Journal of Dental Biomaterials
Shiraz University of Medical Sciences, Shiraz, Iran

Journal of Dental Biomaterials.2015;**2(**3)

Original Article

Comparison of Bone Biomechanical Behavior around Three Different Mini-Implant Systems Employing Finite Element Method

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ARTICLE INFO

Article History
Received 8 April 2015
Accepted 21 July 2015

Key words:
Dental implants
Biomechanical phenomena
Compressive strength
Finite element analysis

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Abstract

Statement of Problem: Placement of mini-dental implants when single-tooth restorations are needed and the space is not sufficient to insert a standard diameter implant is indicated. There are many different mini-implant brands with various materials and surface characteristics; however, there are just few studies comparing them with each other.

Objectives: In this study, finite element analysis (FEA) was applied to evaluate stress distribution in two different types of bone (D2, D3) around three different mini-implant systems (Dio, Dentis, and Osteocare).

***Materials and Methods*:** Three different mini- implant systems consisting of Dentis (Dentis Co., Ltd., Dalseo-gu, Daegu, Korea), Dio (DIO Medical Co., Jungwon-gu Seongnam-si, Kyunggi-do, S.Korea) and Osteocare (OsteoCare™, Slough, Berkshire, UK) were evaluated using FEA. At the same time, a vertical loading of 100N and a lateral loading of 30N at an angle of 45° were applied on the coronal part of the abutment in 2 different bone qualities: D2 bone quality, a thick layer (2 mm) of the compact bone surrounding a core of dense trabecular bone; and D3 bone quality, a thin layer (1 mm) of the cortical bone surrounding a core of dense trabecular bone of favorable strength. Stress levels in the bone surrounding mini-implants were analyzed using Ansys software (Ver.14), which provides the ability to simulate every structural aspect of a product. Descriptive statistics were used to compare the results.

Results: After applying the loads and performing FEA, it was observed that in all three types of mini-implants for both static and dynamic analyses, the Von Mises stress values in D3 bone were more than those in D2 bone. The stresses in the cortical bone were obtained more than cancellous bone stresses.

Conclusions: In all the studied systems, stress remained in the physiologic limits of the bone. In the cortical bone, stress distribution pattern in the three kinds of mini-implant was similar. Crestal bone stress, according to the amount of force applied, remained in acceptable levels.

Cite this article as:Arabsolghar M, Mohammadi M, Razani M, Moosaali F. Comparison of Bone Biomechanical Behavior around Three Different Mini-Implant Systems Employing Finite Element Method. J Dent Biomater, 2015;2(3): 83-91.

Introduction

Today, dental implants are an ideal treatment plan to replace the missing teeth in patients exhibiting partial or complete edentulism. The implant approach has proved to be a reliable and predictable treatment for both re-establishment of function and aesthetics, and their long-term success rate is proven [1,2].Clinicians most often face problems due to the lack of sufficient bone as the result of bone loss occurring after periodontal disease, trauma and tooth extraction. In addition, sometimes due to the insufficient mesiodistal distance, there is not enough space for standard diameter implants; thus, implants with small diameter, so-called “mini-implant” (with diameter less than 3mm) are used with the same long-term success rate in comparison to standard implants [3].

Mini-dental implants (MDI) were first successfully used as interim implants to support provisional prostheses. However, dentists found that they could not easily be removed, because they had already been integrated with the bone, so that the implant manufacturers recommended it for long-term usage [4].The load bearing capacity of implants supporting the restoration must be greater than the anticipated loads during function; otherwise, implant overload may result in mechanical (mini implant failure) or biological (degrading of the bone around implant) failure. An increase in the implant diameter will lead to an increase in the surface area of the implants. Consequently, the bone implant contact area will increase. This leads to a decrease in the stresses around the implants, and a decrease in the risk of overloading. For each millimeter of implant diameter decrease, the functional surface area decreases by 30% to 200%, depending on the implant design, so MDIs are prone to problems such as overloading in the adjacent bone due to their small diameter; therefore, they increase the risk of loss of osseointegration [3-6].

