Implant-Supported First Molar Restorations: Correlation of Finite Element Analysis with Clinical Outcomes

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Purpose: *This study aimed to evaluate the effect of the placement of wide-diameter implants on bone stress concentrations and marginal bone loss in the first molar region. Study hypotheses held that increasing implant diameter would decrease peri-implant bone stress levels, but that statistically significant reductions in clinical bone loss would either (1) not be observed for any implant diameter or (2) be observed only for the widest implant diameter.* ***Materials and Methods:*** *Three-dimensional finite element analysis (3D FEA) was used to analyze the relationship between implant diameter and peri-implant bone thickness, cortical bone thickness, occlusal load direction, and percentage of bone-to-implant contact on bone stress levels in the first molar region. A retrospective review of patient records was also conducted in three private practices to assess clinical outcomes and bone level changes around one implant design in three diameters (3.7, 4.7, and 6.0 mm) placed in first molar locations. Categorical variable summaries and comparisons of 3D FEA and clinical findings were made using the FREQ procedure, t test procedures (Student t tests, folded F tests, Satterthwaite t tests), and the NONPAR1WAY procedure (Wilcoxon nonparametric test).* ***Results:*** *Cumulative implant success was 98.4% and survival was 98% after a mean of 49.2 months. Although increasing implant diameter always reduced peri-implant stress concentrations in 3D FEA experiments, clinically, only 6.0-mm implants exhibited a statistically significant reduction in bone loss (0 mm) as compared to 3.7-mm and 4.7-mm implants.* ***Conclusion:*** *Only 6.0-mm implants were effective in reducing marginal bone loss in the first molar region. 3D FEA results supported previous clinical findings that maintaining approximately 1.8 mm of buccal plate thickness can help reduce bone stress concentrations and preserve buccal bone height. A history of periodontitis may adversely affect long-term marginal bone stability.* Int J Oral Maxillofac Implants 2012;27:e1–e12

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The size and relatively central anteroposterior positions of the first molars make them essential for maintaining proper arch form and occlusal schemes.[1,2]

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As the first permanent teeth to erupt in the human arches, however, they also have the ironic distinction of being among the first permanent teeth to be lost as a result of disease or decay.[2–5] Restoration of missing first molars is essential but presents a variety of clinical challenges. Conventional fixed partial dentures can offer improved stability and function, but the ethics of preparing healthy adjacent teeth to support prostheses and uncertainty about the long-term prognosis of preparing previously restored teeth have raised concerns.[6–8]

Dental implant restorations can help preserve adjacent teeth[6] but have traditionally exhibited slightly reduced survival rates in posterior arches, which are subject to high occlusal forces and typically exhibit low bone density.[9–12] The proximity of the maxillary sinus and mandibular canal to the first molar regions can necessitate placement of short implants (10 mm or less), which historically tend to be less predictable than longer implants.[9–12] Restoring the wide interdental space can also present biomechanical challenges.

Table 1 3D FEA Experimental Variables	
Variable	**Examined factors/assumptions**
Primary variable	Influence of implant diameter on peri-implant bone stress
Secondary variables	
Experiment 1	Influence of peri-implant bone width (radial bone volume): Bone model A,* 100% BIC,[†] and 30-degree impact angle
Experiment 2	Influence of cortical bone height (vertical bone volume): bone models B and C,* 100% BIC, and 30-degree impact angle
Experiment 3	Influence of applied load direction: Bone model B,* 100% BIC, 30-degree and 0-degree impact angles
Experiment 4	Influence of mean %BIC: Bone model B,* < 100% BIC,[§] 30-degree impact angle

*See Table 2.
[†]Percentage of bone-to-implant contact assumed for test purposes.
[‡]Angle = 222 N of load applied load at (1) a 30-degree angle (θ = 30 degrees) angle with 1.5-mm buccolingual offset from vertical axis of the implant or (2) a 0-degree angle (θ = 0 degrees) from the long axis of the implant model.
[§]Modeled as 100% BIC in the cervical and apical regions and 8% to 100% BIC in the remaining thread regions.

Overcontouring a prosthesis to restore a large occlusal surface may result in increased nonaxial forces on standard-diameter implants (3.7 mm diameter) and more intense peri-implant stress concentrations in bone during occlusal loading.[13,14] These forces may lead to peri-implant bone loss, component metal fatigue, and secondary fracture of the prosthetic screw, abutment, and/or implant body.[13,14]

To improve load distribution in bone, some clinicians[15] have advocated the placement of two narrow-diameter (3.7 mm or less) or standard-diameter implants to support single molar restorations. The ability to do this, however, is limited by numerous variables, such as arch morphology,[12] proximity of adjacent teeth,[16] vertical access, and skill of the surgeon. The use of wide-diameter (> 3.7-mm) implants to support a single molar prosthesis has been advocated as an alternative to placing single or multiple standard-diameter implants,[12] but few data have been published to adequately support evidence-based treatment planning. Conversely, some clinicians have reported that wide-diameter implants placed in posterior areas may be more susceptible to failure than standard-diameter implants.[17]

Three-dimensional finite element analysis (3D FEA) can theoretically measure stresses generated by implants in bone during occlusal loading. Although there is currently no clinical consensus on the relationship between occlusal overloading and peri-implant marginal bone level changes, several researchers[18–20] have hypothesized that stress below a threshold of approximately 50 MPa will preserve marginal bone levels in a balanced steady state, but that stresses of 50 MPa or higher will trigger pathologic overload that may result in bone resorption. However, such 3D FEA findings have not been adequately correlated to an actual clinical context.

The aim of the present report is to convey the findings of a two-part study that used 3D FEA and retrospective clinical data to analyze the relationship between implant diameter and the crestal bone response around implant-supported, single-tooth restorations in first molar regions. The study hypothesis was that an increase in implant diameter would result in a corresponding decrease in peri-implant bone stress in the 3D FEA portion of the study, but that differences in implant diameter would not be significant in the clinical portion of the study. An alternate hypothesis was that an increase in implant diameter would result in a corresponding decrease in peri-implant bone stress in the 3D FEA portion of the study, but a statistically significant decrease in bone loss would manifest only around the widest-diameter implants in the clinical portion of the study.

