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Evaluation of Stress Levels of Dental Implants in Different Macrogeometry in Type 2 Bone: A Finite Element Analysis

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ABSTRACT

Objective: Implant geometry has an impact on the initial implant stability in the surrounding bone, stress distributions, and long-term success. The purpose of this finite element study was to measure and compare the stress values formed during the stepwise placement of conical and cylindrical implants in the Type 2 bone.

Methods: Conical and cylindrical implants (3.75-mm in diameter, 10-mm in length) were planned to be placed in the Type 2 bone. Stresses during insertion of the implants with clockwise torque of 450 N were measured 0.5-, 1-, and 1.5-mm distance from the implant and 2-10 mm depths between two millimeters apart. Maximum and minimum principal stresses and von Mises stresses in the cortical and trabecular bone were evaluated with a three-dimensional finite element analysis.

Results: The conical implant was created higher stress values than the cylindrical implant in the same condition, and the cortical bone showed higher stresses than the trabecular bone during the placement of both implants. Besides, the stress values were decreased as the depth increased and the distance from the implant decreased, as the depth increased from 2-mm to 10-mm and the distance from the implant decreased from 1.5-mm to 0.5-mm.

Conclusion: When the stresses generated in the cortical and trabecular bone surrounding the implant were evaluated, the cylindrical implant was found to be more advantageous than the conical implant of the same length and diameter.

Keywords: dental implant, dental implantation, dental stress analysis, finite element analysis

1. INTRODUCTION

The concept of osseointegration, which is a sign of implant success, was first described by Branemark and defines structural and functional linkage between living bone tissue and the surface of the implant (1-3).

Successful osseointegration depends on many factors. The first of which is the bony dependent factors such as bone quality and density, a width of the bone around the implant. Another factor is the macro-geometry of the implant because the implant geometry may influence the initial implant stability and stress distributions in the surrounding bone (4-8). The surgical technique is also an effective factor in successful osseointegration and plays a role in the success of osseointegration by acting in the implant placement process and final fixation. In addition to the surgical technique, the placement process of implants also plays a role in the success of osseointegration by affecting the stress distribution in the surrounding structures. It is very important to place the implants with controlled insertion torque in the implant slots. Because this process supports bone healing, helps to minimize stress distribution, and prevents bone fracture (9-13).

The stress in the cortical and trabecular bones around the implant is known to play an important role in the success of the implant. The response of bone healing or resorption is directly related to the stress within the bone, as stated in Wolf's theory (14,15). Low-stress levels around the implant may cause disuse atrophy; conversely, abnormally high-stress levels can cause pressure necrosis and failure of the implant due to this necrosis (16,17). Because of these facts, successful osseointegration can be achieved by optimization of stress and biomechanical interaction between bone and implant. The optimization of the stress in the surrounding bone during implant insertion was thought to increase clinical success. Damage to the bone at the microscopic level, along with increased stress, affects bone formation and remodeling, leading to bone resorption and decreased success of the osseointegration process, thereby reducing implant success (18). Understanding of relations between stress distribution in the surrounding bone, implant

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geometry, and osseointegration principles is so important for successful implant applications. In the literature, studies evaluating the stresses that occur during implant placement and the effects of different implant geometries on these stresses are insufficient (19,20).

The purpose of this this research was to measure and compare the stress values formed during the stepwise placement of conical and cylindrical implants in the Type 2 bone in mandibular posterior jaw models at each 2-mm depth and 0.5-mm to 1.5-mm distance from the implant, using three-dimensional finite element analysis (3D FEA). The hypothesis was: In implants of the same length and diameter applied to bones with the same properties, the implant with cylindrical macro-geometry will create less bone stress than the one with conical macro-geometry.

2. METHODS

In this experimental study, FEA was used to analyze stress around cylindrical and conical implants caused by placement in the mandible. Implants and bone structures were modeled on a personal computer (Intel Xeon® CPU 3.30 GHz, USA) using a 3D FEA program (ALGOR Fempro, ALGOR, Inc. USA) from computed tomography (CT) images. Data attainment for bone dimensions was based on CT images. According to the classification system of Lekholm and Zarb, a mandibular bone model representing Type 2 bone was selected (21). The jaw section modeled presented with a height of more than 10-mm and a width of more than 7-mm, representing the section of the mandibular molar region. Gingival soft tissue was not modeled. Trabecular bone was modeled as a solid structure in the cortical bone (Fig. 1a, 1b).

