Finite Element Analysis of Effect of Prosthesis Height, Angle of Force Application, and Implant Offset on Supporting Bone

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Purpose: *This finite element analysis was conducted to determine the magnitude of stress in the supporting bone when implants were arranged in either a straight-line or an offset configuration. In addition, the effects of axial and nonaxial loading and changes in prosthesis height were assessed.* ***Materials and Methods:*** *An 8-node hexahedral solid-element 3-dimensional finite element analysis model of the mandible was created using PATRAN software. Three titanium endosseous implants were placed in the model 7 mm apart. The center implant was placed on the line from the centers of the terminal implants (no offset), 1.5 mm lateral to this line (1.5-mm offset), or 3.0 mm lateral to this line (3.0-mm offset). Forces of 200 N were applied to a point corresponding to the center of the middle implant when the implants were in a straight-line configuration. Forces were applied in a straight vertical direction or in 15-degree increments to the vertical to a maximum of 60 degrees. Simulated type IV gold prostheses were made to simulate heights of 6 and 12 mm.* ***Results:*** *The least stress in the supporting bone was found with vertical loading of the no-offset implants with the 6-mm prosthesis (3.12 MPa) followed by the same alignment with the 12-mm prosthesis (3.86 MPa). Changing the angle of force application by 15 degrees resulted in increased stress to the underlying bone, and the creation of an offset did not fully compensate for this increased stress.* ***Discussion:*** *In contrast to previous studies, this study examined 3 elements not previously studied together in a single finite element analysis, using the maximum offset defined by normal anatomic contours of mandibular premolar and molar teeth, thereby describing the relative importance of clinically relevant methods for stress reduction.* ***Conclusions:*** *Vertical loading of an implant-supported prosthesis produced the lowest stress to the supporting bone. Changes in the angle of force application resulted in greater stress to supporting bone. Reduction in prosthesis height or use of an offset implant location for the middle implant reduced stress, but the reduction did not compensate for the increase found with off-axis loading.* INT J ORAL MAXILLOFAC IMPLANTS 2004;19:819–825

Key words: *dental implants, dental prostheses, finite element analysis, nonaxial loading, offset implants, prosthesis height*

Brånemark and associates[1–5] introduced the concept of osseointegration as a predictable method of anchoring implants for the support of dental prostheses. Although the early prosthetic designs were used to replace full arches of teeth, implants are now used to support prostheses in completely and partially edentulous jaws.[6–10] The biomechanical situation in complete edentulism is likely to be favorable, as implants are placed in a curvilinear pattern to follow the dental arch. Conversely, implants used to support prostheses in the partially edentulous jaw are normally placed in a relatively straight alignment. Rectilinear arrangements of implants have been implicated in the generation of adverse forces on the supporting implants, a situation that could result in damage to the prosthesis or to the bone-implant interface.[11–17]

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Rangert and coworkers[12,15,16,18] have suggested that when 3 or more implants are planned, they be placed in such a way as to create an intentional offset, rather than in a straight-line configuration.[12,16,19,20] The establishment of an offset is thought to create a more favorable force distribution to the prosthetic components, implants, and bone. This is generally illustrated by drawings that depict a triangulated base used to support a prosthesis. The rationale is that such a base is more stable than one that has all supports in a straight line. Such simple geometric and engineering drawings have been used to support the concept of a favorable offset, but little information exists on the magnitude of effect when the offset is within the anatomic confines of the natural teeth. Testing, in the form of controlled clinical trials of rectilinear or curvilinear designs, has not been conducted, but reports of complications, such as implant fracture, suggest different results with different implant alignments. In a study of implant fractures, Eckert and associates demonstrated a 5-fold increase in implant fractures in the partially edentulous jaw compared with the edentulous jaw.[21] Since the edentulous jaw generally provides a curvilinear arrangement of implants, it may be hypothesized that this factor is responsible for the lower implant fracture rate in the edentulous jaw.

