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

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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 ϕ4×6 mm implant was placed on the bone quantity C model with bicortical anchorage and sinus augmentation, and the ϕ4×13 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 ϕ4×13 mm implants placed on the bone quantity C with sinus augmentation increased in comparison with that for ϕ4×6 mm implants placed on the bone quantity C with bicortical anchorage, because while ϕ4×6 mm implants placed on the bone quantity C with bicortical anchorage was only influenced by bicortical anchorage as a stress-reducing factor, ϕ4×13 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, ϕ4×13 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 ϕ4×6 mm implants placed on the bone quantity C with bicortical anchorage was less than that of ϕ4×6 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 ϕ5×6 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 ϕ5×6 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 ϕ5×6 mm implants placed on the bone quantity C with bicortical anchorage was much smaller than that for ϕ4×13 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, ϕ5×6 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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REFERENCES

1) Scholander S. A retrospective evaluation of 259 single-tooth replacements by the use of Brånemark implants. Int J Prosthodont 1999;12:483-491.

2) Priest G. Single-tooth implants and their role in preserving remaining teeth: a 10-year survival study. Int J Oral Maxillofac Implants 1999;14:181-188.

3) Ribeiro-Rotta RF, Lindh C, Pereira AC, Rohlin M. Ambiguity in bone tissue characteristics as presented in studies on dental implant planning and placement: a systematic review. Clin Oral Implants Res 2011;22:789-801.

4) Pietrokovski J, Massler M. Alveolar ridge resorption following tooth extraction. J Prosthet Dent 1967;17:21-7.

5) Wallace SS, Tarnow DP, Froum SJ, et al. Maxillary sinus elevation by lateral window approach: evolution of technology and technique. J Evid Based Dent Pract 2012;12:161-171.

6) Boyne PJ. Augmentation of the posterior maxilla by way of sinus grafting procedures: recent research and clinical observations. Oral Maxillofac Surg Clin North Am 2004;16:19-31, v-vi.

7) Bedrossian E, Tawfilis A, Alijanian A. Veneer grafting: a technique for augmentation of the resorbed alveolus prior to implant placement. A clinical report.

Int J Oral Maxillofac Implants 2000;15:853-858.

8) McAllister BS, Haghighat K. Bone augmentation techniques. J Periodontol 2007;78:377-396.

9) Fernández Díaz JÓ, Naval Gías L. Rehabilitation of edentulous posterior atrophic mandible: inferior alveolar nerve lateralization by piezotome and immediate implant placement. Int J Oral Maxillofac Surg 2013;42:521-526.

10) Peleg M, Mazor Z, Chaushu G, Garg AK. Lateralization of the inferior alveolar nerve with simultaneous implant placement: a modified technique. Int J Oral Maxillofac Implants 2002;17:101-106.

11) Friberg B, Gröndahl K, Lekholm U, Brånemark PI. Long-term follow-up of severely atrophic edentulous mandibles reconstructed with short Brånemark implants. Clin Implant Dent Relat Res 2000;2:184-189.

12) Wennerberg A, Albrektsson T. Effects of titanium surface topography on bone integration: a systematic review. Clin Oral Implants Res 2009;20 Suppl 4:172-184.

13) Pierrisnard L, Renouard F, Renault P, Barquins M. Influence of implant length and bicortical anchorage on implant stress distribution. Clin Implant Dent Relat Res 2003;5:254-262.

14) Mertens C, Meyer-Bäumer A, Kappel H, Hoffmann J, Steveling HG. Use of 8-mm

and 9-mm implants in atrophic alveolar ridges: 10-year results. Int J Oral Maxillofac Implants 2012;27: 1501-1508.

15) Anitua E, Orive G. Short implants in maxillae and mandibles: A retrospective study with 1 to 8 years of follow-up. J Periodontol 2010;81:819-826.

16) Renouard F, Nisand D. Short implants in the severely resorbed maxilla: a 2-year retrospective clinical study. Clin Implant Dent Relat Res 2005;7:S104-110.

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

18) Monje A, Chan HL, Fu JH, Suarez F, Galindo-Moreno P, Wang HL. Are short dental implants (<10 mm) effective? a meta-analysis on prospective clinical trials. J Periodontol 2013;84:895-904.

19) Esposito M, Grusovin MG, Rees J, et al. Interventions for replacing missing teeth: augmentation procedures of the maxillary sinus. Cochrane Database Syst Rev 2010;17;CD008397.

20) Sánchez-Garcés MA, Costa-Berenguer X, Gay-Escoda C. Short implants: a descriptive study of 273 implants. Clin Implant Dent Relat Res 2012;14:508-16.

21) Romeo E, Bivio A, Mosca D, Scanferla M, Ghisolfi M, Storelli S. The use of short dental implants in clinical practice: literature review. Minerva Stomatol

2010;59:23-31.

22) Buser D, von Arx T, ten Bruggenkate C, Weingart D. Basic surgical principles with ITI implants. Clin Oral Implants Res 2000;11 Suppl 1:59-68.

23) Malo P, de Araujo Nobre M, Lopes A, Moss S. Posterior maxillary implants inserted with bicortical anchorage and placed in immediate function for partial or complete edentulous rehabilitations. A retrospective clinical study with a median follow-up of 7 years. Oral Maxillofac Surg 2015;19:19-27.

24) Noda K, Arakawa H, Kimura-Ono A, Yamazaki S, Hara ES, Sonoyama W, Maekawa K, Okura K, Shintani A, Matsuka Y, Kuboki T. A longitudinal retrospective study of the analysis of the risk factors of implant failure by the application of generalized estimating equations. J Prosthodont Res 2015;59:178-84.

