Dental Research Journal

Original Article

The effect of microthread design on magnitude and distribution of stresses in bone: A three-dimensional finite element analysis

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ABSTRACT

Background: The researches regarding the influence of microthread design variables on the stress distribution in bone and a biomechanically optimal design for implant neck are limited. The aim of the present study is to compare the effect of different microthread designs on crestal bone stress.
Materials and Methods: Six implant models were constructed for three-dimensional finite element analysis including two thread profile (coarse and fine) with three different lengths of microthreaded neck (1 mm, 2 mm, and 3 mm). A load of 200 N was applied in two angulations (0° and 30°) relative to the long axis of the implant and the resultant maximum von Mises equivalent (EQV), compressive, tensile, and shear stresses were measured.
Results: Regardless of loading angle, the highest EQV stress was concentrated in the cortical bone around the implant model using a 1 mm neck of fine microthreads. Under axial loading, there was a negative correlation between the length of the microthreaded neck and stress level in both profiles. However, the same pattern was not observed for coarse microthreads under oblique loads. All types of measured stresses in all constructed models were increased with oblique loading.
Conclusion: Peak stress levels in implant models varied with microthread profile and direction of loading. The microthread profile seemed more important than the length of the neck in reducing loading stresses exerted on the surrounding bone. Fine microthreads on a 3 mm implant neck showed consistently higher cortical bone stress than other models.

Key Words: Bone, dental implant-abutment design, finite element analysis, mechanical, stress

Received: October 2017
Accepted: February 2018

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INTRODUCTION

Marginal bone loss after dental implant placement is observed in many implant systems and after different surgical approaches.[1] It usually begins at the neck of the implant and spreads to the first thread of the body or the first contact between the bone and the rough surface of the implant.[2]

Implant crest module (i.e., transosteal region of dental implants that transfers stress to the adjacent crestal compact bone during loading)[3] is considered as one of the plausible etiologic factors that have been hypothesized for early crestal bone loss.[1] Originally, a machined implant neck was proposed to prevent plaque

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How to cite this article: Golmohammadi S, Eskandari A, Movahhedy MR, Shirmohammadi A, Amid R. The effect of microthread design on magnitude and distribution of stresses in bone: A three-dimensional finite element analysis. Dent Res J 2018;15:XX-XX.

accumulation.[4] However, later studies revealed a positive correlation between the length of the polished implant neck and the amount of crestal bone loss.[5] Interestingly, some finite element studies have shown that there is a concentration of greater stress contours at the crestal bone region,[6] which could potentially contribute to marginal bone loss. These new findings led to several modifications in crest module design. To diminish the marginal bone loss progression in the crestal region, Hansson in 1999, suggested considering retentive elements (e.g., a rough surface of suitable microarchitecture and/or a microthread) in the implant neck design from a biomechanical viewpoint.[7] Thereafter, numerous solutions were introduced with the aim of reducing the crestal bone resorption including platform switching,[8] different approaches of surface roughening, namely, TiOblast surface modification,[9] sandblast acid etched,[10] titanium plasma spray,[11] and laser microtexturing.[12] The incorporation of very small threads, so-called microthreads, with a favorable profile optimizes the stress distribution similar to commonly sized threads (i.e., macrothreads)[13] and its efficacy in preserving marginal bone has been documented in some animal studies[14] and clinical investigations.[2] In a short-term human study evaluating the bone loss there was no significant difference between the implants with macro- and micro-thread in the neck after 1 year of loading.[15]

Contrary to previous reports, a controversial publication by Schrotenboer *et al.*[16] indicated an increase in von Mises stress adjacent to microthreaded implant as compared to smooth neck. However, some questions regarding the condition of bone-implant interface, reliability of the material properties and precision of two-dimensional finite element modeling were raised.[17] Later, Hudieb *et al*.[18] stated that more compressive and less shear stress arising from a microthreaded implant neck clarifies the biomechanical aspect of this design.

Similar to extensive variability in main (macro) threads on the implant body the term "microthread" also could include myriads of design forms. In view of this great diversity and considering the controversy in previous finite element studies, we formulated this investigation to examine some of the microthread design parameters and introduce the most effective geometry which gives the biomechanical advantage of optimal stress distribution.