Finite element analysis (FEA) is an engineering method that allows investigators to assess stresses and strains within a solid body.[22–24] An FEA model is constructed by breaking a solid object into a number of discrete elements that are connected at common nodal points. Each element is assigned appropriate material properties that correspond to the properties of the structure to be modeled. Boundary conditions are applied to the model to simulate interactions with the environment.[25] This model allows simulated force application to specific points in the system, and it provides the resultant forces in the surrounding structures. FEA is particularly useful in the evaluation of dental prostheses supported by endosseous implants.[24,26,27] The resultant forces on the implants, transmucosal abutments, or underlying bone can easily be evaluated once a detailed 3-dimensional model has been created.

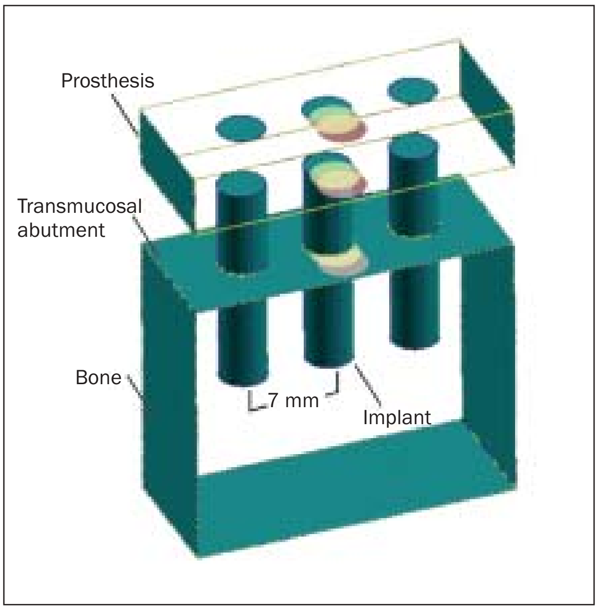
In designing any prosthesis, the clinician endeavors to re-create the natural anatomy. With an implant-supported prosthesis, the coronal tooth structure should be aligned with the supporting implants to avoid contours that would otherwise alter the tooth anatomy. Anatomic descriptions suggest that the buccolingual dimension of natural posterior teeth at the cervical region is, on average, 8 mm or less.[28] Using implants with 4.0-mm prosthetic platforms, the maximum offset for the center implant will be 3.0 mm, assuming that the implants must be encased in 0.5 mm of prosthetic material. Assessment of a clinically relevant offset must therefore be limited to an offset of 3 mm or less.

The purpose of this study was to evaluate, through finite element modeling, the effect of an offset on the force transmission to bone-supporting implants aligned in either a straight-line configuration or an offset configuration. In addition, the study evaluated the effect of differing prosthesis heights and different directions of force application.

MATERIALS AND METHODS

A 3-dimensional FEA model was developed to compare the stress distribution of a 3-implant straight-line configuration to 3-implant configurations with various offsets. The model simulated the anatomic structure of the posterior mandible. The mesiodistal dimension of the model was 25 mm, the buccolingual dimension was 11 mm, and the superior-inferior dimension was 22 mm. At the superior and inferior surfaces a cortical bone layer, 2 mm thick, was simulated. All other bone modeling was done to simulate cancellous bone. Three titanium implants (3.75 mm diameter and 10 mm length) were placed in the model. These implants were placed 7 mm apart (from implant center to implant center) and 3.5 mm from the mesial and distal surfaces of the model. An implant-supported prosthesis with a type IV gold alloy framework with a mesiodistal dimension of 25 mm, a buccolingual dimension of 11 mm, and an occlusogingival dimension of 5 mm was simulated (Fig 1). The model was created using PATRAN finite element software (MSC Software, Santa Ana, CA).

Six different FEA models were created and meshed with 8-node hexahedral solid elements (Fig 2). The models represented a straight-line configuration of the implants (no offset), a configuration with the center implant placed 1.5 mm buccal to the straight line (1.5-mm offset), and a configuration with the center implant placed 3.0 mm buccal to the straight line (3.0-mm offset). Prostheses were fabricated to fit to the 3 implant configurations at heights of 6 and 12 mm. The models were constrained in all directions on the inferior surface. Assumptions were made that all materials in the FEA model were homogenous, isotropic, and linearly elastic. Moduli of elasticity and Poisson's ratios (Table 1) were used in the modeling of the bone, implants, gold alloy prosthesis framework, and retaining screws. The number of elements for



