The Staggered Installation of Dental Implants and Its Effect on Bone Stresses

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ABSTRACT

Purpose: The aim of this study was to investigate the effect of offsetting the middle or peripheral implant on the compressive stress values in the crestal bone around the neck of the dental implant.

Materials and Methods: Three finite element models describing three titanium implants installed in quadrilateral pieces of bone was executed. A 2-mm nickel chromium superstructure representing a bridge was modeled over the implant abutments. In model 1, implants were installed along a straight line. Model 2 had the middle implant installed outside the line connecting the two peripheral implants buccally. Model 3 had the mesial implant installed out of alignment. Six 100-N loads were modeled on top of the mesial and middle implants of the three models individually. Loads 1 and 2 were directed vertically on the mesial and middle implants, while loads 3 and 4 represented the horizontal loads in the buccal direction. Loads 5 and 6 were directed mesially on the mesial and central implants. Maximal compressive stress levels in the crestal bone of the three models were then investigated.

Results: The results demonstrated that offset implant installation revealed slightly lower bone stresses under buccally or lingually directed horizontal forces. Slightly higher bone stresses under vertical loads were observed. Horizontal mesial or distal loads resulted in slightly higher bone stresses than those caused by buccal or lingual loading.

Conclusions: The in-line implant alignment clearly had the safest compressive stress outcome on the surrounding structure under vertical loads. Under buccolingual loads, implant alignment with peripheral offset would have, relatively, the safest compressive stress outcome on bone.

KEY WORDS: bone stress, finite element analysis, implant loading, in-line implants, offset implant

INTRODUCTION

The use of dental implants for replacing missing teeth had now become a widely recognized and practiced treatment modality. Failure of implant restorations was attributed to either biological or mechanical factors. Biological factors comprise peri-implant radiolucencies, signs of peri-implantitis such as deepening of the peri-implant pocket probing depths, and radiographic signs of loss of osseointegration, that is, horizontal bone loss and vertical defects.[1] Mechanical failure of implant restoration was attributed to many factors such as overload of the implants,[2–6] nonvertical direction of force,[7,8] lack of enough supporting bone volume and density[9,10], low number of prosthesis-supporting implants, and incorrect angulation of the implants within the bone.[11,12]

Several reports that investigated the distribution of forces in peri-implant bone emphasized that horizontal loading should produce higher stresses in the bone than

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vertical loading.[2–13] However, there were conflicting views on the benefits of offset over in-line positioning of implants.[5,14–18]

A recent study investigated the biomechanical effects of in-line and offset placements of implants on implant-supported partial prostheses using three-dimensional finite element models.[18] When a force of 200 N was applied, an insignificant difference was observed in implant stresses between the in-line and offset placements under the vertical loading mode. On the other hand, under oblique loading, the offset placement decreased only the implant assembly stress by a maximum of 17% but not the bone stress. The maximum stress at the cortical and trabecular bone around each implant did not show conspicuous difference between the in-line and offset placements.[18]

In another recent study, the effect of staggered (offset) implant placement configuration and the placement of wider-diameter implants in a straight-line configuration were evaluated.[16] A 400-N static load was applied perpendicular to the buccal inclination of the buccal cusps on each unit. Lower stress values were recorded for the configuration with wider implants placed in a straight line. Other configurations, including staggered implant placement, did not lower the stress values. It was concluded that despite the offset implant placement, the stresses were not decreased; however, the straight placement of wider implants decreased bending moments.[16] The same was concluded by Sato and colleagues,[15] where the offset placement did not always decrease tensile force at the implant components.

The aim of this study was to investigate the effect of offsetting the middle or peripheral implant on the compressive stress values in the crestal bone around the neck of the dental implant. Moreover, one model was reproduced in three copies with different mesh densities (different numbers of elements) to evaluate the effect of mesh refinement on compressive stress values.

MATERIALS AND METHODS

The finite element analysis program NISA (Cranes Software Inc., Troy, MI, USA), was used to construct three models. Each model described three titanium implants of 4-mm-diameter and 10-mm-long osseointegrated portions. Five-millimeter-long abutments were simulated and were installed in quadrilateral pieces of bone (28.5 × 12 × 8 mm). The quadrilateral pieces of bone were composed of trabecular bone covered by a 1-mm layer of cortical bone (Figure 1). All of the nodes at the base of the bone model were restrained. A 2-mm nickel chromium superstructure representing a bridge was modeled over the implants connecting their abutments (Figures 2 and 3; see also Figure 1).