25) Abu-Hammad O, Khraisat A, Dar-Odeh N, El-Maaytah M. Effect of dental implant cross-sectional design on cortical bone structure using finite element analysis. Clin Implant Dent Relat Res 2007;9:217-21.

26) Yamanishi Y, Yamaguchi S, Imazato S, Nakano T, Yatani H. Influences of implant neck design and implant-abutment joint type on peri-implant bone stress and abutment micromovement: three-dimensional finite element analysis. Dent Mater 2012;28:1126-1133.

27) Huang HL, Fuh LJ, Ko CC, Hsu JT, Chen CC. Biomechanical effects of a maxillary implant in the augmented sinus: a three-dimensional finite element analysis. Int J Oral Maxillofac Implants 2009;24:455-62.

28) Pessoa RS, Vaz LG, Marcantonio E Jr, Vander Sloten J, Duyck J, Jaecques SV. Biomechanical evaluation of platform switching in different implant protocols: computed tomography-based three-dimensional finite element analysis. Int J Oral Maxillofac Implants 2010;25:911-919.

29) Inglam S, Suebnukarn S, Tharanon W, Apatananon T, Sitthiseripratip K. Influence of graft quality and marginal bone loss on implants placed in maxillary grafted sinus: a finite element study. Med Biol Eng Comput 2010;48:681-689.

30) Chang SH, Lin CL, Lin YS, Hsue SS. Huang SR. Biomechanical comparison of a single short and wide implant with monocortical or bicortical engagement in the atrophic posterior maxilla and a long implant in the augmented sinus. Int J Oral Maxillofac Implants 2012;27:e102-111.

31) Bulaqi HA, Mousavi Mashhadi M, Geramipanah F, Safari H, Paknejad M. Effect of the coefficient of friction and tightening speed on the preload induced at the dental implant complex with the finite element method. J Prosthet Dent 2015;113:405-411.

32) Ding X, Liao SH, Zhu XH, Zhang XH, Zhang L. Effect of diameter and length on

stress distribution of the alveolar crest around immediate loading implants. Clin Implant Dent Relat Res 2009;11:279-287.

33) Reilly DT, Burstein AH. The elastic and ultimate properties of compact bone tissue. J Biomech 1975;8:393-405.

34) Hessling K-H, Neukam FW, Scheller H, Günay H, Schmelzeisen R. Die extreme Atrophie des Ober- und Unterkiefers. Klinische Gesichtspunkte bei der Versorgungmit enossalen Implantaten. Z Zahnärztl Implantol 1990;6:35–39.

35) Tepper G, Haas R, Zechner W, Krach W, Watzek G. Three-dimensional finite element analysis of implant stability in the atrophic posterior maxilla: a mathematical study of the sinus floor augmentation. Clin Oral Implants Res 2002;13:657-665.

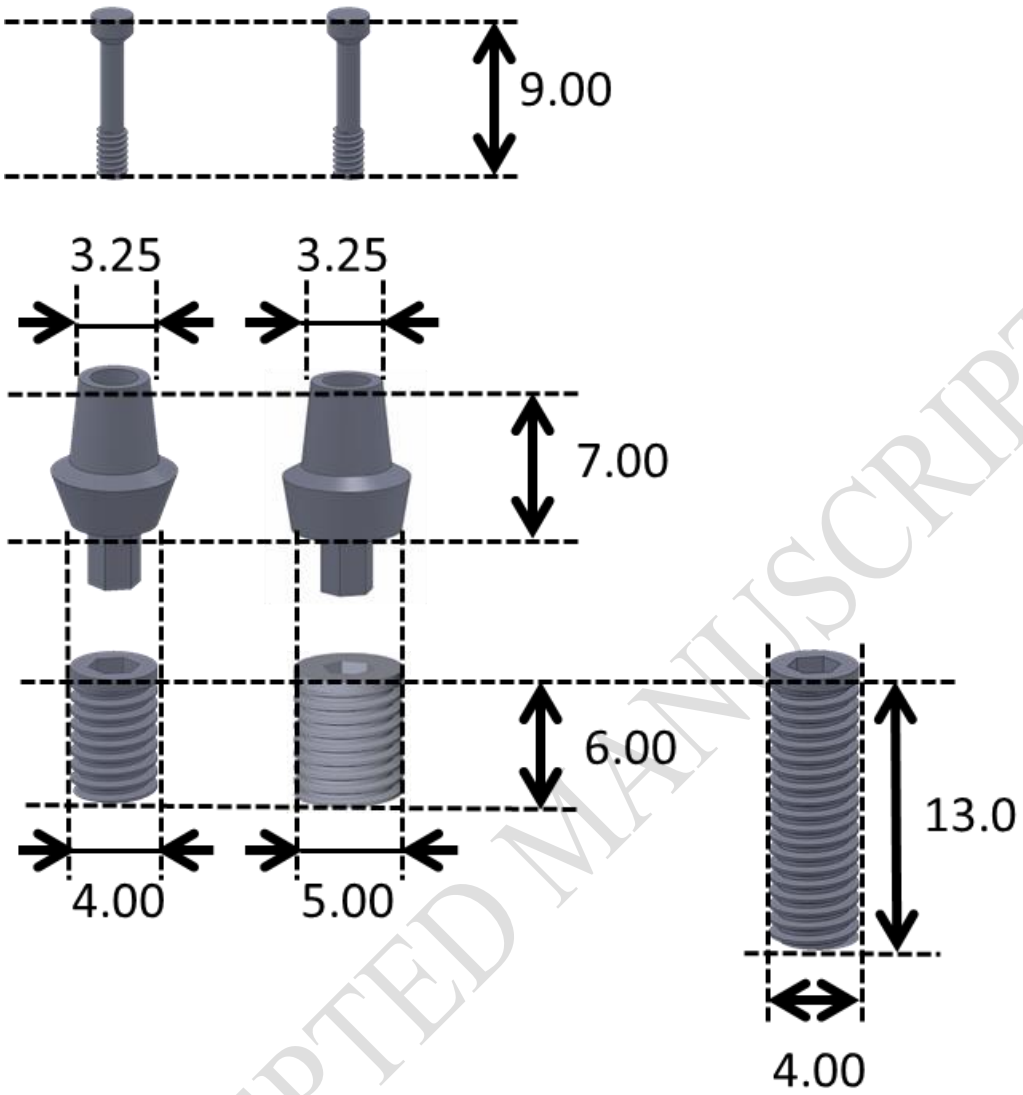
36) Vairo G, Sannino G. Comparative evaluation of osseointegrated dental implants based on platform-switching concept: influence of diameter, length, thread shape, and in-bone positioning depth on stress-based performance. Comput Math Methods Med 2013;doi:10.1155/2013/250929.

