Three-dimensional finite element analysis of the effects of implant diameter and photofunctionalization on peri-implant stress

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Abstract: Previous finite element analyses of peri-implant stress assumed a bone-implant contact (BIC) ratio of 100\%, even though the BIC ratio is known to be approximately 50\% or less. However, the recent development of ultraviolet treatment of titanium immediately before use, known as photofunctionalization, significantly increased the BIC ratio, to 98.2\%. We used a unique finite element analysis model that enabled us to examine the effects of different BIC ratios on peri-implant stress. A three-dimensional model was constructed under conditions of vertical or oblique loading, an implant diameter of 3.3, 3.75, or 5.0 mm, and a BIC ratio of 53.0\% or 98.2\%. Photofunctionalization and larger implant diameters were associated with reduced stress on surrounding tissues. Under vertical loading, photofunctionalization had a greater effect than increased implant diameter on stress reduction. Under oblique loading, increased implant diameter had a greater effect than photofunctionalization on stress reduction.

Introduction

Reduction of excessive mechanical stress on peri-implant tissues can improve outcomes of implant therapy, because concentration of stress on tissues surrounding the implant causes marginal bone resorption (1,2) and eventual implant failure (2). A previous large-scale study (1) examined the marginal bone resorption for the effects of fixture overload, marginal bone height, and loss of osseointegration. Clinical studies revealed an association of loading conditions with marginal bone loss around oral implants and complete loss of osseointegration. In addition, finite element analysis (FEA) showed that stress on peri-implant tissues occurs under various conditions (3-5). Kitamura et al. (3) found that biomechanical adaptation of bone to stress may result in conical resorption. Prië et al. (4) found that if the objective is to minimize peri-implant strain in the crestal alveolar bone, a wide and relatively long untampered implant is the best choice. Baggi et al. (5) reported that cortical peri-implant areas vulnerable to overloading were affected primarily by implant diameter, irrespective of bone-implant interface length.

FEA of magnitude and distribution is useful and effective in biomechanics research. However, the accuracy...
of FEA results depends greatly on the biomechanical equivalence (form, dimensions, boundary conditions, material properties) between the analytic model and human body. Until now, almost all FEA studies of dental implant treatment assumed a bone-implant contact (BIC) ratio of 100% (6-8). However, the BIC ratio is not 100%: the true value was reported to be 45 ± 16% in one study (9) and 40 to 70% in other studies (10,11). Further, the recent discovery of titanium photofunctionalization has significantly improved the BIC ratio, thus enabling unprecedented enhancement of osseointegration (12,13). Therefore, it is necessary to incorporate BIC variability in biomechanical research. The present authors developed a method that arbitrarily sets the BIC ratio in three-dimensional (3D) FEA (14). Photofunctionalization is more effective than implant length in improving the distribution and diffusion of peri-implant stress (14). However, length is not the only variable that has a biomechanical effect; implant diameter should also be considered in stress analysis of surrounding tissue.

This study used 3D FEA to investigate the biomechanical effects of implant diameter and photofunctionalization on implant tissues.

Materials and Methods
The 3D finite element model comprised the implant, abutment, cortical bone, and cancellous bone. A non-tapered screw-type implant was designed in order to have the diameter and length of a typical commercial implant (Bränemark system implant MkIII, Nobel Biocare, Zurich, Switzerland) (Fig. 1). Implant length was fixed at 10 mm. Implants with diameters of 3.3, 3.75, and 5 mm were constructed. The BIC ratio was set at 53.0% (conventional type) or 98.2% (photofunctionalization type) (12). Thus, six analytic models were required in order to include all permutations of diameter and BIC ratio. BIC ratio was controlled by the number of force transfer nodes at the bone-implant interface (14). The active transfer nodes capable of transmitting force were selected at random for BIC ratios of 53.0% or 98.2% (photofunctionalization type) (12). Thus, six analytic models were required in order to include all permutations of diameter and BIC ratio. BIC ratio was controlled by the number of force transfer nodes at the bone-implant interface (14). The active transfer nodes capable of transmitting force were selected at random for BIC ratios of 53.0% or 98.2% at the bone-implant interface (14). The active transfer nodes capable of transmitting force were selected at random for BIC ratios of 53.0% or 98.2% at the bone-implant interface (14). Ten random assignments of active force transfer nodes permitted statistical analysis in this study. Bone surrounding the implant was constructed with cortical bone, as described previously (15,16).