MATERIALS AND METHODS

3D FEA Experiments

Four 3D FEA experiments were performed to evaluate the influences of implant diameter (3.7, 4.7, and 6.0 mm) on bone stress levels relative to one or more secondary experimental variables (Table 1). Design software (SolidWorks Professional 2006, SolidWorks) and 3D FEA software (ANSYS Workbench 11.0, ANSYS) were used on a personal computer to create digital study models that simulated an implant embedded in a cylindric bone block and restored with an abutment and coping (Fig 1).

To approximate a variety of clinical conditions in these experiments, cylindric bone blocks were modeled with different mechanical properties (Table 2)[21] and peri-implant bone thicknesses (Tables 3a to 3c). The implant, abutment, and coping assembly models

(Figs 1a and 1b) corresponded in design and material characteristics (elastic modulus = 110 GPa, Poisson ratio = 0.34 GPa[22]) to those of the titanium alloy implants used in the clinical portion of the study. Bone-to-implant contact (BIC) was assumed to be an interfacial bond between the modeled bone blocks and implants, but the overall percentage of BIC varied according to the experiment. A standard occlusal force of 222 N was applied to each implant model. The selected force represented a slightly higher-than-median value within a range of 1.74 to 356.98 N[23,24] of mean maximum bite force values reported for the first molar region. In most experiments, loading was applied at a 30-degree angle with a 1.5-mm offset in an attempt to approximate normal mastication.

Experiment 1 investigated the influence of implant diameter and radial peri-implant bone volume on stress levels generated by the implant in bone (Table 1). Results were compared to the findings of a previous clinical study that measured buccal plate thickness of newly prepared implant osteotomies and correlated the findings with future buccal plate bone loss and implant failure.[25] The earlier study found that, as buccal plate thickness decreased below a critical threshold of 2 mm, buccal plate resorption and implant failure rates increased.[25] When buccal plate thickness was ≥ 2 mm, however, implant survival rates increased and some evidence of marginal bone gain was noted.[25]

In the present 3D FEA analysis, to eliminate differences in the moduli of elasticity, cortical and cancellous bone were merged into a single, hypothetical bone model with a homogenous modulus of elasticity (cortical + cancellous bone combined) (Table 2) (Fig 1b). In creating this hypothetical bone model, the authors acknowledged that the extrapolation of 3D FEA data to clinical findings would be highly limited in general, especially with this theoretical bone model. However, 3D FEA is the most accurate and reproducible theoretical method of evaluating load and stress distribution in the region of BIC and can provide more accurate data than bench testing or other experimental methods. While patient variables are extremely important in any clinical context, they cannot all be simulated in a theoretical or experimental analysis. For this reason, 3D FEA was used to obtain and evaluate stresses in bone that could not be accurately measured in a clinical context. To facilitate model convergence for the evaluation of a 1-mm peri-implant radial bone dimension, the bone materials were merged to form a homogenous modulus of elasticity that ranged between types 2 and 3 bone.[21] This model was specifically selected based on more than 1,900 clinical evaluations that found that types 2 and 3 bone[21] predominated in both mandibles and maxillae.[26] Despite its limitations, 3D FEA was best able to provide important information pertaining to
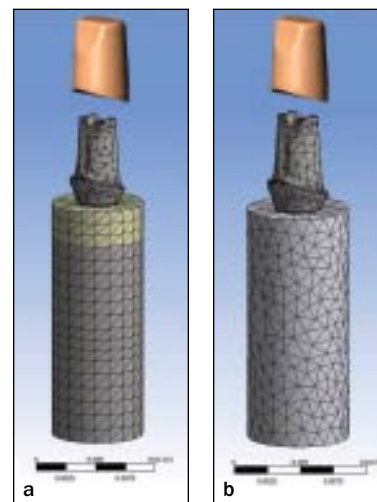
Fig 1 Typical FEA model and meshes simulating a two-piece implant embedded in bone with *(a)* defined cortical and cancellous layers or *(b)* a homogenous structure.

the influence of implant diameter, occlusal load direction, bone volume, bone density, and other variables on stress levels, which could be used as general guidelines for case planning.

Experiment 2 examined the influence of implant diameter and the vertical volume of cortical bone on stress levels generated by the implant in two bone models that differed in cortical bone thickness (Tables 1 and 2) (Fig 1a). In both segments, osseointegration was assumed to be complete (BIC = 100%). To evaluate the effect of variations in cortical bone thickness, all the other variables were held constant. The decision to assume 100% BIC was based on the common use of this assumption in other FEA studies.[27–29]

Experiment 3 evaluated the influence of implant diameter and occlusal load direction on peri-implant stresses in bone (Tables 1). Bone model B (Table 2) was used, and osseointegration was assumed to be complete (BIC = 100%). Vertical compressive loading at a 0-degree angle ($\theta = 0$ degrees) from the long axis of the implant model was also applied as part of the stress distribution analysis. For this experiment, it was hypothesized that the linearly elastic model used in this study would cause a linear increase in the maximum stress in the bone.

Experiment 4 used bone model B to evaluate the influence of implant diameter and the percentage of BIC (% BIC) on bone stress levels (Tables 1 and 2). BIC was 100% in the cervical and apical regions of the implant models but ranged from 8% to 100% in the thread regions to approximate a total of 30% BIC to represent the less-than-100% osseointegration that occurs in actual clinical practice, regardless of implant design.[26]

Table 2 3D FEA Bone Models

| | Peri-implant bone dimensions[†] | | Bone type | | | | | |
| | | | Cortical | | Trabecular | | Homogenous | |
Model*	Vertical	Radial[†]	Vertical dimension	Elastic modulus	Vertical dimension	Elastic modulus	Vertical dimension	Elastic modulus
A[†]	20 mm	Various	N/A	N/A	N/A	N/A	20 mm	3.5 GPa
B[§]	20 mm	2 mm	3 mm	15 GPa	17 mm	1.5 GPa	N/A	N/A
C[§]	20 mm	2 mm	1 mm	15 GPa	19 mm	1.5 GPa	N/A	N/A

