International Journal of Innovation and Applied Studies
ISSN 2028-9324 Vol. 6 No. 3 July 2014, pp. 376-391

http://www.ijias.issr-journals.org/

Influence of variations in thickness of buccal cortical bone on stress distribution around immediately loaded mandibular implants: A non-linear finite element study

Dr. Faisal Moeen[1], Muhammad Saeed[2], and Dr. Adnan Aslam[3]

[1]BDS, MSc,
Associate Professor, Department of Dental Materials,
Riphah University Dental College,
7th Avenue, G-7/4,
Islamabad, 44000, Pakistan

[2]BS, MS,
Assistant Professor, Department of Mechanical Engineering,
Muhammad Ali Jinnah University,
Islamabad, Pakistan

[3]BDS, FCPS (Pakistan), FFD RCS (Ireland),
Assistant Professor, Department of Oral and Maxillofacial Surgery,
Margalla Institute of Health Sciences,
Rawalpindi, Pakistan

ABSTRACT: Objective: To investigative the influence of immediate loading on the stress distribution around dental implants with reductions in buccal cortical bone thickness.
Materials and Methods: Three bone level dental implants (3.8mm, 4.5mm and 5.0mm diameters and a standard length of 10mm) were modeled and each placed in three mandibular bone segments having variations in buccal cortical bone thickness (2.0mm, 1.5mm and 1.0mm). A total of 9 such models were created and discretized with tetrahedral elements of parabolic displacement function. Implant-bone interface was simulated with non-linear contacts zone with friction. Implants were assumed to be placed at an insertion torque of 40Ncm and the fixation force was mathematically calculated for each of the three implants. A uniformly distributed vertical static load of a 150N was applied to the horizontal surfaces of the abutments. The overall stress distribution of von Mises criteria and micro-strain were recorded along the contact areas of implant and surrounding bone and statistically analyzed.
Results: At an insertion torque of 40Ncm the pre-load calculations indicate a reduction in the compressive stresses as the diameters of the implants increase with fixation forces of 93.14N, 83.49N and 75.49N for the 3.8mm, 4.5mm and 5.0mm diameter implants. The maximum stresses were seen in the upper one third of the buccal cortical bony plates which tends to reduce as the diameter of the implant increases. The peak von Mises stresses were 173MPa, 126MPa and 98MPa for the 3.8mm, 4.5mm and 5.0mm implants. The total maximum mesh displacement seen for the 3.8mm, 4.5mm and 5.0mm models was 55µm, 32µm and 12µm respectively.
Conclusions: Implants placed at the same level of insertion torque seem to be at different levels of stability as a consequence of implant thread variations. Stresses reduce with an increase in diameter of the implants. With reductions in thickness of the buccal bone there is an increase in stress transmission and micro-movements. The magnitude of stress transmission however does not vary significantly with reductions in thickness of the buccal bone for the larger diameter implants.

KEYWORDS: Immediate loading, buccal bone thickness, Maximum stress and micro-strain.

INTRODUCTION

Successful implant treatment requires the formation of a predictable bond between the implant and the surrounding bone. The original Brånemark protocol required the implant to be submerged beneath or at the level of the alveolar crest, with soft tissue well approximated, in an un-loaded capacity for 3-6 months. The countersinking of the implant with the pretext of preventing bacterial infection, apical proliferation of the oral epithelium and load induced disruption on the bone healing led to predictable results (1).

Immediate loading not only has the advantages of the one stage protocol which includes avoiding a second stage surgery and the maturation of soft tissue prior to the fabrication of the prosthesis but also involves non-functional loading of the implant with a provisional restoration placed at the time of implant insertion or within 2 weeks of placement (3). These implants have yielded a variety of clinical results, with some studies revealing more crestal bone loss and higher failure rates as compared to the delayed loading protocol, while other researchers indicating no differences in the success rates of the two modalities (2-5).

Upon placement of a dental implant, the threads of the fixture bite into mature lamellar bone and although the cellular connection is yet to form, the implant is considered more stable at the time of insertion than after 3 months(6). The surgical trauma triggers a cellular response leading to woven bone appositional growth which starts as early as 2 weeks after placement. The implant is considered most susceptible to over load failure between 3-5 weeks of placement since the interface comprises of weak, unorganized bone(7). The biomechanical environment from the time of immediate loading and during healing till a healthy osseointegration is established needs to be carefully maintained such that micro-motions of the implant, bone deflections or fracture of bone due to over loading is circumvented to avoid failure (8).

The anatomy of the implant site presents with variations that influence treatment planning. Following extraction of a tooth, bone undergoes resorption with the magnitude of this change been described along with soft tissue volume changes following the extraction of single premolars and molars(9, 10). It is observed that the buccal–lingual/palatal dimension during the first 3 months is reduced by about 30% and after 12 months the edentulous site can lose up to 50% of its original width with maximum reductions from the buccal cortical side(11). When encountering thin buccal cortical bony plates, clinicians hence have to carefully choose the correct implant diameter and design. Bone augmentation procedures are widely advocated to increase the width of the ridge however this translates into a larger cost of the overall treatment and a possible extension of the surgical intervention(12, 13).

Finite element analysis has long served as a method to study the biomechanical behavior of dental implants and the associated stress distribution in the peri-implant environment(14, 15). As occlusal forces can lead to damaging micro-motions of fixtures, the magnitude of loading on a freshly placed dental implant is of paramount importance to the success of such a treatment modality. Literature reveals biomechanical factors such as length, diameter, surface topography, load magnitude along with patient physiological factors such as density of bone, absence of infection, medical conditions etc influencing success of immediate loaded dental implants(16). Additionally, a number of clinical studies have shown a strong correlation between thickness of the cortical bone and the primary stability achieved prior to immediate loading(17).Okumura et al showed a strong influence of maxillary cortical bone thickness on stress distribution around implants loaded in the posterior maxilla. A recent FEM study by Chou et al examined the effect of implant neck design on stress transmission with variations in maxillary bone thicknesses and showed an increase in stress with reductions in bone thickness (18).

There however, remains a paucity of evidence that identifies an acceptable, sub-critical force that can be subjected onto immediately loaded implants placed in mandibular bony ridges with reduced buccal cortical plate thicknesses. The purpose of this FEA study is therefore to investigate the effect of vertically applied static load on the stress and strain distributions on freshly placed dental implants with variations in the thickness of the buccal cortical bone.

MATERIALS AND METHODS:

FE Modeling

A 3D finite element model of a bone block representing the second pre-molar region of a sectioned mandible was created in SolidWorks Premium 2012 software (Dassault Systèmes SolidWorks Corporation, Concord, MA, USA). The bone block consisted of two bodies modeled separately having an inner trabacular structure surrounded with cortical bone with variations only in the thickness of the buccal cortical layer (2.0mm, 1.5mm and 1.0mm).

The bone level implants along with the prescribed solid abutments selected in this study were designed and modeled in Solidworks Premium 2012 with dimensions acquired from the manufacture (SM internal, DIO Corp, 1464 Wooclong, Haeul'ldae-iw, Pusan City, Korea). The fixture diameters were 3.8mm, 4.5mm and 5.0mm with a standard length of 10mm. The diameter of the abutment for the 3.8mm implant is 3.9mm while those for the 4.5mm and 5.0mm implants is 4.8mm as mentioned in the product catalog. All abutments were 4mm in height. The dimensions of the simulated bony segment included a height of 16mms with a 6mm distance from the apex of all implants to the base of the models. The maximum bucco-lingual dimension of the 3.8mm. 4.5mm and 5.0mm implant models were 9.11mms, 9.73 and 9.89mms respectively. The positioning of the dental implant assemblies within each bone block model was kept such that an equal area of buccal bone made identical contacts with the threads of the three implants. A total of 9 models were created.

The geometries were imported into ANSYS Mesh separately to create meshes for the four solid bodies and assembled as high quality tetrahedral models (Figure 1a-1e). To capture fine geometrical features such as curves of threads or curvatures advanced size function was used to reduce element sizes to 0.05mm (Figure 2). Similarly, it was expected that mesh cells would cluster in regions of high gradients of stress and strains and hence contact sizing was used at interfaces where the pre-selected element size ranged from 0.03 to 0.09mm consequently resulting in finer mesh density. The maximum size of the parabolic tetrahedral elements was 0.5mm kept at regions of the models where stress transfer was not expected such as the base of the models and hence where a finer meshing was not needed (Figure 3).

