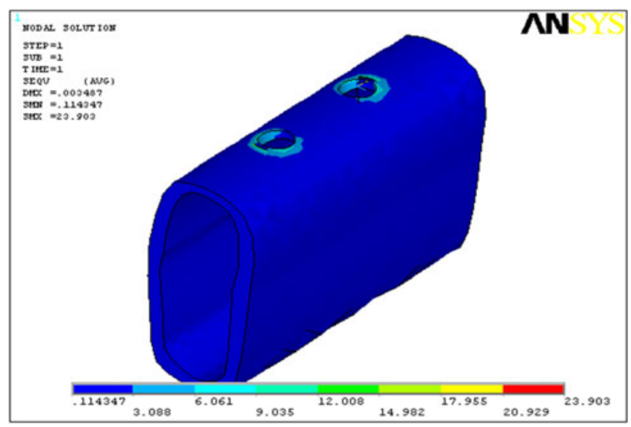

Fig. 8 Stresses on cortical bone-titanium–axial loading-model-3

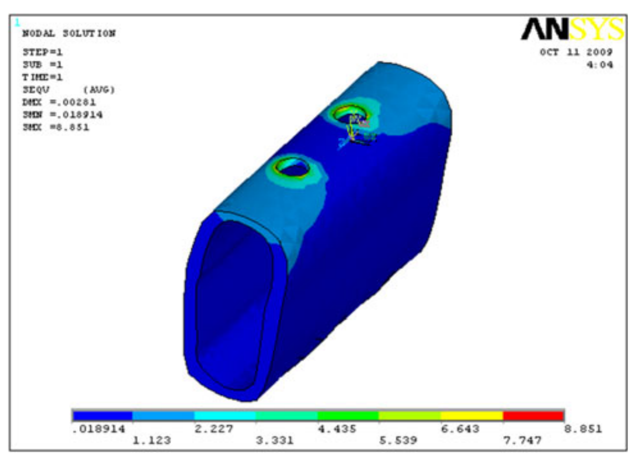

Fig. 9 Stresses on cortical bone-titanium–non-axial loading-model-1

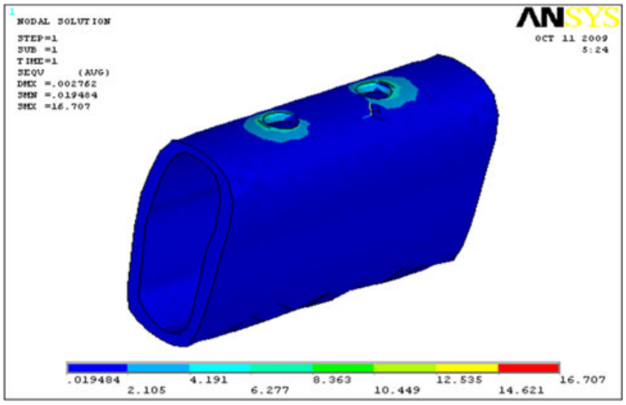

Fig. 10 Stresses on cortical bone-titanium–non-axial loading model-2

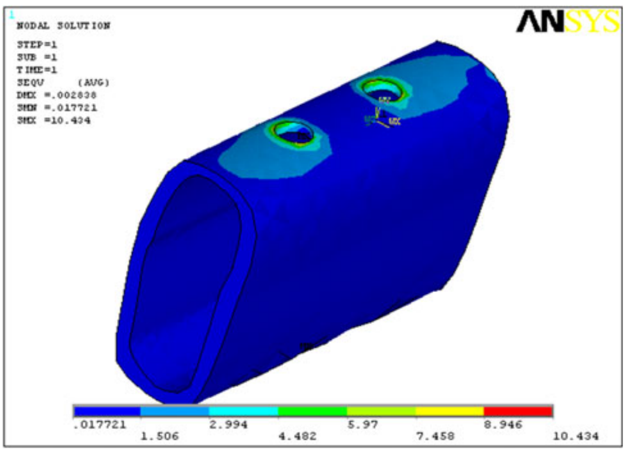

Fig. 11 Stresses on cortical bone-titanium–non-axial loading model-3

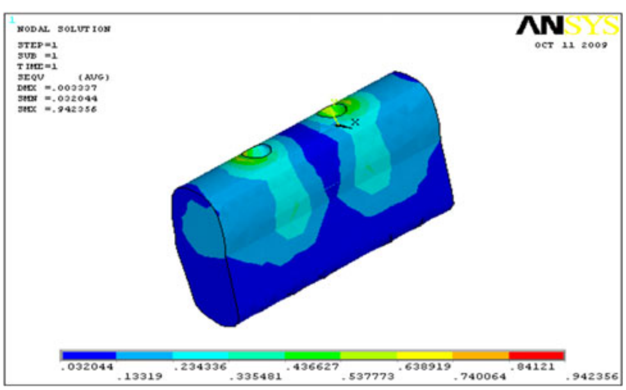

Fig. 12 Stresses on cancellous bone—titanium–axial loading-model-1