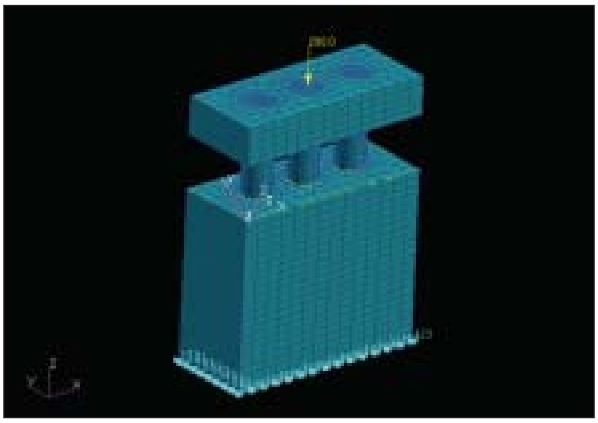


Fig 1 *(Left)* Three-dimensional model. The simulated transmucosal abutments and implants are simulated commercially pure titanium, and the simulated prosthesis is simulated type IV gold. The modeled bone simulated cortical and cancellous bone. All measurements are shown in millimeters.

Fig 2 *(Above)* Three-dimensional FEA model.

the 6 models ranged from 9,102 to 9,911, and the number of nodes ranged from 9,686 to 10,900.

Simulated occlusal loading of the implant-supported prosthesis was accomplished by applying 200 N to the prosthesis in a location corresponding to the center of the middle implant with no offset. Forces were applied to this same position for all testing conditions of offset, angle of force, or prosthesis height. Forces were applied at 0, 15, 30, 45, and 60 degrees to the vertical direction. Analysis of the FEA model was performed using ABAQUS finite element software (HKS, Pawtucket, RI).

Stress in the superior surface of the simulated bone adjacent to the implant platform was analyzed. Data were used to determine maximum principal stress (tensile), minimum principal stress (compressive), and Von Mises stress in the cortical bone of each model under the different loading conditions.

RESULTS

The highest stress concentrations were found in the cortical bone surrounding the superior surface, or platform, of the implant (Figs 3 to 5). Stress is expressed in MPa.

Stresses were measured in the cortical bone surrounding the superior aspect of the implant body. The lowest stresses were seen with vertical application of force simulating force application along the long axis of the implant. This was true for both prosthesis heights and all types of stress (Von Mises, maximum principal, and minimum principal) (Table 2). As the angle of force changed from the vertical, increasing in 15-degree increments, stresses in the bone increased (Table 2). The application of an offset to the middle implant reduced stresses for all loading conditions except for the condition when the forces were directed along the long axis of the implant. In that situation there was a small increase in stress within the bone. Most stresses were increased when the height of the prosthesis increased from 6 to 12 mm. This was true regardless of angle of force application or amount of offset.

Table 1 Material Properties

Material	Modulus of elasticity (GPa)	Poisson's ratio
Titanium	110	0.35
Cortical bone	15	0.30
Cancellous bone	1.5	0.30
Gold alloy (type IV)	96	0.35

Changes in the angle of force application had a greater impact on resultant stress than did the offset. For example, a 15-degree change in force angle created more than a 3-fold increase in Von Mises stress with a 6-mm-high prosthesis. By contrast, the 3.0-mm offset reduced the stress by less than one half (Table 2).

DISCUSSION

The use of implants to support fixed prostheses in partially edentulous jaws has become a common treatment option. When 3 or more implants are

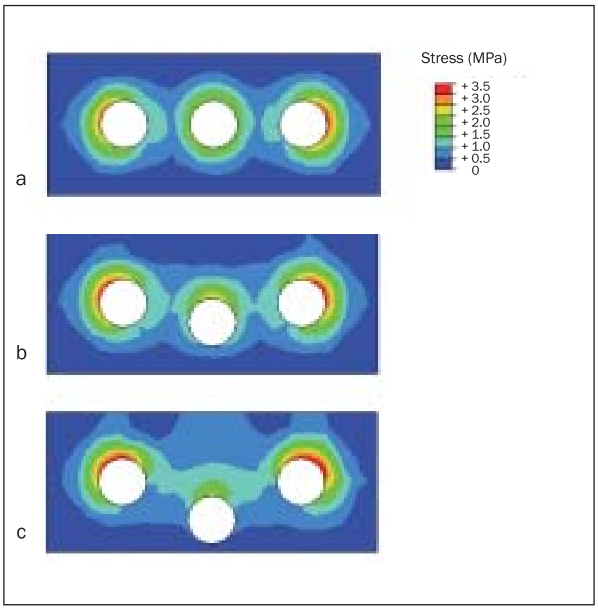


Fig 3 Von Mises stress for 0-degree load condition and 12-mm prosthesis height. *(a)* No offset; *(b)* 1.5-mm offset; *(c)* 3.0-mm offset.