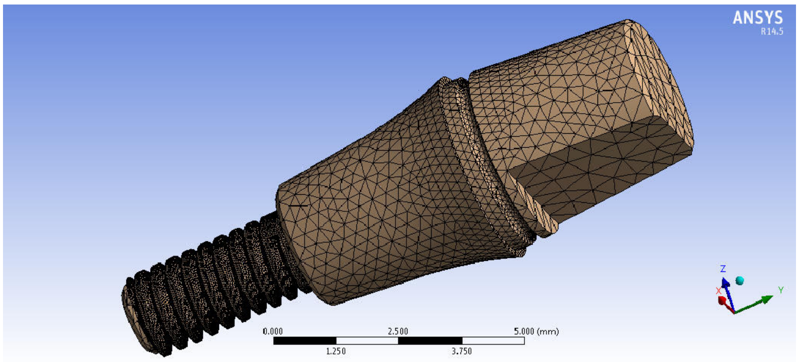


Figure 1a: Abutment.

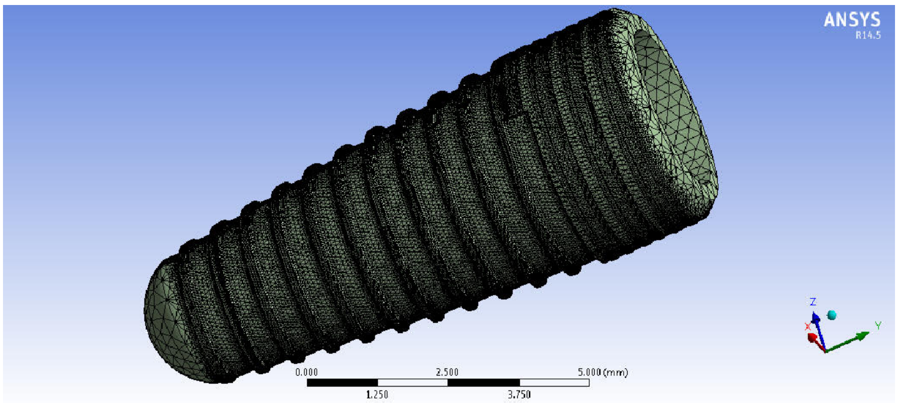


Figure 1b: Implant/Fixture.

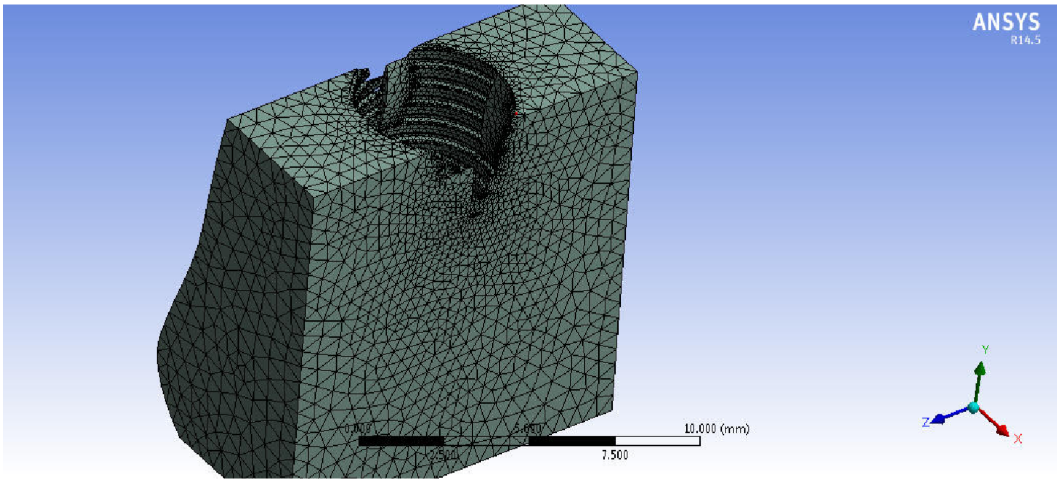


Figure 1c: Inner trabacular bone.

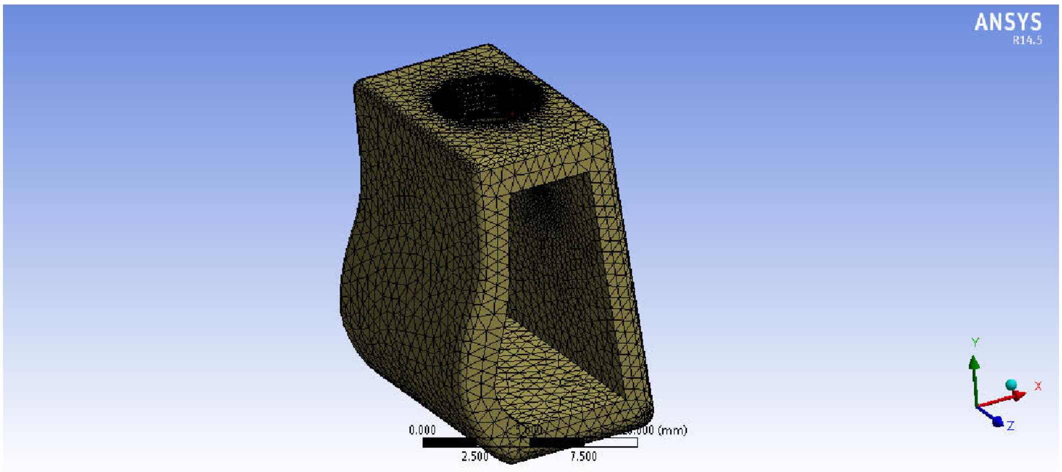


Figure 1d: Cortical shell.

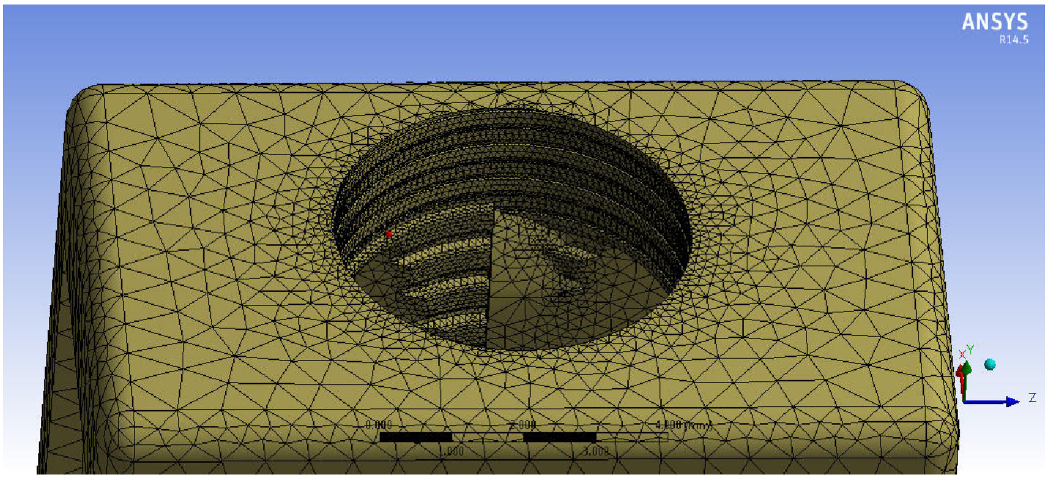
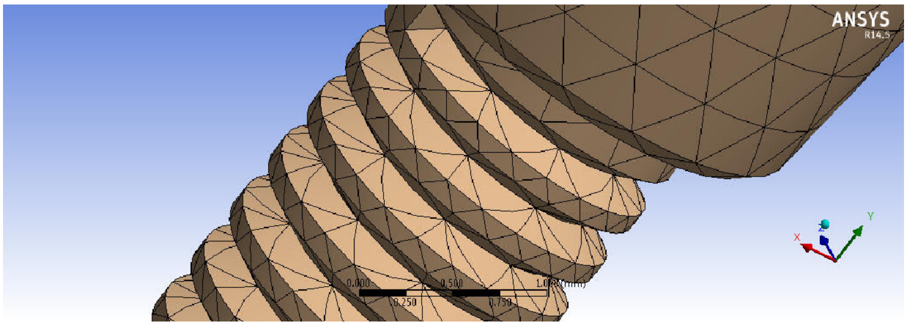
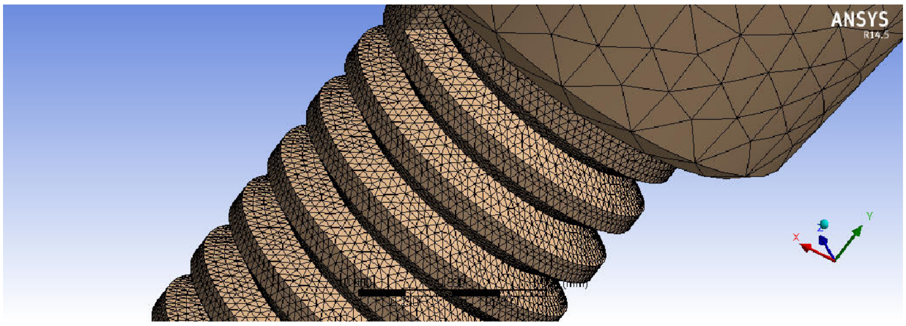