There are many studies focusing on the analysis of biomechanical characteristics of dental implants [5-14].However, a variety of implant systems currently exist in the market offering mini-implants with different designs but a few studies were carried out on these systems to compare their biomechanical characteristics.

Recent evidence on the evaluation of the effect of implant diameter on stress in the bone by using finite element method (FEM) suggests that normal occlusal forces induce non- physiologic stress around the mini-dental implant with a diameter of 1.8 mm that causes bone destruction [6].

It has been observed that small diameter implants which support over-denture produced a significant bone loss but by splinting of the mini-dental implants, the amount of stress was decreased [15]. The aim of this study was to evaluate stress distribution in two different types of bone (D2, D3) around three different conventional mini-implant systems (Dio, Dentis, and Osteocare) using FEA.

Materials and Methods

Because of the nature of the study, there was no need for written informed consent. In the present study, finite element method was used to evaluate three different post-type mini-implant systems consisting of Dentis (Dentis Co., Ltd., Dalseo-gu, Daegu, Korea), Dio (DIO Medical Co., Jungwon- guSeongnam-si, Kyunggi-do, S.Korea) and Osteocare (OsteoCare™, Slough, Berkshire, UK). All of these fixtures were post-type with a diameter of 2.5mm and length of 10 mm assessed in a cylindrical bone model and bone qualities of D2 and D3.In Type 2 (D2) bone quality, a thick layer (2 mm) of the compact bone surrounds a core of dense trabecular bone. In Type 3 (D3) bone quality, a thin layer (1 mm) of the cortical bone surrounds a core of dense trabecular bone of favorable strength. The abutment height and thread thickness in all types were 6 mm and 0.22 mm, respectively. Implant thread pitch in Dio, Dentis and Osteocare were 1mm, 0.61mm and 1.08mm, respectively.

The 3-D models of the bone were constructed using solid model of the bone.Besides, the 3-D models of implans (fixture and abument) with design precision of 0.01 mm was created using Solid Works software package. For all the studied implants, the 3D scanning technique was used to obtain the construction of the models such as thread pitch, thread angle and thread form.The finiteelement analysis was carried out using Ansys 14.0 software.ANSYS provides the ability to simulate every structural aspect of a product, including nonlinear static analysis which provides stresses and deformations, modal analysis that determines vibration characteristics, through the advanced transient nonlinear phenomena involving dynamic effects and complex material behavior.

The finite element models of the bone and implant are automeshed employing tetrahedral elements with quadratic shape functions.This type of element has three degrees of freedom in each node including the displacement along the coordinate axis.In general, for a complex model with the same number of elements, Quadratic elements yield better results than first order elements, firstly because of the better coverage of the curved boundaries, and secondly due to the better mathematical approximation.

Interaction between the bone and implant during dynamic simulation of the implantation process is complex and requires the definition of contact conditions. In this study, contact is defined in Ansys using "surface-to-surface" discretization with completely constrained boundaries due to more accurate results than node-to-surface discretization. The size and shape of the elements have to comply with the specified node spacing function or metric in the FE model, so it's appropriate to perform mesh sensivity analysis in all the samples to ensure that sufficient mesh density is achieved. The final generated finite element mesh for each model contained approximately 60000 to 80000 elements and 14891 to 15089 nodes, which was sufficient to obtain the solution convergence. All degrees of freedom of cross sections and bone in all samples were set to zero

Loading and boundary conditions

In this study, the assumptions are that the materials are linear, homogeneous, and isotropic and the bone-implant interface has been completely osseointegrated. All the bone around the mini-implant were considered to be limited and the boundary conditions were extended to the corresponding nodes. The implant and its surrounding bone should be stressed within a certain range for dynamic physiologic remodeling. In static load studies, it is necessary to include oblique bite forces for achieving more realistic modelling. Most studies concluded that excessive horizontal force should be avoided.