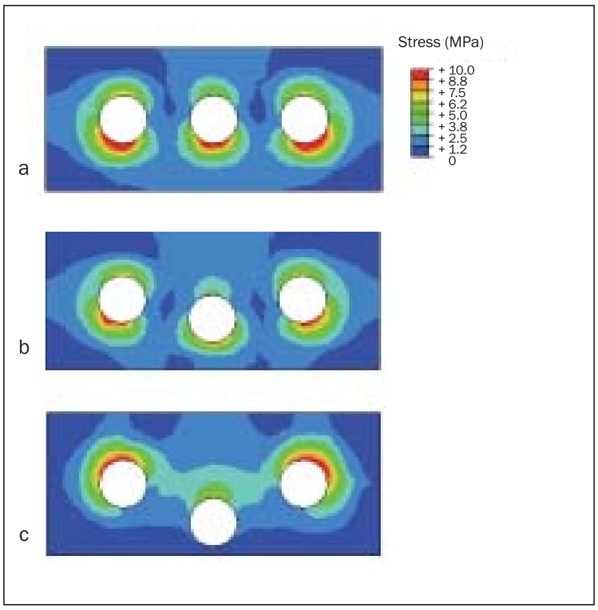


Fig 4 Von Mises stress for 15-degree load condition and 12-mm prosthesis height. *(a)* No offset; *(b)* 1.5-mm offset; *(c)* 3.0-mm offset.

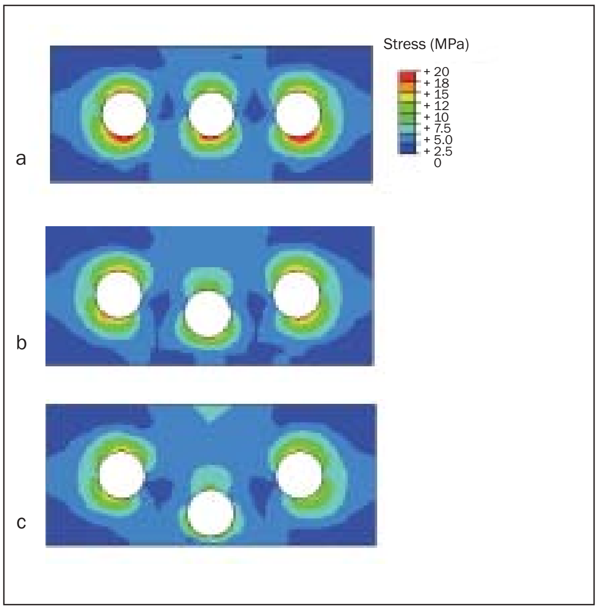


Fig 5 Von Mises stress for 30-degree load condition and 12-mm prosthesis height. *(a)* No offset; *(b)* 1.5-mm offset; *(c)* 3.0-mm offset.

used, Rangert and coworkers[12] suggested that the implants be placed in such a way as to create an intentional offset of the middle implant. This design is suggested to improve the biomechanical stability of the definitive restoration. It is assumed that better mechanical stability will result in a decreased frequency of loose or fractured screws and a decrease in implant fractures.