Figure 1e: Inner view of buccal cortical bone.

Each model presented with a total of 15, 73,748 nodes and 10, 78,904 elements. The implant presented 96, 8868 nodes and 14, 11,373 elements. The cancellous and cortical bones presented 10, 9917 and 52,458 nodes and 75,999 and 34,037 elements, respectively.



(a)



(b)

Figure 2: Mesh of threads without (a) and with (b) size function.

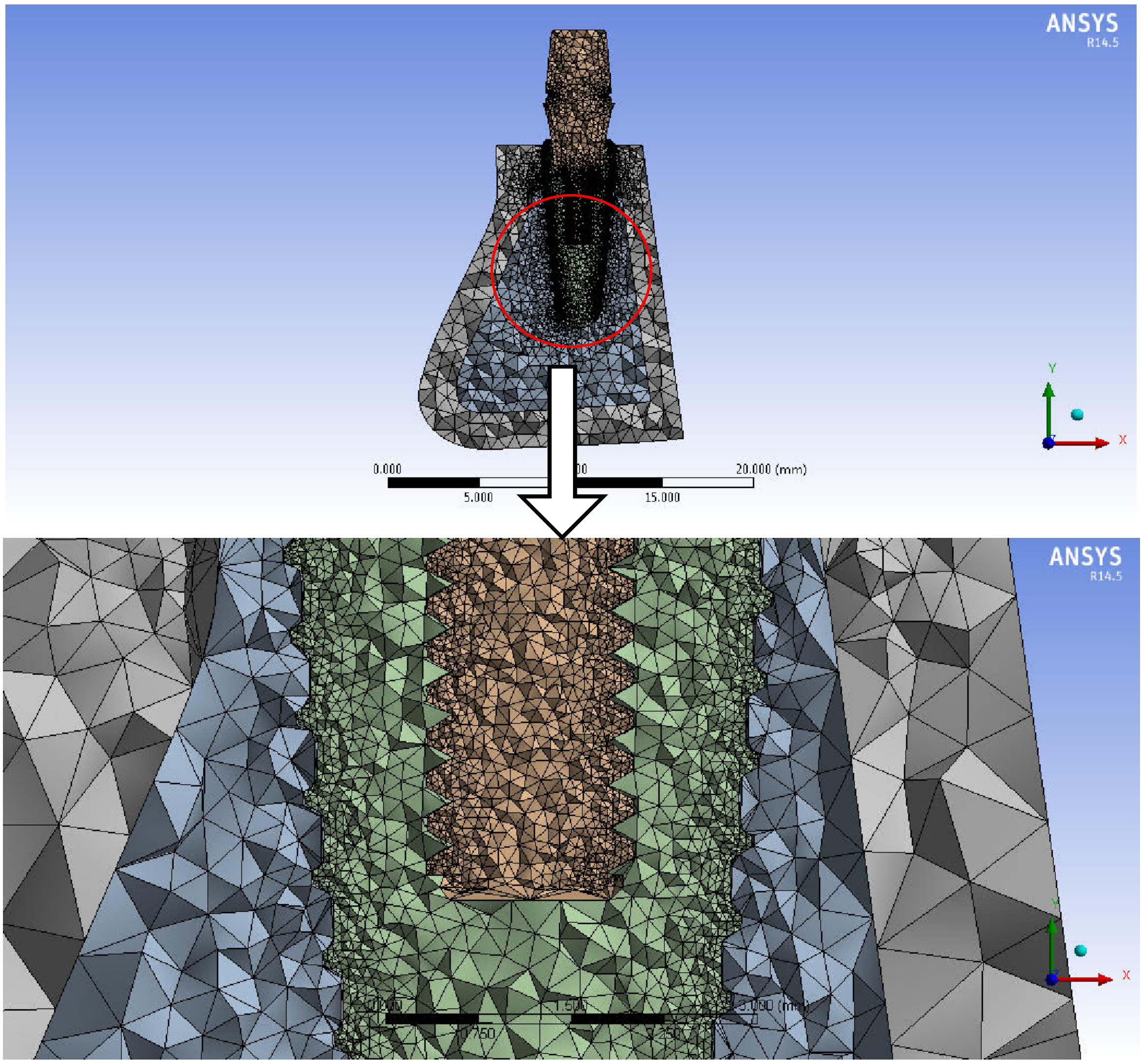


Figure 1:-Mesh on central plane of (Full and enlarged view).

Material Properties

The mechanical properties of all the materials were assumed to be homogenous, isotropic and linearly elastic. The values of Young's elastic modulus (E) and Poisson's ratio (n) were E = 13.7 GPa and n = 0.3 for the cortical bone, and E = 1.37 GPa and n = 0.3 for the cancellous bone. The elastic properties of the titanium implant were E = 103.4 GPa and n = 0.35(15).

Implant–Bone Interface Design

To investigate stress distribution immediately after implantation, the implant–bone interface was assumed as before the occurrence of osseointegration and simulated by non-linear contact zones with friction. The coefficient of friction was set to 0.3(19).This means that the contact zones transfer only pressure and tangential frictional forces, whereas tension is not transferred. The interface between cortical and cancellous bones and the threads of the abutments with those present inside the implants were assumed to be bonded (Figure 4).

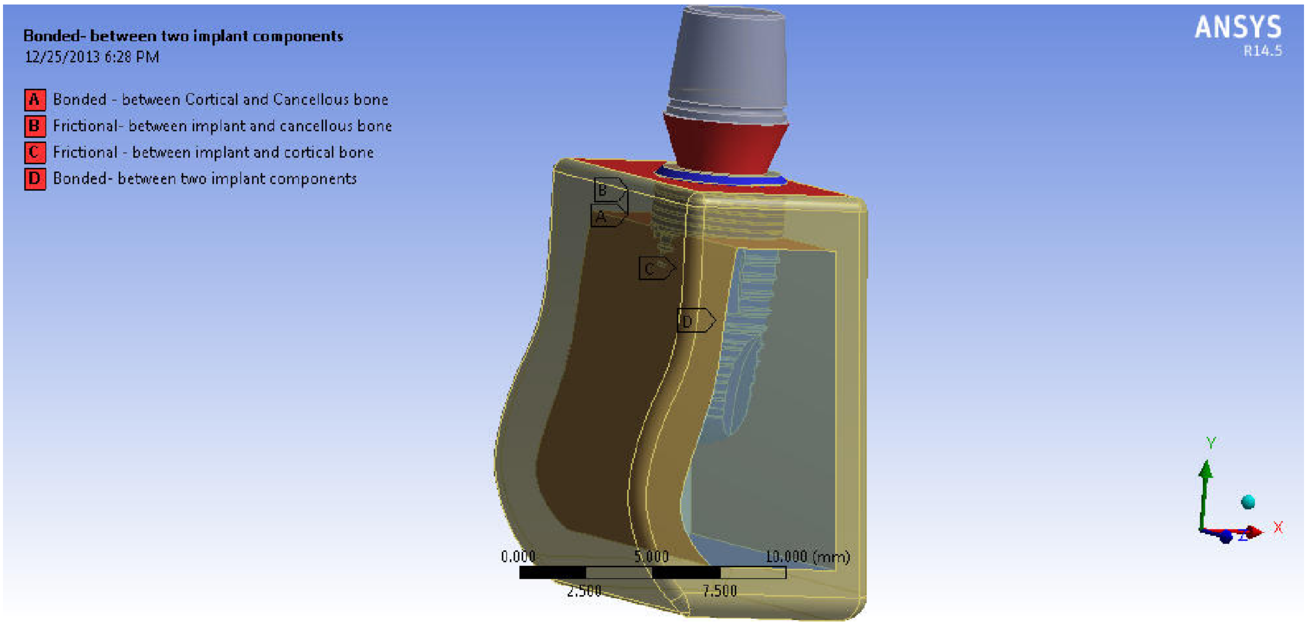


Figure 4:- Contacts between different components.