37) Ormianer Z, Ben Amar A, Duda M, Marku-Cohen S, Lewinstein I. Stress and strain patterns of 1-piece and 2-piece implant systems in bone: a 3-dimensional finite element analysis. Implant Dent 2012;21:39-45.

38) Queiroz TP, Aguiar SC, Margonar R, de Souza Faloni AP, Gruber R, Luvizuto ER. Clinical study on survival rate of short implants placed in the posterior mandibular region: resonance frequency analysis. Clin Oral Implants Res 2014; doi: 10.1111/clr.12394.

FIGURES

Fig. 1



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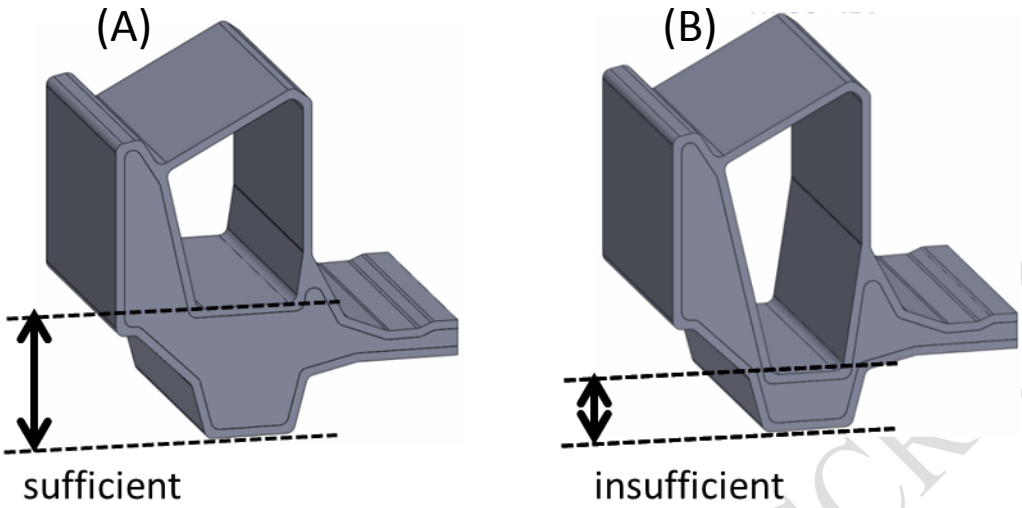

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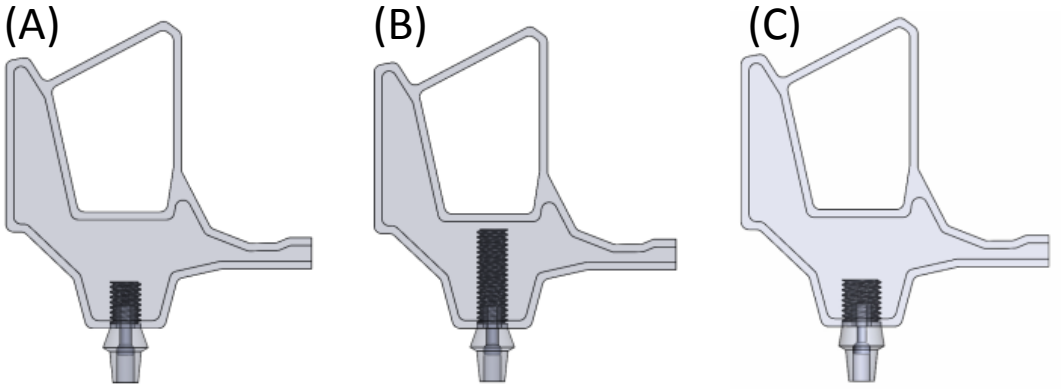
1 Fig. 3