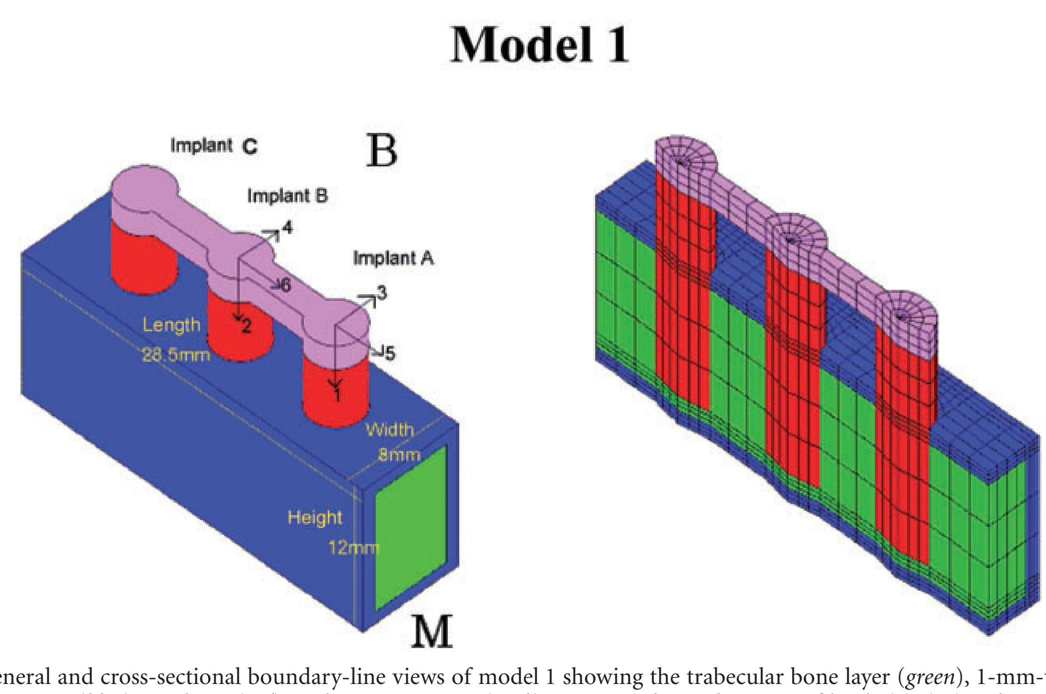

Figure 1 General and cross-sectional boundary-line views of model 1 showing the trabecular bone layer (*green*), 1-mm-thick cortical bone layer covering (*blue*), implants (*red*), and superstructure (*pink*). *Arrows* indicate direction of loads (1–6). (B = buccal side; M = mesial side).

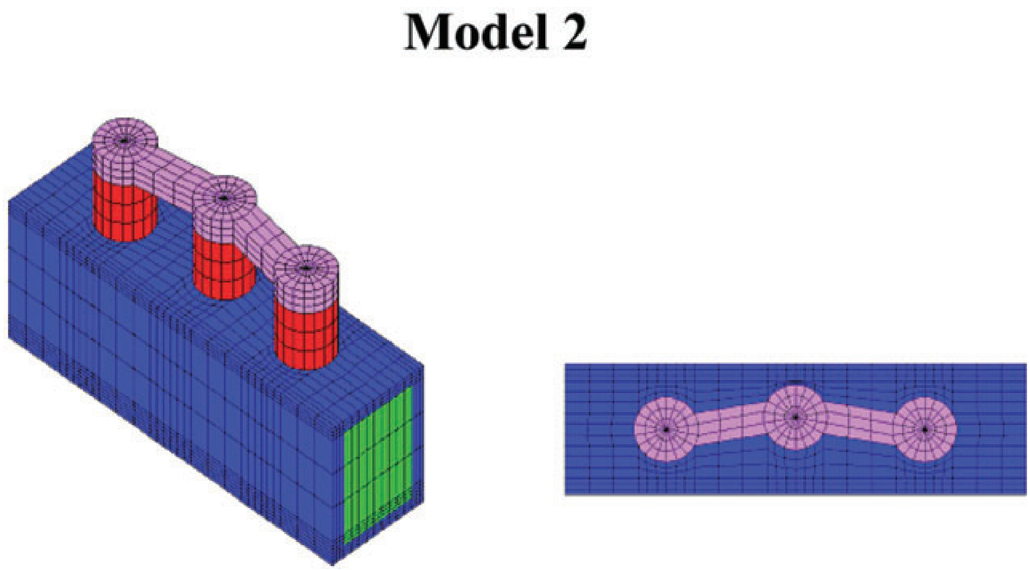

Figure 2 General and top views of model 2 showing the out-of-alignment implant B.

