Original Article

Developing a New Dental Implant Design and Comparing its Biomechanical Features with Four Designs

Mansour Rismanchian[1], Reza Birang[2], Mahdi Shahmoradi[3], Hassan Talebi[4], Reza Jabar Zare[4]

ABSTRACT

Background: As various implant geometries present different biomechanical behaviors, the purpose of this work was to study stress distribution around tapered and cylindrical threaded implant geometries using three-dimensional finite element stress analysis.

Methods: Seven implant models were constructed using Computer Assisted Designing system. After digitized models of mandibular section, the crowns were created. They were combined with implant models, which were previously imported into CATIA software. The combined solid model was transferred to ABAQOUS to create a finite element meshed model which was later analyzed regarding the highest maximum and minimum principal stresses of bone.

Results: For all models, the highest stresses of cortical bone were located at the crestal cortical bone around the implant. Threaded implants, triangular thread form and taper body form showed a higher peak of tensile and compressive stress than non-threaded implants, square thread form and straight body form, respectively. A taper implant with triangular threads, which is doubled in the cervical portion of the body, had a significantly lower peak of tensile and compressive stress in the cortical bone than straight/taper triangular or square threaded implant forms.

Conclusion: For the investigation of bone implant interfacial stress, the non-bonded state should be studied too. Confirmative clinical and biological studies are required in order to benefit from the results of this study.

Keywords: Dental implant, Elastic modulus, Finite element analysis, Stress, Strain.

Received: *January 2010*
Accepted: *April 2010*

Dent Res J 2010; 7(2): 70-75

Introduction

Advances in oral implant research have led to the development of several different types of implants, and it is anticipated that continued research will lead to even more improved systems. Endosseous implant systems include a range of sizes, shapes, coatings, and prosthetic components. A variety of lengths and widths should be available to better incorporate the implant fixture within osseous structures.

Prosthetic components can also be selected in a variety of size and angles to perfectly accommodate the final restoration. Also, implant surface morphology has been shown to influence osseointegration. Porous coating (i.e., acid-etched, sand-blasted) can achieve more bone-to-implant contact than smooth subcrestal surfaces.[1]

It has been a continuing goal to optimize the present systems and develop new systems that not only omit the limitations of previous systems also have better biomechanical, clinical and histomorphometrical advantages. For evaluating the biomechanical features of newly developed implant designs, the stress transmission between the implant and the surrounding bone is of uttermost importance.

* This paper derived from a thesis and research project No. 387160 in Isfahan University of Medical Sciences.

[1] Associate Professor, Department of Prosthodontics, School of Dentistry and Torabinejad Dental Research Center, Isfahan University of Medical Sciences, Isfahan, Iran.
[2] Associate Professor, Department of Periodontics, School of Dentistry and Torabinejad Dental Research Center, Isfahan University of Medical Sciences, Isfahan, Iran.
[3] Dental Student, School of Dentistry, Isfahan University of Medical Sciences, Isfahan, Iran.
[4] Bs in Mechanical Engineering, Isfahan, Iran.
Correspondence to: Reza Birang, Email: birang@dnt.mui.ac.ir

Finite element analysis (FEA) can simulate the interaction phenomena between the implants and the surrounding tissues.[2] Load transmission and resultant stress distribution is significant in determining the success or failure of an implant. Factors that influence the load transfer at the bone implant interface include the type of loading, material properties of the implant and prosthesis, implant geometry-length, diameter as well as shape, implant surface structure, the nature of the bone-implant interface, quality and quantity of the surrounding bone.[3]

Among the biomechanical factors that influence the load transfer at the bone-implant, the length, diameter, and body/thread shape are easily changed and are of the most importance. The optimum length and diameter necessary for long term implantation success depends on the bone support condition. If the bone is in normal condition, length and diameter appear not to be significant factors for implant success. However, if the bone condition is poor, large diameter implants are recommended and short implants should be avoided.[4-7] Optimum implant shape is related to the bone condition and implant material properties. Implant designs have adopted various shapes and FEA seems to indicate that for commercially pure titanium implants (CPTI), smoother profiles engender lower stress concentrations. The optimal thread design to achieve the best load transfer characteristics is the subject of current investigations.[5,8-11]

If we could modify implant body and thread form to maintain the beneficial stress level in a variety of loading scenarios, we may conquer one of the most important challenges in implant bone biomechanics.