*Theoretical bone model designed for test purposes only; structure is not analogous to actual bone. The isotropic, homogenous elastic modulus was based on moduli of 15 GPa for cortical bone (E_1) and 1.5 GPa for trabecular bone (E_2). Calculations of average elastic modulus utilized volume fractions of cortical bone (v_1 = 15%) and trabecular cancellous bone (v_2 = 85%) where v_1, v_2, E_1, and E_2 are volume fractions and elastic moduli of cortical and cancellous bone, respectively; equation 1: $E = v_1 E_1 + v_2 E_2$. A two-time decay model was used to describe the FEA analysis data presented in equation 2 where C_1 and C_2 (MPa) are constants dependent on the implant assembly size and platform, t (mm) is the bone volume surrounding the implant in mm, and τ_1 and τ_2 (mm) are decay constants; equation 2: $\sigma(t) = C_1 \exp(-t/\tau_1) + C_2 \exp(-t/\tau_2)$.
[†]Uniform peri-implant bone volume.
[‡]Generally representative of type 1 or type 2 bone.[21]
[§]Generally representative of type 2 or type 3 bone.[21]
Peri-implant radial bone volume was gradually decreased in 0.5-mm increments from 5 mm (max) to 1 mm (min) to during the study.

Table 3a Results of 3D FEA Experiment No. 1: Influence of Peri-implant Bone Width and Implant Diameter on Peri-implant Stresses*

| Bone model[†] | | Peri-implant radial bone dimension (mm) | Stresses (MPa) generated by implant diameter (mm) | | |
Classification	% BIC		3.7 mm	4.7 mm	6.0 mm
A	100	1.0	37	24	17
A	100	1.5	31	20	14
A	100	2.0	28	18	13
A	100	2.5	26	16	12
A	100	3.0	25	16	11
A	100	3.5	25	15	11
A	100	4.1	24	15	11
A	100	4.5	24	15	11
A	100	5.0	24	15	11

*Applied load = 222 N at a 30-degree angle and a 1.5-mm offset from the vertical axis of the implant.
[†]See Table 2.
% BIC = percentage of bone-to-implant contact.

Table 3b Results of Experiment No. 2: Influence of Cortical Bone Height and Implant Diameter on Peri-implant Stresses*

| Bone model[†] | | Cortical bone vertical dimension (mm) | Stresses (MPa) generated by implant diameter (mm) | | |
Classification	% BIC		3.7 mm	4.7 mm	6.0 mm
B	100	3.0	24	16	13
C	100	1.0	55	41	36

*Applied load = 222 N at a 30-dergee angle and a 1.5-mm offset from the vertical axis of the implant.
[†]See Table 2.
% BIC = percentage of bone-to-implant contact.

Table 3c Results of Experiment No. 3: Influence of Applied Load Direction and Implant Diameter on Peri-implant Stresses

| Bone model* | | Direction of applied load | Stresses (MPa) generated by implant diameter (mm) | | |
Classification	% BIC		3.7 mm	4.7 mm	6.0 mm
B	100	30 deg[†]	41	24	22
B	100	0 deg[‡]	24	16	13

*See Table 2.
[†]Applied load = 222 N at a 0-degree angle and a 0.0-mm offset from the vertical axis of the implant.
% BIC = percentage of bone-to-implant contact.

Clinical Analysis

The second phase of the study consisted of a non-randomized, uncontrolled, retrospective review and evaluation of patient treatment records to determine whether implant diameter influenced clinical outcomes and marginal bone stability. To avoid bias resulting from additional variables of implant design, study inclusion was limited to a tapered, multi-threaded implant design with a microtextured surface from one manufacturer (Tapered Screw-Vent MTX, Zimmer Dental). Study inclusion criteria also included all patients who had been treated for one or more missing first molar teeth located between two clinically healthy teeth and restored with a nonsplinted, cement-retained, porcelain-fused-to-metal crown on a straight titanium abutment. Data from patient charts and treatment databases from three private dental practices were collected in digital spreadsheets (Excel, Microsoft) in a personal computer. Peri-implant bone change data calculated by each clinician from non-standardized periapical radiographs taken at implant placement (baseline) and at the last annual follow-up appointment were also recorded. In all cases, measurements were made from the crest of the ridge to the first implant thread.

Subjects were treated with implants in diameters of 3.7, 4.7, and 6.0 mm; these supported one- or two-implant first molar restorations. To analyze the relationship between implant diameter and crestal bone response, study subjects were assigned to three different database groups based on the diameters of implants used for their respective restorations. This enabled data to be analyzed both at the subject level and at the implant level. For implant-level analyses, subjects treated with two-implant restorations were assigned to two different groups if their implants differed in diameter, or they were listed twice in the same group if both implants matched in diameter.

Implants were considered to be survivors if they were immobile when tested manually, did not exhibit peri-implant radiolucency, had no irresolvable clinical symptoms or mechanical problems, and fully met their prosthodontic purpose. All clinically failed implants were recorded as failures in the database. Implants were considered successful if they met the implant survival criteria, had no irresolvable non–failure-related adverse events, did not have peri-implant bone loss that exceeded 1.5 mm, and met the patient's clinical and esthetic needs and expectations, as determined by the patient records.

Statistical Analysis

Spreadsheet data were divided into five study groups based on implant diameter. The data were analyzed with software (SAS 8.02, SAS) on a personal computer.

Categorical variable summaries and comparisons were made using the FREQ procedure; Student t tests, (folded) F tests, Satterthwaite t tests were performed using the TTEST procedure; and the Wilcoxon nonparametric test was performed using the NONPAR1WAY procedure. Statistical significance was inferred at the nominal level of type 1 (alpha).

## RESULTS

3D FEA Experiments

Experiment 1. Stresses increased significantly as peri-implant bone thickness decreased to approximately 1 mm around the implant (Table 3a). This difference diminished as the peri-implant bone thickness increased to approximately 2 mm or greater (Fig 2, Table 3a). Based on a two-time decay model (Table 3a), the variable of implant diameter influenced the degree, but not the rate, of change in the level of peri-implant bone stresses that occurred simultaneously with changes in peri-implant bone thickness. All observed stresses under the prescribed boundary and loading conditions were below 50 MPa, the theoretical threshold for bone loss.[18–20]

Experiment 2. Maximum stresses were concentrated in the crestal bone region and gradually diminished in intensity along the implant surface deeper within the bone, regardless of the bone model used. In bone model B, all stresses observed under the prescribed boundary and loading conditions were below 50 MPa (Table 3b) (Fig 3). In bone model C, stress concentrations observed under the prescribed boundary and load conditions were above the 50-MPa threshold for implants with diameters of 3.7 and 4.1 mm, but they dropped below 50 MPa for implant diameters of 4.7 and 6.0 mm (Table 3b).