In the simulation of average natural masticatory force, a force similar to the masicatory force in adolescents was considered in the bone-implant model. Accordingly, each mini- implant was subjected to two forces concurrently: one 30N at the angle of 45° with respect to the Y-axis and the other a vertical load of 100N. The forces were applied to the most cronally part of the post-type mini-implants. Boundary condition was set to complete constraint in the bone surface. After the simulation, the stress in the bone surrounding the mini- implants was measured and compared in three types of mini-implants.

For dynamic analysis, a time dependent masticatory load, so called cyclic load (Figure 1) was applied. Under the cyclic loading, while the cracks and radial cracks may propogate, the damage of the material in the plastic zone may accumulate and lead to the deterioration of the strength property of the implant. The number of loading cycles was based on the assumption that an individual has 3 episodes of chewing per

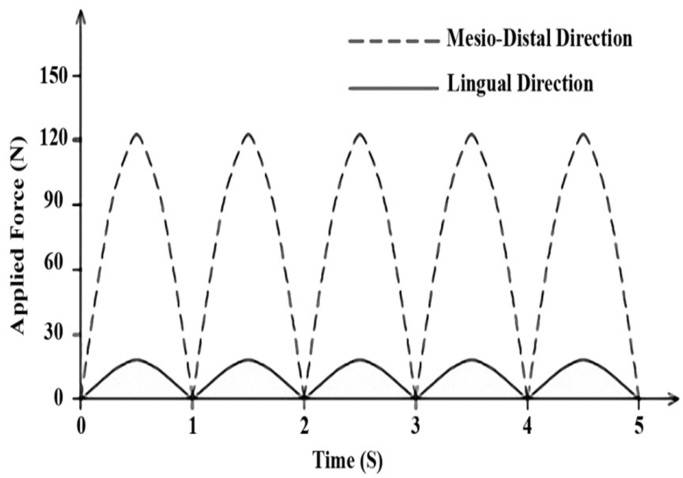

Figure 1: Timehistory of the dynamic load components for 5s

Table 1: Material properties [11,15]

Description	Cancellous bone	Cortical bone	Titanium Implant
Young's modulus, E ($\times 10^3$N/mm^2)	1.37	13.7	110
Poisson's ratio, v	0.3	0.3	0.35
Density, ρ($\times 10^{-7}$Kg/mm^3)	5.3	18	45.4
Yield stress (N/mm^2)	35	180	800
Plastic strain	0.135	0.015	
Friction coefficient of contact interface	0.61	0.61	

day, each in duration of 15 minutes at a chewing rate of 60 cycles per minute (1Hz). This is equivalent to 2700 chewing cycles per day [16,17]. Table 1 demonstrates the mechanical properties of the bone and the implants used in this study. Von Mises stress was used as an index to measure the magnitude of stress and evaluate the stress ditribution in the cortical and cancellous bone in dynamic and static loadings. The most important indications are: 1- stress distribution in the axial direction in bone-implant interface, 2- the highest Von Mises stress values.

Results

Stress distribution was represented numerically and was colour coded in Figures 2-5 .As seen, the Von Mises stress for the post-type mini-implants of Dentis and Dio showed almost an even distribution of stress in both cortical and cancellous bone.The stress distribution in osteocare in the cortical and cancellous bone was seen in almost irregular contours. The distribution of stresses around the bone changed considerably with the thread type.