Model Variations

The three implants (A [mesial], B [central], and C [distal]) in model 1 were installed along a straight line, with the middle implant being at the center of the piece of bone. The other two implants were installed 4 mm at its either side (see Figure 1). Model 2 was similar to model 1, but the middle implant (B) was installed outside the line, connecting the two peripheral implants (A and C) by 0.75 mm buccally (see Figure 2). Model 3 was similar to model 1, but the peripheral implant (A) was installed out of alignment by 0.75 mm buccally (see Figure 3). A quarter-of-a-millimeter distance was kept between the out-of-alignment implants and the cortical bone layer. This was performed to keep the offset implant within the trabecular bone. The implants were allocated the properties of titanium, while the superstructure was allocated the properties of nickel chromium.[19]

All models were constructed using three-dimensional, 20-noded hexahedral elements. The number of elements in each of the models was 7,722. All nodes in the models were merged, including those between the implant and the bone, to assume osseointegration.

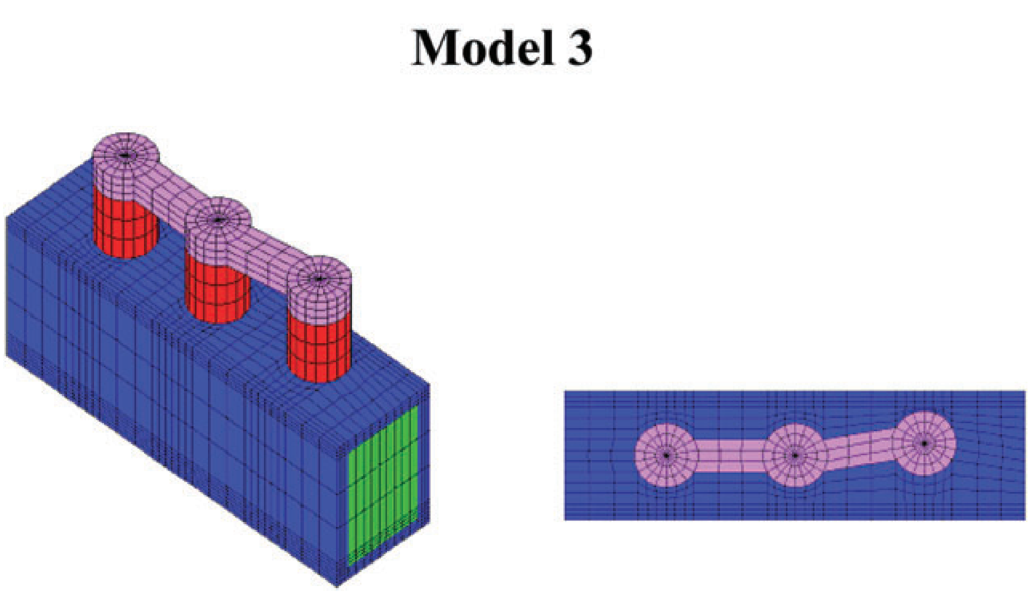

Figure 3 General and top views of model 3 showing the out-of-alignment implant A.