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1 Fig. 4

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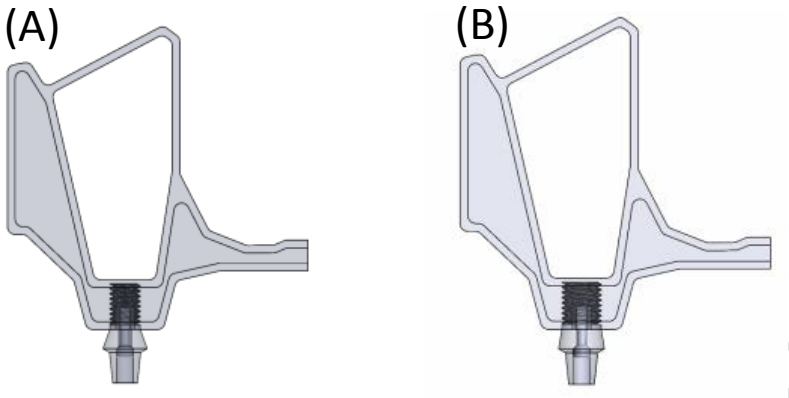

1 Fig. 5

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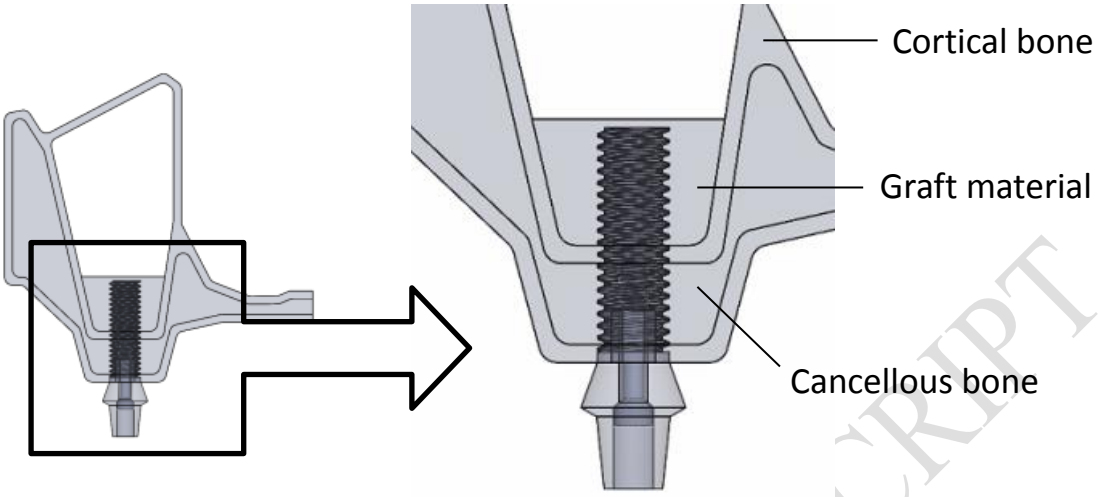

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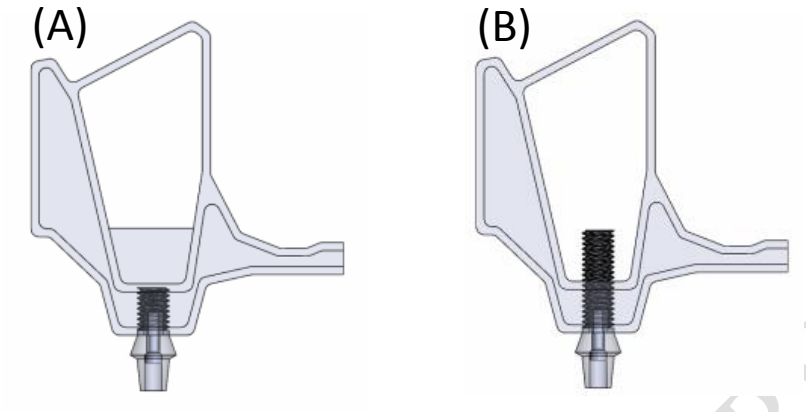

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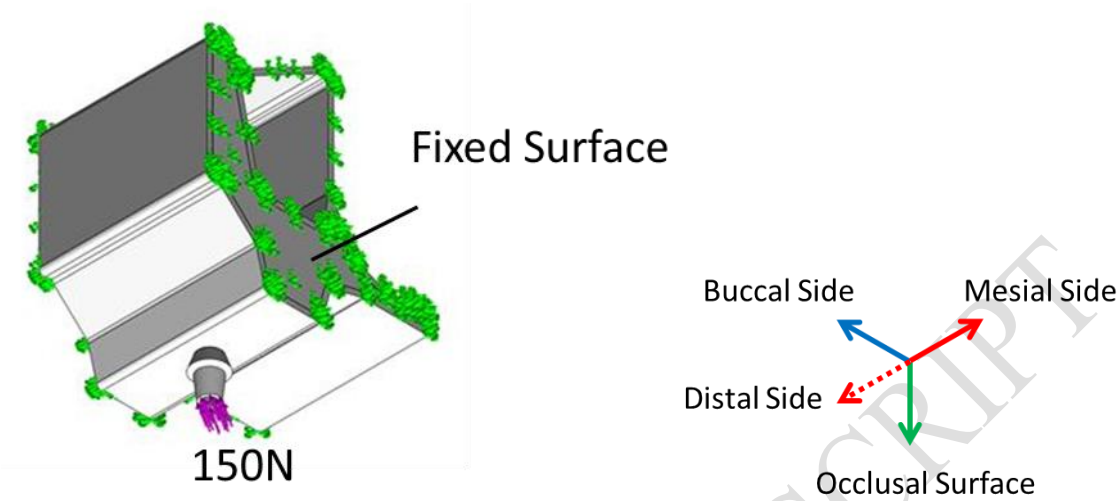