Experiment 3. Maximum stress concentrations observed under the boundary and loading conditions were below the 50-MPa threshold in bone model B, regardless of implant diameter or angle of applied load (Table 3c). These results do not account for the nonlinear response of bone. Increasing the implant diameter reduced the maximum stress concentrations, regardless of loading angle (0 versus 30 degrees).

Experiment 4. Maximum bone stress levels did not change as the overall percentage of BIC diminished from 100% to 50%; however, maximum bone stress levels gradually increased in localized stress patterns around individual implant threads as % BIC dropped below 50%. Figure 4 represents the effect of BIC on the maximum stress within the bone at the threads only when there was an assumed 100% bonded contact (osseointegration) in the cervical collar, apex, and the apical vent regions of the implant body. Figure 5
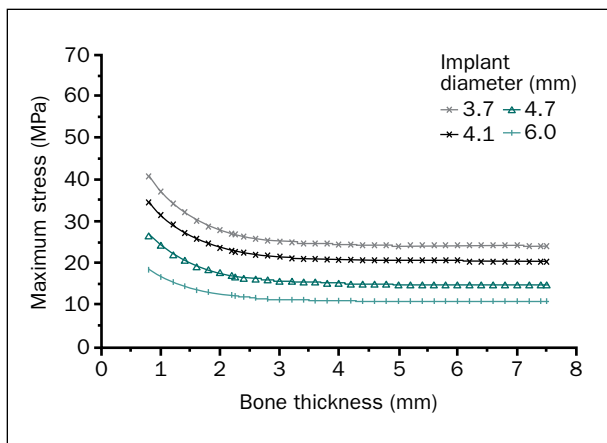
Fig 2 Effects of peri-implant bone thickness and implant diameter on maximum stresses in bone subjected to 222 N of applied load at a 30-degree angle.
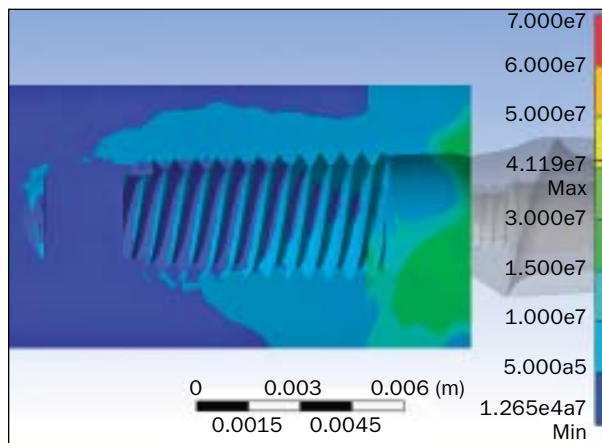
Fig 3 Von Mises stress distributions for 3.7 mm-diameter implants in bone. Note that the highest stress concentrations are located in the crestal bone region and decrease deeper within the bone.

illustrates the distribution of stresses within the peri-implant bone for 30% BIC. The highest stress contour bands were located at the bone crest, and stress levels decreased progressively within the trabeculae. For most cases, stress levels within trabecular bone were less than 5 MPa under the prescribed boundary conditions based on stress contours (refer to Fig 2 as typical von Mises stress contours).

Clinical Analysis. The database consisted of 120 subjects with a mean age of 52.6 years (Table 4a). Subjects were treated with 128 implants in diameters of 3.7 mm (27%), 4.7 mm (23%), and 6.0 mm (50%); these were distributed as either one- (93%) or two- (7%) implant–supported restorations per patient (Table 4a). In the eight patients who received two restorations, three subjects were treated with a combination of 3.7 mm- and 4.7 mm-diameter implants, one subject was treated entirely with 3.7-mm-diameter implants, and four subjects received only 6.0-mm-diameter implants.

At the patient level (n = 120), the average length of follow-up was 49.2 months. At the implant level, average follow-up time did not differ significantly between the 3.7-mm and 4.7-mm implant groups (P = .82), but both groups differed significantly (P = .001 and P = .03, respectively) from the 6.0-mm group (Table 4c). In addition, average follow-up for the combined 4.7-/6.0-mm group differed significantly from follow-up for the 3.7-mm group (P = .02). The distribution of implant lengths and diameters is summarized in Table 4a.

Bone grafting was used only in immediate implant cases and only when the void between the implant collar and the crestal bone exceeded 1.0 mm in width (n = 9/128, 7%) (Table 4a). Concomitant health risks were not common at the patient level, with 82% reporting the absence of a comorbidity. At the implant level, freedom from concomitant health risks was reported for 71% of subjects in the 3.7-mm group, 83% of subjects in the 4.7-mm group, and 88% of subjects in the 6.0-mm group. Pairwise comparisons of concomitant health risk (any versus none) at the implant level did not achieve statistical significance (P > .05) for three of the four comparisons (3.7-mm versus 4.7-mm, 4.7-mm versus 6.0-mm, and 3.7-mm versus 4.7- and 6.0-mm combined); however, the 3.7-mm group differed statistically significantly from the 6.0-mm group (P = .049). Inspection of the frequency distributions across types of comorbidities indicated that the statistical difference was caused by a greater prevalence of perio-dontitis in the 3.7-mm group (24%) as compared to the 6.0-mm group (2%) in combination with a smaller prevalence of smoking in the 3.7-mm group (0%) as compared to the 6.0-mm (9%) group.

