Original Paper

Influence of Implant Length and Diameter, Bicortical Anchorage, and Sinus Augmentation on Bone Stress Distribution: Three-dimensional Finite Element Analysis

Hiroyoshi Moriwaki, DDS; * Satoshi Yamaguchi, PhD; † Tamaki Nakano, DDS, PhD; * Yasufumi Yamanishi, DDS, PhD; * Satoshi Imazato, DDS, PhD; † Hirofumi Yatani, DDS, PhD*

[1]Department of Fixed Prosthodontics, Osaka University Graduate School of Dentistry, 1-8 Yamadaoka, Suita, Osaka 565-0871, Japan

[2]Department of Biomaterials Science, Osaka University Graduate School of Dentistry, 1-8 Yamadaoka, Suita, Osaka 565-0871, Japan

Correspondence should be addressed to:
Satoshi Yamaguchi
Tel.: +81-6-6879-2919, Fax: +81-6-6879-2919
Email: yamagu@dent.osaka-u.ac.jp

No conflict of interest

ABSTRACT

Purpose: Clarification of the protocol for using short implants is required to enable widespread use of short implants as an available treatment option. The purpose of this study was to investigate the influences of implant length and diameter, bicortical anchorage, and sinus augmentation on peri-implant cortical bone stress by three-dimensional finite element analysis.

Materials and Methods: For bone models with bone quantity A and C in the maxillary molar region, three-dimensional finite element analysis was performed using different lengths and diameters of implant computer-aided design models, and the degree of maximum principal stress distribution for each model was calculated.

Results: For bone quantity A models, the degree of stress distribution of 4-mm-diameter and 6-mm-length implant was greatest. For bone quantity C models, the degree of stress distribution of 5-mm-diameter and 6-mm-length implant with bicortical anchorage was much smaller than that for 4-mm-diameter and 13-mm-length implant with sinus augmentation.

Conclusions: Our results suggest that 6-mm-length implants should be selected in cases with bone quantity C where the bone width permits increasing implant diameter from 4 mm to 5 mm.

Keywords: dental implants, sinus floor augmentation, biomechanics, finite element analysis

1. INTRODUCTION

Implant therapy has been applied to various clinical cases as a prosthetic treatment option because of its positive clinical performance[1, 2]. However, alveolar bone quantity C[3] caused by severe periodontal disease, and a long-term edentulous jaw[4], restricts the use of implant therapy. While bone augmentation such as sinus augmentation[5, 6] and veneer grafting[7, 8], and lateralization of the inferior alveolar nerve[9, 10] are adopted to allow insertion of implants, these therapies still have disadvantages such as surgical invasion and infection, risks of sensory nerve paralysis, prolonged treatment time, and an increase in treatment cost[11].

Meanwhile, short implants have achieved a significant market share owing to the improvement in implant surface characteristics[12], and have been released by various manufacturers. *In silico* study[13] reported that there was no difference in peri-implant bone stress caused by changing the length of the implant body when measured by finite element analysis using simplified computer-aided design models. Clinical studies have reported that the survival rates of standard length and short implants were equivalent[14, 15]. Recent clinical evidence has mentioned that the use of short implants may be considered an alternative to more complicated bone augmentation surgeries[16]. They have concluded that the use of short implants gives patients lower risk, shorter clinical time, and decreased cost when compared with bone augmentation surgeries[17]. These advantages of using short implants as compared with bone augmentation surgeries were also mentioned in other studies[18-20] and there were few differences in survival rate between short and standard length implants.

However, the risk for bone resorption in osseointegrated implants is greater for treatment involving short implants[8]. Clinicians must follow certain protocols when using short implants, e.g., splinting to other implants[21, 22], no use for single-tooth replacement in molar sites[22], and the use of wider diameter for short implants[21]. In cases that cannot satisfy these protocols, bone augmentation surgery is selected, especially in the maxilla.

The purpose of this study was to investigate the influences of implant length and diameter, bicortical anchorage[23], and sinus augmentation on peri-implant cortical bone stress using three-dimensional finite element analysis. For bone quantity A[3] and C models in the maxillary molar region, three-dimensional finite element analysis was performed using two-piece implant computer-aided design models composed of an implant body, abutment, and abutment screw.

2. MATERIALS AND METHODS

The models composed of an implant body, abutment, and abutment screw were created using computer-aided design software (SolidWorks Premium 2011; SolidWorks Corporation, Waltham, MA, USA) as shown in Fig. 1. The short-length and regular-platform implant body was defined as ϕ4×6 mm[24]. The long length and regular platform implant body was defined as ϕ4×13 mm[24]. The short-length and wide-platform implant body was defined as ϕ5×6 mm[24]. The implant-abutment joints comprised an internal joint. The pitch of threads with 0.66-mm intervals and the shape of the threads were the same in all implants. The height of the abutment was 7.0 mm. The implant and abutment were connected by the abutment screw.

Two computer-aided design models of posterior maxillary bone were created with missing premolars and molars (Fig. 2). Alveolar bone quantity A and C models were designed to enable insertion of implants 13.0 mm and 6.0 mm in length, respectively. The overlying cortical bone of both models was designed to be 1.0 mm thick[12, 25]. The remaining areas were designed as cancellous bone.

The ϕ4×6 mm, ϕ4×13, and the ϕ5×6 implants were placed on the bone quantity A model (Fig. 3). Although not used in a clinical situation, these models were prepared as controls to investigate the influence of implant length, bicortical anchorage, and implant diameter. Similarly, 6-mm length implants were placed on the bone quantity C model with bicortical anchorage (Fig. 4). The 13-mm length implant was placed on the bone quantity C model with sinus augmentation, which was composed of maxillary bone and graft materials (Fig. 5). As a control model, the $\phi 4\times 6$ mm implant was placed on the bone quantity C model with bicortical anchorage and sinus augmentation, and the $\phi 4\times 13$ mm implant was placed on the bone quantity C model without sinus augmentation (Fig. 6).

The mechanical properties of bone, titanium, and the graft material used for the three-dimensional finite element analysis[25-30] are shown in Table 1. In this study, the properties of the graft material were equalized for cancellous bone by assuming 100% substitution. For simulations of osseointegrated implants, a “fixed bond” condition was set at the interface between the bone or graft material and the implant body[26]. A “contact” condition with a static friction coefficient of 0.2[31], which accepts possible microscopic sliding, was set at the interfaces among components of the implants[24]. The mesial and distal surfaces of the maxillary bone were fixed, and a static load of 150 N[32] was applied to the basal ridge surface of the abutment at 30° in a direction oblique to the long axis of the implants[30] (Fig. 7). The elements for three-dimensional finite element analysis were tetrahedrons with 16 nodes. To determine the mesh size that offers an accurate result in a reasonable amount of computation time (less than 40 min), the number of elements was increased until the maximum principal stress converged. The results of convergence analysis[30] are shown in Table 2. The mesh size was standardized to 0.3 mm in all models. Three-dimensional finite element analysis was performed using the add-in function of the computer-aided design software.