Boundary conditions and loading

Boundary conditions were set by constraining the mesial and distal surfaces of the bone block along with the base of the model with zero degrees of freedom(20). A uniformly distributed vertical load of a 150N was applied to the horizontal surfaces of the abutments. Softwares from the ANSYS package were used and integrated through ANSYS 14.5 workbench (Swanson Analysis Inc., Huston, PA, USA).

Pre-load of the dental implants:

The pre-load of a dental implant is a consequence of the level of insertion torque at which the implant is finally placed into the bony compartment. Insertion torque is a measure of the resistance upon rotation as the dental implant advances apically, imparting compressive stresses onto the walls of the adjacent body. The inclined plane of the implant thread helix converts torque into a force transmitted as compressive stress. The implants in this study were assumed to be placed into the bony segment at an insertion torque of 40Ncm and hence the compressive stresses created due to a tightened implant or bolt would need to be computed using the following equation (21):

$$P_i = \frac{T}{K\,D}$$

Where,

P_i = bolt preload (called F_i in Shigley)

T = bolt installation torque (40Ncm)

K = torque coefficient

D = bolt nominal shank diameter (i.e. 3.8mm, 4.5mm and 5.0mm)

Torque coefficient K is a function of thread geometry, thread coefficient of friction μ_t, and collar coefficient of friction μ_c. K can be calculated using relation

$$K = \left\{\left[\frac{(0.5\,d_p)(\tan\lambda + \mu_t\sec\beta)}{1 - \mu_t\tan\lambda\sec\beta}\right] + [0.625\,\mu_c D]\right\} / D$$

Where

D = bolt nominal shank diameter (3.8mm, 4.5mm and 5.0mm)
p = thread pitch (0.65mm)
α = thread profile angle (60°)
β = thread profile half angle = 60°/2 = 30°.
$\tan\lambda$ = thread helix angle = $\tan p/(p\, d_p)$.
d_p = bolt pitch diameter (3.56mm. 4.26mm and 4.76mm)
μ_t = thread coefficient of friction (0.3)
μ_c = collar coefficient of friction (0.3)

The torque coefficient K for the 3.8mm, 4.5mm and 5.0mm implant diameters was 0.381, 0.377 and 0.376 respectively according to the above equation.

STATISTICAL ANALYSIS

Pearson's correlation was employed for evaluating the association between bone thickness, implant diameter and maximum stress and micro-strain. Since there were two outcome variables being measured, two separate linear regression models were generated using SPSS version 17.0.

RESULTS

At an insertion torque of 40Ncm the pre-load calculations indicate a reduction in the compressive stresses as the diameters of the implants increase. Forces of 93.14N, 83.49N and 75.49N for the 3.8mm, 4.5mm and 5.0mm diameter implants suggest that as the diameter of the implant increases the compressive force with which the tapered solid body is held within the bony segment reduces at the same level of insertion torque.

At a static load of a 150N applied along the long axis of the abutment-implant assemblies, the maximum stresses were seen in the upper one third of the buccal cortical bony plates (Figure 6) which tends to reduce as the diameter of the implant increases (Figures 7a-7c). The stresses in the buccal cortical plates however diminish further apically as indicated by a plane cut along the y co-ordinate with measurements taken at 9 equal intervals between the coronal and apical extent of the buccal plates for all 9 models (Figure 8).

Table 1

Implant diameter	3.8mm			4.5mm			5mm		
Buccal bone thickness	Max stress [Mpa]	Min Stress [Mpa]	Micro Strain [micro meter]	Max stress [Mpa]	Min Stress [Mpa]	Micro Strain [micro meter]	Max stress [Mpa]	Min Stress [Mpa]	Micro Strain [micro meter]
2mm	155	6.2	41	119	6	20	93	5.9	6
1.5mm	165	6.2	49	123	6	27	96	5.9	8
1mm	173	6.2	55	126	6	32	98	5.9	12

The simulation results show that the occlusal forces are primarily distributed in the crestal bone surrounding the neck of the implant and hence the coronal one-third of the implants transfer the maximum stresses to the adjacent bone in particular the buccal bone. The peak von Mises stresses were 173MPa, 126MPa and 98MPa for the 3.8mm, 4.5mm and 5.0mm implants indicating a reduction in stress with an increase in implant diameter (Table 1).

Considering that micro-movements in excess of 150 µm at the implant-bone interface can jeopardize healing and can result in fibrous encapsulation, the total maximum mesh displacement seen for the 3.8mm, 4.5mm and 5.0mm models was

55µm, 32µm and 12µm respectively. The micro-movements increase with a reduction in either the implant diameters or the thickness of the buccal cortical bone (Table 1).

With a reduction in the thickness of the buccal cortical bone the peak von-Mises stresses tend to increase, with the maximum stresses seen in the 1mm thick cortical bone adjacent to the 3.8mm immediately loaded implant (Figure 9).

A very strong negative correlation was calculated for the association between implant diameter and micro-strain ($r = -0.96$, $p < 0.05$). The correlation between the bone thickness and micro-strain association was comparatively weak ($r = -0.26$, $p > 0.05$).Results also showed that with a unit decrease in implant diameter at the same bone thickness, the stress levels showed an increase of 32.95 MPa.

