Original Article

Factors affecting stresses in cortical bone around miniscrew implants
A three-dimensional finite element study

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ABSTRACT

Objective: To evaluate various types of stress in cortical bone around miniscrew implants using finite element analysis.

Materials and Methods: Twenty-six three-dimensional assemblies of miniscrew models placed in alveolar bone blocks were constructed using Abaqus (Dassault Systèmes Simulia Corp, Providence, RI), a commercial finite element analysis software package. The model variables included implant design factors and bone-related factors. All miniscrew implants were loaded in the mesial direction with a linear force equal to 2 N. Peak von Mises and principal stress values in cortical bone were compared between the different models for each factor.

Results: The results demonstrated that some factors affected the stresses in bone (implant diameter, implant head length, thread size, and elastic modulus of cancellous bone), while other factors did not (thread shape, thread pitch, and cortical bone thickness).

Conclusions: Miniscrew implant diameter, head length, and thread size as well as the elastic modulus of cancellous bone affect the stresses in cortical bone layer surrounding the miniscrew implant and may therefore affect its stability. (*Angle Orthod.* 2012;82:875–880.)

KEY WORDS: Miniscrew; Implant; TAD; Stress; Cortical bone

INTRODUCTION

Several clinical and in vitro studies evaluated and compared different miniscrew designs, but the results were often inconclusive and conflicting, which makes predicting the stability of miniscrew implants very difficult.[1–21] A few studies utilized the finite element method to study the effects of different miniscrew designs and variables.[10,21–25] Finite Element Analysis (FEA) is a computerized mathematical method that can be used to simulate mechanical systems to predict stresses within an object.

The von Mises stress can be used to predict failure according to the von Mises yield criterion, which states that yielding of a material occurs when the von Mises stress exceeds the yield strength in tension.[26] The von Mises yield criterion applies best to ductile materials such as metals. However, for brittle materials such as bone, the maximum principal stress criterion is commonly used instead of the von Mises yield criterion. The maximum principal stress criterion states that failure occurs when the maximum principal stress reaches either the ultimate tensile strength or the ultimate compressive strength.[27]

The objectives of the study were to use FEA to:

- evaluate the effects of miniscrew design factors and bone-related factors on the peak stresses within the peri-implant cortical bone layer and
- determine the risk of mechanical failure of peri-implant cortical bone.

MATERIALS AND METHODS

Miniscrew models were constructed using Abaqus 6.9 (Dassault Systèmes Simulia Corp, Providence, RI), a commercial FEA software package. Bone blocks

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Table 1. Material Properties Used in the Analysis

Material	Elastic Modulus	Poisson Ratio
Cortical bone[28]	13,700 MPa	0.3
Cancellous bone[28]	1300 MPa	0.3
Titanium[29]	110,000 MPa	0.3

were modeled as solid cubes with 20 mm height, width, and depth. The implant models were positioned inside the blocks, and a hole was created in each bone block using Boolean subtraction. The blocks were then sectioned into two layers corresponding to cortical and cancellous bone layers. All materials were assumed to be linear elastic, homogeneous, and isotropic. Material properties were obtained from previous studies and are presented in Table 1.[28,29]

Miniscrew implants and bone block models were meshed using 10-node quadratic tetrahedral elements C3D10M that are optimized for use in contact analyses.[30]

A mesh convergence analysis was carried out to determine the adequate mesh density to produce accurate results. The mesh was refined and the element size in the region of interest was reduced until the changes in node displacements and maximum von Mises stresses in two consecutive models were less than 5% as represented in the following formula: $[S(i+1)-S(i)]/S(i) < 5\%$, where S is the maximum von Mises stress.

The total number of elements per model ranged from 48,210 to 133,436, and the number of nodes ranged from 112,304 to 304,141, depending on the size of the miniscrew model. Implant threads were omitted within the cortical bone area, which is the primary region of interest in order to avoid stress singularities caused by the sharp edges of the threads.

The relationship between implant and bone models was defined as a contact interaction with finite sliding and a coefficient of friction equal to 0.2 as suggested by Lombardo et al.[24] Friction was imposed using the stiffness method for friction in Abaqus/Standard.[30]

A linear concentrated force equal to 2 N was applied in the mesial direction to the midpoint of the top surface of the miniscrew on a plane parallel to the bone surface.

Boundary conditions were applied to immobilize all sides and the bottom surface of the bone blocks. Additional boundary conditions were applied to the point of force application to restrain movement in all directions except the direction of applied force.

The investigated factors were studied in the following order: miniscrew design variables (intrabony length, diameter, taper, implant head length, thread shape, thread size, and thread pitch) and bone-related factors (cortical bone thickness and elastic modulus of cancellous bone). The study was carried out in a stepwise manner in which one variable was investigated at a time, while all other variables were controlled. The control variables are presented in Table 2.