According to Ash and Nelson,[28] the average buccolingual dimension of posterior teeth is 8 mm or less. When posterior restorations are planned, the distance from the center of the implant to the anticipated facial and lingual surfaces of the restoration should be considered. Placing an implant too far from the facial or the lingual surface will result in restoration overcontour. Maintaining the implant and restorative components within the anatomic limits of the restoration will limit the amount of offset that can be achieved. Using a minimum 4-mm diameter implant to avoid implant fracture,[21] and understanding that restorative materials will add a minimum of 0.5 mm facially and lingually to

Table 2 Von Mises, Maximum Principal and Minimum Principal Stress Reported (MPa)

	6-mm prosthesis			12-mm prosthesis		
Loading angle	0 mm offset	1.5 mm offset	3.0 mm offset	0 mm offset	1.5-mm offset	3.0-mm offset
Von Mises stress						
0 degrees	3.12	3.49	5.16	3.86	4.05	5.19
15 degrees	10.46	8.09	5.93	16.91	12.54	9.24
30 degrees	17.72	13.55	9.85	30.09	21.42	16.56
45 degrees	23.82	18.12	13.76	41.23	29.63	25.85
60 degrees	28.31	21.49	18.64	49.57	37.50	33.46
Maximum principal stress						
0 degrees	2.12	1.75	2.20	1.71	1.70	2.06
15 degrees	4.33	3.58	2.70	8.39	7.90	5.55
30 degrees	10.32	9.79	7.54	18.52	18.51	15.40
45 degrees	15.74	15.45	13.05	27.43	27.86	24.21
60 degrees	20.11	20.06	17.70	34.56	35.31	31.37
Minimum principal stress						
0 degrees	3.06	3.37	4.81	3.78	3.89	5.02
15 degrees	9.83	7.70	6.24	15.67	11.77	8.88
30 degrees	16.50	12.85	10.47	27.65	20.18	15.66
45 degrees	22.08	17.17	13.09	37.74	27.22	21.38
60 degrees	26.25	20.34	15.79	45.33	32.41	25.65

each implant or restorative component, the dimensions of the definitive restoration were established. A 3-mm offset was considered the maximum for a posterior restoration, as this offset would maintain prosthetic tooth dimensions that mimic natural tooth anatomy. Previous research failed to assess the maximum available offset[26,27] or discussed offset as an engineering concept without considering the limits established by natural tooth anatomy.[12]

The original concept of reducing biomechanical stress through the use of an offset implant appears to have engineering merit. However, in the dental setting there are limits to the magnitude of offset that can be achieved without distorting the anatomy of the teeth. Weinberg and Kruger[14] applied mathematical calculations to prosthetic designs that use an offset implant configuration and found that the mechanical advantage would be limited. Akca and Iplikcioglu[27] performed FEA with a small offset and also found limited advantage from the nonlinear arrangement of implants. In their study the offset was limited to 1.9 mm, while the current study used a 3.0-mm offset. The 3.0-mm offset was chosen as the maximum offset that would not alter anatomic tooth form and as such provided the upper limit to the beneficial effects from an offset configuration of implants. With this larger offset, the a reduction in stress was demonstrated, but this reduction was not proportionally as great as the reduction observed with a 15-degree change in force application. The current study directly compared force application, offset, and prosthesis height using 1 model. The combination of these 3 clinically relevant factors in 1 study provides a better understanding of the relative importance of each.

An implant-supported prosthesis framework made from type IV gold alloy was simulated in this study. The dimensions of the frame were larger than would be anticipated in a clinical setting, but simulated loading was within the confines of the natural tooth anatomy. These dimensions were selected to ensure that the framework was as rigid as possible to eliminate the possibility of framework bending, as this would alter the stress in the underlying bone. Frame rigidity was thought to be a clinical goal for most dental prostheses, although it must be recognized that in some situations the prosthetic frame could deflect under functional loading. The effect of such deflection was not evaluated in this study.

The decrease of prosthetic height from 12 mm to 6 mm created a proportional stress reduction that was slightly less than the reduction seen when a maximum offset was compared with a straight implant configuration. Given an association between increased prosthesis height and higher stress in the supporting bone, it may be prudent for the clinician to consider compensatory offsetting of implants when there is an anticipation of a prosthesis with greater than average occlusogingival height. Unfortunately, bone resorption generally occurs more rapidly on the facial aspect,[29,30] thereby making the residual ridge narrower and limiting the potential for implant offset. In such a situation, if high forces are anticipated, ridge augmentation may be indicated prior to implant placement to reduce the anticipated prosthesis height and to allow an increase in offset.