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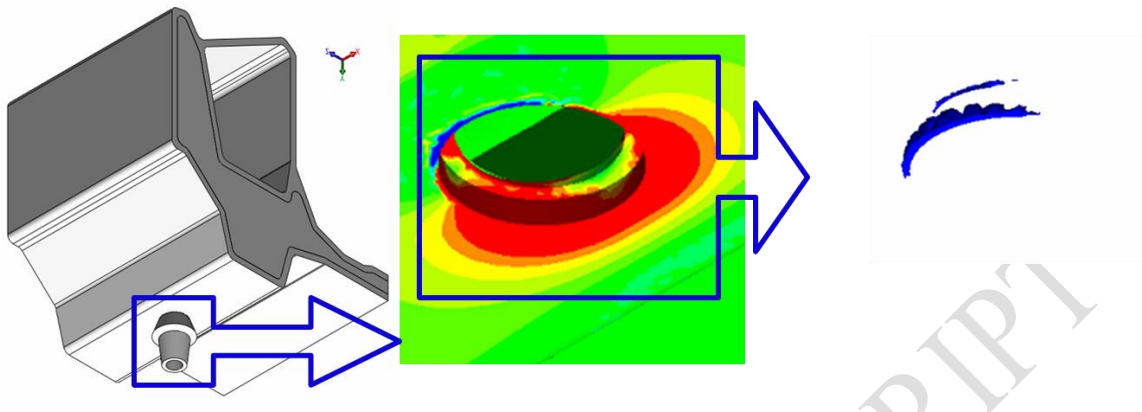
1 Fig. 8



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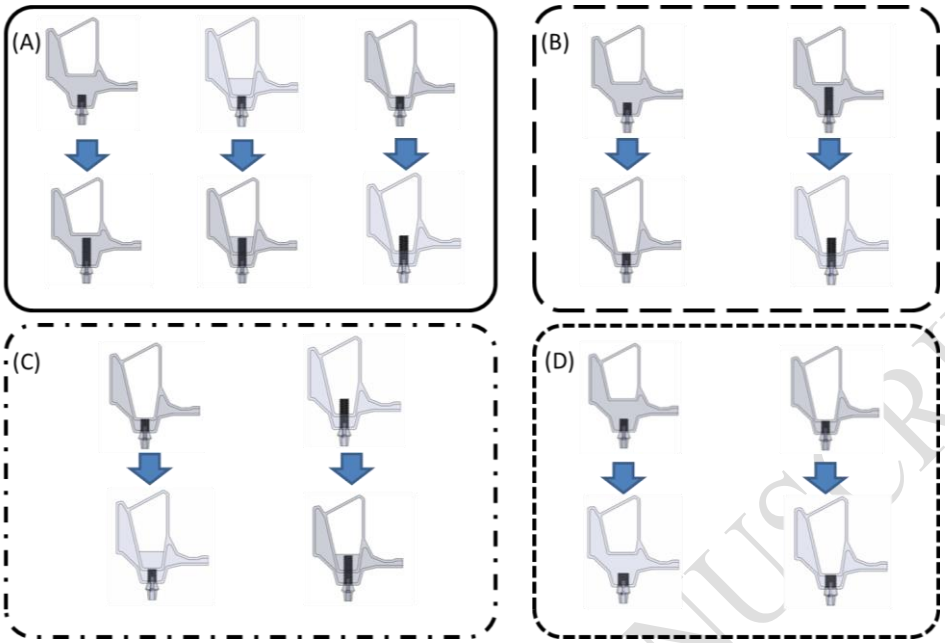