Table 3 represents the maximum von Mises stress values in MPa under a unit Non-axial load of 50 N on titanium and zirconium implants in three models on cortical bone and cancellous bone. (Figs. 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29)

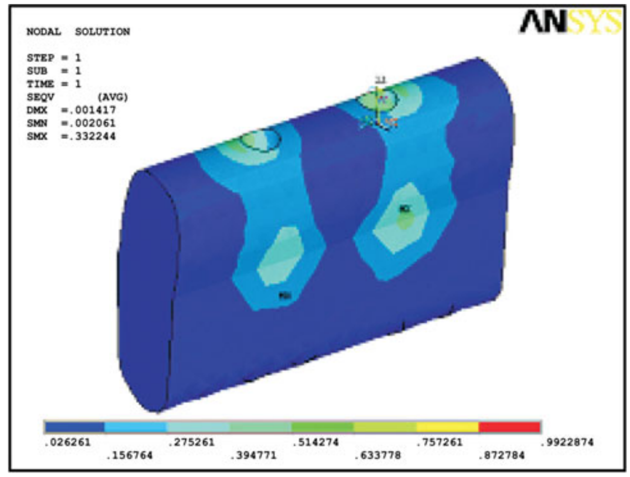

Fig. 13 Stresses on cancellous bone—titanium–axial loading-model-2

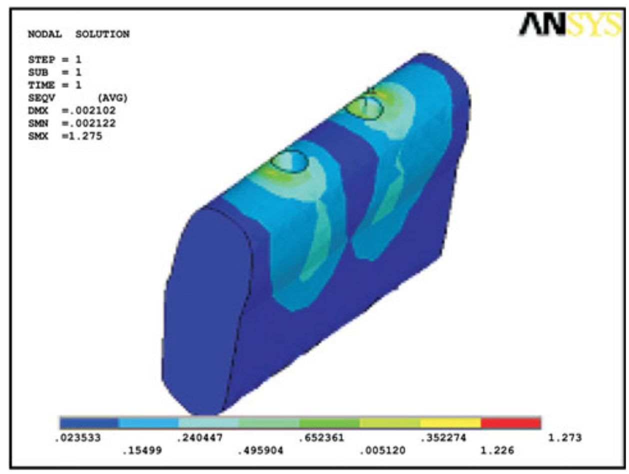

Fig. 14 Stresses on cancellous bone—titanium–axial loading-model-3

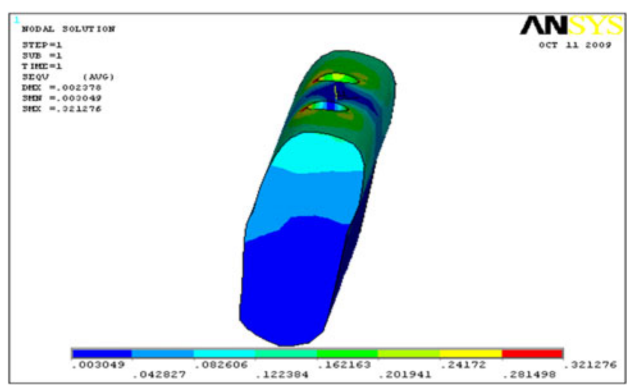

Fig. 15 Stresses on cancellous bone—titanium–non-axial loading-model-1

Discussion

A dental implant serves to accept the physiologic loads or forces into the surrounding tissues. The resultant force per