The aim of this study was to analyze the effect of microthread designs in crest module of the implant models under axial and oblique static loading to find out the optimal microthread design with the best stress transferring pattern.

MATERIALS AND METHODS

Construction of three-dimensional models

Six three-dimensional implant models as illustrated in Figure 1 were constructed with the ANSYS finite element analysis (FEA) program (ANSYS11.0, ANSYS, Canonsburg, PA).

The dimensions of constructed implant models were 4 mm diameter and 12 mm total length, the apical 4.5 mm of which was tapered by 4°. The implants were connected to an abutment of 5 mm height and 3 mm diameter through a polished collar of 0.5 mm height beveled by 45°. Six implants were categorized in two distinct groups of coarse and fine microthread profiles. Models number 1–3 had a neck length of 1, 2, and 3 mm, respectively, incorporating coarse microthreads, the depth and pitch of which were 0.15 mm and 0.3 mm. Models number 4–6 had fine microthreads, and the neck length was 1, 2, and 3 mm, respectively. The depth and pitch of fine microthreads were 0.07 mm and 0.15.

A bone model resembling the premolar region of an edentulous mandible was constructed as a block measuring 20 mm vertical height, 13 mm wide buccolingually, and 14 mm mesiodistally as a

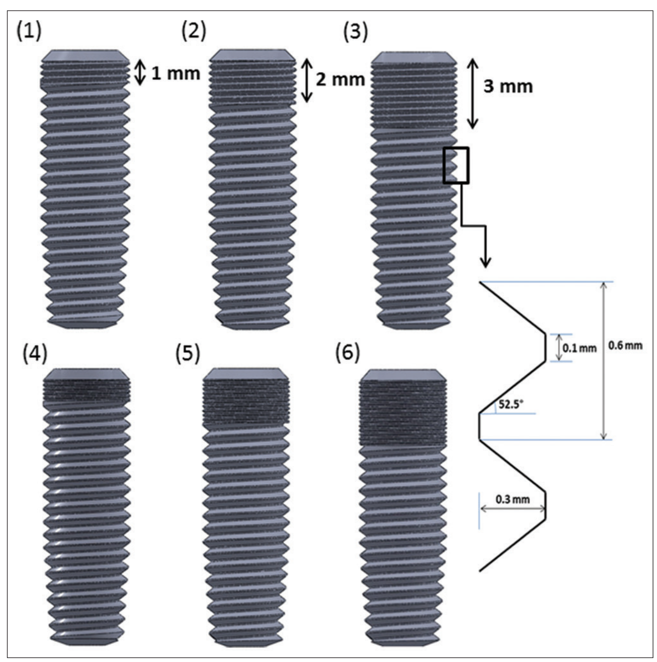

Figure 1: The solid models of six implant models and the design properties of main threads.

cancellous core with a 2 mm uniform thickness of the compact bone.

The physical properties of the different components used in this study are summarized in Table 1.[19,20] The material properties of cortical and cancellous bone were modeled as being transversely isotropic and linearly elastic, while the titanium alloy was assumed to be isotropic, homogeneous, and linearly elastic. The models were constrained on nodes of the mesial and distal surface in all directions. The bone-implant interface was assumed to be completely osseointegrated, i.e., it was rigidly anchored in the bone model along its entire surface. The same type of contact was provided at implant-abutment interface.

Elements and nodes

A 10-node tetrahedral element was used for the mesh in the bone and implant while the mesh in abutment consisted of 20-node hexagonal elements.

The finer mesh was generated at the interface of the implant and crestal bone, with the element size set to 0.1 mm in the cortical bone, while it was 1 mm elsewhere. Figure 2 illustrates one of the meshed models. Models were composed of 121298–144608 elements and 209597–247793 nodes with the least and most values for models number 2 and 5, respectively.

A static load of 200 N (i.e., the average maximum occlusal load for fixed partial dentures supported by implants in the premolar region[21]) was applied axially and 30° obliquely (buccal-to-lingual) to a surface corresponding the top of each abutment. Maximum and minimum principal stresses along with von Mises, shear and tensile stresses generated in the bone were calculated.

RESULTS

In both loading angles, the highest stress as a whole was concentrated in the cortical bone around the implant. Considering the differences between stress values in cortical and cancellous bone, the amounts and contours of stresses are discussed separately.