Table 2. Control Variables

Variable	Control Value
Intrabony length	6 mm
Total diameter	1.4 mm
Taper	Cylindrical
Miniscrew head length	3 mm
Thread size	0.1 mm
Thread shape	Asymmetric triangle
Thread pitch	0.5 mm
Cortical bone thickness	1 mm
Elastic modulus of cancellous bone	1300 MPa

Peak von Mises stress values were reported for the cortical bone layer to provide an indication of the average stress levels and to compare the stresses in different models. Peak first and third principal stresses were reported to determine local risk indicators of physiologic bone failure, which is assumed to occur when the ultimate strength is exceeded. In the present study, the first principal stress had positive values indicating tension, while the third principal stresses had negative values indicating compression. Based on the maximum principal stress theory, local overloading within the cortical bone was assumed to occur when the peak first principal stress reached the ultimate tensile strength (100–130 MPa) or when the peak third principal stress reached the ultimate compressive strength (170–190 MPa).[31,32]

All tables and charts were created using Microsoft Excel 2007 (Microsoft Corporation, Redmond, Wash). Statistical significance analyses were not carried out since the results of FEA are individual values without any statistical spread.

RESULTS

Stress distribution was similar among all models. Figure 1 shows an overall view of von Mises stress contours in bone in one of the models. Peak von Mises stress values in cortical bone were located at the edge surrounding the implant neck on the side of compression.

Peak von Mises, first and third principal stress values in cortical bone for all models are presented in Table 3.

Intrabony Length

Changing the intrabony length of the miniscrew did not have a considerable effect on the maximum von Mises stress in cortical. Peak principal stress values in

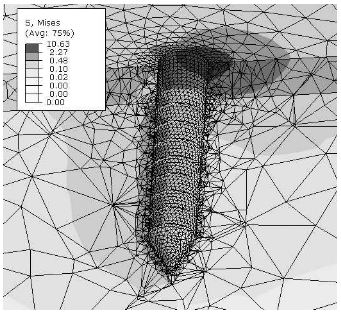

Figure 1. A cross section in a bone block demonstrating von Mises stress contours in alveolar bone (MPa).

cortical bone were well below the ultimate tensile and compressive strengths of cortical bone.

Diameter

The maximum von Mises stress in cortical bone decreased by increasing the diameter (Figure 2). The percentage decrease when the total diameter of the miniscrew was increased from 1.4 mm (10.6 MPa) to 2.0 mm (3.7 MPa) was 65%. None of the peak stresses within cortical bone exceeded their respective ultimate strength limits.

Taper

The fully-tapered (conical) miniscrew produced the highest maximum von Mises stress in cortical bone (11.7 MPa) compared to the cylindrical (10.6 MPa) and half-tapered miniscrew (9.7 MPa). Local overloading did not occur in any of the miniscrews with different tapers.

Implant Head Length

Increasing the miniscrew head length caused a proportional increase in the maximum von Mises stresses in cortical bone (Figure 3). Compared to the 6-mm head length, the maximum von Mises stresses for the miniscrew with 2-mm head length decreased 59% in cortical bone (18.9 to 7.9 MPa). Local overloading did not occur in any of the models.

Table 3. Peak von Mises, First, and Third Principal Stresses (MPa) in Peri-implant Cortical Bone for All Models

		Cortical Bone		
		von Mises Stress	First Principal Stress	Third Principal Stress
Intrabony length	4 mm	10.72	3.57	−10.48
	6 mm	10.63	3.34	−10.61
	8 mm	10.51	3.34	−10.45
	10 mm	9.96	3.32	−9.77
	12 mm	10.51	3.35	−10.43
Total diameter	1.4 mm	10.63	3.34	−10.61
	1.6 mm	6.94	2.32	−6.72
	1.8 mm	5.10	1.76	−4.87
	2.0 mm	3.74	1.37	−3.46
Taper	Cylindrical	10.63	3.34	−10.61
	Half-tapered	9.66	3.37	−9.55
	Fully tapered	11.73	3.66	−11.90
Miniscrew head length	2 mm	7.76	2.67	−7.40
	3 mm	10.63	3.34	−10.61
	4 mm	13.06	4.00	−13.40
	5 mm	16.23	4.68	−17.13
	6 mm	18.91	5.43	−19.97
Thread size	No thread	7.12	2.36	−6.81
	0.1 mm	10.63	3.34	−10.61
	0.2 mm	16.41	5.21	−16.62
	0.3 mm	27.57	9.11	−27.97
Thread shape	No thread	10.51	3.34	−10.33
	Asymmterical triangle	10.63	3.34	−10.61
	Symmterical triangle	10.44	3.34	−10.42
Thread pitch	0.5 mm	10.63	3.34	−10.61
	0.75 mm	10.44	3.34	−10.40
	1.0 mm	9.65	3.32	−9.73
Cortical bone thickness	0.5 mm	10.53	4.07	−10.34
	1.0 mm	10.63	3.34	−10.61
	1.5 mm	10.59	3.26	−10.43
	2.0 mm	9.94	3.24	−9.66
Elastic modulus of cancellous bone	100 MPa	11.91	3.80	−11.89
	700 MPa	10.75	3.41	−10.73
	1300 MPa	10.63	3.34	−10.61