The degree of maximum principal stress distribution to peri-implant cortical bone, which was greater than or equal to the absolute value of the threshold, was extracted using computer-aided design software (Fig. 8). The threshold for each value obtained by three-dimensional finite element analysis was set once every 10 MPa from −40 to 40 MPa.

To investigate the influence of implant length, bicortical anchorage, sinus augmentation, and implant diameter, the degree of loss of maximum principal stress distribution in four groups with; (A) different implant lengths (ϕ4×6 mm implants placed on the bone quantity A→ϕ4×13 mm implants placed on the bone quantity A, ϕ4×6 mm implants placed on the bone quantity C with sinus augmentation→ϕ4×13 mm implants placed on the bone quantity C with sinus augmentation, and ϕ4×6 mm implants placed on the bone quantity C with bicortical anchorage→ϕ4×13 mm implants placed on the bone quantity C with bicortical anchorage), (B) the implementation of bicortical anchorage (ϕ4×6 mm implants placed on the bone quantity A→ϕ4×6 mm implants placed on the bone quantity C with bicortical anchorage, ϕ4×13 mm implants placed on the bone quantity A→ϕ4×13 mm implants placed on the bone quantity C with bicortical anchorage), (C) the implementation of sinus augmentation (ϕ4×6 mm implants placed on the bone quantity C with bicortical anchorage→ϕ4×6 mm implants placed on the bone quantity C with sinus augmentation, ϕ4×13 mm implants placed on the bone quantity C with bicortical anchorage→ϕ4×13 mm implants placed on the bone quantity C with sinus augmentation), and (D) different implant diameters (ϕ4×6 mm implants placed on the bone quantity A→ϕ5×6 mm implants placed on the bone quantity A, ϕ4×6 mm implants placed on the bone quantity C with bicortical anchorage→ϕ5×6 mm implants placed on the bone quantity C with bicortical anchorage) were compared (Fig. 9).

3. RESULTS

3.1. *Degree of maximum principal stress distribution in peri-implant cortical bone*

Figure 10 shows the degree of maximum principal stress distribution in peri-implant cortical bone for the bone quantity A model. The degree of maximum principal stress distribution for ϕ4×6 mm implants was greater than that for ϕ4×13 mm implants (Fig. 10A and Fig. 10B). The degree of maximum principal stress distribution for ϕ5×6 mm implants was smaller than that for ϕ4×6 mm implants (Fig. 10A and Fig. 10B). However, the degree of compressive stress (negative value of the maximum principal stress) distribution for ϕ5×6 mm implants was greater than that for ϕ4×13 mm implants (Fig. 10A), and the degree of tensile stress (positive value of the maximum principal stress) distribution for ϕ5×6 mm implants was smaller than that for ϕ4×13 mm implants (Fig. 10B).

For the bone quantity C model, the degree of tensile stress distribution for ϕ5×6 mm implants with bicortical anchorage was much smaller than that for ϕ4×13 mm implants with sinus augmentation (Fig. 11B), while the degree of compressive stress distribution for ϕ4×6 mm implants with bicortical anchorage was greater than that for ϕ4×13 mm implants with sinus augmentation (Fig. 11A).

3.2. *Degree of loss of maximum principal stress distribution*

Figure 12 shows the results of the degree of loss of maximum principal stress distribution in each model.

In terms of compressive stress distribution (Fig. 12A), the implant diameters highly influenced the degree of loss of maximum principal stress distribution for all thresholds. The implant lengths and the use of bicortical anchorage were similar among thresholds of 20, 30, and 40 MPa. The decrease in maximum principal stress distribution related to sinus augmentation was less when compared with the other three factors.

In terms of tensile stress distribution (Fig. 12B), the implant diameter again highly influenced the degree of loss of maximum principal stress distribution, similar to the compressive stress distribution, and the implementation of bicortical anchorage was second in line.

4. DISCUSSION

For ϕ4×13 mm implants placed on the bone quantity A, the degree of maximum principal stress distribution of the peri-implant cortical bone was reduced in comparison with ϕ4×6 mm implants placed on the bone quantity A. This result was caused by obtaining a larger cancellous bone surface area in ϕ4×13 mm implants placed on the bone quantity A. Occlusal forces were dispersed within the cancellous bone holding the implant. Therefore, stress distribution to the peri-implant cortical bone, causing peri-implant bone resorption, decreased. For the same reason, the degree of maximum principal stress distribution to the peri-implant cortical bone for ϕ5×6 mm implants placed on the bone quantity A was reduced in comparison with ϕ4×6 mm implants placed on the bone quantity A. In addition, the 5-mm-diameter implant could be well stabilized by cancellous bone against occlusal loading along the long axis of the implant because of the large surface area of the implant apex. On the basis of these factors, ϕ5×6 mm implants placed on the bone quantity A showed an equivalent degree of compressive stress distribution to ϕ4×13 mm implants placed on the bone quantity A, and the degree of tensile stress distribution for ϕ5×6 mm implants placed on the bone quantity A was smaller than that for ϕ4×13 mm implants placed on the bone quantity A. The ultimate strength of human bone under tension is lower than under compression[33]. These results suggest that the 5-mm-diameter implant may be resistant to bone resorption when compared with the 4-mm-diameter implant.

It is thought that the degree of maximum principal stress distribution for $\phi 4\times 13$ mm implants placed on the bone quantity C with sinus augmentation increased in comparison with that for $\phi 4\times 6$ mm implants placed on the bone quantity C with bicortical anchorage, because while $\phi 4\times 6$ mm implants placed on the bone quantity C with bicortical anchorage was only influenced by bicortical anchorage as a stress-reducing factor, $\phi 4\times 13$ mm implants placed on the bone quantity C with sinus augmentation was influenced by the implant length in addition to bicortical anchorage. The implementation of bicortical anchorage could reduce the stress on peri-implant bone[27]. The success rate doubled for monocortically anchored implants, especially in the maxilla, in a prospective clinical short-term study of bicortical anchorage[34]. On the basis of these two factors, $\phi 4\times 13$ mm implants placed on the bone quantity C with sinus augmentation displayed a reduced degree of stress distribution. However, the degree of stress distribution for $\phi 4\times 6$ mm implants placed on the bone quantity C with bicortical anchorage was less than that of $\phi 4\times 6$ mm implants placed on the bone quantity A, because the use of bicortical anchorage leads to the dispersion of occlusal forces to the cortical bone at sinus floor. In a conventional finite element analysis study, the placement of a $\phi 5\times6$ mm implant reduced stress on the peri-implant bone, causing a large surface area of contact with the wide implant, and stiff cortical bone[29]. They concluded that the placement of $\phi 5\times6$ mm implants was more effective than that of long-length implants with sinus augmentation in terms of treatment cost, treatment length, and the risk of additional surgeries for patients[30]. In this study, the degree of maximum principal stress distribution for $\phi 5\times6$ mm implants placed on the bone quantity C with bicortical anchorage was much smaller than that for $\phi 4\times13$ mm implants placed on the bone quantity C with sinus augmentation. It is thought that the combination of implant diameter and bicortical anchorage had a bigger influence in reducing maximum principal stress distribution than implant length, implant diameter, and sinus augmentation.