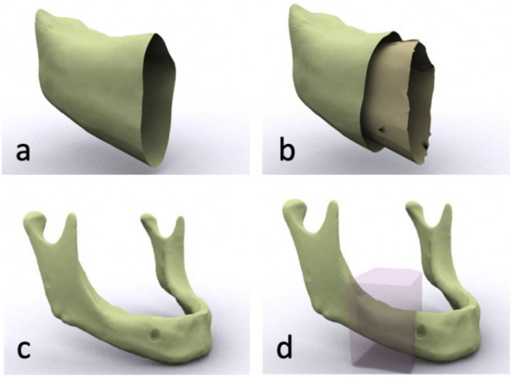

Figure 1. *a,b. Cortical and trabecular bone solid structures. c,d. Mandibular model and selection of the study model with Boolean operation*

The thickness of cortical bone created in the crestal region was 2.0-mm, and 1.0-mm in the buccal and lingual regions, with Rhinoceros 4.0 (Robert Mcneel & Associates, USA). The mesiodistal and inferior planes were not covered by cortical bone. When aggregating the components, Boolean operations were used to subtract the mandibular posterior region from the modeled mandible (Fig. 1c, 1d).

Implants were created with two different geometries. Using Rhinoceros 4.0, cylindrical and conical implant models were constructed, followed by meshing. The length (L) and diameter (D) of the implants were assumed to be L: 10 mm and D: 3.75 mm. For the implants, V-shaped threads were prepared, and the thread pitch was designed to be 0.6-mm. An initial cylindrical insertion cavity diameter was created less than the inner diameters of the cylindrical and conical implants.

All materials used in modeling were assumed to be isotropic, homogeneous, and linearly elastic (19,22-24). The elastic properties of the materials such as Young's modulus (E) and Poisson ratio (μ) were taken from literature, and these parameters were summarized in Table 1. After the materials data were defined in the system/software (Rhinoceros 4.0), models have mashed with 10-node-tetrahedron elements. A finer mesh was used around the implants. In cylindrical implant models 399 472 – 427 088 elements and 73 852 – 76 272 nodes, and in conical implant models 430 281 – 464 151elements and 79 315 – 82 497 nodes were used.

Table 1. *Material properties of materials used in the 3D FEM models.*

Materials	Young's modulus (Gpa)	Poisson ratio (μ)	References
Cortical Bone	13.0	0.3	(24)
Trabecular Bone	1.37	0.3	(18)
Titanium	102	0.3	(24)

An important criterion for simulating implant insertion technique is the boundary. The applied torque is positioned at the top of the implant. To analyze the model standing in space, it was fixed from peripheral points to prevent rigid body motions of assembly, and the boundaries were defined. The rigid implant was only allowed to rotate and move downward in the Z direction. A clockwise torque of 450 N mm was applied to the top of the implants. The insertion process was modeled in a step-wise manner with a torque applied to the implants that do not change with time.

After the torque application, stress values were measured at each depth of 2-mm and distances of 0.5-, 1-, and 1.5-mm from cylindrical and conical implants within the cortical and trabecular bone. These stress values were measured in the distal, mesial, buccal, and lingual aspects of the implant and evaluated by taking the average of these values. The analyses were made by von Mises, maximum (tensile stress), and minimum (compressive stress) principal stress in the cortical and trabecular bone around the implant system. Data were indicated numerically, color-coded, and compared among the models.

The descriptive statistic general linear model was used for the comparison of the stresses formed for both implants. Evaluations and comparisons of both implant systems were done with univariate analysis.

3. RESULTS

The von Mises stress, which is the maximum principal and minimum principal stresses for conical and cylindrical implants, were evaluated within the trabecular and cortical bone. Stress values were measured along with implants each 2-mm and three different distances from implants. The stress distributions within cortical and trabecular bone for each stage of insertion are shown in Figure 2 with color-coding.