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Fig. 10A

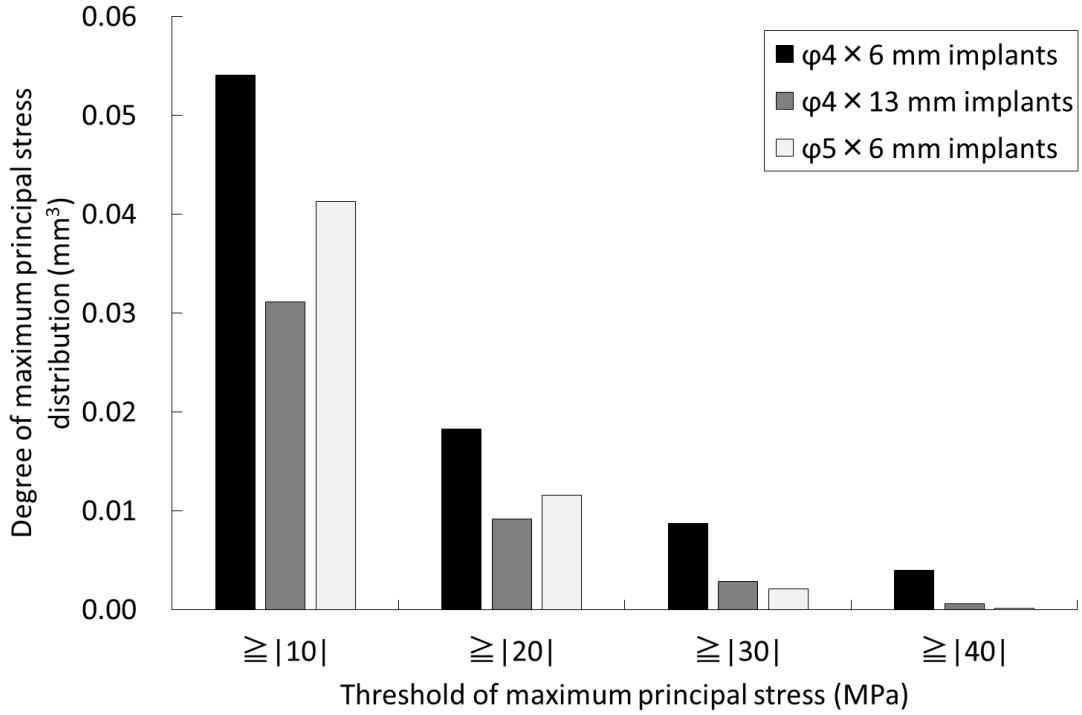
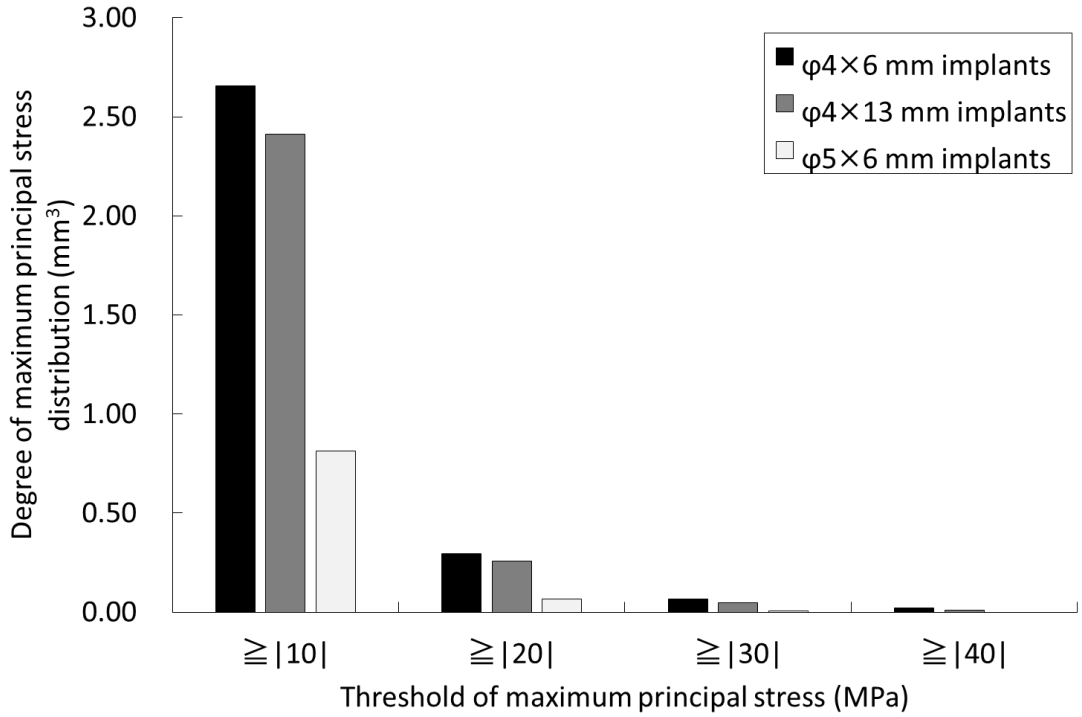
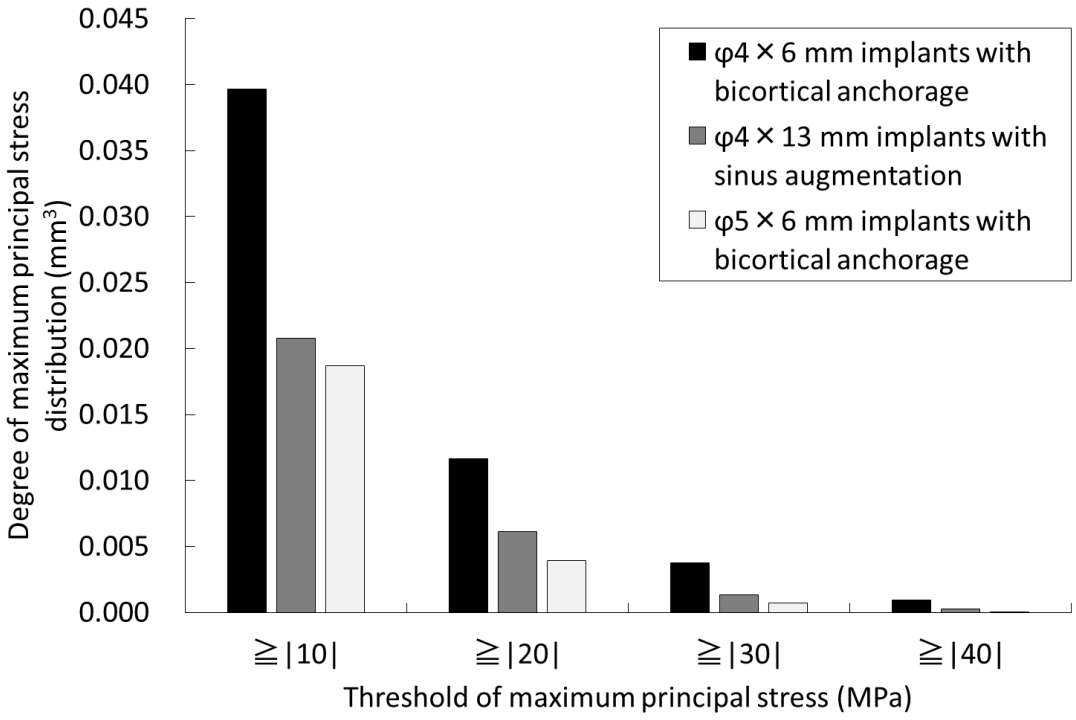