Considering that overloading is included as one of the causes of peri-implant bone resorption, all results suggest that selecting a longer implant is clinically desirable when there is alveolar bone quantity A. When the bone quantity C is present, $\phi 5\times6$ mm implants may be useful in cases where the bone width remains sufficient to permit increasing the implant diameter from 4.0 mm to 5.0 mm.

There are various treatment methods available to reduce the stress on peri-implant bone. Nevertheless, there are few reports of the comparison among these methods in terms of stress reduction. Thus, this comparison study is expected to clarify the guideline for clinical implant treatment where an alveolar bone quantity C is present. Additionally, the long-term prognosis of clinical implant treatment can be expected as an outcome of this study. The degree of loss of maximum principal stress distribution by increasing implant length and that by implementing bicortical anchorage was similar. This is because the dispersion of the occlusal forces to the cancellous bone caused by increasing implant length and the dispersion to the cortical bone at the implant apex caused by implementing bicortical anchorage were equal.

A conventional finite element analysis study reported that extensive bone augmentation by sinus augmentation reduced the stress on peri-implant bone[35]. In this study, the influence of sinus augmentation was less significant than implant length, diameter, and bicortical anchorage. This occurred because the contact area with the maxillary bone was not increased even if a longer implant was inserted after sinus augmentation. Thus, much of the occlusal loading on the implant had spread to the maxillary bone rather than the sinus augmentation graft material.

Implant diameter was a more influential design parameter of the implant for stress on the peri-implant bone than implant length and thread shape, especially for short implants[36]. Additionally, the implant diameter influenced stress levels and the wider diameter implant could help to reduce bone stress[37]. In this study, the degree of loss of maximum principal stress distribution by increasing implant diameter was much higher than the effect of implant length, bicortical anchorage, and sinus augmentation. This result is caused by obtaining strong support, which resists subsidence of implants, and retention, which resists rolling of implants, as a result of increasing the contact area with cortical bone, which has better mechanical strength properties when compared with cancellous bone. The increase in implant length in this study was 7.0 mm. In comparison with 6- and 10-mm-length implants, the influence of bicortical anchorage may become greater than the influence of implant length because the increase in implant length is 4.0 mm. Analyses of implants of various lengths are ongoing.

The lack of simulation of the inhomogeneous and isotropic material properties of human bone and of the graft material is one of the limitations of the three-dimensional finite element analysis in this study. In addition, the evaluation of primary mechanical stability and secondary biologic stability[38] is not possible by static three-dimensional finite element analysis without the simulation of bone-implant interface using the various ratios of osseointegration in this study. However, our results with homogeneous and isotropic material properties definitively clarified the influence of implant length, bicortical anchorage, sinus augmentation, and implant diameter even if these results were biased.

5. CONCLUSION

Our results suggest that 4-mm-diameter implants with increased length should be selected to reduce the maximum principal stress of peri-implant cortical bone when bone quantity A is available. When there is bone quantity C, 6-mm-length implants should be selected if the bone width is sufficient to permit increasing the implant diameter from 4.0 mm to 5.0 mm.

The 6-mm-length implants with bicortical anchorage have the potential to become a useful treatment in achieving a reduced risk of surgical invasion, shortening clinical time, and presenting a lower cost to patients.

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FIGURES

Fig. 1

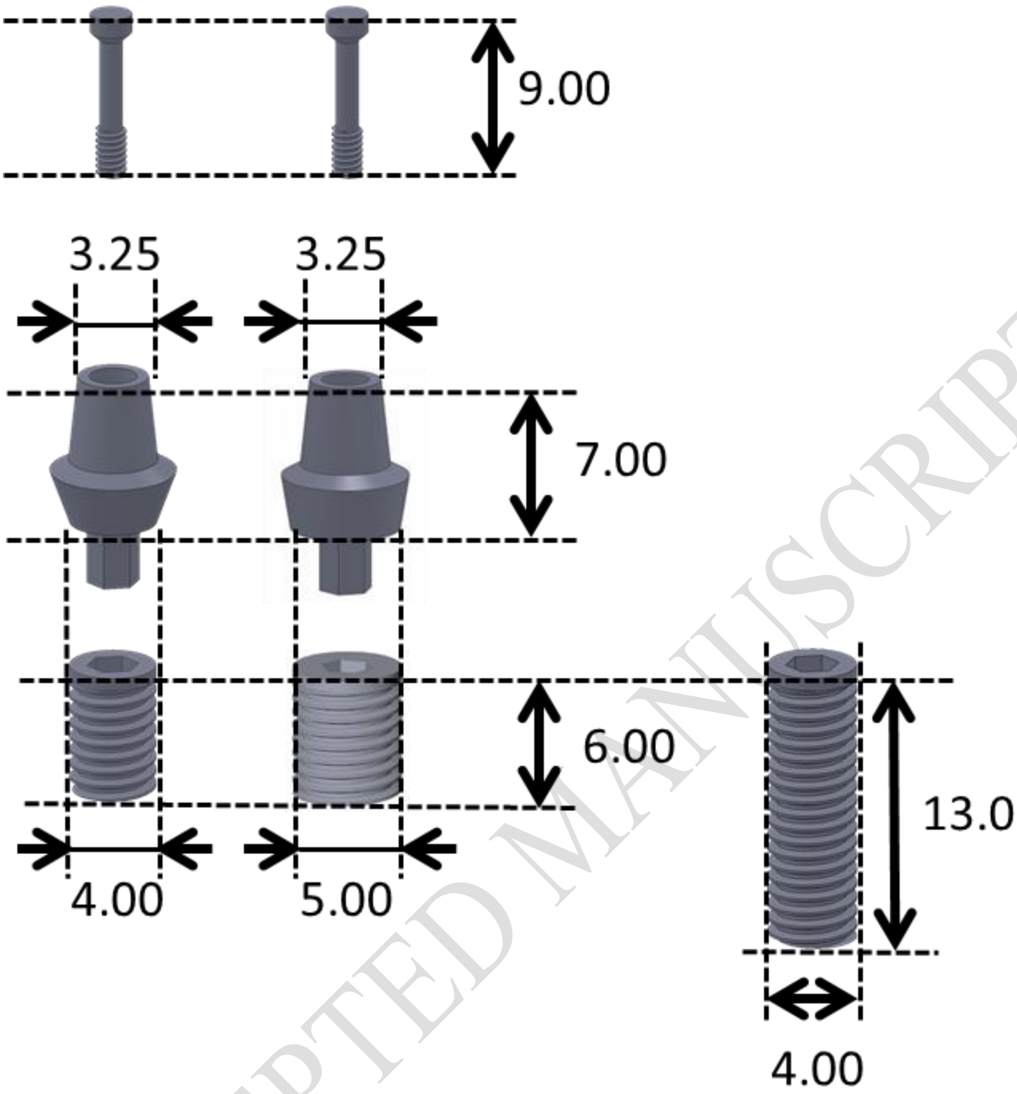
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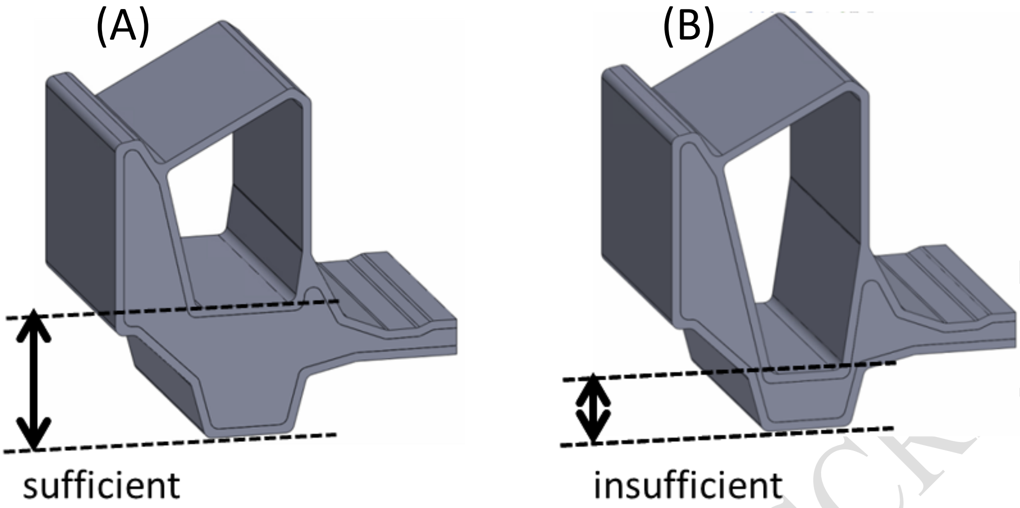
Fig. 2