Cortical bone

Under axial load, the highest cortical bone stress was located buccally around the implant neck in model number 4 followed by 5. However, the least equivalent (EQV) stress was observed around model number 3. On the other hand, the model number 2 had the second most EQV stress under oblique load, after model number 4. The most favorable implant model in terms of EQV stress reduction in cortical bone was model number 3 [Figure 3]. Intragroup comparisons showed that under axial loading for each microthread profile the least stresses were generated around the 3 mm length of microthreaded neck. In other words, the more the length of the microthreaded neck, the less the maximum EQV stress in the cortical bone under 0° load. However, under oblique loads, although the same pattern was observed for fine microthreads; in the coarse group, the model number 2 generated the highest stress, followed by models number 3 and 1.

Cancellous bone

EQV stress magnitude in the cancellous region under axial load showed differences, depending on the length of the microthreaded portion and whether the microthreads were coarse or fine.

Table 1: Mechanical properties of the materials used in the study

Material	Young'sModulus E (MPa)	Poisson's ratio (υ)	Shear modulus G (MPa)
Ti–6Al–4V	110,000	0.32	
Cortical bone	E_x: 12,600	υ_{xy}: 0.300	G_{xy}: 4850
		υ_{yz}: 0.253	
	E_y: 12,600	υ_{xz}: 0.253	G_{yz}: 5700
		υ_{yx}: 0.300	
	E_z: 19,400	υ_{zy}: 0.390	G_{xz}: 5700
		υ_{zx}: 0.390	
Cancellous bone	E_x: 1148	υ_{xy}: 0.055	G_{xy}: 68
		υ_{yz}: 0.010	
	E_y: 210	υ_{xz}: 0.322	G_{yz}: 68
		υ_{yx}: 0.010	
	E_z: 1148	υ_{zy}: 0.055	G_{xz}: 434
		υ_{zx}: 0.322	

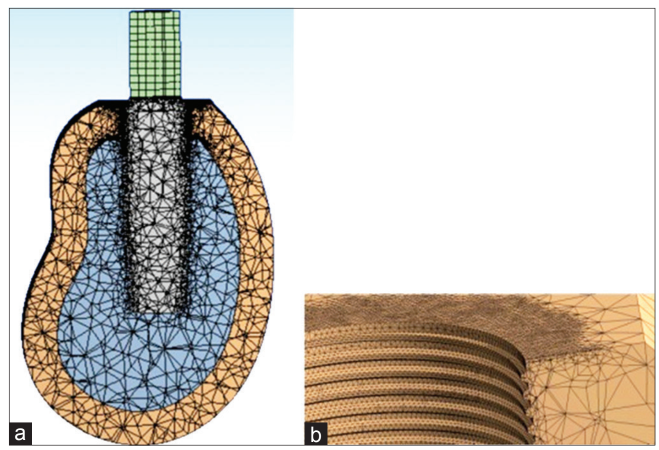

Figure 2: Cross-sectional view of the meshed model (a) and close-up view of the mesh in cortical bone adjacent to implant surface (b).

Highest stresses were present in models number 2 and 5 under axial and oblique loads, respectively. In both loading conditions, implant number 1 yielded the least amount of stress in the cancellous bone [Figure 4].

With regard to stress distribution, under 30° load, although the stress distribution showed a highly concentrated pattern on the pressure side of cortical bone, it followed a relatively homogeneous pattern with decrease in magnitude from bone-implant interface outward.

In cancellous bone, however, under axial loading only limited areas of stress could be observed in apical and coronal end of the trabecular portion of the bone block, while under oblique load higher stress with a uniform distribution along the implant body was observed, due to buccolingual component of the force. The compressive, shear, and tensile stresses of six implant models in two loading angles are shown in Table 2. In all tested models and under both loading angles, the highest stresses were of the compressive type, either in cortical or cancellous bone.