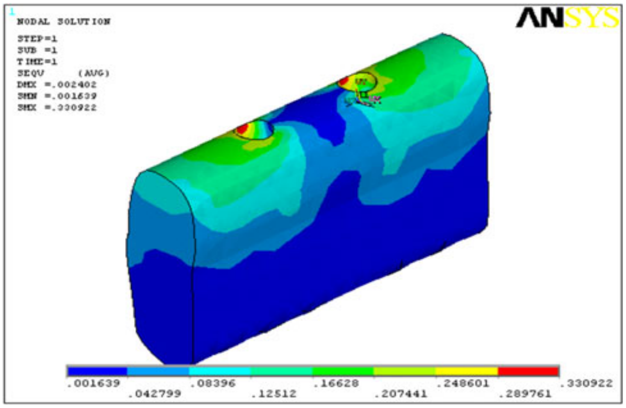

Fig. 16 Stresses on cancellous bone—titanium–non-axial loading-model-2

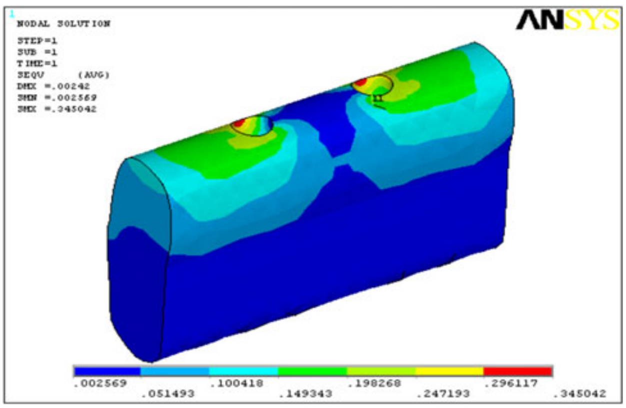

Fig. 17 Stresses on cancellous bone—titanium–non-axial loading-model-3

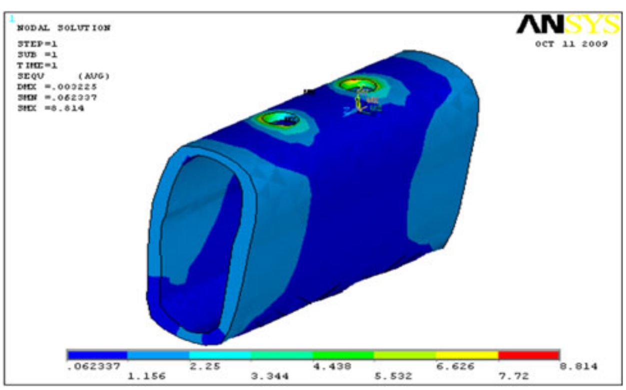

Fig. 18 Stresses on cortical bone zirconium–axial loading-model-1

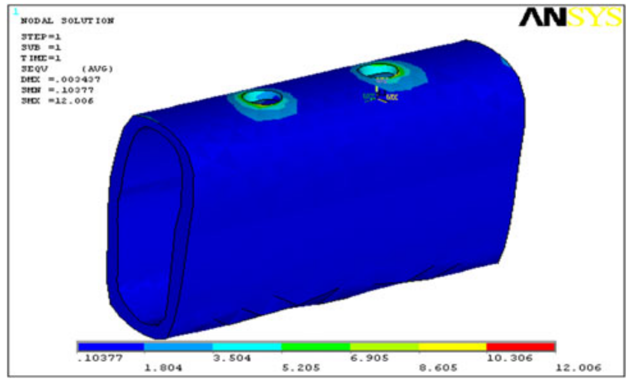

Fig. 19 Stresses on cortical bone zirconium–axial loading-model-2

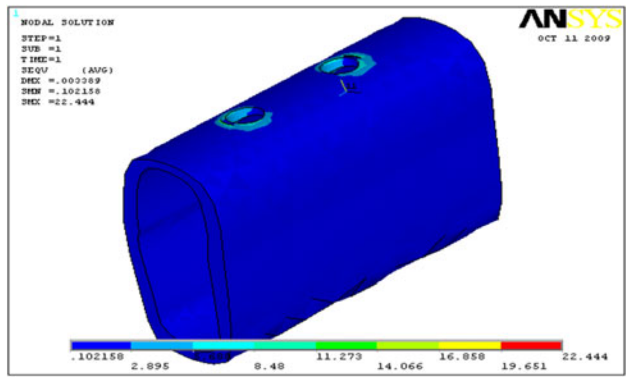

Fig. 20 Stresses on cortical bone zirconium–axial loading-model-3

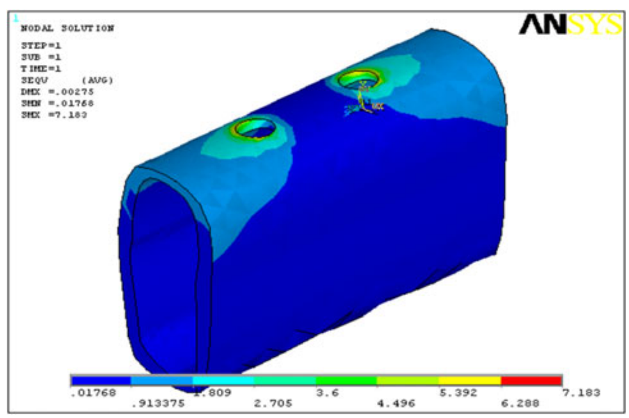

Fig. 21 Stresses on cortical bone zirconium–non-axial loading-model-1

unit area is referred to as stress and bone is known to remodel to applied stress. Therefore, the manner in which implants distribute stress in interfacial tissues is of paramount importance. Analyzing force transfer at the bone-implant interface is an essential step, which determines the success or failure of an implant. Overload can cause bone resorption or fatigue failure of the implant while under load may lead to disuse atrophy and to subsequent bone loss as well [1].

There are various methods advocated for stress analysis. In this study finite element method was adopted. In 1976, Weinstein et al. were the first to use FEA in implant dentistry; subsequently it was applied rapidly in this field [13].