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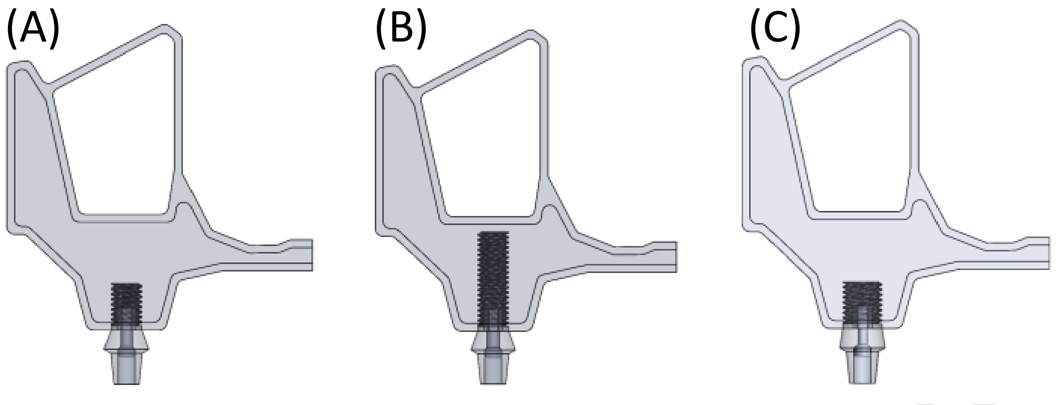

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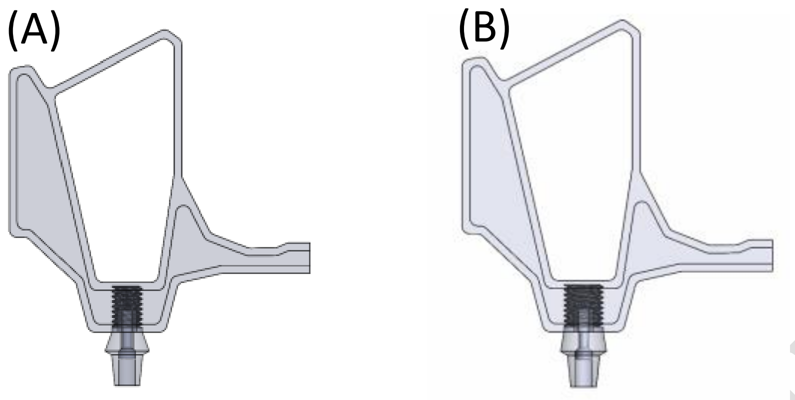

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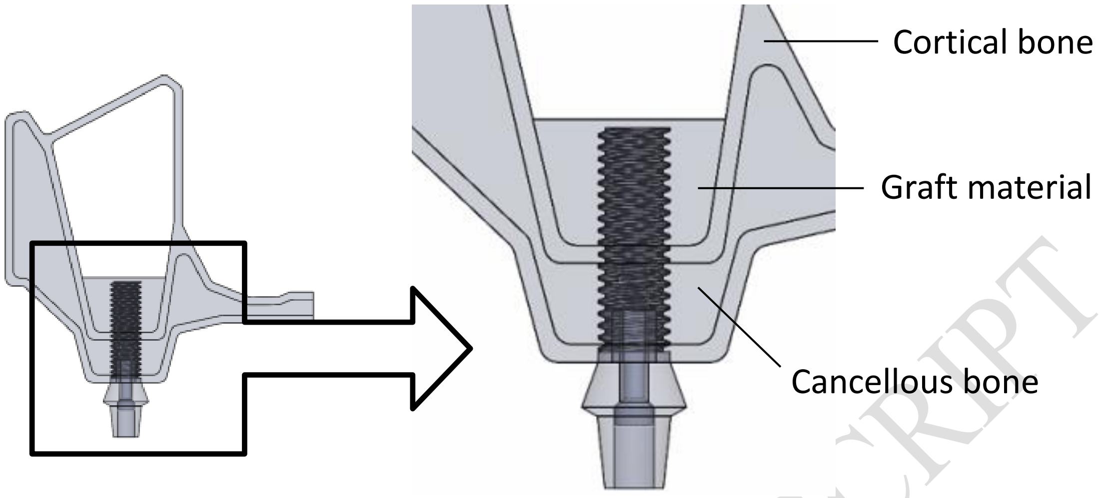

1 Fig. 6

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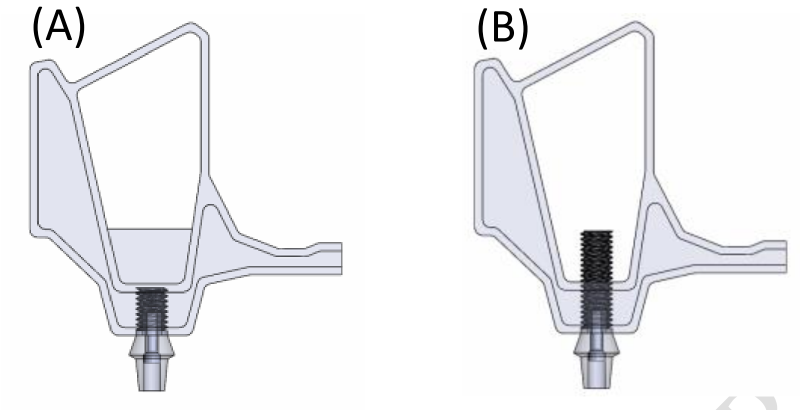