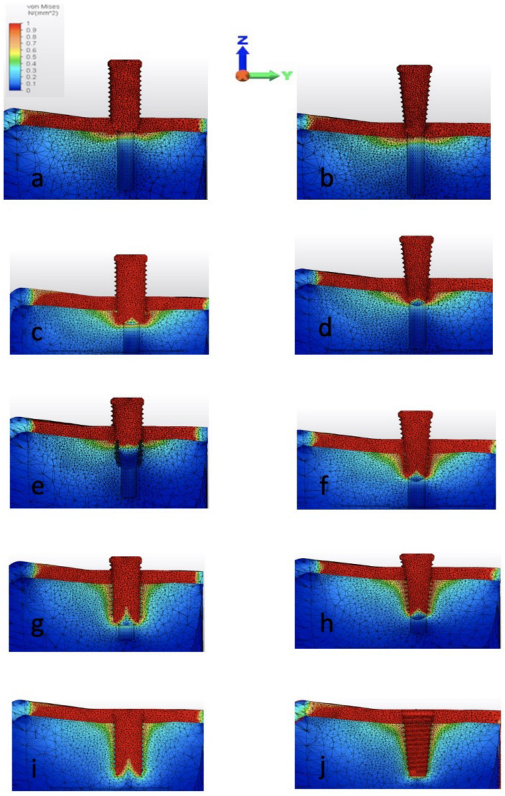

Figure 2. *von Mises stress with color coded projections of each 2-mm depth of cylindrical and conical implants. The stress distribution in the bone at a depth of 2-mm is (a) and (b), the stress distribution at the depth of 4-mm (c) and (d), the stress distribution in the bone at a depth of 6-mm is (e) and (f), the stress distribution in the bone at a depth of 8-mm is (g) and (h) and the stress distribution in the bone at a depth of 10-mm is (i) and (j)*

The implant design tended to obviously influence the bone stresses of both bone components. When comparing two different implant geometries, the conical implant created more von Mises stress than the cylindrical implant in the cortical bone at all depths. In the trabecular bone, although stress values fluctuate as the depth increases, at 10-mm depth, which is exactly located in the insertion hole, the conical implant was found to have more stress than the cylindrical implant. Maximum and minimum principal stress values also show similar results (Table 2 and 3).

The maximum stress values for both implants were observed in the cortical bone adjacent to the implant surface. The von Mises stress in the cortical bone is significantly higher than that in the trabecular bone for both implants (Table 2 and3). For instance, whereas the average stress value was 15.75 MPa when the conical implant was 2-mm in the cortical bone and 1-mm away from the implant, the stress value in the trabecular bone at the same conditions was 0.97 MPa. The highest average von Mises stress in the cortical bone concentrated at 0.5-mm away from the conical implant and the average value was 32.18 MPa. Similar results were obtained for maximum and minimum principal stress values (Table 3)

Table 2. *Average stress values during the placement of the cylindrical implant into the cortical and trabecular bone (MPa)*

	Distance from implant	2 mm	4 mm	6 mm	8 mm	10 mm
		von Mises stress				
Cortical bone	**0.5 mm**	21.84	17.70	17.56	15.29	16.03
	1 mm	11.18	9.63	9.70	8.52	9.67
	1.5 mm	6.60	5.88	5.97	5.22	5.74
	Maximum principal stress					
	0.5 mm	12.90	10.32	10.15	8.75	9.44
	1 mm	6.67	5.64	5.64	4.91	5.61
	1.5 mm	3.85	3.35	3.43	3.01	3.30
	Minimum principal stress					
	0.5 mm	-12.30	-10.10	-10.11	-8.89	-9.06
	1 mm	-6.44	-5.47	-5.55	-4.92	-5.49
	1.5 mm	-3.76	-3.42	-3.45	-3.00	-3.32
Trabecular bone	**von Mises stress**					
	0.5 mm	1.09	0.97	1.37	0.75	0.72
	1 mm	1.05	0.74	1.03	0.62	0.62
	1.5 mm	0.88	0.61	0.77	0.52	0.53
	Maximum principal stress					
	0.5 mm	0.64	0.58	0.77	0.43	0.41
	1 mm	0.61	0.43	0.59	0.35	0.36
	1.5 mm	0.51	0.35	0.44	0.30	0.30
	Minimum principal stress					
	0.5 mm	-0.61	-0.53	-0.80	-0.43	-0.42
	1 mm	-0.60	-0.42	-0.60	-0.35	-0.35
	1.5 mm	-0.50	-0.34	-0.20	-0.29	-0.30

Table 3. *Average stress values during the placement of the conical implant into the cortical and trabecular bone (MPa)*