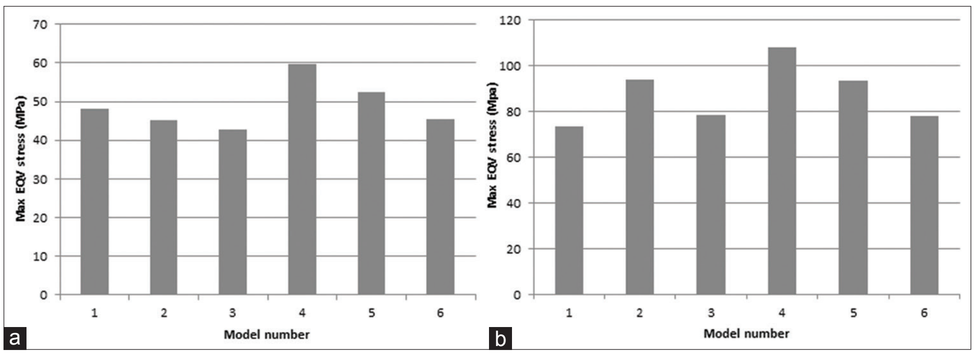

Figure 3: Maximum equivalent stress in cortical bone under axial (a) and oblique (b) loads.

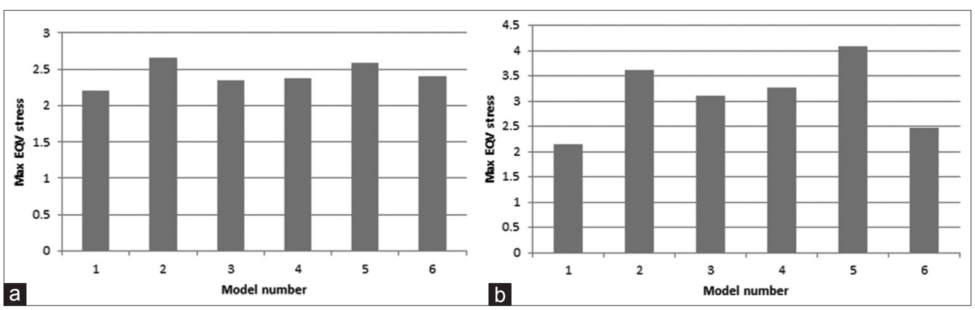

Figure 4: Maximum equivalent stress in cancellous bone under axial (a) and oblique (b) loads.

Table 2: Maximum stress values (MPa) shown separately for compressive, tensile, and shear types in cortical and cancellous bone

Microthread profile	Model number	Force angle (°)	Cortical bone			Cancellous bone		
			Compressive	Tensile	Shear	Compressive	Tensile	Shear
Coarse	1	0	58.53	48.97	26.47	0.72	2.59	1.25
		30	105.5	34.35	40.54	0.61	2.21	1.53
	2	0	57.82	45.07	25.11	0.76	3.18	1.49
		30	114.65	33.12	52.12	0.86	4.25	2.06
	3	0	48.83	40.93	24.48	0.79	3.12	1.3
		30	75.61	45.67	45	0.62	3.54	1.77
Fine	4	0	72.05	41.82	32.74	0.75	2.92	1.33
		30	136.3	46.67	61.05	0.66	3.79	1.87
	5	0	60.09	50.94	29.18	0.74	3.09	1.46
		30	97.38	46.59	53.8	0.75	4.83	2.32
	6	0	54.49	45.51	25.73	0.79	2.93	1.35
		30	87.83	41.85	44.61	0.78	3.13	1.58

DISCUSSION

The role of unfavorable loading conditions in bone loss around dental implants that might lead to implant failure has been emphasized in many animal[22] and clinical studies.[23] To cope with this resorption, macroscopic or microscopic modification of implant surface structure has been proposed.[24] However, the effectiveness of different neck configurations in preserving the marginal bone could not be established in a systematic review by Bateli *et al.*,[25] due to lack of sufficient evidence.

Microthread design as a macro-roughness and retentive element[7] has been used by several manufacturers in the implant neck, primarily due to the biomechanical advantage of the threads in converting the potential deleterious shear forces into compressive,[1] which the cortical bone withstands the best.[26] There are variable designs of small threads in implant neck all under the same name of "microthread" and all with a postulate of maintaining the bone, that makes it of benefit to investigate stress in bone and its relation to different design parameters of implant neck. The present study used FEA for evaluating the influence of implant neck design particularly microthreads on stress distribution in bone. Although FEA offers multiple advantages over other methods in simulating the complexity of clinical situations, it is also sensitive to the assignment of proper material properties, loading and boundary conditions.[27] Due to the simplifications made throughout the process of analysis, it only gives a general concept of stress variations under certain conditions, without resembling individual clinical situations. Thus, it is better to focus on qualitative comparison of stress distribution pattern rather than quantitative data.[28]