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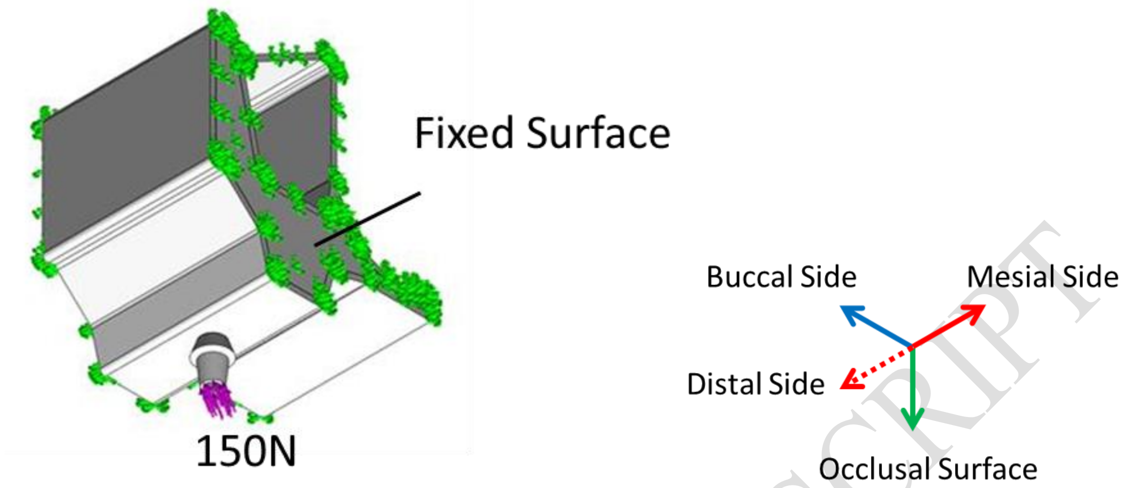
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Occlusal Surface

