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Three-dimensional finite element analysis of buccally cantilevered implant-supported prostheses in a severely resorbed mandible

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PURPOSE. The aim of the study was to compare the lingualized implant placement creating a buccal cantilever with prosthetic-driven implant placement exhibiting excessive crown-to-implant ratio. **MATERIALS AND METHODS.** Based on patient's CT scan data, two finite element models were created. Both models were composed of the severely resorbed posterior mandible with first premolar and second molar and missing second premolar and first molar, a two-unit prosthesis supported by two implants. The differences were in implants position and crown-to-implant ratio; lingualized implants creating lingually overcontoured prosthesis (Model CP2) and prosthetic-driven implants creating an excessive crown-to-implant ratio (Model PD2). A screw preload of 466.4 N and a buccal occlusal load of 262 N were applied. The contacts between the implant components were set to a frictional contact with a friction coefficient of 0.3. The maximum von Mises stress and strain and maximum equivalent plastic strain were analyzed and compared, as well as volumes of the materials under specified stress and strain ranges. **RESULTS.** The results revealed that the highest maximum von Mises stress in each model was 1091 MPa for CP2 and 1085 MPa for PD2. In the cortical bone, CP2 showed a lower peak stress and a similar peak strain. Besides, volume calculation confirmed that CP2 presented lower volumes undergoing stress and strain. The stresses in implant components were slightly lower in value in PD2. However, CP2 exhibited a noticeably higher plastic strain. **CONCLUSION.** Prosthetic-driven implant placement might biomechanically be more advantageous than bone quantity-based implant placement that creates a buccal cantilever. [J Adv Prosthodont 2021;13:12-23]

KEYWORDS
Dental prosthesis, Implant-supported; Bone resorption; Dental stress analysis; Finite element analysis

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INTRODUCTION

A cantilever is a projecting beam or member supported on one end.[1] A cantilever fixed dental prosthesis is a fixed complete or partial denture in which the pontics are cantilevered, retained, and supported by one or more abutments.[1] By incorporating a cantilever, the possibility of using more units in a fixed dental prosthesis (FDP) is enabled in some clinical situations to save time, effort, and cost and prevent preparation of sound tooth structure in some clinical situations. As for jaw rehabilitation with implants, compromised bone could necessitate bone regenerative procedure such as bone grafting which involves more complicated treatment than cantilevered prosthesis. Therefore, cantilever could act as an alternative treatment option if performed under careful planning.[2]

As cantilever length increases, the bending moment of occlusal forces increases by leverage. Therefore, stress and strain in the bone surrounding implants adjacent to the cantilever increase, as was shown in previous finite element analysis (FEA) studies on dental implants.[2,3] This increase in stress, which might express an overload to the implant, could lead to biologic complications such as marginal bone loss.[4,5] Contradictory findings were reported by other authors who confirmed the absence of the correlation between marginal bone loss and the cantilever prosthesis.[2,6,7] Many authors reported a minimum implant survival rate of 97% for implants supporting a cantilever prosthesis after various observation periods ranging from 5 to 10 years.[5,8-10] The high survival rate could refer to the fact that the bone surrounding the implants can withstand the amplified occlusal load by the cantilever prosthesis, if proper planning was achieved. Aside from biologic complications, cantilevers could lead to prosthetic mechanical complications including implant fracture,[4,11] framework fracture,[8] veneer fracture,[11,12] abutment screw fracture[12] and screw loosening.[6,8,11-13]

In many studies, the location of cantilever was shown not to influence the outcome,[5,6,9,13] in contrast to length of the cantilever. When multiple teeth are extracted, bone resorption occurs in vertical and horizontal trends.[14,15] The bone resorption may also occur when curative surgeries are performed. In the posterior maxilla, vertical buccal bone resorption may force implants to be placed palatally to the natural position of the teeth, creating a buccal cantilever.[16] As for posterior mandible, if no bone grafting was considered, the buccal bone resorption would force implants to be placed lingually to the natural position of the teeth, creating a buccal cantilever. However, if the buccal bone was not resorbed entirely, prosthetic-driven implant placement in the remaining buccal bone would prevent the formation of a buccal cantilever. Besides, the prosthetic-driven placement might result in a higher crown-to-implant ratio.

To compare different implant-supported FDP designs, the finite element method is a useful tool. This method allows for the investigation of the prosthesis behavior, different implant designs, materials, and the bone under different loading directions and magnitudes.[17,18] Through FEA, tracing stress and visualizing its distribution and the corresponding deformation are possible.[18] Then, by reflecting FEA findings on the real clinical situation, predictions about implant longevity can be made because the stress and strain transferred by implants to the surrounding bone leads to biologic bone reactions, which are known as bone modeling and remodeling as to adapt to mechanical loads.[19,20] The buccal cantilever situations are hardly reported in the literature. Therefore, scientific evidence is necessary to help make a clinical decision when buccal cantilever situations are met.