The present analytic models consisted of 118,639 elements and 175,275 nodes for 3.3-mm-diameter implants, 118,303 elements and 175,220 nodes for 3.75-mm-diameter implants, and 137,611 elements and 203,157 nodes for 5-mm-diameter implants. The bone-implant interface comprised 10,541 nodes for the 3.3-mm implant, 10,597 nodes for the 3.75-mm implant, and 12,769 nodes for the 5-mm implant. The Young modulus and Poisson ratio were 1.04 × 10⁴ MPa and 0.33, respectively, in cortical bone, 83.3 MPa and 0.33 in cancellous bone, and 1.10 × 10⁵ MPa and 0.33 in titanium implants. The properties assigned to these materials were equivalent or similar to those described in the literature (6,7,17-19).

Boundary conditions were established at the inferior border of the cortical bone. The nodes in this area were completely fixed, with a movement of six degrees of freedom. In addition, a test for finite element models was conducted under simulated loading settings on a single implant, with 50 N applied vertically or obliquely (buccolingually; 45 degrees) via an abutment (Fig. 1). All material properties used in testing the models were considered to be isotropic homogeneous and linearly static elastic. The models were constructed with FEM software (ANSYS Mechanical Rel.13.0 ANSYS, Inc., Canonsburg, PA, USA). The analytic models were meshing with a tetrahedral shape, as constructed using the mesh tool in ANSYS software.

The counter image of stress fields in bone and values at the implant-bone interface during minimum and maximum principal stress (in MPa) were used for evaluating diffusion/distribution and the magnitude of mechanical stress, respectively. Ten random assignments of force transfer nodes permitted statistical analysis in this study. The effect of BIC ratio and implant diameter on minimum and maximum principal stress was investigated by two-way ANOVA, using BellCurve for Excel.
Furthermore, the post-hoc Bonferroni test was used for individual comparisons. A $P$ value of $<0.05$ was considered to indicate statistical significance.

## Results

### Vertical loading

The stress distribution at the bone-implant interface and in bone around the implant is shown in contour images indicating minimum and maximum principal stress (Fig. 2). During minimum principal stress, the high stress area was localized at the bone-implant neck, regardless of implant diameter or BIC. A distinct increase in stress concentration was observed for narrow implants at 53.0% BIC. The stress distribution was less uniform for 53.0% BIC implants than for 98.2% BIC implants.

During maximum principal stress, no significant stress concentration was observed at the bone-implant interface. The stress distribution was less uniform for 53.0% BIC implants than for 98.2% BIC implants.

In specimens with the same diameter, photofunctionalization was associated with a statistically significant decrease in stress values, during both minimum and maximum principal stress ($P < 0.05$; Fig. 3). During minimum principal stress, there was no significant difference in stress values between 3.3-mm and 3.75-mm implants, regardless of photofunctionalization. However, there was a significant difference between implants with a diameter of 3.3 mm/3.75 mm and those with a diameter of 5 mm. In addition, stress was lower for 98.2% 3.3-mm implants than for 53.0% 5-mm implants. During maximum principal stress, there was no significant difference in stress values between a 98.2% 3.3-mm implant and a 98.2% 3.75-mm implant. However, there were significant differences among the three types of implant with a BIC ratio of 53.0% and between implants with a diameter of 3.3 mm/3.75 mm and those with a diameter of 5 mm. In scalar quantity, the maximum principal stress was about 25-33% minimum principal stress. In addition, even during maximum principal stress, stress was lower for a 98.2% 3.3-mm than for a 53.0% 5-mm implant.