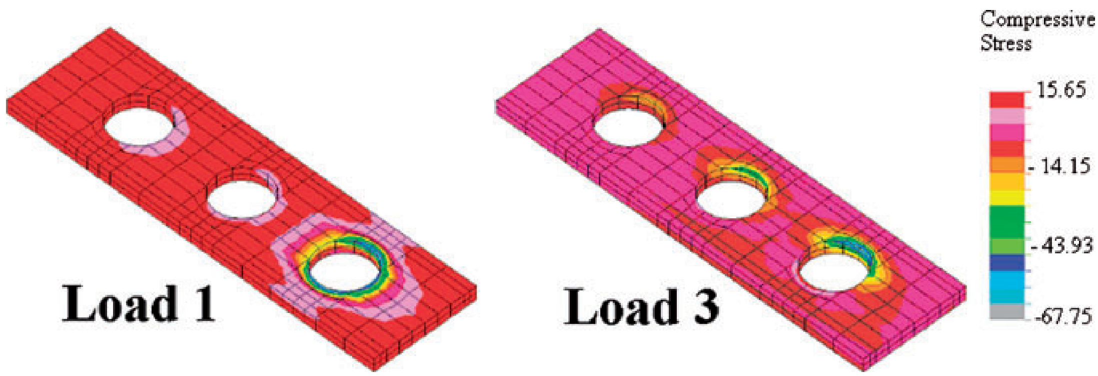

Figure 4 Compressive stress distribution in the coronal 1 mm of bone in model 1 following the application of loads 1 and 3 on implant A.

Loading

Six 100-N loads were modeled on top of implants A and B for the three models individually, as shown in Figure 1. Loads 1 and 2 were directed vertically with the long axis of implants A and B, respectively. Loads 3 and 4 represented the horizontal loads in the buccal direction on implants A and B, respectively. Loads 5 and 6 were directed mesially on implants A and B, respectively (see Figure 1).

Compressive stresses were recorded in the collar of the bone immediately around the neck of the implant under each of the modeled six loads. Linear static analysis was performed to investigate the maximal compressive stress levels in the crestal bone of the three models.

Convergence Tests

In the present study, the model is constructed in terms of volumes that are then meshed into finite elements. The mesh density can be altered to produce similar models with different numbers of elements in them.

A convergence test was carried out on model 1 after producing three copies of the model. In the first copy, a rough mesh was constructed with only 286 elements. In the second, a fine model was produced with 2,288 elements (about seven times the number of rough-model elements). In the third model, the mesh was with 7,722 elements (about 3.5 times the number of fine-model elements), and this was the same number of elements used in the above-mentioned comparisons.

The compressive stress values were registered in the crestal bone around the necks of the dental implants under the different loads. The stress values were then compared to evaluate the effect of mesh refinement on the results.

RESULTS

Generally, the lowest compressive stress values were recorded under vertical load conditions (loads 1 and 2), while the highest values were recorded under horizontal loads (loads 3 and 4) in the three models. As an example, the compressive stress distribution and recordings in the coronal 1 mm of cortical bone around the necks of the implants in model 1 under loads 1 and 3 are presented in Figure 4.

In each model and under different loading conditions, the directly loaded implant (A or B) always had the highest compressive stress value (Table 1). Under loads 1 and 2 in model 1, the three implants (A, B, and C) showed, relatively, the lowest bone stress values when compared with their corresponding implants in models 2 and 3. Load 1 in model 3 revealed the highest bone stress value around the same implant (with a slight increase than that of model 2), although implants B and C showed the lowest values. On the other hand, load 2 in model 3 had lower bone stress values around the three implants than those in model 2 (see Table 1).

Horizontal buccal load on implants A and B (loads 3 and 4) resulted in the lowest bone stress values around the three implants of model 3. Model 1 had the highest bone stress values around the three implants (see Table 1).

Under horizontal mesial load (loads 5 and 6), bone compressive stress values were more uneven than the above-mentioned loading conditions (see Table 1). With

TABLE 1 Maximum Compressive Stress Values (MPa) in the Crestal Bone Sections around the Necks of the Implants following Application of Different Loads

			Horizontal loads			
	Vertical loads		Buccal		Mesial	
Implant	1	2	3	4	5	6
			Model 1			
A	10.80	1.44	76.58	37.72	14.52	11.72
B	1.49	8.88	39.76	53.19	12.81	13.18
C	1.10	1.44	18.71	37.72	9.75	10.03
			Model 2			
A	11.14	1.84	74.83	35.19	16.78	11.90
B	1.57	9.93	39.29	51.31	13.44	15.20
C	1.12	1.84	17.15	35.19	8.71	10.07
			Model 3			
A	11.16	1.62	74.17	35.47	16.21	12.18
B	1.44	9.49	38.53	50.52	13.36	14.47
C	1.10	1.72	17.14	35.06	9.72	10.12

load 5, the bone around implants A and B had the lowest stress values in model 1 and, conversely, the highest stress values in model 2, when each value was compared with that of the corresponding implant in the other models. Bone around implant C had the lowest stress value in model 2, whereas load 5 produced the highest bone stress value in model 1. Bone stress values around the implants of model 3 were in between the corresponding values in models 1 and 2. Under load 6, the lowest bone stress value around implant B was recorded in model 1, and the highest value was in model 2. Bone stress values around implants A and C were the lowest in model 1 and the highest in model 3 (see Table 1).