Most of the 128 study implants were placed in the mandible (n = 94, 73%) as compared to the maxilla (n = 34, 27%). In the mandible, the frequency of 3.7-mm implants (60%) did not significantly differ from the frequency of 4.7-mm implants (59%) (P > .99), but there were significant differences in the frequencies of both the 3.7-mm (P = .002) and 4.7-mm (P = .003) implants as compared to the 6.0-mm implants (88%). In the combined 4.7- and 6.0-mm group, the distribution of mandibular implants also differed significantly from that of the 3.7-mm group (P = .04). In the maxilla, only 24% (n = 8) of the implants were 6.0 mm wide as comparedto 4.7 mm (35%, n = 12) and 3.7 mm (41%, n = 14).
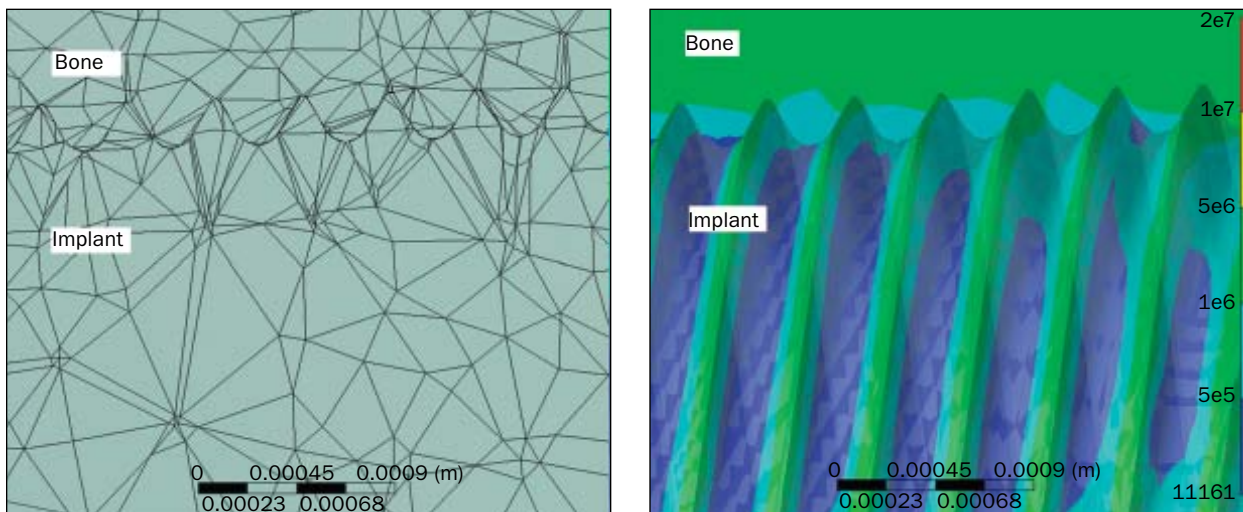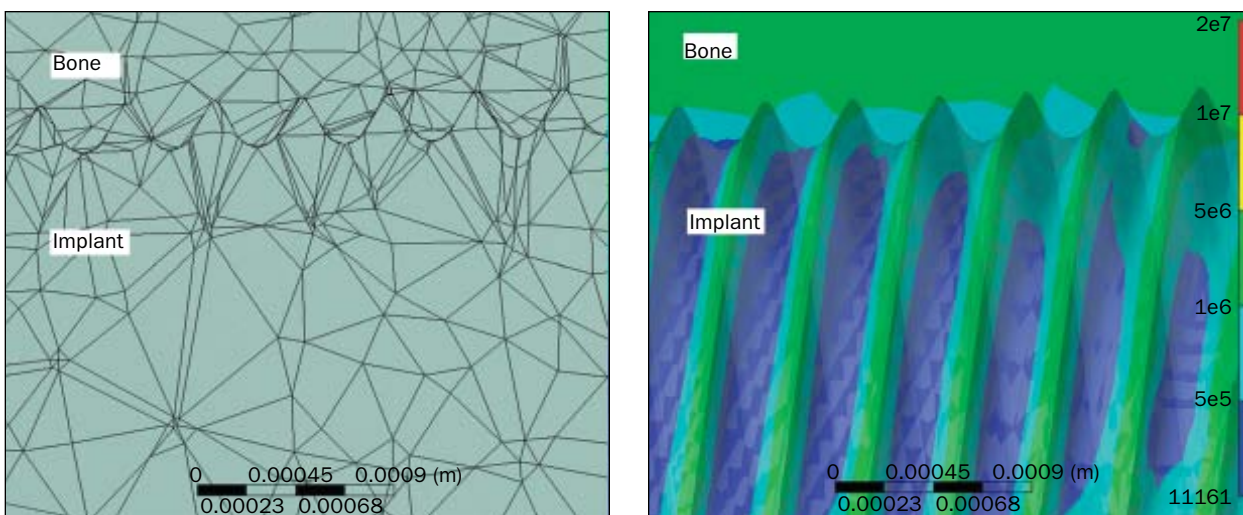
Fig 4 Maximum stress levels with 100% BIC.

Fig 5 Maximum stress levels with 30% BIC.

Table 4a	Summary of Patient and Implant Data by Implant Diameter*					
Variable	**3.7 mm (n = 35)**	**4.7 mm (n = 29)**	**6.0 mm (n = 64)**	**4.7 + 6.0 mm (n = 93)**	**All implants (n = 128)**	**Group comparisons**
Sex						3.7 vs 4.7, P = .613 4.7 vs 6.0, P = 1.00 3.7 vs. 6.0, P = .667 3.7 vs (4.7 + 6.0), P = .678
Male	20 (58.8%)	19 (65.5%)	38 (64.0%)	57 (64.0%)	75 (62.5%)	
Female	14 (41.2%)	10 (34.5%)	33 (36.0%)	32 (36.0%)	45 (37.5%)	
Age (y)						3.7 vs 4.7, P = .419 4.7 vs 6.0, P = .001 3.7 vs 6.0, P = .000 3.7 vs (4.7 + 6.0), P = .000
18–29	4 (11.8%)	1 (3.4%)	0 (0.0%)	1 (1.1%)	5 (4.2%)	
30–39	12 (35.3%)	8 (27.6%)	3 (5.0%)	11 (12.4%)	23 (19.2%)	
40–49	6 (17.6%)	9 (31.0%)	8 (13.3%)	17 (19.1%)	22 (18.3%)	
50–59	9 (26.5%)	5 (17.2%)	11 (18.3%)	16 (18.0%)	23 (19.2%)	
60–69	2 (5.9%)	4 (13.8%)	27 (45.0%)	31 (34.8%)	33 (27.5%)	
70+	1 (2.9%)	2 (6.9%)	11 (18.3%)	13 (14.6%)	14 (11.7%)	