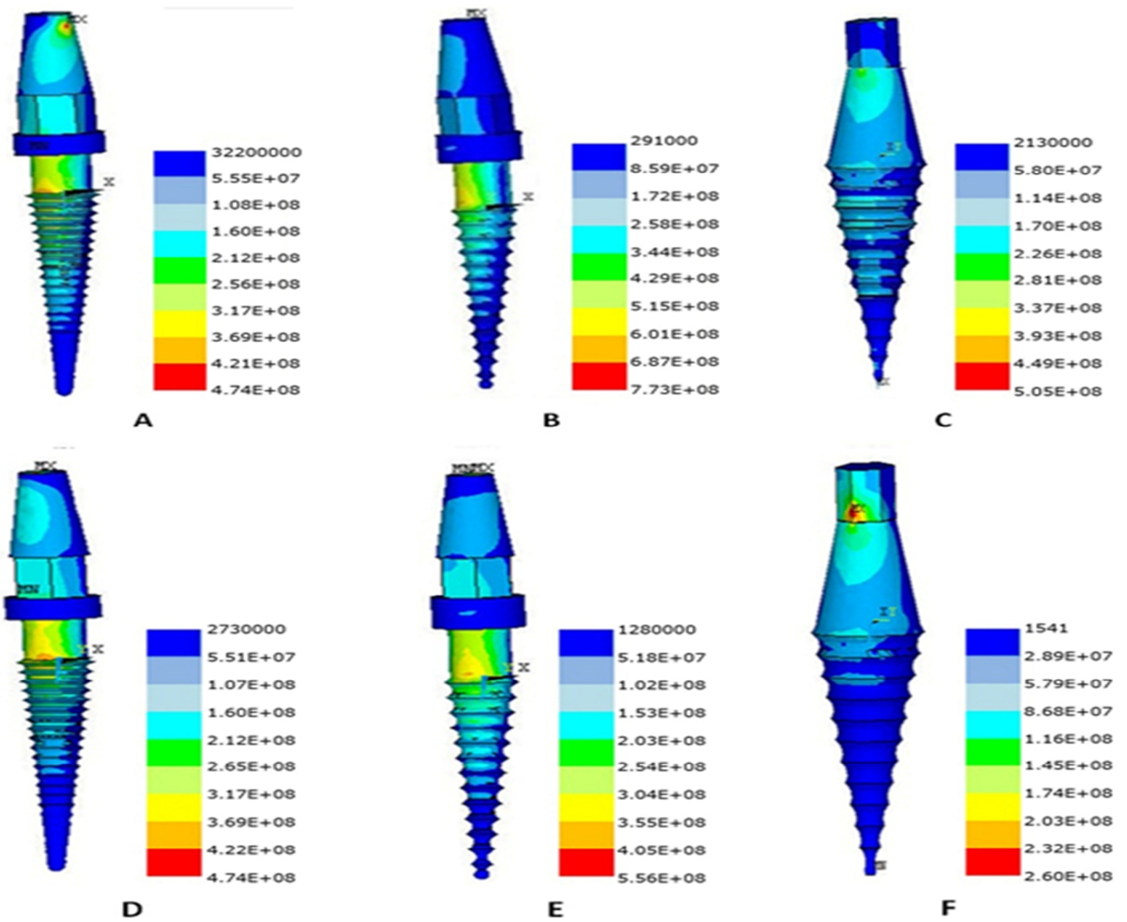

Figure 2: VonMises stress distribution within three MDIs under static loading.A to C, D3 bone; D to F, D2 bone; (A, D) Dentis; (B,E) Dio; (C,F) Osteocare.