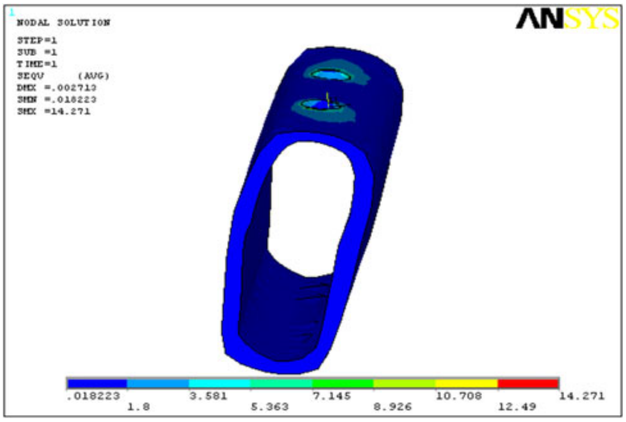

Fig. 22 Stresses on cortical bone zirconium–non-axial loading-model-2

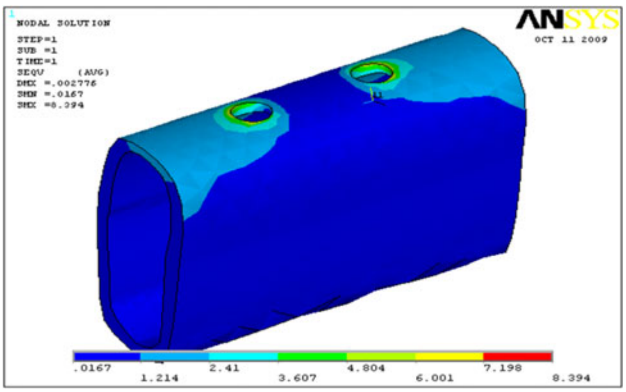

Fig. 23 Stresses on cortical bone zirconium–non-axial loading-model-3

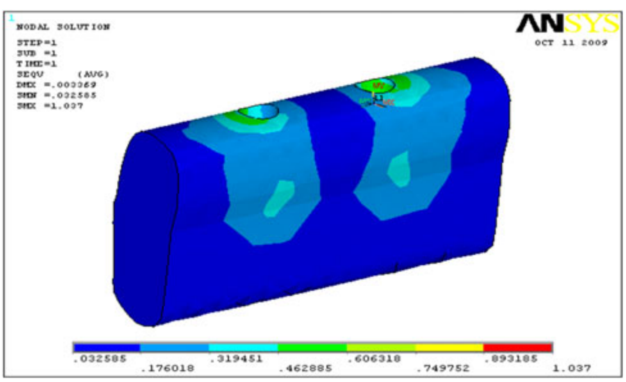

Fig. 24 Stresses on cancellous bone zirconium–axial loading-model-1

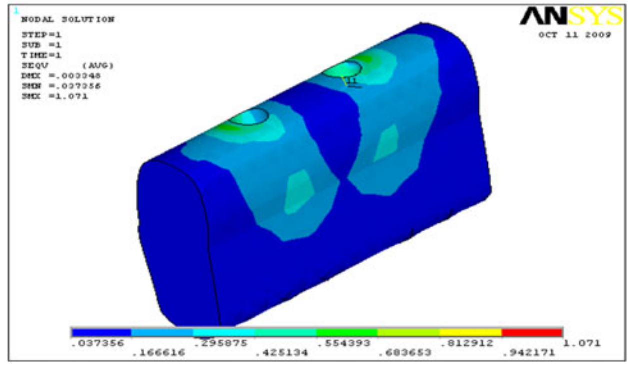

Fig. 25 Stresses on cancellous bone zirconium–axial loading-model-2

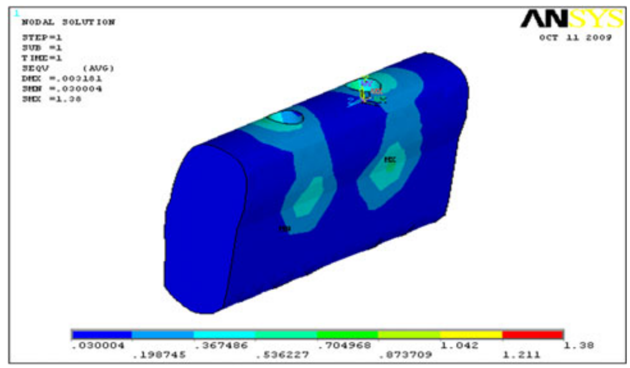

Fig. 26 Stresses on cancellous bone zirconium–axial loading-model-3

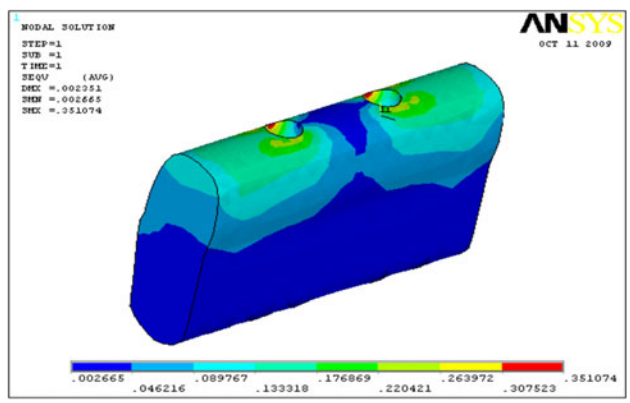

Fig. 27 Stresses on cancellous bone zirconium–non-axial loading-model-1

This method offers several advantages, including accurate representation of complex geometries, easy model modification and representation of the internal state of stress and other mechanical quantities. The FEA has been established as a standardized procedure for qualitative assessment of the stress distribution in various structures [4]. With the FEA, the behavior of the bone and implant system on application of load can be evaluated [11], [13].

In this study, a segment of bone was modeled to simulate the posterior region of the mandible. Three situations were modeled which are similar for titanium and zirconium. In the first situation two implants were embedded, parallel to each other(model-1) in the second situation bucco-lingually inclined(model-2), and in the third situation mesio-distally inclined(model-3). They differ only in simulation of those particular implant material properties.