### Oblique loading

The stress distribution at the bone-implant interface and in bone around the implant is shown in contour images indicating minimum and maximum principal stress (Fig. 4). During minimum principal stress, contour images show that the stress concentration surrounding the implant neck area was present on the side contralateral to the oblique force. Stress was intense under oblique loading—2 to 3 times that of vertical loading—regardless of BIC ratio or implant diameter. Under oblique loading, the wide stress concentration area was deeper for the 3.3-mm diameter implant. In addition, the stress distribution was less uniform for 53.0% BIC implants than for 98.2% BIC implants. During maximum principal stress, at the implant-bone interface, the stress concentration...
surrounding the implant neck area was observed on the side ipsilateral to the oblique force on contour images. However, photofunctionalization had little effect on 5-mm implants. The stress distribution was less uniform for 53.0% BIC implants than for 98.2% BIC implants.

During minimum principal stress, there was no significant difference in stress values for 98% 3.3-mm and 98% 3.75-mm implants ($P < 0.05$, Fig. 5). However, there were significant differences between implants under all other experimental conditions. In addition, the stress was greater for 98.2% 3.3-mm implants than for 53.0% 5-mm implants. During maximum principal stress, there was no significant difference in stress values between 53% and 98% 5-mm implants ($P < 0.05$, Fig. 5). However, there was a significant difference between implants under all other experimental conditions ($P < 0.05$, Fig. 5). In addition, even during maximum principal stress, the stress was greater for 98.2% 3.3-mm implants than for 53.0% 5-mm implants.

Discussion

Analytic model

A BIC ratio of 100% was used in almost all previous FEA studies of dental implant treatment, even though research indicates that the BIC ratio is never 100% (9-11). Thus, it has been difficult to reproduce BIC by the finite element method. This study was able to simplify structural analysis, as it did not rely on nonlinear analysis using a contact element. This study did not examine change in contact conditions but instead investigated differences between BIC ratios of 53.0% (conventional type) and 98.2% (photofunctionalization type) and implants with different diameters. In addition, previous studies reported the contact ratio of bone and implant but not the contact position. The present analysis therefore assumed a random contact position. This method allowed for analysis of varied clinical contact conditions. Previous studies (6-8) examined stress concentration by assessing the stress distribution of concentric circles in peri-implant tissue. However, the present findings indicate that stress concentration sites depend on bone-implant contact. In the present comparison of 98.2% and 53.0% BIC ratios, the concentration of stress on peri-implant tissue did not differ. However, a 53.0% BIC ratio resulted in an uneven stress distribution in peri-implant tissue.

Vertical loading

This study used 3D finite element analysis of the minimum and maximum principal stress around implant tissue to assess the biomechanical effects of implant diameter and photofunctionalization. Minimum and maximum principal stress values around the implant were less for a 98.2% BIC than for a 53.0% BIC, under vertical loading. Minimum and maximum principal stress values were significantly lower for a BIC ratio of 98.2% than for a ratio of 53.0% ($P < 0.05$, Fig. 3), regardless of implant diameter. However, neither minimum nor maximum principal stress significantly differed between 3.3-mm and 3.75-mm implants ($P < 0.05$).
BIC ratio. Both minimum and maximum principal stress values were lower for a 98.2% 3.3-mm implant than for a 53.0% 5-mm implant. Therefore, photofunctionalization had a greater effect than diameter on minimum and maximum principal stress, under a vertical load.

An implant length/diameter of 10 mm/3.75 mm was reported to be a potential threshold in determining the risk of unfavorable biomechanical behavior (20-22). From a biomechanical perspective, under vertical loading, minimum and maximum principal stress values around the implant neck were acceptable at every diameter for implants with a BIC ratio of 98.2%.