	Distance from implant	2 mm	4 mm	6 mm	8 mm	10mm
		von Mises stress				
Cortical bone	0.5 mm	32.18	28.03	25.48	19.56	17.48
	1 mm	15.75	14.12	12.95	10.65	10.17
	1.5 mm	8.89	8.35	7.62	6.31	6.25
	Maximum principal stress					
	0.5 mm	25.79	16.42	14.70	11.33	10.04
	1 mm	11.91	8.22	7.59	6.12	5.85
	1.5 mm	6.31	4.84	4.46	3.60	3.63
	Minimum principal stress					
	0.5 mm	-17.92	-15.92	-14.69	-11.23	-10.13
	1 mm	-8.92	-8.07	-7.35	-6.17	-5.89
	1.5 mm	-5.13	-4.79	-4.33	-3.67	-3.58
Trabecular bone	von Mises					
	0.5 mm	1.04	1.29	1.01	0.90	0.77
	1 mm	0.97	1.02	0.82	0.74	0.67
	1.5 mm	0.86	0.80	0.66	0.61	0.56
	Maximum principal stress					
	0.5 mm	0.61	0.74	0.58	0.52	0.45
	1 mm	0.56	0.58	0.48	0.44	0.39
	1.5 mm	0.50	0.46	0.38	0.35	0.33
	Minimum principal stress					
	0.5 mm	-0.58	-0.75	-0.58	-0.51	-0.44
	1 mm	-0.56	-0.58	-0.47	-0.42	-0.38
	1.5 mm	-0.49	-0.46	-0.38	-0.35	-0.32

As the distance from the implant surface decreased, the stress values formed in both the cortical and trabecular bones diminished significantly. The highest stress values in three stresses obtained in the study were measured at a distance of 0.5-mm from the implant in cortical bone, and the stress values in the trabecular bone support this result (Table 2 and 3).

As the implant is placed into the insertion hole, that is, as the depth of the implant in the bone increases, the stress values affecting the trabecular and cortical bone decrease. This result was common for both implants and all types of stress. Values at a depth of 2-mm are significantly higher than values at 10-mm (Table 2 and 3). For instance, the average von Mises stress value in the cortical bone at 0.5-mm distance from the cylindrical implant was found to be 21.84 MPa when measured at 2-mm depth. At a depth of 10-mm, the value decreased to 16.03 MPa (Table 2). Similarly, Table 2 and 3 show that the maximum and minimum principal stress values decrease from 2-mm depth to 10-mm depth.

The minimum and maximum principal stress values, which express the compression and tension, were also high during the placement of the conical implant in the bone, similar to von Mises stress (Table 3).

4. DISCUSSION

Implant stability is explained by the concept of primary and secondary stability. Primary stability describes the mechanical connection between the bone-implant after implant placement and hinges on the implant's micro-mobility, bone density, implant placement, and implant design (25,26). Bone strains and stresses function in the threshold range of bone modeling, and modeling creates a stronger bone structure. On the other hand, strains and stresses surpass the range, micro damages and cracks in the bone matrix occur, and bone resorption occurs inevitably (26,28). Direct mathematical approaches, especially FEA is widely used as it has the advantage of measuring stress, strain, and deformation in bone structures (29,30).

To the best of our knowledge, few studies have used the FEA models to simulate dental implant insertion and the specific issue of primary stability (20,31). It has been stated that a torque of 300 to 500 N was observed to be suitable for implant placement. In the current study, similar to other studies, we planned for measurement and comparison of stresses occurring during cylindrical and conical implants with 450 N torque in type 2 bone. We can evaluate and compare the stress independently and objectively by keeping the diameter and length of implant constant.

The stress distribution in the bone is multifactorial and among these, macro-geometry is one of the most important factors (6,19,31,32). The understanding of the effects of different geometries in different bone qualities is important in the selection of implants and long-term success (16). The earlier implants were produced with a cylindrical shape. However, this design has not been yielded a successful result in all situations (7,8). Conical implants were introduced for immediate insertion into an extraction socket due to the capacity of engaging the bone walls and minimizing the need for bone graft procedures (33,34). Despite the developments of new implant models, the implants used today are gathered under two main designs, cylindrical and conical; and, minimizing the stress distribution they create in the bones is one of the main issues of dental implantology. Using FEA, the previous studies compared the von Mises stress concentrations of conical and cylindrical implant shapes at the site of implant entry into bone, and they reported that cylindrical implants were preferred to the conical implant (35,36). Patra et al. and Himmlova et al. also found similar results in their studies (37,38). As Siegele and Soltesz also compared cylindrical, conical, stepped, screw, and hollow cylindrical implant shapes, the researchers reported that implant shapes lead to significant variations in stress distribution in the bone under loading (39). By evaluating the stress values of the two most commonly used implant geometries placed in type 2 bones in this study, we aimed to create a question mark in the minds of clinicians about the circumstances in which conical or cylindrical implants should be preferred. The results were found to be parallel to the previous studies that the conical implants had high values in von Mises stress compared with cylindrical implants into the bone.