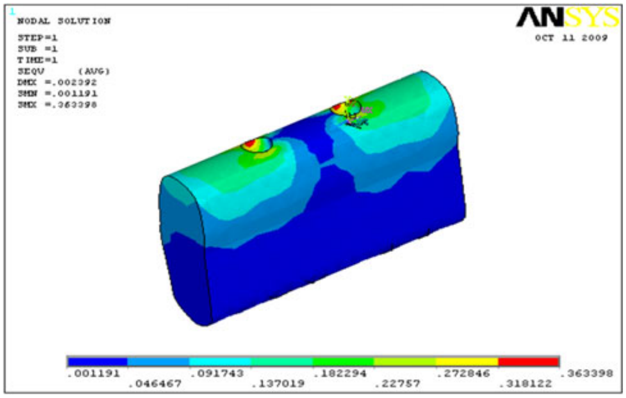

Fig. 28 Stresses on cancellous bone zirconium–non-axial loading-model-2

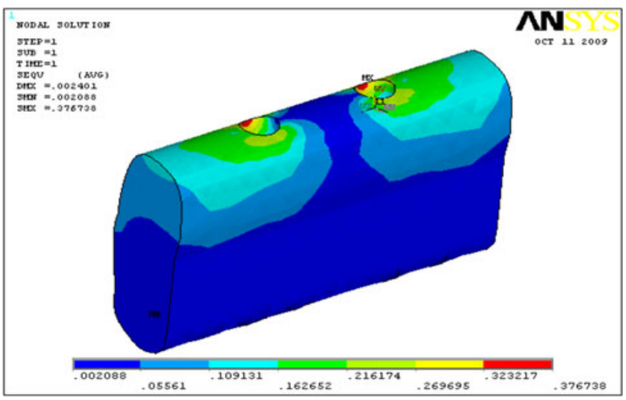

Fig. 29 Stresses on cancellous bone zirconium–non-axial loading-model-3

Table 3 Stress values in different conditions on Ti and Zr implants on non-axial loading

Stress values in different conditions	Titanium (MPa)		Zirconium (MPa)	
	Cortical	Cancellous	Cortical	Cancellous
M_1	8.851	0.321	7.183	0.351
M_2	16.707	0.330	14.271	0.363
M_3	10.434	0.345	8.814	0.376

An axial load of 200N and non-axial load of 50N were applied to all the models.

Rieger et al. [14] have studied bone stress distribution for three endosseous implants of different geometries with ten different implant materials of various modulus of elasticity and found out low modulus of elasticity material implants showed fairly high stresses at crest and uniform distribution around implant and low stresses around the apex of the implant. As the elastic modulus of implant material increases the stresses at crestal region decreases and around the apex increases.

According to Jianping Geng, Weiqui Yan, Wei Xu [1] several FEA studies of osseointegrated implants demonstrated that maximum stress concentration is located at crestal part of cortical bone. When maximum stress concentration is in trabecular bone, it occurs around the apex of the implant. In cortical bone, stress dissipation is restricted to the immediate surroundings of the implant, whereas in trabecular bone a fairly broader distant stress distribution occurs.

In this study in addition to material properties, angulation of the implants (M_1, M_2, M_3 situations) also taken as a criteria to make comparison of stress distribution between M_1, M_2, and M_3 of titanium implants and between M_1, M_2, and M_3 of zirconium implants, on axial and non-axial loading.

According to results of this study, in general the stresses in cortical bone were more on axial and non-axial loading in all the models of both titanium and zirconium. Zirconium implants were shown less stresses on cortical bone and more stresses on cancellous bone than titanium implants in all three similar situations (M_1, M_2, M_3). This is because of difference in modulus of elasticity of titanium and zirconium. Zirconium shows high modulus of elasticity than titanium. These findings were supported by previous studies of FEA of implant geometries and various implant materials.

In parallelly placed implants (model-1) least stresses were observed in cortical and cancellous bone on axial and non-axial loading. In bucco-lingually angulated (model-2) implants, cortical and cancellous stresses were more than parallelly placed (model-1) and less than mesio-distally inclined (model-3) implants on axial and non axial loading. An exception here was cortical stresses on horizontal loading in model-2 implants showed maximum stress values than remaining two models. In mesio-distally inclined (model-3) implants more stresses were found than parallel (model-1) and bucco-lingually (model-2) inclined implants.

On axial loading in cortical bone more stresses were observed in M_3 followed by M_2 and least in M_1. On non-axial loading more stresses were observed in M_2, followed by M_3 and least in M_1 in both titanium and zirconium models.

On axial and non-axial loading in cancellous bone stresses were more in model-3 followed by model-2 and least in model-1 in both titanium and zirconium models.

The above reported results of this analysis correlate with findings of other studies [13, 15, 16] that used different investigation methods. Therefore, the model employed in this study is considered to be satisfactory to simulate reality.

Limitations of the Study

Certain limitations of finite element study should be taken into consideration. Viz., geometry of the model was simplified, with a rectangular section. The resultant stress values obtained may not be accurate quantitatively but are generally accepted qualitatively. Chewing forces are dynamic in nature, whereas the study was conducted with static loads. Force was applied on a flat plane and not with the actual morphology of the tooth.

Due to the limitations pertaining to the study, further research regarding three-dimensional FEA combined with long term clinical evaluation has been suggested.