Fig. 8

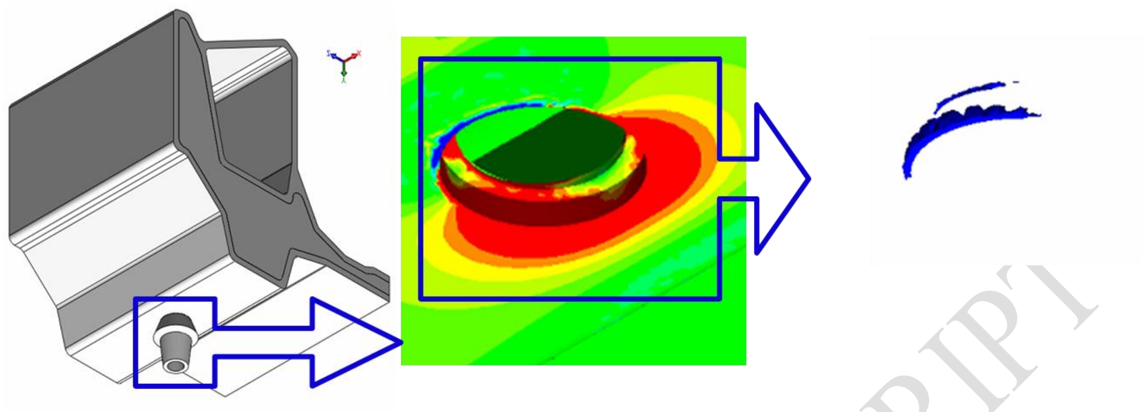


Fig. 9

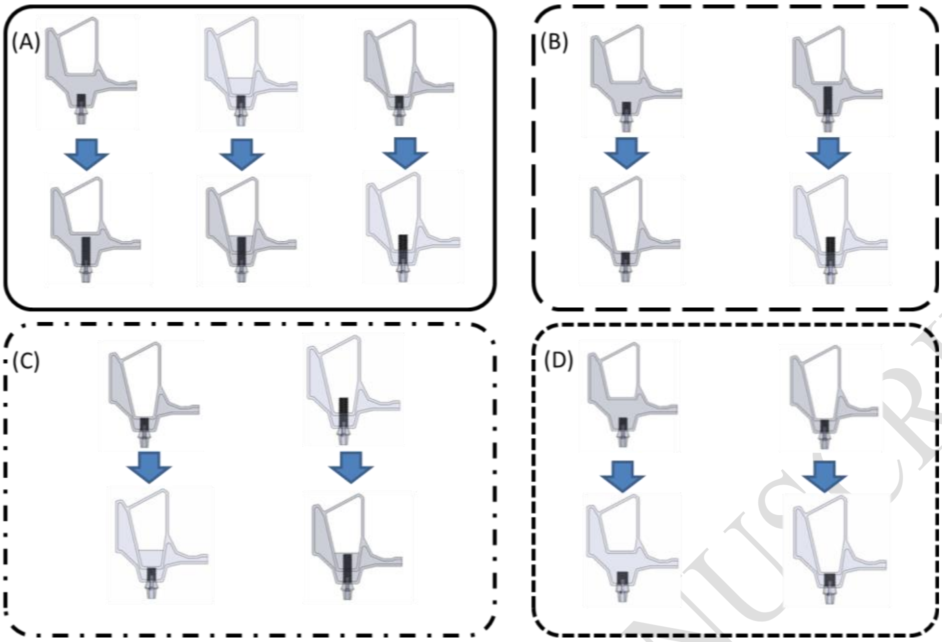


Fig. 10A

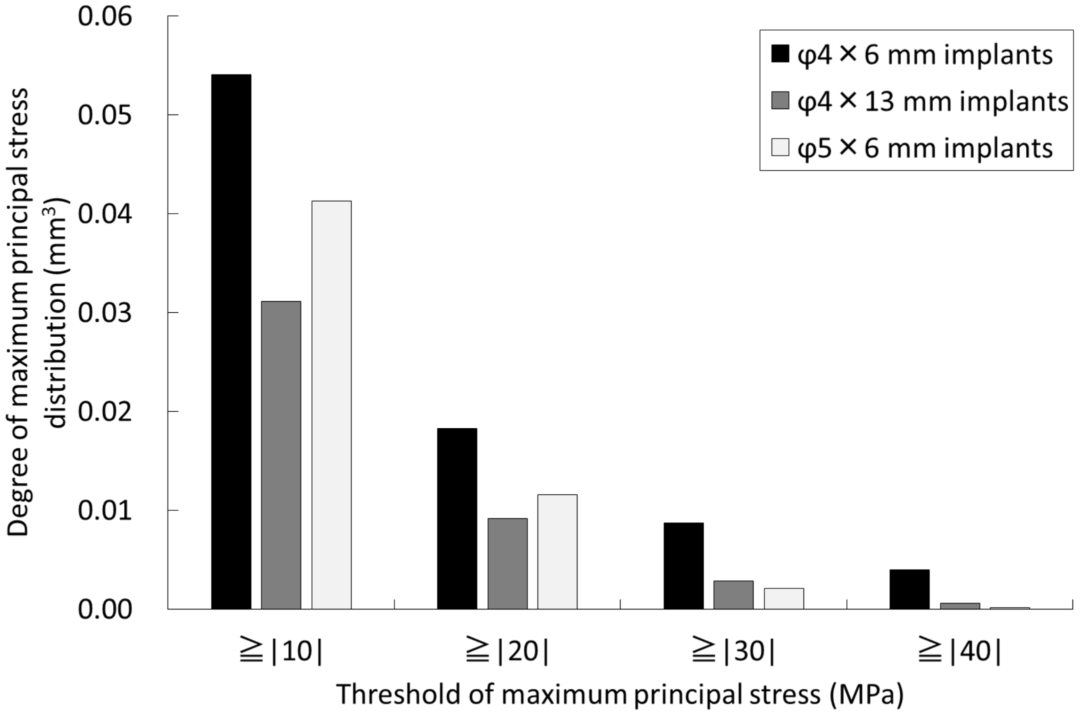


Fig. 10B

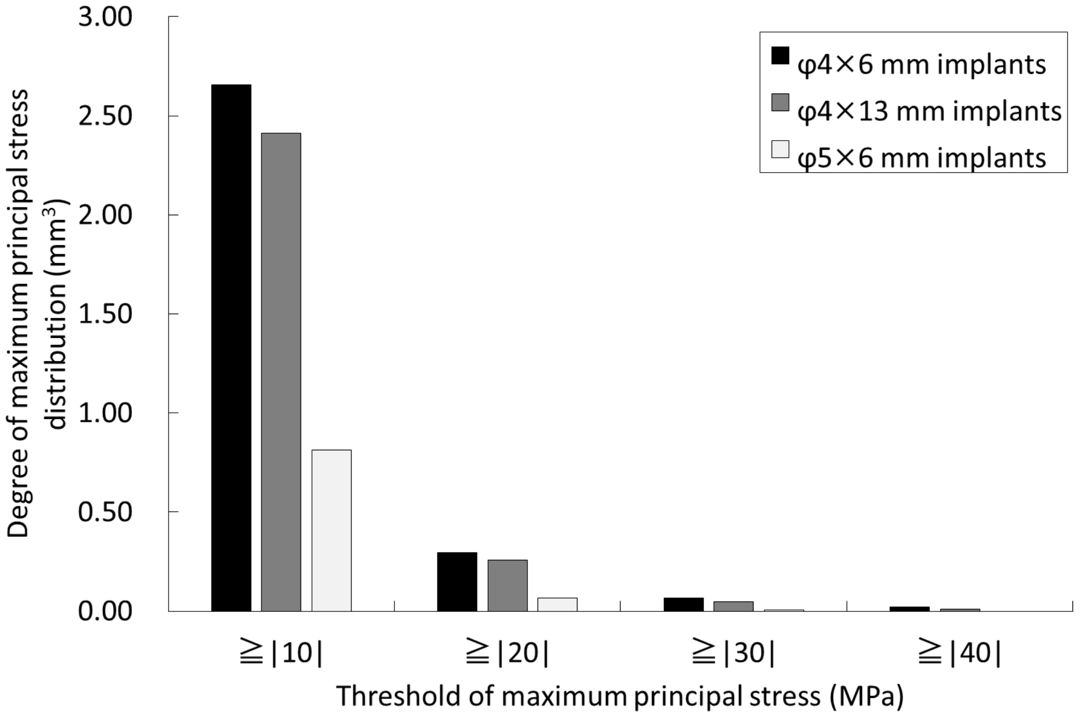