**Oblique loading**

Oblique loading is an unfavorable condition for implant prosthodontics (23). This study used high oblique loads—2 to 3 times the vertical loads—in all models. Stress levels were significantly lower for 98.2% BIC implants than for 53.0% BIC implants, regardless of implant diameter. However, there was no significant difference between the 53.0% 5-mm and 98% 5-mm implants during maximum principal stress.

In addition, stress was greater for the 98.2% 3.3-mm implant than for the 53.0% 5-mm implant during minimum and maximum principal stress. Therefore, under oblique loading, diameter had a greater effect than photofunctionalization.

There was a wide range of stress concentration in the deeper area of the 3.3-mm implant on counter images, regardless of BIC, under oblique loading and during minimum principal stress. Thus, 3.3-mm implants are vulnerable to oblique loads even after photofunctionalization.

In this study, photofunctionalization and larger implant diameters reduced stress on surrounding tissue. Under vertical loading, photofunctionalization had a greater effect than increased implant diameter on stress reduction. Under oblique loading, implant diameter had a greater effect than photofunctionalization on stress reduction. However, implant diameter is limited clinically by the bone width at the embedding site, while photofunctionalization is not affected by bone width. Therefore, photofunctionalization has a considerable advantage in terms of surgical risk. A previous study (24) of implant placement in complex cases concluded that clinical outcome was associated with increased rate of implant stability for photofunctionalized implants.

The present analytic method allows researchers to set the BIC ratio arbitrarily and to randomly control the position of implant-bone contact and is therefore useful for biomechanical FEA studies of implants.

Within the limits of this study, our results indicate that photofunctionalization and increased implant diameter reduce stress on surrounding tissue. Under vertical loading, photofunctionalization has a greater effect than implant diameter on stress reduction. Under oblique loading, implant diameter has a greater effect than photofunctionalization on stress reduction.

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**Conflict of interest**

The authors declare no financial interest, whether direct or indirect, in the products or information included in the article.

**References**

1. Quirynen M, Naert I, van Steenberghhe D (1992) Fixture design and overload influence marginal bone loss and fixture success in the Brånemark system. Clin Oral Implants Res 3, 104-111.
2. Isidor F (2006) Influence of forces on peri-implant bone. Clin Oral Implants Res 17, Suppl 2, 8-18.
3. Kitamura E, Stegaroiu R, Nomura S, Miyakawa O (2004) Biomechanical aspects of marginal bone resorption around osseointegrated implants: considerations based on a three-dimensional finite element analysis. Clin Oral Implants Res 15, 401-412.
4. Petrie CS, Williams JL (2005) Comparative evaluation of implant designs: influence of diameter, length, and taper on strains in the alveolar crest. A three-dimensional finite-element analysis. Clin Oral Implants Res 16, 486-494.
5. Baggi L, Cappelloni I, Di Girolamo M, Macci E, Vairo G (2008) The influence of implant diameter and length on stress distribution of osseointegrated implants related to crestal bone geometry: a three-dimensional finite element analysis. J Prosthet Dent 100, 422-431.
6. Naini RB, Nokar S, Borghesi H, Alikhani M (2011) Tilted or parallel implant placement in the completely edentulous mandible? A three-dimensional finite element analysis. Int J Maxillofac Implants 26, 776-781.
7. Gomes ÉA, Barão VA, Rocha EP, de Almeida ÉO, Assunção WG (2011) Effect of metal-ceramic or all-ceramic superstructure materials on stress distribution in a single implant-supported prosthesis: three-dimensional finite element analysis. Int J Oral Maxillofac Implants 26, 1202-1209.
8. Xiao JR, Li YF, Guan SM, Song L, Xu LX, Kong L (2011) The biomechanical analysis of simulating implants in function under osteoporotic jawbone by comparing cylindrical, apical tapered, neck tapered, and expandable type implants: a 3-dimensional finite element analysis. J Oral Maxillofac Surg 69, e273-281.
9. Weinlaender M, Kenney EB, Lekovic V, Beumer J 3rd, Moy
PK, Lewis S (1992) Histomorphometry of bone apposition around three types of endosseous dental implants. Int J Oral Maxillofac Implants 7, 491-496.