Fig. 10B



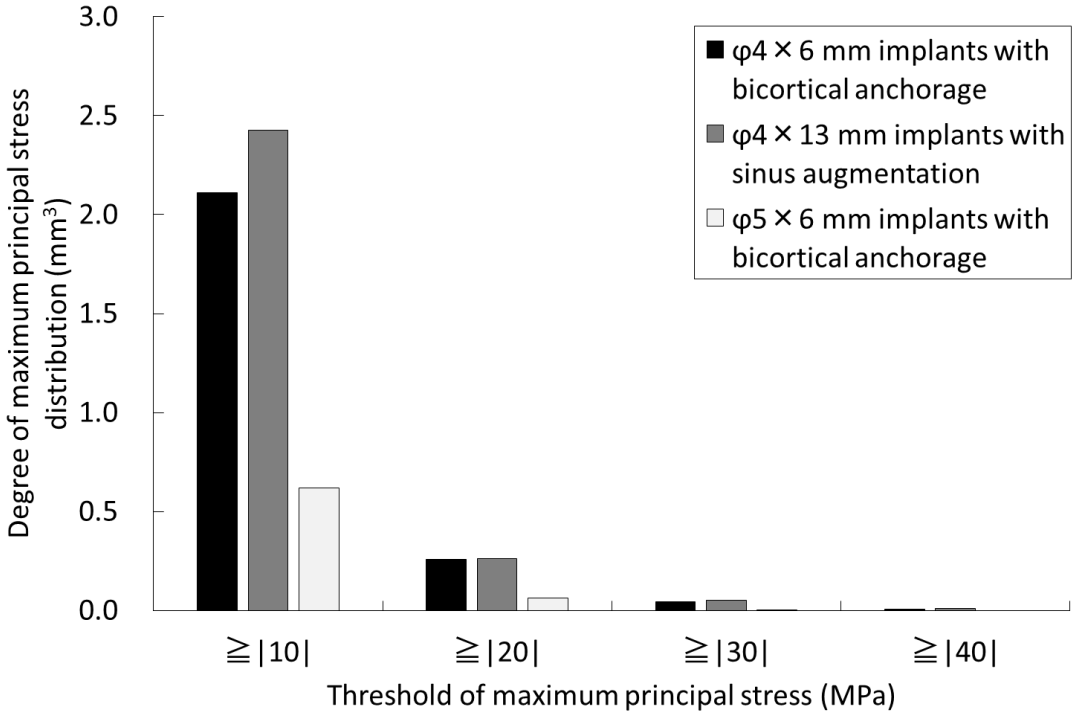
1 Fig. 11A



2

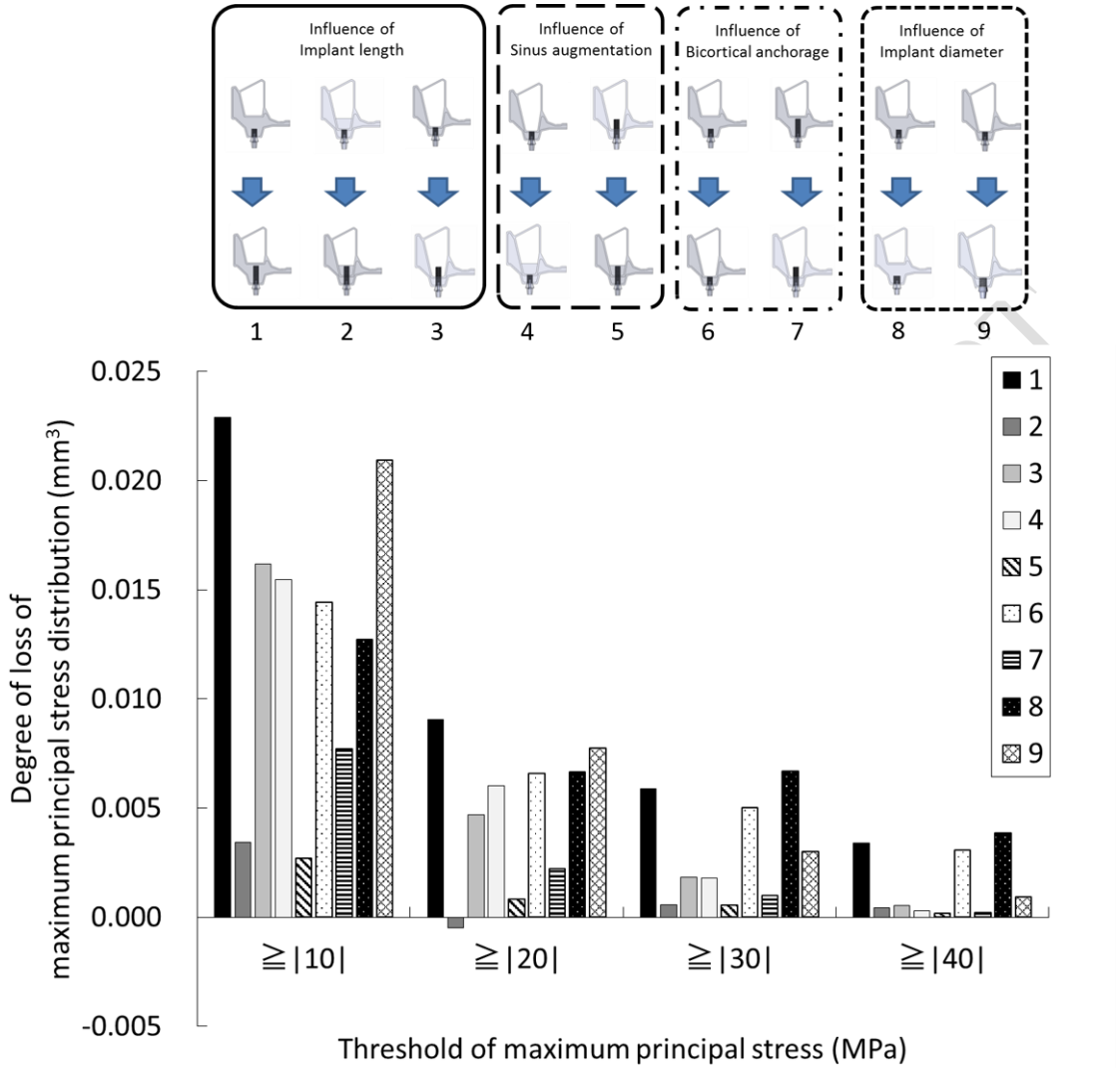
3

4 Fig. 11B



5

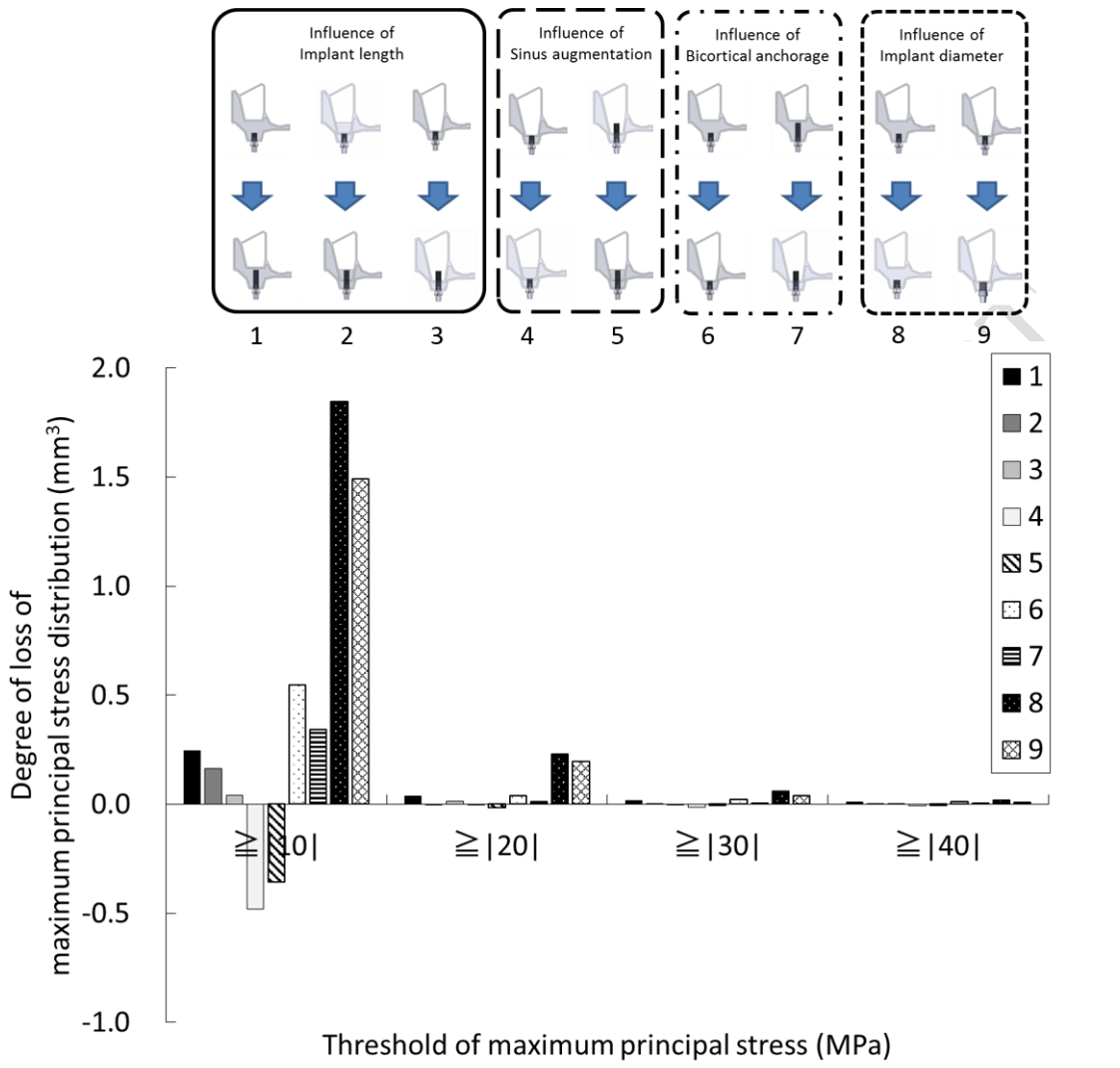
1 Fig. 12A


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)

2

3

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
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
Degree of loss of maximum principal stress distribution (mm³)
≧|10|
≧|20|
≧|30|
≧|40|
Threshold of maximum principal stress (MPa)

2

3

1 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

2

3

4

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) ϕ4×6 mm implants placed on the bone quantity C with bicortical anchorage and sinus augmentation. (B) ϕ4×13 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.