Fig. 11A

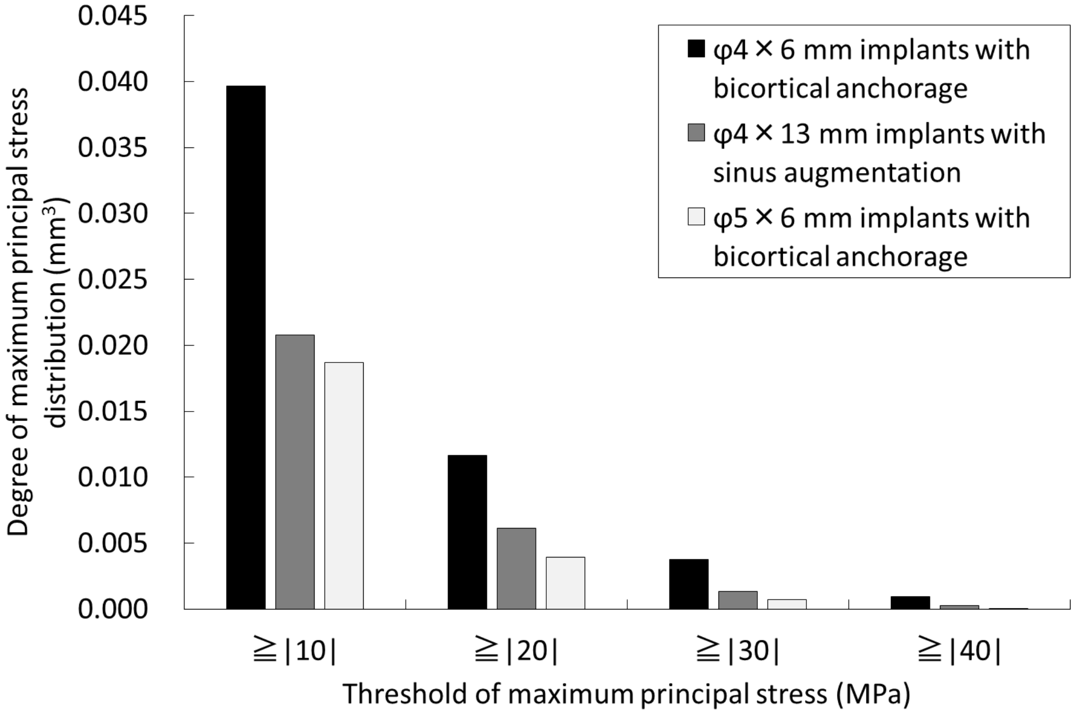


Fig. 11B

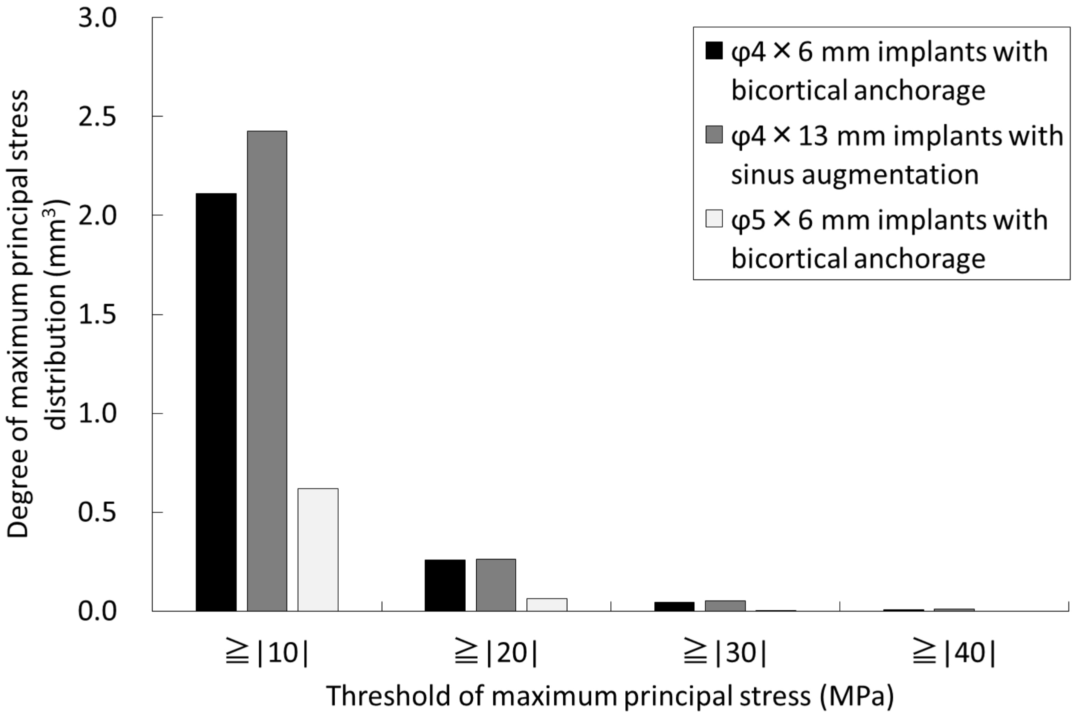
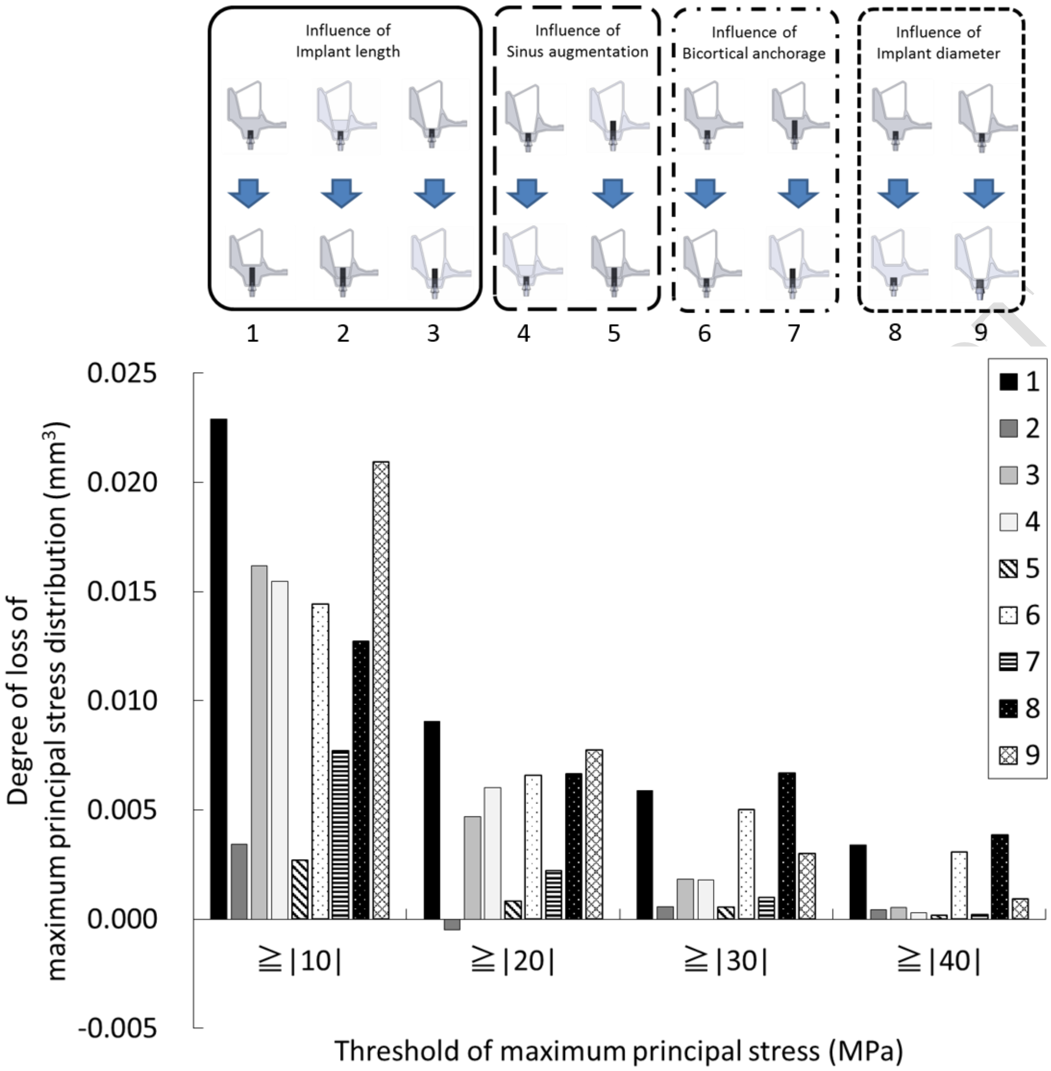
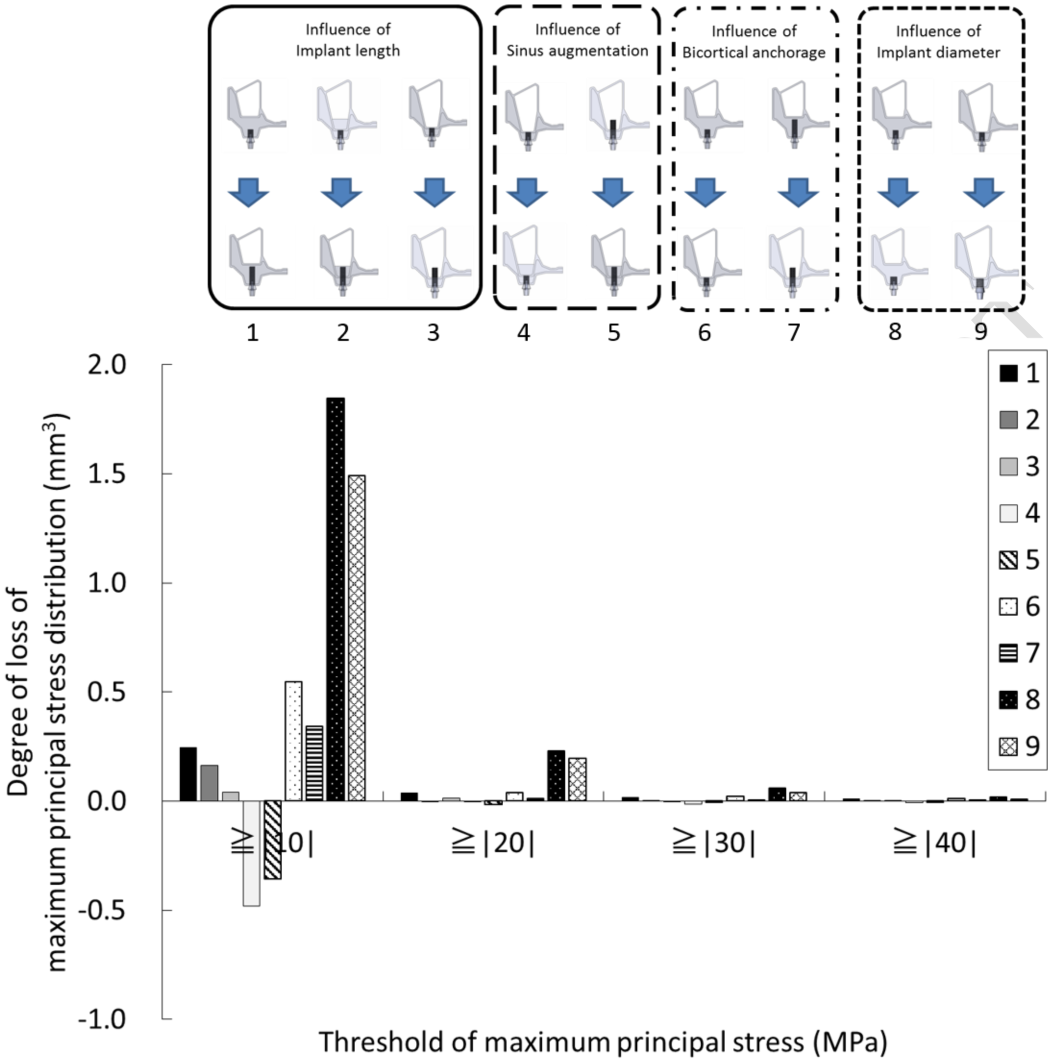