Table 4a   Summary of Patient and Implant Data by Implant Diameter* cont

Variable	3.7 mm (n = 35)	4.7 mm (n = 29)	6.0 mm (n = 64)	4.7 + 6.0 mm (n = 93)	All implants (n = 128)	Group comparisons
Bone graft used						3.7 vs 4.7, *P* = 1.00 4.7 vs 6.0, *P* = .008 3.7 vs 6.0, *P* = .005 3.7 vs (4.7 + 6.0), *P* = .062
Yes	5 (14.3%)	4 (13.8%)	0 (0.0%)	4 (4.3%)	9 (7.0%)	
No	30 (86.0%)	25 (86.2%)	64 (100%)	89 (96.0%)	119 (93.0%)	
Implant length						3.7 vs 4.7, *P* = .756 4.7 vs 6.0, *P* = .002 3.7 vs 6.0, *P* = .009 3.7 vs (4.7 + 6.0), *P* = .348
8 mm	0 (0.0%)	1 (3.4%)	1 (1.6%)	2 (2.2%)	2 (1.6%)	
10 mm	8 (22.9%)	6 (20.7%)	30 (46.9%)	36 (38.7%)	44 (34.4%)	
11.5 mm	5 (14.3%)	6 (20.7%)	1 (1.6%)	7 (7.5%)	12 (9.4%)	
13 mm	20 (57.1%)	14 (48.3%)	31 (48.4%)	45 (48.4%)	65 (50.8%)	
16 mm	2 (5.7%)	2 (6.9%)	1 (1.6%)	3 (3.2%)	5 (3.9%)	
Implant diameter						3.7 vs 4.7, *P* = .000 4.7 vs 6.0, *P* = .000 3.7 vs 6.0, *P* = .000 3.7 vs (4.7 + 6.0), *P* = .000
3.7 mm	35 (100%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	35 (27.3%)	
4.7 mm	0 (0.0%)	29 (100%)	0 (0.0%)	29 (31.2%)	29 (22.7%)	
6.0 mm	0 (0.0%)	0 (0.0%)	64 (100%)	64 (68.8%)	64 (50.0%)	
Concomitant health risks (any/none)						3.7 vs 4.7, *P* = .375 4.7 vs 6.0, *P* = .516 3.7 vs 6.0, *P* = .049 3.7 vs (4.7 + 6.0), *P* = .063
None	24 (70.6%)	24 (82.8%)	53 (88.3%)	77 (86.5%)	98 (81.7%)	
Health risk(s)	10 (29.4%)	5 (17.2%)	7 (11.7%)	12 (13.5%)	22 (18.3%)	
Concomitant health risks (type)						3.7 vs 4.7, *P* = .358 4.7 vs 6.0, *P* = .020 3.7 vs 6.0 *P* = .001 3.7 vs (4.7 + 6.0), *P* = .006
None	24 (70.6%)	24 (82.0%)	53 (89.8%)	77 (87.5%)	98 (82.4%)	
Diabetes	1 (2.9%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	1 (0.8%)	
Hypertension	1 (2.9%)	2 (6.9%)	0 (0.0%)	2 (2.3%)	3 (2.5%)	
Periodontitis	8 (23.5%)	3 (10.3%)	1 (1.7%)	4 (4.5%)	12 (10.1%)	
Smoking	0 (0.0%)	0 (0.0 %)	5 (8.5 %)	5 (5.7%)	5 (4.2%)	
No. of treatment sites per patient						3.7 vs 4.7, *P* = 1.000 4.7 vs 6.0, *P* = .678 3.7 vs 6.0 *P* = .454 3.7 vs (4.7 + 6.0), *P* = .494
1	30 (88.2%)	26 (89.7%)	56 (51.6%)	43 (46.2%)	59 (46.1%)	
2	4 (11.8%)	3 (10.3%)	4 (48.4%)	50 (53.8%)	69 (53.9%)	
NFR[†] adverse event (any/none)						3.7 vs 4.7, *P* = 1.000 4.7 vs 6.0, *P* = .533 3.7 vs 6.0 *P* = .280 3.7 vs (4.7 + 6.0), *P* = .294
None	32 (94.1%)	28 (96.6%)	62 (98.4%)	90 (97.8%)	122 (96.8%)	
Adverse event(s)	2 (5.9%)	1 (3.4%)	1 (1.6%)	2 (23.2%)	4 (3.2%)	
NFR[†] adverse event (type)						3.7 vs 4.7, *P* = .236 4.7 vs 6.0, *P* = .570 3.7 vs 6.0, *P* = .117 3.7 vs (4.7 + 6.0), *P* = .045
None	32 (94.1%)	28 (96.6%)	62 (98.4%)	90 (97.8%)	122 (96.8%)	
Cement failure	2 (5.9%)	0 (100%)	0 (0.0%)	0 (0.0%)	2 (1.6%)	
Loose screw	0 (0.0%)	1 (3.4%)	1 (1.6%)	2 (2.2%)	2 (1.6%)	

*Fisher exact (2 × 2), likelihood ratio chi-square. Used significance levels from Satterthwaite t test and Wilcoxon nonparametric test when sample variances were unequal (significant, folded *F* test ≤ .05).
†NFR = Non–failure-related.

Table 4b Summary of Implant Survival and Peri-implant Bone Loss by Implant Diameter*