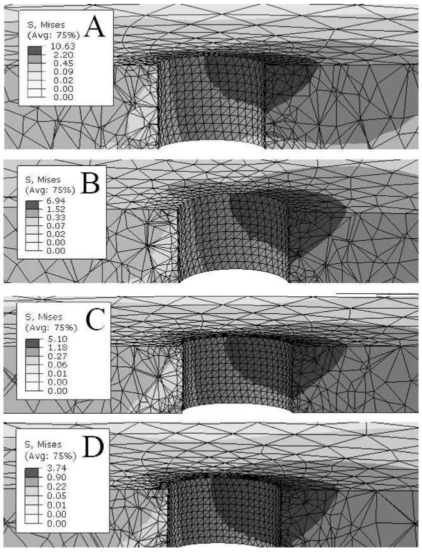

Figure 2. Von Mises stress contours in cortical bone (MPa) for miniscrews with (A) 1.4-mm, (B) 1.6-mm, (C) 1.8-mm, and (D) 2.0-mm total miniscrew diameter. Increasing the diameter reduces the maximum stress.

Thread Shape

Thread shape did not influence the maximum von Mises stress values in cortical bone. Local overloading did not occur in any of the models.

Thread Size

Increasing the thread size (height and width) while decreasing the miniscrew core diameter to maintain the total diameter caused an increase in stresses in cortical bone. The miniscrew without threads of a total 1.4-mm diameter produced the lowest stress in cortical bone (7.1 MPa), while the miniscrew with 0.3-mm thread and 0.8-mm core diameter produced the highest stresses in cortical bone (16.5 MPa). Reducing the thread size from 0.3 mm to 0.1 mm decreased the maximum von Mises stress in cortical bone by 61%.

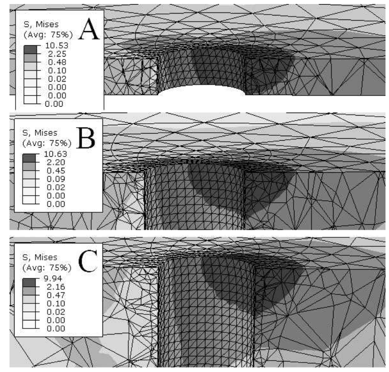

Figure 4. Von Mises stress contours in cortical bone for (A) 0.5-mm, (B) 1.0-mm, and (C) 2.0-mm cortical bone thickness.

Peak stresses did not indicate a risk of overloading in any of the models.

Thread Pitch

Increasing the distance between miniscrew threads from 0.5 mm to 1.0 mm decreased the stress in cortical bone from 10.6 MPa to 9.6 MPa (9% decrease). Local overloading did not occur in any of the models.

Cortical Bone Thickness

Cortical bone thickness had negligible effects on the maximum von Mises stresses in cortical bone (Figure 4). Local overloading did not occur in any of the models with different cortical bone thicknesses.

Elastic Modulus of Cancellous Bone

Increasing the elastic modulus of cancellous bone from 100 MPa to 700 MPa reduced the maximum von Mises stress in cortical bone from 11.9 MPa to 10.8 MPa (10% decrease). Changing the elastic modulus from 700 MPa to 1300 MPa caused negligible changes in the maximum von Mises stresses. Local overloading did not occur in any of the models.

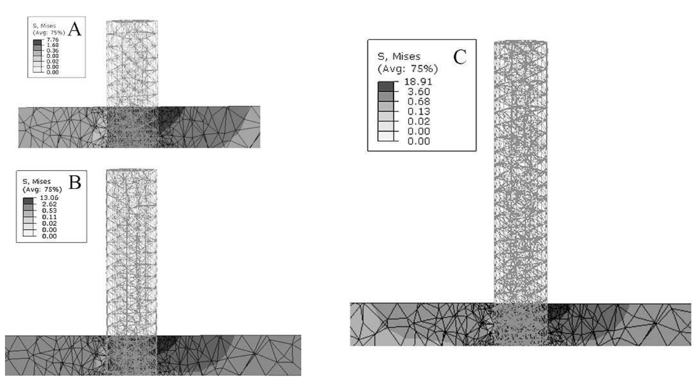

Figure 3. Von Mises stress contours in cortical bone (MPa) for miniscrews with (A) 2-mm, (B) 4-mm, and (C) 6-mm extra-body miniscrew head length. Increasing the length increases the maximum stress.