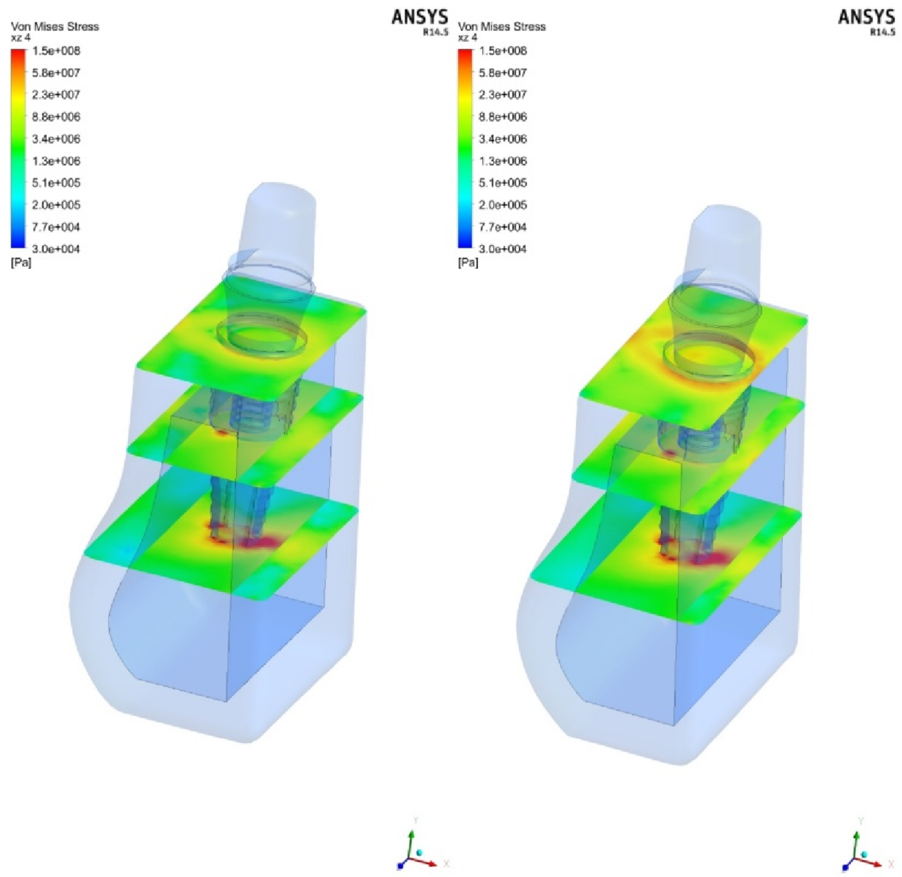
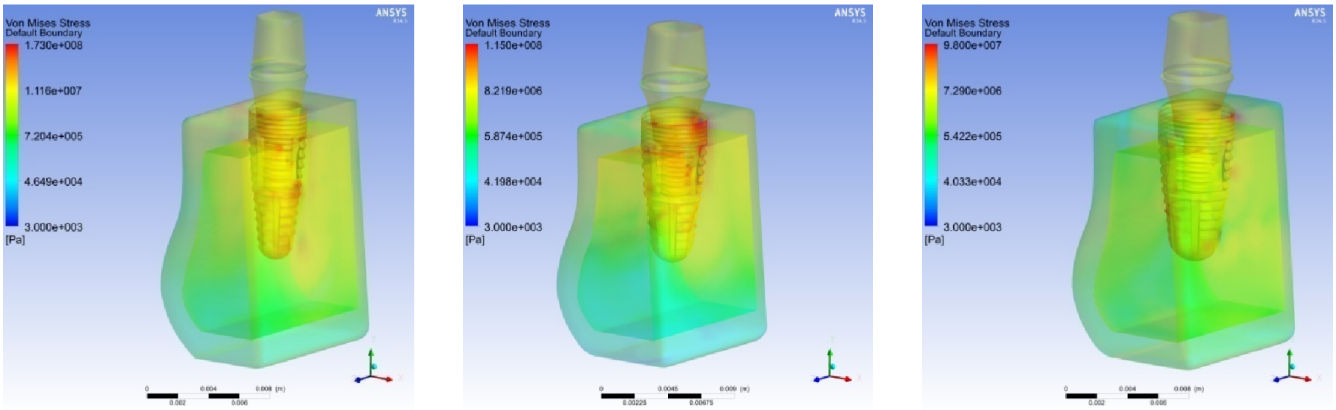


Figure 6: Comparison of stresses at different plains for the 5.0mm diameter implant with buccal wall thickness of 2mm and 1mm showing stress concentration primarily around the neck of the implant and beneath the apex.



(a) *(b)* *(c)*

Figures 7a-7c: Reduction in stresses with an increase in diameter from 3.8mm (a), 4.5mm (b) and 5.0mm (c) diameters with the buccal bone having a thickness of 1mm.

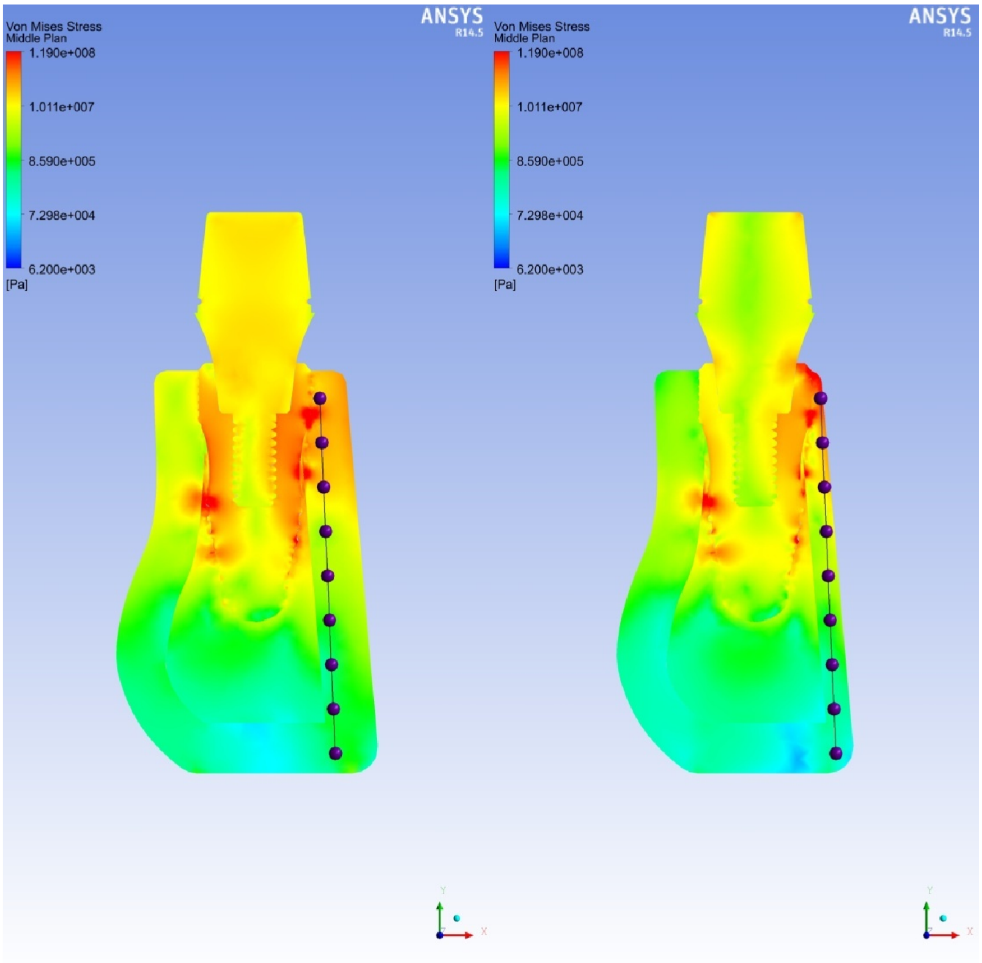


Figure 8: Plane cut along the Y-axis at a similar thickness in the 2mm and 1mm bone showing a reduction in stress from the buccal crest to the base of the model apical to the implant.