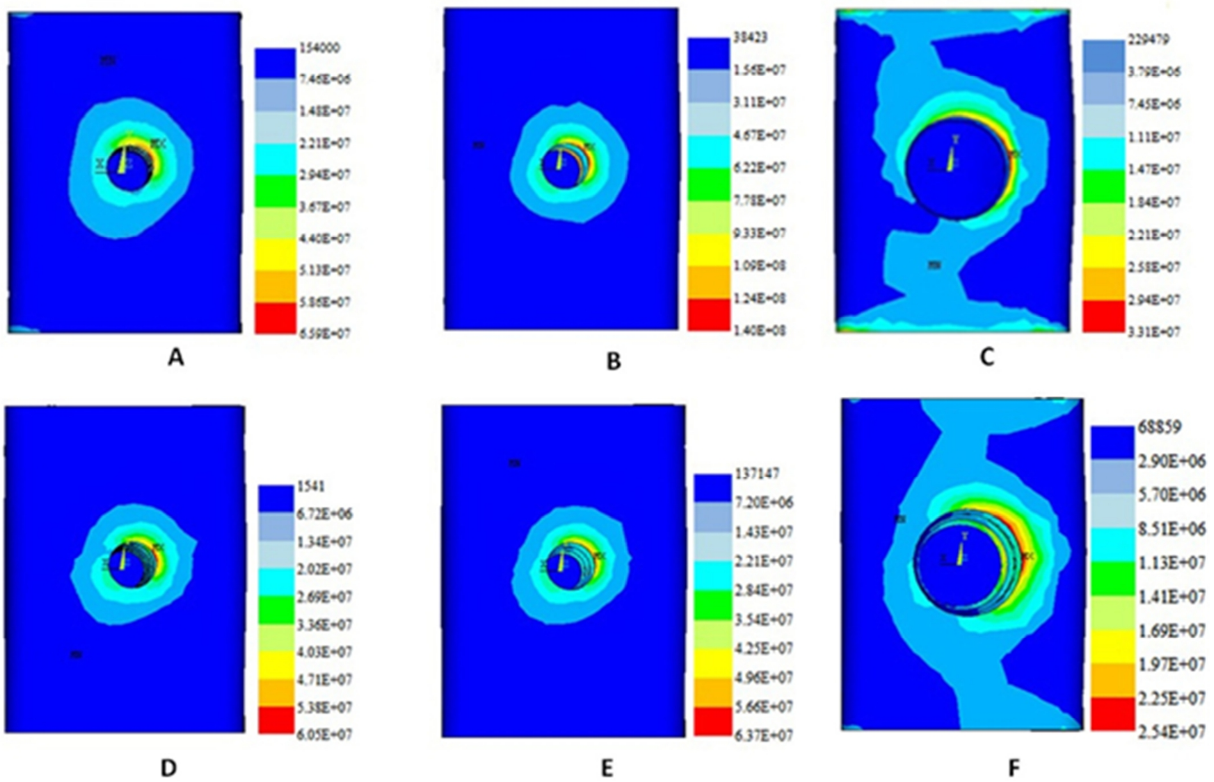

Figure 3: VonMises stress distribution within cortical bone under static loading.A to C, D3 bone; D to F, D2 bone; (A,D) Dentis; (B,E) Dio; (C,F) Osteocare.

Irrespective of the bone quality and mini-implant type, the results showed that the maximum stress occurred on the uppermost threads at the neck of the mini-implants near the margin of the bone in both statistic and dynamic loading conditions .With respect to the static anslysis in D3 bone type, the amount of stress in mini-implant-bone complex for Dentis, Dio and Osteocare was 474, 773 and 504 Mpa, respectively. Moreover, the correspondingmaximum Von Mises stress was 65.9, 76.77 and 33.2 in the cortical bone and 8.75,18.5 and 8.25 in the cancellous bone, respectively .In D3 bone, cortical bone Von Mises Stresses are 7.53, 4.1 and 4 times more than the concanellous bone in Dentis, Dio and Osteocare mini-implants (Table 2).

In addition, the ratio of the maximum Von Mises stress in the cortical and cancellous bone to the mini-implants Von Mises stress in the dentis was 0.14 and 0.018, respectively .The corresponding ratio for Dio and Osteocare was 0.1, 0.07 in the cortical bone and 0.024, 0.016 in the cancellous bone. In dynamic load study, Von Mises stress in Dentis, Dio and Osteocare mini-implants and the resulting stresses in the cortical and cancellous bone are illustrated in Figures 4-5.