DISCUSSION

The miniscrew-bone interface was modeled with 100% contact, which does not represent a real-life situation. Nevertheless, a 100% contact was assumed for simplicity and to represent the best possible relationship between bone and the implant.

The material properties used in the present study assumed that all materials are linear, homogeneous, and isotropic. In reality, bone is neither homogeneous nor isotropic,[25] but those properties were assumed for simplicity and because of lack of information on bone behavior. Additionally, all similar FEA studies assumed the same properties.[10,21,24,25]

Stress contours shown in Figure 1 show that the majority of stress in bone is transferred to the cortical layer on the side of compression. Similar results were found by Dalstra et al.[29] and Gracco et al.,[25] indicating that cortical bone absorbs most of the stress and therefore may be the determining factor in miniscrew stability.

The study results show that miniscrew design may have a significant influence on the stresses in peri-implant bone thereby affecting the stability. The importance of miniscrew length has been investigated in several studies, most of which concluded that it does not significantly affect the miniscrew stability.[1,3,5,19,33] Some studies, however, found some differences in stability between miniscrews of different lengths.[14,17,25] The results of the present study indicate that intrabony miniscrew length does not affect stresses in cortical bone.

Increasing the miniscrew extrabony head length caused an increase in the stresses in bone and may therefore compromise the stability. Using miniscrews with longer heads is inevitable in palatine alveolar sites because of increased soft tissue thickness. In those instances, using a miniscrew with a larger diameter is recommended to enhance stability.

Most previous studies reported that the total miniscrew diameter has a major influence on miniscrew stability.[1,11,13,14,16] Two aspects of miniscrew diameter were investigated in this study: total miniscrew diameter and thread size. The findings suggest that the core diameter has a larger effect on stress levels as opposed to the total diameter. This means that for two miniscrews with the same outer diameter, the miniscrew with the larger core diameter may be more stable.

Implant taper had a minimal effect on the stresses in bone, although, miniscrews with half-tapered shanks have some advantage over cylindrical and fully tapered miniscrews when comparing the stresses in cortical bone.

Thread shape and pitch also had minimal effects on the stresses in bone. Similarly, Brinley et al.[18] found a minimal advantage of miniscrews with more threads per unit length. As a result, thread design and pitch should be determined by other factors such as ease of insertion, which is better when threads have an asymmetrical profile according to Carano et al.[2]

Based on what we found in this study and what was found in other studies, it appears that the most critical miniscrew design factors affecting the stability are the diameter and extrabony head length. Therefore, clinicians should use miniscrews with larger diameters and shorter heads whenever possible.

It is generally believed that cortical bone thickness and cancellous bone quality are principal factors contributing to the stability of miniscrews.[34] Miyawaki et al.[1] suggested that cortical bone thickness may affect miniscrew stability. Motoyoshi et al.[6,10,23] concluded that the minimum cortical bone thickness to ensure miniscrew stability was 1 mm. The results of this study indicate that cortical bone thickness had minimal effect on peak stress levels in cortical bone. Motoyoshi et al.[10] reported a similar finding but observed that the stresses in cancellous bone increased significantly when the cortical bone thickness was less than 1 mm. In this study, the stress contours show that if mechanical overloading and fracture occurs in the highest stress areas in cortical bone. The miniscrew would lose almost all cortical bone support if the thickness is 0.5 mm, while some support will be maintained if cortical bone thickness was 1 mm or more (Figure 4).

The elastic modulus of cancellous bone depends on the bone density and quality. The results indicate that the elastic modulus has little effect on the stresses in cortical bone unless it is below 700 MPa. The recommendation, based on the findings of this study, is to select sites for miniscrew placement with adequate cortical bone thickness and cancellous bone density to ensure proper stability. Some studies examined miniscrew placement sites to provide such information about bone thickness and density in different locations.[35,36]

CONCLUSIONS

Within the limitations of this study, we concluded the following:

- The intrabony length, thread shape, and thread pitch of the miniscrew implant and cortical bone thickness did not affect the stresses within the peri-implant cortical bone layer.
- Increasing the implant diameter reduces stresses in cortical bone. The core diameter of the miniscrew implant is more critical than the total diameter.
- Cylindrical and half-tapered implants caused less stress in cortical bone than fully-tapered implants.
- Increasing the extrabony head length of implants increases the stresses in bone.

- Decreasing the elastic modulus of cancellous bone increases stresses in cortical bone.

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