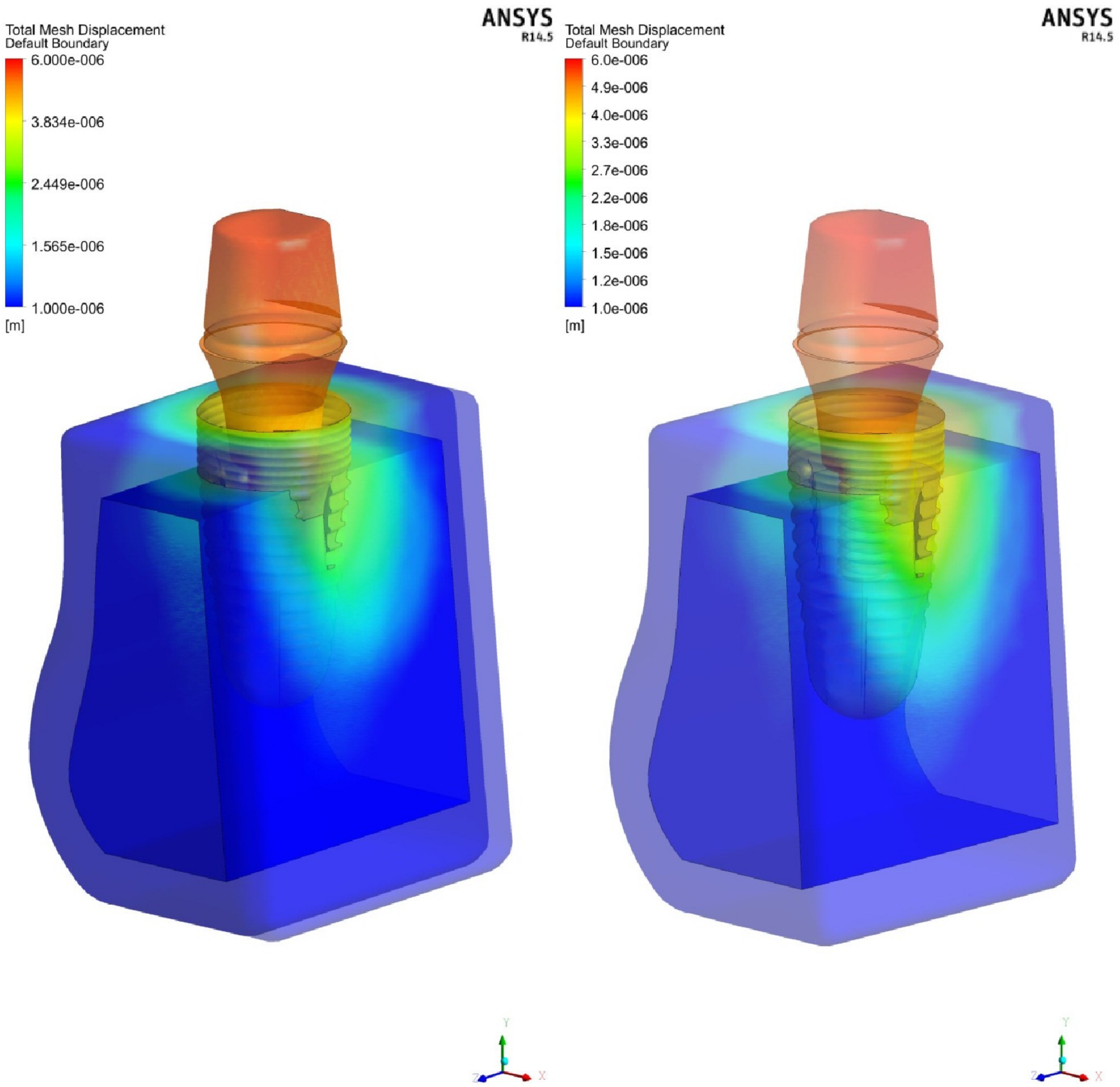


Figure 9:- Comparison of total displacement (implant diameter 5mm) with buccal wall thicknesses of 2mm and 1mm.

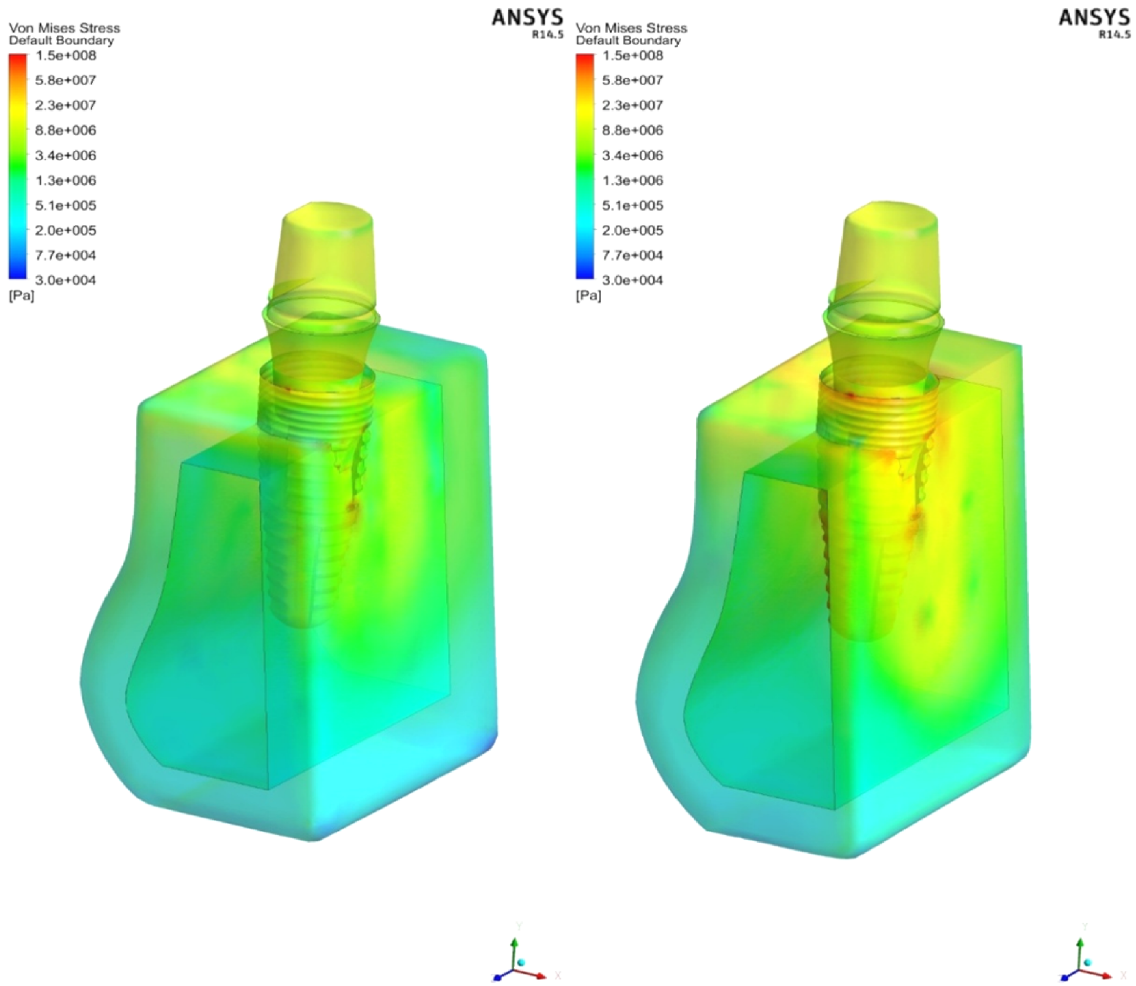


Figure 10:- Comparison of stresses between 3.8mm diameter implants with buccal wall thickness 2mm and 1mm.

DISCUSSION

With a rise in the number of implant placements each year worldwide, along with an increase in general dentists engaged in implant treatments, there exists a need to establish additional biomechanical guidelines when encountering compromised bony ridges(22). Bone loss as a consequence of infection, occlusal trauma, periodontal disease and finally resorption following extraction can lead to a compromised implant bed, with the buccal cortical bone thickness as less as 1mm as mentioned in clinical studies(23). The implant surgeon has to decide from a biomechanical view point whether a bone augmentation procedure is essential in situations when a dental implant has otherwise been satisfactorily placed without any fenestrations adjacent to a thin buccal cortical plate.

Since our study involved an assessment of the variations in thickness of the buccal cortical bone, conversion of the medical images into a patient specific 3D model would not have allowed us to create bone thicknesses of 2.0mm, 1.5mm and 1.0mm without alterations.

Of all the surgery-related factors involved, primary stability seems to be the most important determining factor on immediate implant loading(16). Functional loading on an implant rigidly placed at an adequate installation torque is an essential ingredient in avoiding fibrous encapsulation and achieving osseointegration. Dental implants would behave as blots which are fastened into the receiving channels created in bone for each of these metal bodies. As the implant is being advanced into such a space, an increase in resistance to tightening should ideally be experienced which is a measure of the magnitude of fixation achieved or primary stability. The dental implant in such a state imparts forces on the walls of the bony surfaces. A quantification of the compressive force with which our implants were assumed to be fixated into the bony segments at the same level of insertion torque was therefore necessary. Our calculations indicate that as the diameter of the implant increases the pre-load decreases. Although, primary stability of an implant is clinically measured by the achieved insertion torque, variables such as diameter, thread type, thread pitch, thread profile angle, depth etc seem to effect the magnitude of implant fixation and therefore different implants can be in different states of true primary stability even at the same insertion torque.

In order to restrict the computational solving time, this parametric study employed 9 models with a static load applied along the long axis of the implants. However, since actual function involves dynamic loading under oblique forces as well, we cannot suggest the clinical feasibility of immediate loading of bone level implants adjacent to buccal bone as thin as 1mm. Having said this, the results of this study indicate that static loads of 150N seem to be well tolerated from the bone-deflection view point for all 9 models. Furthermore, the forces applied on the teeth vary with the type of food being chewed. The force applied to a single tooth is also different to that of total force between all the contacting teeth during chewing. On foods such as biscuits, carrots and cooked meat forces range between 70 and 150 N on a single tooth(24). Also, a static 150N as a loading condition has previously been used in immediate loading FEA studies(14, 25).