Convergence Test

Results of the convergence test are displayed in Table 2. A marked increase in compressive stress values was produced with the increasing number of elements in horizontal buccal load conditions (loads 3 and 4).

DISCUSSION

The results of this study revealed that the application of vertical loads (1 and 2) in the studied models resulted in the highest stresses in the crestal bone immediately around the neck of the loaded implants (A in load 1 and B in load 2) (see Figure 4). The adjacent unloaded implants did not share in the stress transfer as the bone around showed insignificant stress values (see Table 1). On the other hand, the application of horizontal buccal loads (3 and 4) resulted in higher stress recordings around the unloaded implants. The results demonstrated that bone stress values around the unloaded adjacent implants (B in load 3 and A and C in load 4 conditions) were about two-thirds the value of the stress recorded around the neck of the loaded implant. The far implant in load 3 condition (C) had about one-third that value. Furthermore, the application of horizontal mesial loads (5 and 6) resulted in slightly higher stress values compared with the vertical loads (1 and 2). These loads also resulted in higher stresses in the bone around the necks of the unloaded implants (see Table 1).

In this study, buccal and mesial horizontal loading conditions are similarly applicable for lingual and distal loads, respectively. The used nomenclature was considered to simplify description. When the horizontal loading is in the mesial (or distal) direction, the stresses in the bone are only approximately 1.4 times the stress magnitudes under vertical loading. However, when the horizontal loading is in the buccal (or lingual) direction, the stress magnitudes are approximately 4.5 times those recorded under vertical loading (see Table 1). It would therefore appear that loading the implants toward a lower bone volume, buccolingually, might result in

TABLE 2 The Effect of Different Mesh Refinement of Model 1 on Compressive Stress Values in the Bone around the Neck of the Loaded Implant

			Horizontal loads			
	Vertical loads		Buccal		Mesial	
Mesh (number of elements)	Implant A	Implant B	Implant A	Implant B	Implant A	Implant B
Rough (286)	7.71	5.94	54.19	37.09	9.26	7.452
Fine (2,288)	9.74	7.63	67.75	46.95	13.08	11.33
Very fine (7,722)	10.80	8.88	76.58	53.19	14.52	13.18

higher stresses than loading toward a thicker volume of bone, mesiodistally or apically.

In the present study, the implants were modeled parallel-sided and smooth; in addition, the chunk of bone was modeled with definite sizes to standardize the models and establish a baseline data for the study. Material properties for the different regions of the models varied considerably in the literature.[4,8–11,13–16] Although titanium is not always used in its pure form in the construction of dental implants, the values chosen in this study were previously used in a similar finite element study.[19] Nevertheless, the results of this study demonstrated that the loading of implants in a horizontal direction results in higher stresses than loading in a vertical direction. These results matched with those of almost every study carried out using finite element analysis on dental implants.[8–11,13–18]

In the present study, it is interesting to note that loading the peripheral implant (A) always resulted in higher stresses than loading the middle implant (B). A possible explanation for that might be because of the presence of a bilateral (mesiodistal) connection of the middle implant compared with a unilateral connection of the peripheral implant. A bilateral connection would possibly dissipate the applied stress through the framework more than unilateral connections and thus resulted in less bone distortion from both sides. Mesh refinement increased the compressive stress values under all loading conditions, specifically, under horizontal buccolingual load conditions.

Finally, the obtained differences might possibly bring an applicable consequence for the clinical application of peripheral offset when having a wide bone buccolingually. Wide bony platforms are mostly available in the maxillary and mandibular molar regions, where occlusal forces are highest and stress dissipations are usually needed for multiple-unit implant-supported prosthesis.[2,5]

CONCLUSION

It can be concluded that the out-of-alignment placement of the middle implant did not seem to provide a clear biomechanical advantage. The in-line implant alignment clearly had the safest compressive stress outcome on the surrounding structure under vertical loads. However, under buccolingual loads, implant alignment with peripheral offset would relatively have the safest compressive stress outcome on bone.

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