Table 2: Static and dynamic analysis (bone D2)

	System	Mini-Implant		Cancellous		Cortical	
		Static	Dynamic	Static	Dynamic	Static	Dynamic
Von Mises Stress (MPa)	Dio	474	460	4.71	4.61	63.7	26.5
	Dentis	456	245	4.83	4.49	60.5	19.6
	Osteocare	260	232	2.48	1.64	25.4	17.5

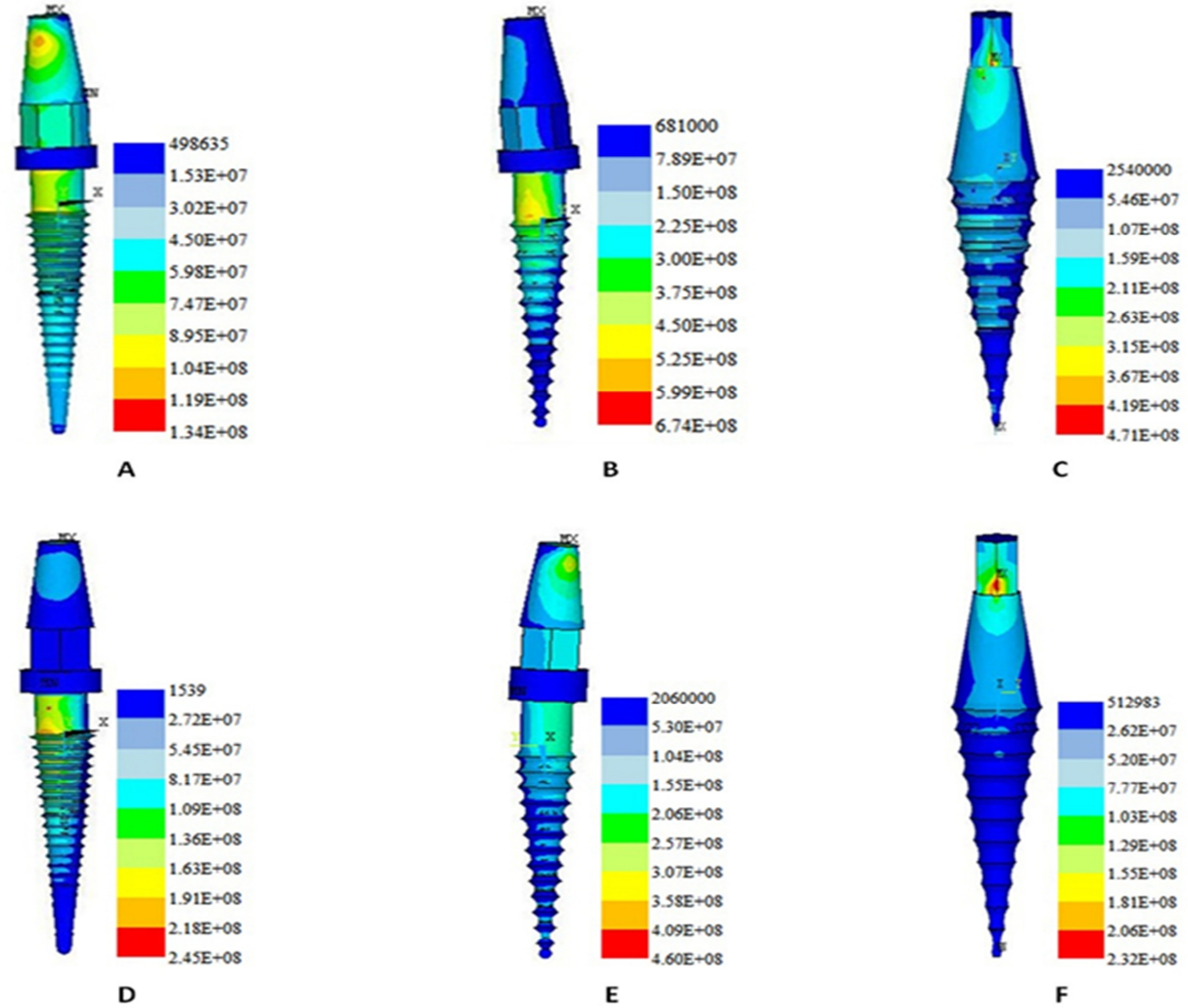

Figure 4: VonMises stress distribution within three MDIs under dynamic loading.A to C, D3 bone; D to F, D2 bone; (A,D) Dentis; (B,E) Dio; (C,F) Osteocare.

Comparison of the results in three kinds of MDIs in static and dynamic loading in D2 and D3 bone showed that the stress value was greater in D3 bone than D2 bone; this can be due to the higher density of D2 bone that in turn resulted in more surface area and more load bearing capacity (Tables 2 and 3).