Variable	3.7 mm (n = 35)	4.7 mm (n = 29)	6.0 mm (n = 64)	4.7 + 6.0 mm (n = 93)	All implants (n = 128)	Comparisons
Implant survival						3.7 vs 4.7, *P* = 1.00 4.7 vs 6.0, *P* = 1.00 3.7 vs 6.0, *P* = 1.00 3.7 vs (4.7 + 6.0), *P* = .474
Surviving	34 (97.1%)	29 (100%)	63 (98.4%)	92 (98.9%)	126 (98.4%)	
Failed	1 (2.9%)	0 (0.0%)	1 (1.6%)	1 (1.1%)	2 (1.6%)	
Peri-implant bone loss (any/none)						3.7 vs 4.7, *P* = .453 4.7 vs 6.0, *P* = .002 3.7 vs 6.0, *P* = .041 3.7 vs (4.7 + 6.0), *P* = .444
None	31 (91.2%)	17 (82.8%)	63 (100%)	87 (94.6%)	118 (93.7%)	
Any	3 (8.8%)	12 (17.2%)	0 (0.0%)	5 (5.4%)	8 (6.3%)	
Peri-implant bone loss (mm)†						3.7 vs 4.7, *P* = .636 4.7 vs 6.0, *P* = .009 3.7 vs 6.0, *P* = .057 3.7 vs (4.7 + 6.0), *P* = .713
None	31 (91.2%)	24 (82.8%)	63 (100%)	87 (94.6%)	118 (93.7%)	
1.0 mm	2 (5.9%)	3 (10.3%)	0 (0.0%)	3 (3.3%)	5 (4.0%)	
1.5 mm	0 (0.0%)	1 (3.4%)	0 (0.0%)	1 (1.1%)	1 (0.8%)	
2.0 mm	1 (2.9%)	1 (3.4%)	0 (0.0%)	1 (1.1%)	2 (1.6%)	

*Fishers exact (2 × 2), likelihood ratio chi-square. Used significance levels from Satterthwaite t test and Wilcoxon nonparametric test when sample variances were unequal (significance, folded *F* test ≤ .05).
†Nonstandardized radiographs were assessed visually on a light box without digital assistance.

Table 4c Analysis of Length of Follow-up with Respect to Implant Diameter*

Implant diameter (mm)	n	Length of Follow-up					Comparison	Test* (value)
		Mean	Median	SD	Min	Max		
3.7 (n = 35)	34	41.91	42.00	21.60	12.00	83.00	3.7 vs 4.7	t (*P* = .817) f (*P* = .134) s (*P* = .821) w (*P* = .983)
4.7 (n = 29)	29	43.48	40.00	28.37	12.00	80.00	4.7 vs 6.0	t (*P* = .005) f (*P* = .000) s (*P* = .026) w (*P* = .107)
6.0 (n = 64)	60	56.35	55.50	4.63	26.00	82.00	6.0 vs 3.7	t (*P* = .000) f (*P* = .009) s (*P* = .001) w (*P* = .001)
4.7 + 6.0 (n = 93)	89	52.12	53.00	20.90	12.00	82.00	3.7 vs (4.7 + 6.0)	t (*P* = .018) f (*P* = .786) s (*P* = .021) w (*P* = .107)
All implants (n = 128)	120	49.21	51.00	21.46	12.00	83.00		

*Fisher exact (2 × 2), likelihood ratio chi-square. T = Student *t* test (pooled sample variance); f = *F* test (folded, equal sample variances); s = Satterthwaite *t* test; w = Wilcoxon nonparametric test. Significance levels from s and w were used when sample variances were unequal (significance, folded *F* test ≤ .05).

The cumulative implant survival rate was 98% (Table 4b). With one failure in each arch, implant survival rates were 99% (n = 93/94) in the mandible and 97% (n = 33/34) in the maxilla. The mandibular implant failed in a 64-year-old systemically healthy man (patient no. 64) for unknown causes after 26 months in function. The maxillary implant failed in a 55-year-old woman (patient no. 24) with a history of moderate periodontitis after 36 months in function. Failure rates were not statistically significantly different between any groups (3.7-mm versus 4.7-mm, *P* > .99; 3.7-mm versus 6.0-mm, *P* > .99; 4.7-mm versus 6.0-mm, *P* > .99; 4.7- and 6.0-mm versus 3.7-mm, *P* = .47) (Table 4d). Single implant failures occurred in both the 3.7-mm (3%) and 6.0-mm (2%) groups, however. The failed maxillary implant mentioned previously was

Implant diameter (mm)	n	Mean	Median	SD	Min	Max	Comparison	Test* (value)
Table 4d							**Analysis of Patient Age with Respect to Implant Diameter***	
3.7 (n = 35)	34	42.91	55.50	12.46	19.00	70.00	3.7 vs 4.7	t (P = .241) f (P = .966) s (P = .241) w (P = .278)
4.7 (n = 29)	29	46.62	47.00	12.34	19.00	70.00	4.7 vs 6.0	t (P = .000) f (P = .623) s (P = .000) w (P = .000)
6.0 (n = 64)	60	60.95	63.50	11.47	35.00	83.00	6.0 vs 3.7	t (P = .000) f (P = .568) s (P = .000) w (P = .000)
4.7 + 6.0 (n = 93)	89	56.28	58.00	13.50	19.00	83.00	3.7 vs (4.7 + 6.0)	t (P = .000) f (P = .616) s (P = .000) w (P = .000)
All implants (n = 128)	120	52.62	53.50	14.63	19.00	83.00		N/A

*Fisher exact (2 × 2), likelihood ratio chi-square. t = Student t test (pooled sample variance); f = F test (folded, equal sample variances); s = Satterthwaite t test; w = Wilcoxon nonparametric test. Significance levels from s and w were used when sample variances were unequal (significance, folded F test ≤ .05).

3.7 mm in diameter, and the failed mandibular implant was 6.0 mm in diameter. The causes of both implant failures could not be determined from the archived data; however, both patients were subsequently treated outside of the present data analysis.

The majority of surviving implants (94%) had no documented bone loss (Table 4b). Of the eight implants (6%) with recorded bone loss, half were placed in patients with a history of mild (n = 2) or moderate (n = 2) periodontitis. A total of 12 patients (9%, 12/128) had a history of mild (n = 3) to moderate (n = 4) periodontitis (five maxillary and seven mandibular implant patients). Within this periodontitis subgroup, one patient lost 2 mm of bone, one patient lost 1.5 mm of bone, and two patients each lost 1 mm of bone. In the nonperiodontitis subgroup, three implants exhibited 1 mm of bone loss and one implant sustained 2.0 mm of bone loss. At the implant level, no bone loss was reported around 6.0-mm implants (0%), while bone loss was reported for both 3.7-mm (9%) and 4.7-mm (17%) implants. Comparisons of bone loss (any/none) between groups did not achieve statistical significance for the 3.7-mm versus 4.7-mm implants (P = .45) or for the combined wide-diameter group (4.7-/6.0-mm) versus the 3.7-mm group (P = .44). Bone loss differed significantly between the 3.7-mm and 6.0-mm groups (P = .04) and between the 4.7-mm and 6.0-mm groups (P = .002). This finding affirmed the alternate study hypothesis.