The maximum stresses were seen concentrated in the buccal cortical bones and around the neck of the implants which is in agreement with other studies and hence validate our findings. Also, according to the findings of Siegele and Soltesz(26) and Patra and colleagues(27), stresses are also concentrated near the apices of immediate loaded implants. We also found stresses focused around the threads of implants as shown in a study by Chun and colleagues (25, 28). The structures in our models were assumed to be homogeneous, isotropic and to possess linear elasticity. The properties of the living tissues, are however different. For instance, it is well described that the actual cortical bone of the mandible is transversely isotropic and inhomogeneous(29). Therefore, the absolute stress and strain values cannot be related to results computed under different conditions. The stress of 5.0mm diameter implants was significantly lower ($p < 0.05$) than those of 3.8 mm diameter but not statistically different from that of the 4.5 mm diameter.

The reduction in stress values in the buccal cortical bones with a progression from the crest towards the apex of an implants, as seen along the points on the Y co-ordinate (Figure 8) seem to validate the stress absorbing properties of cancellous bone, however such a inference can be more accurately observed when bone is modeled as an anisotropic structure with all anatomic variations of trabacular bone realistically simulated (30). The un-supported cortical plates on either side of the implants are subjected to the maximum stresses with stress increasing with reduction in thickness of the buccal bone(31). Larger diameter implants not only transfer lesser stresses to the adjacent bone, but the reduction in thickness of the buccal bone does not significantly vary stresses as compared to the smaller diameter implants (Figures 11-12).

The ultimate yield strength of cortical and cancellous bone has been mentioned as 190MPa and 40MPa respectively(32). At a static load of 150N there were no indications of fracture in any of the 9 models. Compared to a bonded interface as seen in an osseointegrated simulation, setting a frictional co-efficient between the fixture and bone does yield higher stresses in the cortical bone. A bonded interface transmits forces in both the compressive and tension sites and hence stress transmission is more homogenous and quantitatively less as compared to an immediate loaded implant. Although, in our study the micro-motion has been less than 150μm for all 9 implant models which favors immediate loading, the effect of oblique loading affecting osseointegration and the possibility of long term bone loss especially in thinner buccal cortical bones due to inappropriate loading is also worthy to be investigated.

The change in peri-implant stress around the 5.0mm diameter implant with reductions in buccal bone thicknesses were statistically insignificant as compared to stress values associated with the 3.8mm implant. It would appear that larger diameter implants although require larger osteotomies to be surgically prepared, are more favorable in terms of stress distribution when immediately loaded even when placed adjacent to residual buccal bone as thin as 1mm(33).

Conclusions

Within the limitations of this study, the following conclusions for an immediately loaded mandibular implant are suggested:

1. The stresses transmitted within the peri-implant bony environment upon immediate vertical loading are concentrated in the mesial and distal crestal region and beneath the apex of the implants.
2. With reductions in the thickness of the buccal cortical plate the magnitude of stress increases. The general trend is an increase in the micro-motions at the implant-bone interface with reductions in the thickness of the buccal bone, however at a vertically applied static load of 150N the micro-motions are less than the critical value of 150μm.

3. Stresses reduce with an increase in diameter of the implants.
4. The magnitude of stress transmission does not vary significantly with reductions in thickness of the buccal bone for the larger diameter implants.
5. Primary stability can vary as a consequence of variations in the properties of threads. At the same level of insertion torque the larger diameter implants according to mathematical calculations are less rigidly fixated in bone.

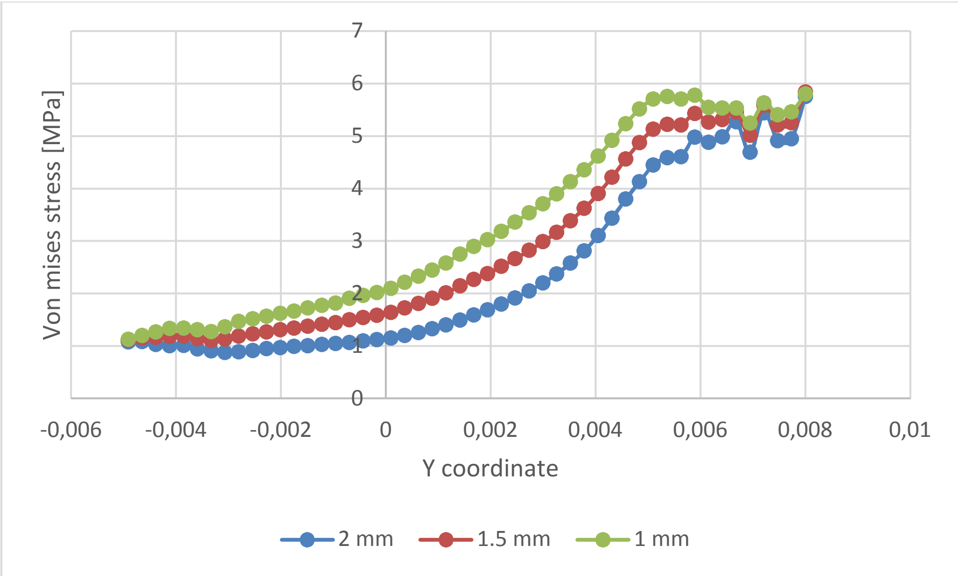


Figure 11:- Comparison of stresses on the Y-axis (implant diameter 5.0mm).

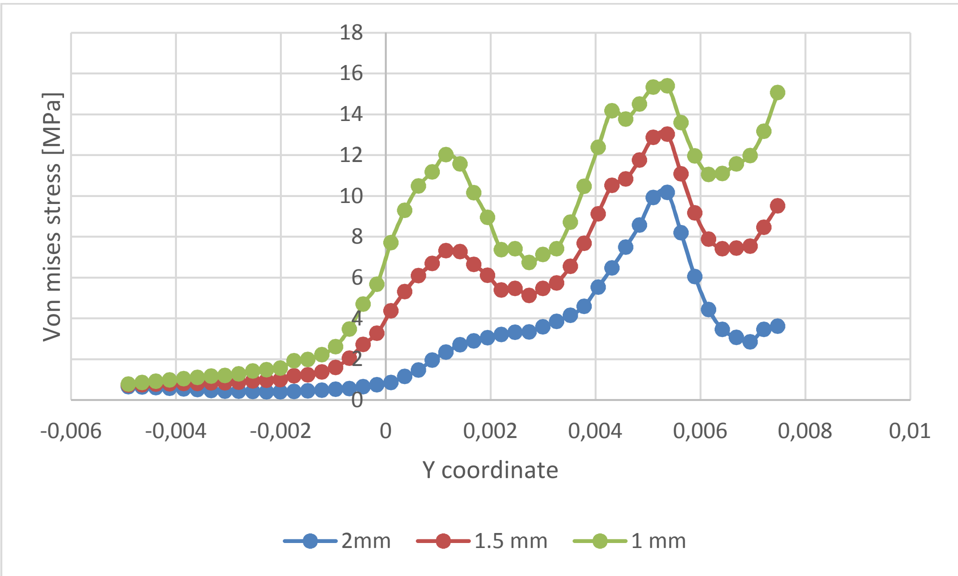


Figure 12:- Comparison of stresses on the Y-axis (implant diameter 4.5mm).

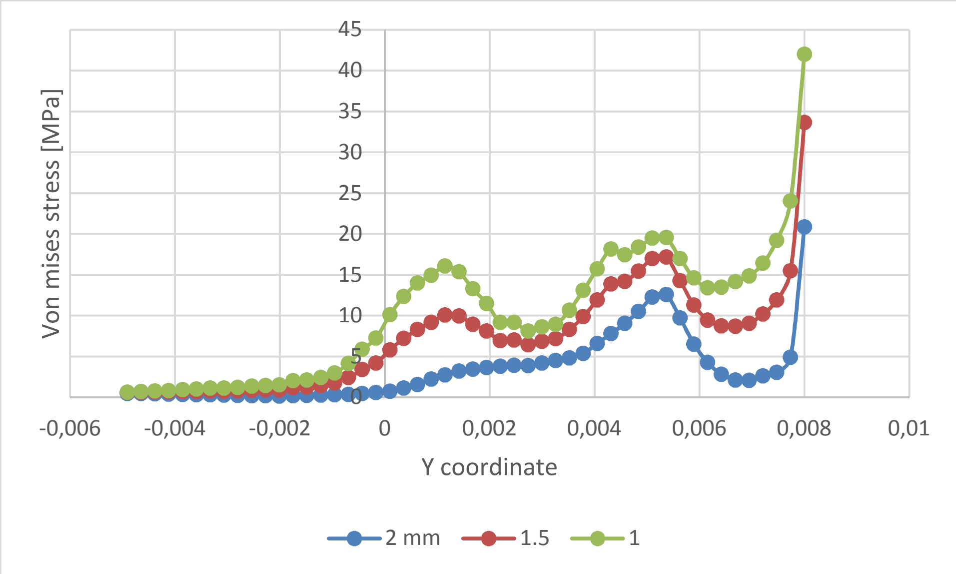


Figure 13:- Comparison of stresses on the Y-axis (implant diameter 3.8 mm).