So, our aim was to design and develop a new dental implant in order to manufacture a system with advantages of previously existing systems and enhanced biomechanical, practical and economical features. As various implant geometries present different biomechanical behaviors, the purpose of this work was to study stress distribution around tapered and cylindrical threaded implant geometries using three-dimensional finite element stress analysis.

Materials and Methods

This study was performed in four phases including designing the implant models, creating solid models of mandible and porcelain crown, creating finite element model and analyzing the process of load transfer and stress distribution. In fact, implant models, mandibular section and the crown were created and modeled separately and were combined and overlapped to create a whole model of all. Then, the analyses were done on this combination.

Designing implant Models

The implant models were constructed using the Computer Assisted Designing (CAD) system (Mechanical Desktop engineering software). For the threaded implants, first the form of the thread was designed and then, the helical sweep function was used to create the geometry of spiral threads. Models were saved as an IGES file and was imported to CATIA software (Dassault Systèmes, Vélizy-Villacoublay, FRANCE) to generate a model of a crowned implant in mandible.

Creating 3D solid models of mandible and a porcelain crown

An implant supported acrylic resin crown for the first premolar was constructed. Mandibular bone segment and the crown were scanned using an advanced topometric sensor digitizer, ATOS II (Capture3D, Costa Mesa, CA, USA) and point clouds of the crown and mandibular section were obtained and saved as Cat part files. The Cat part file of point clouds was transferred to CATIA to create digitized 3D models of mandible and crown. The combined 3D solid model was saved as a Model file in CATIA.

Creating implant-bone finite element model

The combined solid model was transferred to ABAQUS version 6.5 (ABAQUS Inc., Providence, RI, USA) to create a finite element meshed model in order to be analyzed later. For constructing the finite element models, 10 node modified quadratic tetrahedral p-elements (C3D10M) were used.

Finite element analysis of the models under load

The analysis was performed on a Pentium IV 3200 (AMD Anthon) with 1024 MB RAM. The material properties of cortical and trabecular bone were modeled as being transversely isotropic and linearly elastic, which describe an anisotropic material. For the cortical bone, the material properties of the buccal and lingual directions were isotropic along the axis of the mesiodistal direction. Trabecular bones were isotropic in the inferior-superior direction. The material of the implant and crown were assumed to be isotropic and linearly elastic.

The buccal axial force was applied parallel to the long axis of the implant on the buccal cusp as the loading condition. The bottom surface of the mandibular section was constrained in the x, y and z directions (displacement = 0) as the boundary condition.

The bone-implant interface and crown implant interface were rigidly bonded in the models. The highest maximum and minimum principal stresses of bone were used for the comparison. In addition, the interfacial stresses in bone along the implants buccal and lingual surfaces, from the alveolar crest to the apex of the implant were analyzed and compared along the 7 models.

Results

The highest maximum principal (tensile) and minimum principal (compressive) stresses of cortical and trabecular bone of the 7 finite element models are shown in Table 1.

For all models, the highest stresses of cortical bone were located at the crystal cortical bone around the implant which corresponded with the clinical finding of crestal bone loss. For the trabecular bone the stress was concentrated near the endosteal trabecular bone, the tip of the thread and the apex of the implant.