10. Ogawa T, Nishimura I (2003) Different bone integration profiles of turned and acid-etched implants associated with modulated expression of extracellular matrix genes. Int J Oral Maxillofac Implants 18, 200-210.

11. De Maeztu MA, Braceras I, Alava JI, Gay-Escoda C (2008) Improvement of osseointegration of titanium dental implant surfaces modified with CO ions: a comparative histomorphometric study in beagle dogs. Int J Oral Maxillofac Surg 37, 441-447.

12. Aita H, Hori N, Takeuchi M, Suzuki T, Yamada M, Anpo M et al. (2009) The effect of ultraviolet functionalization of titanium on integration with bone. Biomaterials 30, 1015-1025.

13. Hori N, Ueno T, Suzuki T, Yamada M, Att W, Okada S et al. (2010) Ultraviolet light treatment for the restoration of age-related degradation of titanium bioactivity. Int J Oral Maxillofac Surg 25, 49-62.

14. Ohyama T, Uchida T, Shibuya N, Nakabayashi S, Ishigami T, Ogawa T (2013) High bone-implant contact achieved by photofunctionalization to reduce periimplant stress: a three-dimensional finite element analysis. Implant Dent 22, 102-108.

15. Takeuchi K, Saruwatari L, Nakamura HK, Yang JM, Ogawa T (2005) Enhanced intrinsic biomechanical properties of osteoblastic mineralized tissue on roughened titanium surface. J Biomed Mater Res A 72, 296-305.

16. Butz F, Aita H, Wang CJ, Ogawa T (2006) Harder and stiffer bone osseointegrated to roughened titanium. J Dent Res 85, 560-565.

17. Tada S, Stegaroiu R, Kitamura E, Miyakawa O, Kusakari H (2003) Influence of implant design and bone quality on stress/strain distribution in bone around implants: a 3-dimensional finite element analysis. Int J Oral Maxillofac Implants 18, 357-368.

18. Silva GC, Mendonca JA, Lopes LR, Landre J Jr (2010) Stress patterns on implants in prostheses supported by four or six implants: a three-dimensional finite element analysis. Int J Oral Maxillofac Implants 25, 239-246.

19. Fazi G, Tellini S, Vangi D, Branchi R (2011) Three-dimensional finite element analysis of different implant configurations for a mandibular fixed prosthesis. Int J Oral Maxillofac Implants 26, 752-759.

20. Romeo E, Chiapasco M, Ghisolfi M, Vogel G (2002) Long-term clinical effectiveness of oral implants in the treatment of partial edentulism. Seven-year life table analysis of a prospective study with ITI dental implants system used for single-tooth restorations. Clin Oral Implants Res 13, 133-143.

21. das Neves FD, Fones D, Bernardes SR, do Prado CJ, Neto AJ (2006) Short implants—an analysis of longitudinal studies. Int J Oral Maxillofac Implants 21, 86-93.

22. Telleman G, Raghoebar GM, Vissink A, den Hartog L, Huddleston Slater JJ, Meijer HJ (2011) A systematic review of the prognosis of short (<10 mm) dental implants placed in the partially edentulous patient. J Clin Periodontol 38, 667-676.

23. Goodacre CJ, Bernal G, Rungcharassaeng K, Kan JY (2003) Clinical complications with implants and implant prostheses. J Prosthet Dent 90, 121-132.

24. Funato A, Yamada M, Ogawa T (2013) Success rate, healing time, and implant stability of photofunctionalized dental implants. Int J Oral Maxillofac Implants 28, 1261-1271.