Since an increase in prosthesis height causes an increase in stress within adjacent bone, it is also likely that the prosthetic components used to support the restorations are similarly affected. One method that may reduce stress to the screws retaining the prosthesis is to use components that place these screws closer to the occlusal surface of the restoration rather than burying the retentive elements deep within the prosthesis. If cement-retained restorations are used, integrity of the connections between the implants and the prosthetic retentive components is critical. Careful assessment of this interface is indicated to ensure long-term prosthetic function.

Force was applied at 200 N to the same point on each frame regardless of offset. This point of application was centered over the middle implant when the straight-line configuration was established, but it did not change as the offset was tested. It is likely that the increase in stress with the offset design with pure vertical force application was attributable to this single point of force application. In normal chewing it is unlikely that force will be concentrated in this way. Instead, chewing will produce complex patterns of force application, making this result—increased stress with the offset and axial loading—appear anomalous. Unfortunately, in an FEA study, isolation of forces is essential. The clinician must consider this when a clinical application is envisioned.

The forces to which a prosthesis are subjected are difficult to estimate. Dental history, particularly a history of parafunctional activity and rapid tooth wear or frequent tooth fracture, may indicate that a specific patient is at risk for excessive loading forces on a prosthesis. Using the results of this study, it appears that the clinician has a few therapeutic options that may be employed to minimize stress within the bone that supports implants and subsequently to reduce stress within the components of the prosthesis itself. Since changes in the angle of force application resulted in the greatest change in stress, it may be prudent for the clinician to consider flattening of the occlusal table when high stress is anticipated. This suggestion is in keeping with the results and recommendations of studies by Kaukinen and colleagues[31] and Weinberg.[32] To a lesser extent, creation of an anatomically acceptable offset and reduction of the height of the prosthesis may further reduce stress in the supporting structures. Both of these suggestions demand planning prior to implant placement and exquisite execution of the plan at the time of implant placement. However, even when such planning is successful, the result will be less pronounced than that provided by a flattening of the occlusal anatomy.

Natural tooth anatomy, as described previously,[28] is greater in buccolingual dimension than the diameter of an implant. Regardless of the orientation of implants, rectilinear or curvilinear, the occlusal points of contact may be offset relative to the long axis of the implant. When 3 or more implants are arranged exclusively toward the buccal or lingual surface of the restoration, the effective angle of force application to the implant is accentuated. In such a situation, the results of the current study indicate that reduction of cusp angle to achieve a flatter occlusal surface will partially compensate for the unfavorable forces encountered with nonaxial loading. Conversely, should implants be aligned toward the buccal or lingual surface of the restoration, steep cusp angles will increase the magnitude of stress in the surrounding bone. The clinician must consider the effects of increased stress on the bone, implant, and prosthetic components. Once implants are placed, the greatest reduction of stress, according to this finite element study, is achieved by reduction of the angle of force application, and the most obvious way to achieve such reduction is through alteration of occlusal anatomy through reduction of cusp angles.

In this study the direction of force application had a greater influence on the magnitude of force in the supporting bone than did the implant offset. This observation leads to a different method of stress control, namely alteration of the occlusal surface to minimize resultant stress. For example, if a vertical force is applied to a 15-degree cusp incline, a resultant stress will occur in the supporting bone. If the cusp incline were reduced to zero degrees, the resultant stress in bone would decrease. As the angle of force application deviates from vertical, the resultant force in bone increases, but if the occlusal anatomy is flattened, the effect of the change in angle of force will be diminished. The authors' suggestion is thus to decrease cusp inclines or flatten occlusal anatomy. Inclusion of a slight offset will provide additional benefits to the biomechanical situation, but the magnitude of stress reduction is altered more by anatomy than by offset.

CONCLUSIONS

Using finite element models, it was found that

1. Vertical loading of an implant-supported prosthesis produced the lowest stress to the supporting bone.
2. A 15-degree change from vertical in the angle of the force applied to a simulated implant-supported prosthesis caused an increase in stress in the simulated supporting bone.
3. Increasing the angle further resulted in greater stress to simulated supporting bone.
4. Reduction in prosthesis height from 12 to 6 mm or establishment of an offset implant location for the middle of 3 implants can reduce stress, but this reduction does not compensate for the increase in stress found with nonaxial loading.

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