Effect of thread type and presence

Regarding the models of the straight implant, peak tensile stress in the cortical bone was 61% higher for the triangular thread-straight model than for the no thread–straight model. However, peak tensile stress in trabecular bone was nearly the same for the two models. Also, in the square-straight model, the peak tensile stress in the cortical bone was 66% higher than for the no thread–straight model in cortical bone and 45% for trabecular bone. Peak compressive stress in the cortical bone was 9% higher for the tri-straight model and 41% higher for the sq-straight model than for the no-straight model.

Regarding the models of the taper implant, peak tensile stress in the cortical bone was nearly the same for the tri-taper model, no-taper model and square taper models. However, there was a slight difference (tri taper > sq taper > no taper). Peak compressive stress in the cortical bone was 11% higher for the tri-taper model and 7% higher for the sq-taper model than for the no-straight model.

Effect of microthread

In the last model with microthreads in cervical portion, peak tensile stress in the cortical bone was 95% lower than that in tri-taper and square taper implant, and 52% lower than that in tri-straight implant. Peak compressive stress in the cortical bone was also 30% lower than that in tri-taper implant, and 26% lower than that in sq-taper implant. However, the peak compressive stress in trabecular bone was only lower than that in sq-taper model in trabecular and cortical bone but not lower than that in others which indicate that the microthread portion has effect only in cortical bone.

Effect of body tapering

Regarding the body geometry, peak tensile stress was 29% lower for the tri-straight model than for the tri-taper model in the cortical bone and 110% higher in the trabecular bone. Peak compressive stress in cortical bone around taper implant was 51% higher than that in straight model. Also, in the square threaded implants, peak tensile stress was lower for the sq-straight model than for the sq-taper model in the cortical bone and also, it was higher in the trabecular bone. Peak compressive stress in cortical bone around taper implant was 12% higher than that in straight model. In the no threaded models compressive and tensile peak stress were higher in taper models than those in straight models not only in cortical bone also in trabecular bone.

Table 1. The highest maximum and minimum principal stress (MPa) in cortical and trabecular bones around the implant

Model	Straight No thread	Straight Triangular thread	Straight Square thread	Taper No thread	Taper Triangular thread	Taper Square thread	Taper Double thread
			Cortical bone				
P max	195.7	315.4	324.1	405	408.8	407.1	207.9
P min	-307	-336.4	-434	-454.7	-508.3	-489.2	-388
			Trabecular bone				
P max	2.62	2.64	3.82	4.02	1.2	3.48	1.8
P min	-1.38	-3.93	-1.46	-3.03	-1.27	-2.06	-1.4

Discussion

This study was designed to evaluate the influence of different dental implant features including body shape and taper, thread shape and simultaneous micro- and macro- threads on stress distribution and strains in the alveolar bone.

In this study we used finite element modeling of dental implants via spiral threaded implants. Most of the previous studies used non-spiral dental implant models for the purpose of simplicity.[12-13] So, we can claim that our models and our results are closer to the real conditions and are much more accurate on predicting the stress and strain patterns.

All models had a peak stress localized in the crestal region of the cortical bone, which is co-approved by previous studies.[13-17] The peak stress on cortical bone was highest in the threaded implants. However, it should not be concluded that threads lead in a greater amount of implant failure. The main benefit of threads is the resistance against the shear stress which is the most destructive one.

Misch states three functions for threads which are to maximize initial contact, enhance functional surface area and facilitate dissipations of stress at the interfacial area.[18] Interfacial stress analysis showed that threaded designs lower the stress near the valley of the thread. Also, two other clinical advantages can be counted for threaded types which are increased stability[19,20] and stress induced bone formation.[21] Threaded designs show a wavy interfacial stress pattern along the implants surface in trabecular bone while the cylindrical straight model showed one large high stress area. Recent FE studies also has shown that threaded and also stepped characteristics dissipate the stress transfer pathway from a single high stress area into numerous disconnected areas of bone near the threads tips and stepped areas.[22-24] Some authors[25] have demonstrated two reasons for this dissipation. First, the stress concentration yielded by geometric discontinuity and stress shielding effect. Second, the geometric discontinuity of the threaded designs results in high stress at the valley between pitches explainable by flexure formula and concentration factor. Also, in the valley between pitches the radii were smaller than those on the tip of thread which increases non-linearly stress on the implant surface. This is known as the stress shielding effect.