Discussion

Due to their small diameter, mini-dental implants, are susceptible to being overloaded; this increases the risk of the loss of osseointegration .Up to now, many FEA studies [5-14,16-18,21] have investigated the stress in

Table 3: Static and dynamic analysis (bone D3)

	System	Mini-Implant		Cancellous		Cortical	
		Static	**Dynamic**	**Static**	**Dynamic**	**Static**	**Dynamic**
Von Mises Stress (MPa)	Dio	773	674	18.5	8.19	76.77	39.4
	Dentis	473.5	134	8.75	5.34	65.9	26.8
	Osteocare	504.25	471	8.25	4.98	33.1	19.6

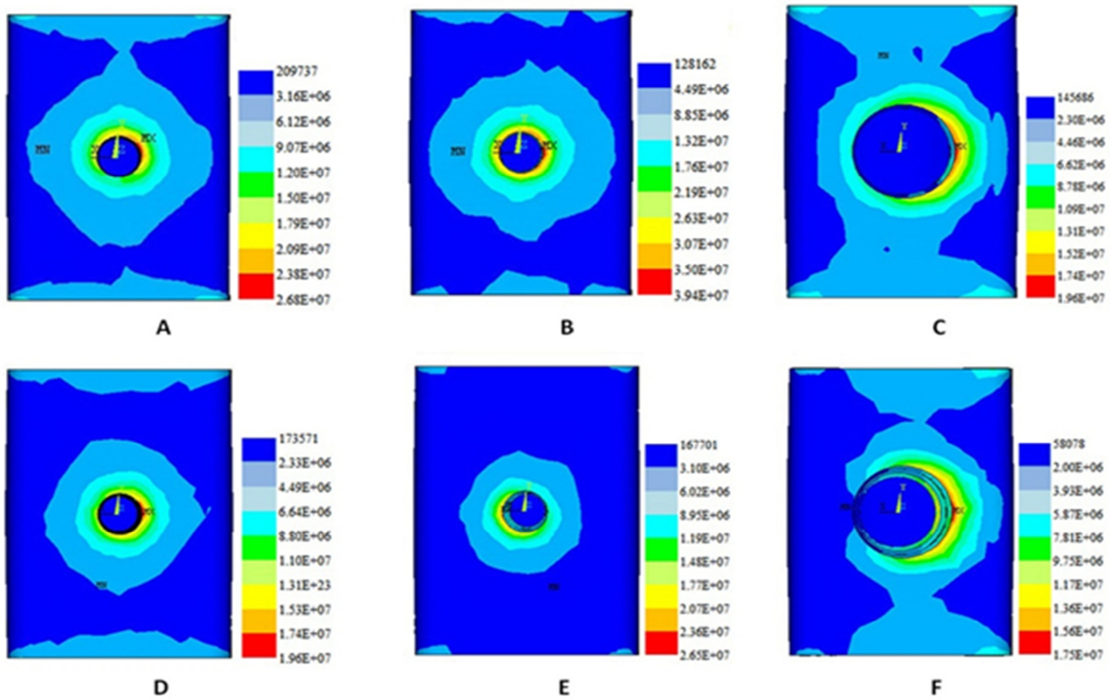

Figure 5: VonMises stress distribution within cortical bone under dynamic loading.A to C, D3 bone; D to F, D2 bone; (A,D) Dentis; (B,E) Dio; (C,F) Osteocare.