Previous FEA studies focusing on microthreads showed great variation in results. Some indicated an increase in marginal bone strain with the incorporation of microthreads in cervical portion of the implant,[29,30] while others emphasized on biomechanical advantage of microthreads due to the generation of compressive stresses.[18,31] This heterogeneity in studies could be the result of differences of the material properties, implant abutment connection designs, the fineness of mesh, element size and shape, and finally, the implant model. Although some studies precisely modeled rounded picks and valleys of the commercially available implants, others used models with sharp edges which could apparently cause stress concentration. We modeled the bone as a transversely isotropic and linearly elastic material which is a more realistic simulation of real bone properties and is believed to cause higher stress and strains in peri-implant bone.[27] Nevertheless, the physical characteristics assigned to bone in studies by Schrotenboer *et al*.[16] and Karimi *et al*.[31] were indicative of a homogenous and isotropic material, which is far from actual condition. Earlier reports on microthreads have compared this design feature either with platform switching,[16,30] or with smooth implant neck[18] or with macrothreads;[29] but different designs of microthreads have not been yet compared under the conditions of a same investigation. This results from a simplistic postulate that categorizes all shapes of small threads under the name of microthreads. Thus, although different studies have modeled various commercial implant systems with inherently dissimilar designs, the results of all these researches are accounted as the performance of microthreads.

In the present study, we could clearly demonstrate the superiority of coarse profile to fine microthreads, since in similar lengths the stress magnitude was consistently lower in coarse group, especially in cortical bone that greater differences in generated values made the comparison reasonable. However, in cancellous bone, given the minor discrepancies among tested models, only the extremities of stress values for each loading direction were compared quantitatively. According to the results of our study, it appears that correlation between the length of the neck incorporating coarse microthreads and the magnitude of stresses in cortical bone does not follow a similar pattern under both loading conditions.

In all models, there was an average of 42% increase in compressive stress values from 0° to 30° axial loading. Nevertheless, the increase in shear component of stress had a range of 35%–52%. Model number 1 showed the most favorable performance in cortical bone under oblique load, considering its low shear stress. Considering the fact that cortical bone is 65% more susceptible to shear forces than compressive ones, an effective reduction in deleterious shear forces, especially under nonaxial loading would be a beneficial characteristic of implant design.[1]

When the microthreaded implants with both coarse and fine profiles were loaded along the long axis of the body, the level of both shear and compressive stresses were enhanced with the increase of the neck length.

The same pattern was observed for fine microthreads under oblique load. However, conflicting results were observed for the coarse microthreads with oblique load, where model number 2 had the highest shear and compressive stresses. In other words, there was a distinction between optimal length of the neck with coarse microthreads under axial and oblique loads in cortical bone.

In cancellous bone, the stresses were higher for the 2 mm length of implant neck, in both loading conditions and for both microthread profiles. Interestingly, these two models were the ones with 2 mm length of microthreaded neck, exactly the same as the thickness of the cortical layer in bone models. However, since all surfaces in the study were considered to be bonded (i.e., with a frictional coefficient of 1) this finding could rather be attributed to the change in material properties from cortical to cancellous bone than concentration of surface stresses.

Frost[32] in 1989 suggested that microdamage arises in normal lamellar bone when the stress exceeds 45–60 MPa. In the present study, the maximum EQV stress values obtained for all models were below this threshold under axial loading. While under the oblique load of 30° all models showed higher stresses. To maximize the capacity of the implant to resist loads, it should be given such a design so that the peak stresses arising in the bone, as a result of a given load, are minimized. This is best addressed in model number 3 with the least amount of stress, especially less shear stress in comparison to other models.

CONCLUSION

Within the limitations of this study, this FEA suggested the following:

1. Oblique loading causes approximately 40% increase of the stress values in cortical bone compared to axial loading
2. The performance of coarse microthread profile was generally more favorable than fine profile since it caused less shear stress in the surrounding bone
3. The optimal length of the microthread area appears to be 3 mm.

Financial support and sponsorship

This paper was a Msc thesis project (n. 140) granted by Tabriz university of medical sciences.

Conflicts of interest

The authors of this manuscript declare that they have no conflicts of interest, real or perceived, financial or nonfinancial in this article.

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