So although the threaded forms had a higher peak of stress, the benefits of threads cannot be neglected. In evaluating the best form of thread for dental implants, three factors should be taken into account: thread shape, thread depth, and thread pitch.[18]

Misch[18] relates all these factors to functional surface area per unit length of implant which is modified by these three parameters. The greater the thread pich and depth, the greater the surface area if all other factors are the same. However, from the surgical ease point of view, the fewer the threads, the easier the bone tap or the insert of the implant.

A FE 3D study reported that V shape and reverse buttress had similar values whereas the square threads had less stress in compressive and more importantly, in shear forces[26]. In another study the square thread exhibited higher reverse torque values after initial healing whereas the V shaped and reverse buttress were similar[27]. High stress is primarily transferred through the implant surface of the valley of the thread reducing the stress in bone near the interface which may improve osseointegration and benefit the threaded implants with greater bone implant contact. By the way, the square thread showed larger areas of low interfacial stress near the tips of the implant in trabecular bone compared to the triangle thread.

Also, Patra et al.[28] reported that the tapered thread design of branmark implant exhibited higher stress levels in bone than the parallel profile thread of BUD implants which seemed to distribute stress more evenly. In our study, the square thread form had a lower peak of stress (tensile and compressive) compared with triangular thread which confirms previous studies. Evaluating the body taper of the implant, the tapered implant body increased peak tensile stress of cortical bone compared to straight body with both triangular and square threads. The tapered body form has been a place for challenge in the studies.

Some studies have shown that the tapered body decreases the stresses in both cortical and trabecular bone compared with straight design.[29]Reiger et al.[30]reported that stress is more dissipated throughout the interfacial area and they claimed that a tapered endosseous implant with a high elastic modulus is the most suitable form. In some researches, it has been claimed that taper design releases stress in the cortical bone and transfers more stress into trabecular bone.[31] However, in a recent FE study by Huang et al.,[32] it was concluded that stress was decreased in both cortical and trabecular bone using the taper body form. They attributed this to the increased depth of the thread in the tapered body which increased the interfacial area for the implant contact. From our point of view, this could not be a precise reason as the increase in interfacial area is seen in the threaded straight implants too.

On the other side, Mailath et al.[8] using FEA have reported that cylindrical implants were preferable to conical implant shapes. In another study, Siegel and Soltesz[10] compared cylindrical, conical stepped screw and hollow cylindrical implant shapes by means of FEA and indicated that implant surface with very small radius of curvature (conical) or geometric discontinuation induced distinctly higher stresses than smoother shapes (cylindrical, screw-shaped).

In our study, the peak tensile stress of cortical and trabecular bone were increased in taper body form compared to straight body with both triangular and square threads. It seems that the idea which claims that the taper body form increases the peak stress is much more realistic. Evaluating the effect of micro/double threaded region, the double threaded area in the cervical region caused a considerable decrease in the peak tensile and compressive stress of cortical bone. These features have some benefits over conventional threads. First, it increases the function contact area which benefits the osseointegration and stability in the cortical bone which is the most critical area. As it was demonstrated, the peak stress in all forms is in the crestal region. Having a wider contact area, because of increased thread pitch, enables better dissipation of stress and prevention of stress concentration.

Second, the reduced peak of stress in the cortical bone prevents resorption caused by overloading forces. This is a very precious finding which may benefit the new designs of dental implants. On the other hand, the ease of surgical placement is achieved using double threaded implants. This ease of surgical process is both in the increased pace of placement and increased bone tap.