Fig. 12A



Influence of Implant length
Influence of Sinus augmentation
Influence of Bicortical anchorage
Influence of Implant diameter
1
2
3
4
5
6
7
8
9
0.025
0.020
0.015
0.010
0.005
0.000
-0.005
Degree of loss of maximum principal stress distribution (mm³)
≧|10|
≧|20|
≧|30|
≧|40|
Threshold of maximum principal stress (MPa)

1 Fig. 12B


Influence of Implant length
Influence of Sinus augmentation
Influence of Bicortical anchorage
Influence of Implant diameter
1
2
3
4
5
6
7
8
9
Degree of loss of maximum principal stress distribution (mm^3)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
≧|10|
≧|20|
≧|30|
≧|40|
Threshold of maximum principal stress (MPa)

2

3

Table 1: Mechanical properties of each component used for finite element analysis

Components	Young's Moduli (MPa)	Poisson's Ratios
Cortical bone	13,000	0.3
Cancellous bone	1,370	0.3
Implant components	117,000	0.3
Graft material	1,370	0.3

Table 2: Total numbers of elements for each model. 1. ϕ4×6 mm implants, 2. ϕ4×13 mm implants, 3. ϕ4×6 mm implants with bicortical anchorage, 4. ϕ4×13 mm implants with sinus augmentation, 5. ϕ5×6 mm implants, 6. ϕ5×6 mm implants with bicortical anchorage, 7. ϕ4×6 mm implants with bicortical anchorage and sinus augmentation, 8. ϕ4×13 mm implants without sinus augmentation.

	1	2	3	4	5	6	7	8
total number of elements	155,499	163,406	146,609	154,254	156,322	146,249	152,438	147,545

FIGURE LEGENDS

Fig. 1: Geometry of computer-aided design models of ϕ4×6 mm implant (left), ϕ5×6 mm implant (middle), and ϕ4×13 mm implant (right) (mm).

Fig. 2: Computer-aided design models of maxillary alveolar bone. (A) Bone quantity A. (B) Bone quantity C.

Fig. 3: Computer-aided design models of each implant in the case of bone quantity A. (A) ϕ4×6 mm implants. (B) ϕ4×13 mm implants. (C) ϕ5×6 mm implants.

Fig. 4: Computer-aided design models of each implant in the case of bone quantity C. (A) ϕ4×6 mm implants with bicortical anchorage. (B) ϕ5×6 mm implants with bicortical anchorage.

Fig. 5: One of the computer-aided design models of each implant in the case of bone quantity C with sinus augmentation, which was composed of maxillary bone and graft materials.

Fig. 6: Two control models were prepared for comparing the influences of implant length and diameter, bicortical anchorage, and sinus augmentation. (A) $\phi 4\times6$ mm implants placed on the bone quantity C with bicortical anchorage and sinus augmentation. (B) $\phi 4\times13$ mm implants placed on the bone quantity C without sinus augmentation.

Fig. 7: Assembled computer-aided design model of bone and implant models. The mesial and distal section surfaces of the bone were fixed. Static load of 150 N was applied to the basal ridge surface of the abutment at 30° in a direction oblique to the long axis of the implants.

Fig. 8: Calculation procedure of the degree of maximum principal stress distributed to peri-implant cortical bone. The maximum principal stress distribution to peri-implant cortical bone greater than or equal to the absolute value of the threshold was extracted by computer-aided design software. Total volume of extracted parts was calculated.

Fig. 9: Influence of four factors; implant length, bicortical anchorage, sinus augmentation, and implant diameter.

Fig. 10: Degree of stress distribution in the bone quantity A model for ϕ4×6 mm implants, ϕ4×13 mm implants, and ϕ5×6 mm implants (mm^3), (A) Compressive stress, (B) Tensile stress.

Fig. 11: Degree of stress distribution in the bone quantity C model for ϕ4×6 mm implants with bicortical anchorage, ϕ4×13 mm implants with sinus augmentation, and ϕ5×6 mm with bicortical anchorage (mm^3), (A) Compressive stress, (B) Tensile stress.

Fig. 12: Degree of loss of compressive and tensile stress distribution (mm^3). 1. ϕ4×6 mm implants placed on the bone quantity A→ϕ4×13 mm implants placed on the bone quantity A, 2. ϕ4×6 mm implants with bicortical anchorage and sinus augmentation on the bone quantity C→ϕ4×13 mm implants with sinus augmentation on the bone quantity C, 3. ϕ4×6 mm implants with bicortical anchorage on the bone quantity C→ϕ4×13 mm implants without sinus augmentation on the bone quantity C, 4. ϕ4×6 mm implants with bicortical anchorage on the bone quantity C→ϕ4×6 mm implants with bicortical anchorage and sinus augmentation on the bone quantity C, 5. ϕ4×13 mm h implants without sinus augmentation on the bone quantity C→ϕ4×13 mm implants

with sinus augmentation on the bone quantity C, 6. ϕ4×6 mm implants on the bone quantity A→ϕ4×6 mm implants with bicortical anchorage on the bone quantity C. 7. ϕ4×13 mm implants on the bone quantity A→ϕ4×13 mm implants without sinus augmentation on the bone quantity C, 8. ϕ4×6 mm implants on the bone quantity A→ϕ5×6 mm implants on the bone quantity A, 9. ϕ4×6 mm implants with bicortical anchorage on the bone quantity C→ϕ5×6 mm implants with bicortical anchorage on the bone quantity C, (A) Compressive stress, (B) Tensile stress.

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