- Implant parallelism should be the prime criteria for the long-term success of the prosthesis. The main problems during implant placement are anatomical constrains, surgical constrains and operator variability.
- The operator variability should be overcome by using pre-surgical aids such as radiographs, CT scans, MRI, etc.
- Using surgical and radiographic stents have also been suggested as mandatory during implant placement.
- FEA provides an important contribution to clinical safety when bone anchored prostheses are used because it explains the mechanism and safety margins of transfer of load at the interface with emphasis on the actual clinical anatomical situation. This makes it particularly useful for the creative clinician and unique in its field. It should also initiate some critical thinking among hardware producers who might sometimes underestimate the short distance between function and failure when changes in clinical devices or procedures are too abruptly introduced.

Conclusion

The following conclusions were drawn from the study:

- In the cortical bone, on axial loading the von Mises stresses were maximum on mesiodistally inclined implants, followed by bucco-lingually inclined implants and least in parallel implants both in titanium and zirconium models. On Non-axial loading the von Mises stresses were maximum on bucco-lingually inclined implants followed by mesio-distally inclined implants and least in parallel implants both in titanium and zirconium models.
- In cancellous bone, on axial and non-axial loading, von Mises stresses were maximum on the mesiodistally inclined implants followed by bucco-lingually inclined implants and least in parallel implants both in titanium and zirconium models.
- Angulated implants, non-axial loading and titanium implants led to greater stresses on both cortical and cancellous bone with exception of zirconium implants creating greater stress on cancellous bone.
- Zirconium implants led to lower peri-implant stresses than titanium implants.

References

1. Geng J, Yan W, Xu W (2008) Application of the finite element method in implant dentistry, 1st edn. Springer, Berlin
2. Oliva J, Oliva X, Oliva JD (2008) Zirconia implants and all-ceramic restorations for the esthetic replacement of the maxillary central incisors. Eur J Esthet Dent 3:174–185
3. Papavasiliou G, Kamposiora P, Bayne SC, Felton DA (1996) Three-dimensional finite element analysis of stress distribution around single tooth implants as a function of bony support, prosthesis type and loading during function. J Prosthet Dent 76:633–640
4. Meijer HJA, Starmans FJM, Steen WHA, Bosman F (1996) Loading conditions of endosseous implants in an edentulous human mandible: a three-dimensional finite element analysis. J Oral Rehabil 23:757–763
5. Canay S, Hersek N, Akpinar I, Asik Z (1996) Comparison of stress distribution around vertical and angled implants with finite element analysis. Quintessence Int 27:591–598
6. ten Bruggenkate CM, Sutter F, Oosterbeek HS, Schroeder A (1992) Indications for angled implants. J Prosthet Dent 67:85–93
7. Winter W, Heckmann SM, Weber HP (2004) A time-dependent healing function for immediate loaded implants. J Biomech 37:1861–1867 2004 Dec
8. Eser A, Tonuk E, Akca K, Cehreli MC (2010) "Predicting time-dependent remodeling of bone around immediately loaded dental implants with different designs". Med Eng Phys 2010 Jan; 32: 22–31. Epub 2009 Nov 1
9. Cook SD, Klawitter JJ, Weinstein AM (1982) A model for the implant bone interface characteristics of porous dental implants. J Dent Res 61:1006–1009
10. Lozada L, Abbate MF, Pizzarello FA, James RA (1994) Comparative three-dimensional analysis of two finite element endosseous implant designs. J Oral Implantol 20:315–321
11. Meijer HJA, Kuiper JH, Starmans FJM, Bosman F (1992) Stress distribution around dental implants: influence of superstructure, length of implants and height of mandible. J Prosthet Dent 68: 96–102
12. Sutpideler M, Eckert SE, Zobitz M, An KN (2004) Finite element analysis of effect of prosthesis height, angle of force application, and implant offset on supporting bone. Int J Oral Maxillofac Implants 19:819–825
13. Geng J-P, Tan KesonBC, Liu G-R (2001) Application of finite element analysis in implant dentistry: a review of the literature. J Prosthet Dent 85:585–598
14. Rieger MR, Fareed K, Adams WK, Tanquist RA (1989) Bone stress distribution for three endosseous implants. J Prosthet Dent 61:223–228
15. Clelland NL, Gilat A, McGlumphy EA, Brantley WA (1993) A photoelastic and stain gauge analysis of angled abutments for an implant system. Int J Oral Maxillofac Implants 8:541–548
16. Stegaroiu R, Sato T, Kusakari H, Miyakawa O (1998) Influence of restoration type on stress distribution in bone around implants: a three dimensional finite element analysis. Int J Oral Maxillofac Implants 13:82–90