Conclusion

The findings of the current study indicated that threaded implants, triangular thread form and taper body form had a higher peak of tensile and compressive stress than non-threaded implants, square thread form and straight body form, respectively. A taper implant with triangular threads which are doubled in the cervical portion of the body had a significantly lower peak of tensile and compressive stress in the cortical bone than straight/taper triangular or square threaded implant forms.

Limitations of this study can be stated as follow: first, this study only analyzed a bonded state in bone implant interface. For the investigation of interfacial stress, the non-bonded state is of importance too. Second, biologic variations may cause a significant variation in stress/strain pattern. So, confirmative clinical and biological studies are required in order to benefit the results of this study.

Acknowledgement

This article was prepared based on a thesis and a research project (# 387160) approved by the Medical Ethics and Research Office at the Isfahan University of Medical Sciences.

References

1. Cochran DL, Nummikoski PV, Higginbottom FL, Hermann JS, Makins SR, Buser D. Evaluation of an endosseous titanium implant with a sandblasted and acid-etched surface in the canine mandible: radiographic results. Clin Oral Implants Res 1996; 7(3): 240-52.
2. Cook RD, Malcus DS, Plesha ME. Concepts and Applications of Finite Element Analysis. 3rd ed. Canada: John Wiley & Sons; 2003. p. 234-48.
3. Weinstein AM, Klawitter JJ, Anand SC, Schuessler R. Stress analysis of porous rooted dental implants. Implantologist 1977; 1(2): 104-9.
4. Matsushita Y, Kitoh M, Mizuta K, Ikeda H, Suetsugu T. Two-dimensional FEM analysis of hydroxyapatite implants: diameter effects on stress distribution. J Oral Implantol 1990; 16(1): 6-11.
5. Holmgren EP, Seckingpr RJ, Kilgren LM, Mante F. Evaluating parameters of osseointegrated dental implants using finite element analysis –a two-dimensional comparative study examining the effects of implant diameter, implant shape, and load direction. J Oral Implantol 1998; 24(2): 80-8.
6. Lum LB. A biomechanical rationale for the use of short implants. J Oral Implantol 1991; 17(2): 126-31.
7. Stellingsma C, Meijer HJ, Raghoebar GM. Use of short endosseous implants and an over denture in the extremely resorted mandible: a five-year retrospective study. J Oral Maxillofac Surg 2000; 58(4): 382-7.
8. Mailath G, Stoiber B, Watzek G, Matejka M. Bone resorption at the entry of osseointegrated implants-a biomechanical phenomenon. Finite element study. Z Stomatol 1989; 86(4): 207-16.
9. Rieger MR, Farced K, Adams WK, Tanquist RA. Bone stress distribution for three endosseous