conventional implants, although just a few studies [5,18] were attributed to MDIs; some of them are clinical evaluations and the others focus on the orthodontic mini- implants .In the present study, we evaluated the stress in the bone around MDIs for two bone qualities of D2 and D3 .The results showed that in both static and dynamic loadings, the stress values in D3 bone quality were higher than D2 bone.

In a numerical analysis, the biomechanical behaviors of the mini-dental implants with a diameter of 1.8 mm, an applied vertical load of 100N, and lateral load of 30N at an angle of 45° were studied using finite element method [6].The results showed that the crestal bone stresses and the Von Mises stresses (average of 300 MPa) exceeded both cortical and trabecular yield bone stresses of 100 Mpa and 33 MPa, respectively. In our study, crestal bone stress in both cortical and cancellous bones, with respect to the applied forces similar to the McNally study [6], remained within the physiologic limits and it may be due to the greater diameter of MDIs in our study. Also, in some studies, the characteristics of MDIs were assessed by utilizing a loading of 150N [5,18].

They studied two MDIs with a diameter of 2.5 mm by immediate loading assumption. They concluded that the stress in both cortical and cancellous bones exceeded the physiological limit; this was inconsistent with our results. It is probably because of the greater loading (150N) that they utilized in their study as well as immediate loading assumption versus the smaller exerted loads (100N) and complete osseointegration assumption in our study.

Sevimay *et al.*[12] and Rubo *et al.*[17] in a FEA study assessed the conventional implants and investigated their impacts on the surrounding bone. They found that the stress distributions of the compact bone (D1) was similar to D3 bone model, but because the trabecular bone is weaker and shows less resistance to deformation than the other bone quality models, the stress magnitudes were the greatest for the less dense bone; namely, more stress was observed in the cortical bone than the cancellous bone. Similarly, in the present study, the Von Mises stresses increased by the change of the bone quality from D2 to D3.This is due to the difference in the elastic modulus of the bone and titanium that results in the micro-strain accumulation in the bone-titanium interface.

In addition, in the D2 bone quality, the thickness of the cortical bone is greater than the D3 bone; consequently, the stresses distributed more evenly in D2 bone type. It is noted that the cortical bone has a higher elastic modulus, so it has higher resistance against deformation than the cancellous bone and can withstand greater load. Another reason of the stress accumulation in the cortical bone is that the mechanical stress distributes mainly on the interface of bone-implant. The amount of bone implant contact (BIC) is related directly to the bone density, so the cortical bone has more BIC percentage than cancellous bone [3].

The results of some investigations demonstrate that square thread form has a greater functional surface area; therefore, it generates a smaller shear force than both reverse buttress and V-shape threads [8,3,19].In square and buttress threads, the axial loads of these implants are mostly dissipated through compressive force [20]. V-shaped and reverse buttress-threaded implants transmit the axial force through a combination of compressive, tensile and shear forces. So, the square thread has the lowest stress concentration compared with the other thread shapes. Implants with V-shaped and reverse buttress threads generate more forces, which may lead to bone loss [21]. Therefore, the results of the present study showed that Osteocare induces smaller stress in the bone than Dio and Dentis MDI system; this was because of the buttress-shaped thread of Osteocare which resulted in the compressive forces.

Conclusions

In the three investigated MDI systems, the stress distribution patterns were similar in the surrounded bone. The maximum Von Mises stress occurred at the neck of the mini-implant in its uppermost thread. Crestal bone stress in all three systems remained within the physiological limit with acceptable levels.

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