There are many studies in the literature that optimize the shape of the implant surface and thread and change the fixture design in order to minimize crestal bone resorption by reducing the stress value in cortical alveolar crest (18,40,41). In most studies, it has been found that implant type and length do not affect the stress distribution in the cortical bone (19). Contrary to these studies, in the current study, the von Mises stresses during implant insertion into the cortical bone were significantly higher than in the trabecular bone for all models. In the cylindrical implant model, stress levels measured at a depth of 2-mm and a distance of 0.5-mm were found 21 times higher than the value of von Mises stress occurring in the cortical bone. This result may be due to the fact that the cortical bone has a higher modulus of elasticity (Young's modulus) than the trabecular bone and thus is stronger and more resistant to deformation (15,42,43).

In many finite element studies in the literature; It was determined that the highest von Mises stress values occurred in the bone region adjacent to the implant, while the stress values decreased in the apical region (19,24,38,42,44). Similar to previous finite element analysis studies, in the present study, the lowest von Mises stress values for both implant types were obtained from the apical region.

Up to 1.5-mm bone loss around osseointegrated implants within one year after implantation, and 0.2-mm bone loss within the following years were accepted within the physiological limits (45). In view of this amount of resorption and the physiological limitations of the bone feeding around the implant, the width of the implanted bone should be at least 2-mm greater than the implant diameter (3). One of the factors that can create the resorption process or disturb nutrition is the stress that occurs as a result of implant placement. Therefore, the stress values occurring at 0.5-, 1-, and 1.5-mm distance from the implant were measured and evaluated at all depths in this study. It was observed that in both cortical and trabecular bone, when the implant was removed from all depths, stress values decreased in all three types of stress. These results are similar to previous studies (32). Considering all these results, it has been understood that the width of the bone where the implant will be placed should be wider than the implant.

Clinically, bone height, width, and density are not standard in every patient. However, this study assumes that these parameters are the same for both implants. This assumption has brought the advantage of a clear understanding of the pressures created by the implants at different depths thanks to these constant parameters.

Since there is limited data in the literature about staged implant placement and stress measurement, the stress values measured at 2-mm to 10-mm depths during implant placement have been compared with previous studies investigating the implant length-stress relationship. Some of these studies have shown that the failure rate of short implants is higher than implants with a length of more than 10-mm (46). The previous researches reported that increased implant length reduced von Mises stress in both trabecular and cortical bone under loading (47,48). Steenberge et al. and Horiuchi et al. reported that an implant of at least 10-mm in length should be preferred for success (49). Based on these data, the stress results of 10-mm long implants were evaluated in the current study. Koca et al. (50) in their study evaluating the stress distribution of implants placed at five different bone levels (4-mm to 13-mm), determined the maximum stress value of von Mises at 4 – and 5-mm bone levels and the lowest stress level at 13-mm bone levels.

When the results obtained from the implant in two different geometries are examined in the current study, it has been observed that as the depth of the implant increases, the basic stress values decrease similarly to the previous studies. Although both implants show fluctuations in the trabecular bone strain and pressure strain during implantation, the stress value at a depth of 10-mm is less than 2-mm. In light of these results, the selection of the longest implants allowed by bone height is predicted to help minimize stresses and failures in the bones. For these reasons, modeling of the bone as a nonhomogeneous regenerative and anisotropic tissue that can respond to stress under load in future finite element analysis studies will enable those studies to present results closer to the clinical situation.

5. CONCLUSION

Within the limitations of these finite element analysis studies, when parameters such as the diameter of the implants, the length of the implant, and the density of the bone to which it is placed were kept constant, the following conclusions were obtained.

1. The conical implants caused more stress than the cylindrical implants.
2. The stress values decreased as the distance from the implant increased at all depths in the cortical and trabecular bone.
3. During the implantation of the conical and cylindrical implants in the bone, the stress value decreases as the depth increases at 0.5-mm to 1.5-mm distance from the implant.
4. In all the models, it was found that the stress in the cortical bone was more than that in the trabecular bone.

5. The highest stress values were observed in bone structures adjacent to the implant neck.

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