implants. J Prosthet Dent 1989; 61(2): 223-8.
10. Siegele D, Soltresz U. Numerical investigations of the influence of implant shape on stress distribution in the jaw bone. Int J Oral Maxillofac Implants 1989; 4(4): 333-40.
11. Clift SE, Fisher J, Edwards BN. Comparative analysis of bone stresses and strains in the Intoss dental implant with and without a flexible internal post. Proc Inst Mech Eng H 1995; 209(3): 139-47.
12. Schmid MR, Schiel HJ, lambrecht JT. Torque of endosseous dental screw type implants. Schweiz monatsschr Zahnmed 2002; 112(8): 804-13.
13. Tada S, Stegariou R, Kitamura E, Miyakawa O, Kusakari H. Influence of implant design and bone quality on stress/strain distribution in bone around implants: a 3-dimensional finite element analysis. Int J Oral maxillofac Implants 2003; 18(3): 357-68.
14. Akca k, Cehreli MC, Iplikciogu H. Evaluation of the mechanical characteristics of the implant abutment complex of a reduced-diameter morse-taper implant. A nonlinear finite element stress analysis. Clin Oral Implants Res 2003; 14(4): 444-54.
15. O'Mahony AM, Williams JL, Spencer P. Anisotropic elasticity of cortical and cancellous bone in the posterior mandible increases peri-implant stress and strain under oblique loading. Clin Oral Implants Res 2001; 12(6): 648-57.
16. Akca K, Iplikcigu H. Finite element stress analysis of the effect of short implant usage in place of cantilever extensions in mandibular posterior edentulism. J Oral rehabil 2002; 29(4): 350-6.
17. Eskitascioglu G, Usumez A, Sevimay M, Soykan E, Unsal E. The influence of occlusal loading location on stresses transferred to implant-supported prostheses and supporting bone: A three dimensional finite element study. J Prosthetic Dent 2004; 91(2): 144-50.
18. Misch CE. Dental Implant Prosthetics. 3rd ed. Philadelphia: Mosby; 2007. p. 212-2.
19. Fanuscu MI, Vu HV, Poncelet B. J implant biomechanics in grafted sinus: a finite element analysis. J oral Implantol 2004; 30(2): 59-68.
20. Ivanoff CJ, Sennerby L, Johansson C, Rangert B, Lekholm U. Influence of implant diameters on the integration of screw implants. An experimental study in rabbits. Int J Oral Maxillofac surg 1997; 26(2): 141-8.
21. Simunek A, Vokurkova J, Kopecka D, Celko M, Mounajjed R, Krulichova I, Skrabkova z. Evaluation of stability of titanium and hydroxyappatite-coated osseointegrated dental implants: a pilot study. Clin Oral Implant Res 2002; 13(1): 75-9.
22. Ko CC, Douglas WH, Delong R, Rohrer MD, Swift JQ, Hodges JS. An KN, Rittman EL, EL. Effects of implant healing time on crestal bone loss of a controlled –load dental implant. J Dent Res 2003; 82(8): 585-91.
23. Holmgren EP, Seckinger RJ, Kilgren LM, Mante F. Evaluating parameters of osseointegrated dental implants using finite element analysis-a two – dimensional comparative study examining the effects of implant diameter, implant shape, and load direction. J Oral Implantol 1998; 24(2): 80-8.
24. Huiskes R, Weinans H, Van Rietbergen B. The relationship between stress shielding and bone resorption around total hip stems and the effects of flexible materials. Clin Orthop Relat Res 1992; 274: 124-34.
25. Cook SD. Klawitter JJ, Weinstein AM The influence of implant geometry on the stress distribution around dental implants. J Biomed Mater Res 1982; 16(4): 369-79.
26. Nociti FH Jr J, Al-Shammari K, Misch C, Steigenga, Wang HL. Effects of implant thread geometry on percentage of osseointegration and resistance to reverse torque in the tibia of rabbits. J Periodontol 2004; 75(9): 1233-41.
27. Gao CD, Boring JG, Cooper RC Jr, Bumgardner J, Givaruangsawat S, gilbert JA, Misch CM, Steflik DE. Preliminary evaluation of a new dental implant design in canine models. Implant Dent 2000; 9(3): 252-60.
28. Patra AK, DePaolo JM, D'Souza KS, DeTolla D, Meenaghan MA. Guidelines for analysis and redesign of dental implants. Implant Dent 1998; 7(4): 355-68.
29. Huja SS, Qian H, Roberts WE, Katona TR. Effects of callus and bonding on strains in bone surrounding an implant under bending. Int J Oral Maxillofac Implants 1998; 13(5):630-8.
30. Rieger MR, Mayberry M, Brose MO. Finite element analysis of six endosseous implants. J Prosthet Dent 1990; 63(6): 671-6.
31. Morris HF, Ochi S, Orenstein IH, Petrazzuolo V. AICRG, Part V: Factors influencing implant stability at placement and their influence on survival of Ankylos implants. J Oral Implantol 2004; 30(3): 162-70.
32. Huang HL, Chang CH, Hsu JT, Fallgatter AM, Ko CC. Comparison of implant body designs and threaded designs of dental implants: a 3-dimensional finite element analysis. Int J Oral Maxillofac Implants 2007; 22(4): 551-62.