Non–failure-related adverse events among surviving implants were rare (3%) and restricted to cement failures and screw loosening, each of which exhibited a prevalence rate of 1.6% (Table 4a). Comparisons of adverse event rates (any/none) did not reach statistical significance for any between-group comparisons (3.7 mm [6%] versus 4.7 mm [3%], P > .999; 3.7 mm versus 6.0 mm [2%], P = .280; 4.7 mm versus 6.0 mm, P = .533; combined 4.7/6.0 mm versus 3.7 mm, P = .294). Cement failure was unique to the 3.7-mm group (6%), while a single case of screw loosening was reported in both the 4.7-mm (3.4%) and 6.0-mm (1.6%) groups. The two cases of cement failure were observed for 3.7-mm-wide implants that were 10 mm and 11.5 mm long. Conversely, the two cases of screw loosening were limited to wide-diameter implants (4.7-mm and 6.0-mm) that were 10 mm and 13 mm in length. The cumulative success rate for all surviving implants was 98.4%, because two implants showed more than 1.5 mm of bone loss.

DISCUSSION

Marginal bone loss around dental implants is a complex phenomenon that has been linked to numerous etiologies in the dental literature.[27–30] One such variable is the influence of the hardness of the occlusal material on peri-implant bone strains. In the present study, the material characteristics of the prosthetic restorations used in the FEA models were not identical to those in the clinical database, since the latter were fabricated with a variety of porcelains and base metals that may have differed slightly from each other in mechanical characteristics. In the FEA models, the decision to use the same titanium alloy characteristics as the implant itself was based on the findings of previous FEA[31,32] and in vivo[32] studies that found no significant stress differences when single implants were restored with

acrylic resin, gold alloy, or porcelain crowns, despite differences in their respective Vickers hardness (VHN) values and moduli of elasticity. The reported VHN value for titanium alloy was 320[33] as compared to 775 for alumina-reinforced porcelain,[34] 250 VHN for gold alloy (type IV),[35] and 158 VHN for composite resin.[36]

In creating a hypothetical bone model, the authors acknowledged that the extrapolation of 3D FEA data to clinical findings would be highly limited in general, especially using the present theoretical bone model. However, 3D FEA is the most accurate and reproducible theoretical method of evaluating load and stress distribution in the region of bone-implant contact and can provide more accurate data than bench testing or other experimental methods. While patient variables are extremely important in any clinical context, they cannot all be simulated in a theoretical or experimental analysis. For this reason, 3D FEA was used to obtain and evaluate stresses in bone that could not be accurately measured in a clinical context. To facilitate model convergence for the evaluation of 1 mm of peri-implant radial bone, the bone materials were merged to form a homogenous modulus of elasticity that ranged between types 2 and 3 bone.[21] This model was specifically selected based on over 1,900 clinical evaluations that found that types 2 and 3 bone[21] predominated in the human mandible and maxilla.[37] Despite its limitations, 3D FEA was best able to provide important information pertaining to the influence of implant diameter, occlusal load direction, bone volume, bone density, and other variables on stress levels, which could be used as general guidelines for case planning.

To evaluate the effect of variations in cortical bone thickness, all other variables were kept constant. The decision to assume 100% BIC was based on the common use of this assumption in other FEA studies.[38–40]

The finding that all observed stresses were below the theoretical threshold for bone loss (50 MPa) regardless of buccal plate thickness (Experiment 1) suggested that other clinical factors may have exacerbated the effects of thin (< 2 mm) buccal plate observed in a prospective clinical study reported by Spray et al.[25] Alternatively, the homogenous structure of the experimental bone model may not have accurately reflected the stress concentrations that would be encountered in an actual clinical environment. Since facial plate thickness was not measured in the present clinical analysis, additional experimentation will be necessary to resolve this question.

In sites with thin cortical plates, wide-diameter implants may be preferable to narrower implants (Experiment 2), provided that the residual buccal plate is more than 1 mm thick (Experiment 1). Other FEA research[41] has reported that off-axis loading may significantly increase compressive stresses within the crestal cortical bone, but the present study found that the use of wide-diameter implants in the first molar area may help to greatly reduce bone stress concentrations in this region of high occlusal forces (Experiment 3). In the clinical portion of the study, one patient (no. 1) was restored with mutually occluding maxillary and mandibular right first molars. Both of the patient's 13-mm-long implants exhibited peri-implant bone loss, but the amount of bone loss differed according to implant diameter; the observed losses were 1 mm around a 4.7-mm-diameter maxillary implant and 2 mm around an occluding 3.7-mm-diameter mandibular implant. The patient had no comorbidities at the time of surgery, but the patient records indicated that occlusal overload may have caused or contributed to the observed bone loss. There was no peri-implant bone loss around the widest diameter (6.0-mm) implants, which also represented the greatest number (n = 63) of implants placed per diameter. Although twice as many 4.7-mm implants lost bone (17%, 5/29) compared to 3.7-mm (9%, 3/34) implants, the difference was not statistically significant (P = .45).

The % BIC that an implant develops has a direct bearing on bone stress levels (Experiment 4), indicating that implant design and surface properties are extremely important. While all dental implants are designed to become fully incorporated into the biologic system of the recipient, the ability to achieve 100% BIC has not yet been documented in the dental literature. This is a result, in part, of the nature of bone itself, which is not fully mineralized but contains many marrow spaces and voids within its trabecular structure.

A limitation of the present study was that, except for implant diameter, the many variables examined in the 3D FEA portion of the study could not be directly evaluated in the clinical portion of the study. The finding that patient risk factors, rather than implant diameter, had the greatest influence on crestal bone loss validated the alternate study hypothesis. Despite this shortcoming, however, the 3D FEA data were able to provide some general guidelines for implant selection and treatment planning in the first molar region.

CONCLUSIONS

Implants that were 6.0 mm in diameter were not more susceptible to failure than standard-diameter implants and helped to preserve peri-implant bone levels. The present three-dimensional finite element analyses support previous clinical findings that maintaining approximately 2 mm of residual facial plate can reduce concentrations of bone stresses and help preserve buccal bone height. A history of periodontitis may adversely affect long-term marginal bone stability.

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