References

[1] Misch CE, Wang H-L, Misch CM, Sharawy M, Lemons J, Judy KW. Rationale for the application of immediate load in implant dentistry: Part I. Implant Dentistry. 2004;13(3):207-17.

[2] Aparicio C, Rangert B, Sennerby L. Immediate/early loading of dental implants: a report from the Sociedad Espanola de Implantes World Congress consensus meeting in Barcelona, Spain, 2002. Clinical implant dentistry and related research. 2003;5(1):57-60.

[3] Szmukler-Moncler S, Piattelli A, Favero GA, Dubruille JH. Considerations preliminary to the application of early and immediate loading protocols in dental implantology. Clinical oral implants research. 2000;11(1):12-25.

[4] Ganeles J, Rosenberg MM, Holt RL, Reichman LH. Immediate loading of implants with fixed restorations in the completely edentulous mandible: report of 27 patients from a private practice. The International journal of oral & maxillofacial implants. 2001;16(3):418.

[5] Degidi M, Piattelli A. Immediate functional and non-functional loading of dental implants: a 2-to 60-month follow-up study of 646 titanium implants. Journal of periodontology. 2003;74(2):225-41.

[6] Bra-nemark P-I, Zarb GA, Albrektsson T, Rosen HM. Tissue-integrated prostheses. osseointegration in clinical dentistry. Plastic and Reconstructive Surgery. 1986;77(3):496-7.

[7] Buchs AU, Levine L, Moy P. Preliminary report of immediately loaded Altiva Natural Tooth Replacement dental implants. Clinical implant dentistry and related research. 2001;3(2):97-106.

[8] Cowin SC, Moss-Salentijn L, Moss ML. Candidates for the mechanosensory system in bone. Journal of biomechanical engineering. 1991;113(2):191-7.

[9] Schropp L, Wenzel A, Kostopoulos L, Karring T. Bone healing and soft tissue contour changes following single-tooth extraction: a clinical and radiographic 12-month prospective study. International Journal of Periodontics and Restorative Dentistry. 2003;23(4):313-24.

[10] Araújo MG, Lindhe J. Dimensional ridge alterations following tooth extraction. An experimental study in the dog. Journal of clinical periodontology. 2005;32(2):212-8.

[11] Nevins M, Camelo M, De Paoli S, Friedland B, Schenk R, Parma-Benfenati S, et al. A study of the fate of the buccal wall of extraction sockets of teeth with prominent roots. The International journal of periodontics & restorative dentistry. 2006;26(1):19.

[12] Cordaro L, Amade DS, Cordaro M. Clinical results of alveolar ridge augmentation with mandibular block bone grafts in partially edentulous patients prior to implant placement. Clinical oral implants research. 2002;13(1):103-11.

[13] Buser D, Brägger U, Lang N, Nyman S. Regeneration and enlargement of jaw bone using guided tissue regeneration. Clinical oral implants research. 1990;1(1):22-32.

[14] Hasan I. Computational Simulation of Trabecular Bone Distribution around Dental Implants and the Influence of Abutment Design on the Bone Reaction for Implant-Supported Fixed Prosthesis: Universitäts-und Landesbibliothek Bonn; 2011.

[15] Geng J-P, Tan KB, Liu G-R. Application of finite element analysis in implant dentistry: a review of the literature. The Journal of prosthetic dentistry. 2001;85(6):585-98.

[16] Javed F, Ahmed HB, Crespi R, Romanos GE. Role of primary stability for successful osseointegration of dental implants: Factors of influence and evaluation. Interventional Medicine and Applied Science. 2013;5(4):162-7.

[17] Miyamoto I, Tsuboi Y, Wada E, Suwa H, Iizuka T. Influence of cortical bone thickness and implant length on implant stability at the time of surgery—clinical, prospective, biomechanical, and imaging study. Bone. 2005;37(6):776-80.

[18] Chou I-C, Lee S-Y, Wu M-C, Sun C-W, Jiang C-P. Finite element modelling of implant designs and cortical bone thickness on stress distribution in maxillary type IV bone. Computer methods in biomechanics and biomedical engineering. 2012(ahead-of-print):1-11.

[19] Chung S, Heo S, Koak J, Kim S, Lee J, Han J, et al. Effects of implant geometry and surface treatment on osseointegration after functional loading: a dog study. Journal of oral rehabilitation. 2008;35(3):229-36.

[20] Ding X, Liao SH, Zhu XH, Zhang XH, Zhang L. Effect of diameter and length on stress distribution of the alveolar crest around immediate loading implants. Clinical implant dentistry and related research. 2009;11(4):279-87.

[21] Shigley JE, Mischke CR, Budynas RG, Liu X, Gao Z. Mechanical engineering design: McGraw-Hill New York; 1989.

[22] Jokstad A, Braegger U, Brunski JB, Carr AB, Naert I, Wennerberg A. Quality of dental implants*. International dental journal. 2003;53(S6P2):409-43.

[23] Spray JR, Black CG, Morris HF, Ochi S. The influence of bone thickness on facial marginal bone response: stage 1 placement through stage 2 uncovering. Annals of Periodontology. 2000;5(1):119-28.

[24] Xu W, Lewis D, Bronlund J, Morgenstern M. Mechanism, design and motion control of a linkage chewing device for food evaluation. Mechanism and Machine Theory. 2008;43(3):376-89.

[25] Ding X, Zhu XH, Liao SH, Zhang XH, Chen H. Implant–Bone Interface Stress Distribution in Immediately Loaded Implants of Different Diameters: A Three-Dimensional Finite Element Analysis. Journal of prosthodontics. 2009;18(5):393-402.

[26] Siegele D, Soltesz U. Numerical investigations of the influence of implant shape on stress distribution in the jaw bone. International Journal of Oral & Maxillofacial Implants. 1989;4(4).

[27] Patra AK, DePaolo JM, D'Souza KS, DeTolla D, Meenaghan MA. Guidelines for analysis and redesign of dental implants. Implant Dentistry. 1998;7(4):355-68.

[28] Chun HJ, Cheong SY, Han JH, Heo SJ, Chung JP, Rhyu IC, et al. Evaluation of design parameters of osseointegrated dental implants using finite element analysis. Journal of oral rehabilitation. 2002;29(6):565-74.

[29] Sevimay M, Turhan F, Kilicarslan M, Eskitascioglu G. Three-dimensional finite element analysis of the effect of different bone quality on stress distribution in an implant-supported crown. The Journal of prosthetic dentistry. 2005;93(3):227-34.

[30] Mosekilde L, Mosekilde L, Danielsen C. Biomechanical competence of vertebral trabecular bone in relation to ash density and age in normal individuals. Bone. 1987;8(2):79-85.

[31] Papavasiliou G, Kamposiora P, Bayne SC, Felton DA. Three-dimensional finite element analysis of stress-distribution around single tooth implants as a function of bony support, prosthesis type, and loading during function. The Journal of prosthetic dentistry. 1996;76(6):633-40.

[32] Reilly DT, Burstein AH. The elastic and ultimate properties of compact bone tissue. Journal of biomechanics. 1975;8(6):393-405.

[33] Petrie CS, Williams JL. Comparative evaluation of implant designs: influence of diameter, length, and taper on strains in the alveolar crest. Clinical oral implants research. 2005;16(4):486-94.