The purpose of this study was to compare the lingualized implant placement creating a buccal cantilever with prosthetic-driven implant placement exhibiting excessive crown-to-implant ratio.

MATERIALS AND METHODS

Modeling: The mandible selected for the study has undergone a curative surgery for a localized cancer causing a postsurgical bone resorption. The buccolingual section of the edentulous ridge is shown in Fig. 1. Cone-beam computed tomography (CBCT) images of the mandible were obtained from the patient's record by a protocol approved by the appropriate institutional review board (IRB approval no. CR112016). The cross-sectional images from the CBCT were exported in DICOM format after reconstruction. Cor-

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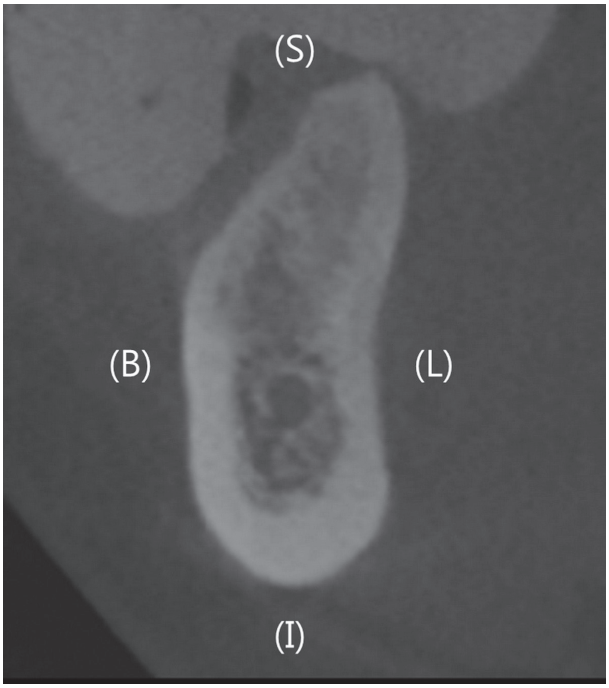

Fig. 1. Buccolingual section of edentulous ridge. Buccolingual section of edentulous ridge taken from computed tomography scan. (B): buccal, (L): lingual, (S): superior, (I): inferior.

tical and cancellous bone and dental tissues were separated by using the segmentation function in an image processing software (Mimics, Materialise, Leuven, Belgium). The segmented images were converted into a three-dimensional model in STL format. The three-dimensional model was then imported to a meshing program (Visual mesh, ESI group, Paris, France) to be meshed. The bone segment to be studied was cut from the entire mandible model and included first premolar to the mesial and second molar to the distal. To eliminate the effect of the model end, the distance from the most mesially planned implant to the mesial side was 8 mm, while the distance from the distal end to the most distally planned implant was 12 mm.[21] Virtual placement of Osstem GS System implants in the designated areas was completed with custom abutments designed by a CAD/CAM program (Ondemand3D, Cybermed, Seoul, South Korea) and crowns designed by another CAD/CAM program (Implant Studio, 3Shape, Copenhagen, Denmark). The morphology of the crowns was identical in the models to allow for the same occlusal contacts. Cement-retained crowns were used in the present study with a cement thickness of 50 µm.[22] The periodontal ligament was also modeled with a thickness of 0.2 mm based on previous studies.[23,24]

Taking into account the bone shape and inferior alveolar nerve canal, 10 mm long internal hex Osstem GS implants were placed. The models used in this study (Table 1, Fig. 2) were as follows: Model CP2 which comprised two 4 mm diameter implants, which were placed based on the bone quantity creating a buccal cantilever; and Model PD2 which consisted of two 4 mm diameter prosthetic-driven implants with excessive crown-to-implant ratio. Crown-to-implant ratios and the buccal cantilever lengths were also provided in Table 1. Crown-to-implant ratio was measured as the distance from the highest occlusal contact point on the crown to the plane of neck of the implant. The buccal cantilever length was measured in the following method: a plane was defined by the long axis of the implant and the closest-to-implant buccal cusp tip. Thereby, the measurement was taken as the distance from the cusp tip to the line, contained in the defined plane, that parallels the long axis of the implant and intersects with the neck of the implant from the buccal side. In both models, the crowns were splinted. The cortical and cancellous

Table 1. The models analyzed in the study

Model		Diameter (mm)	C/I	Buccal Cantilever Length	Nodes	Elements
CP2	Premolar implant	4	1:1	10.43 mm to buccal cusp tip	237,366	1,294,444
	Molar implant	4	1.1:1	5.16 mm to distobuccal cusp tip		
PD2	Premolar implant	4	1.8:1	0.65 mm to buccal cusp tip	182,009	960,446
	Molar implant	4	1.5:1	1.72 mm to distobuccal cusp tip		

C/I refers to crown-to-implant ratio. CP2: two 4 mm diameter implants placed based on the bone quantity. PD2: two 4 mm diameter prosthetic-driven implants.

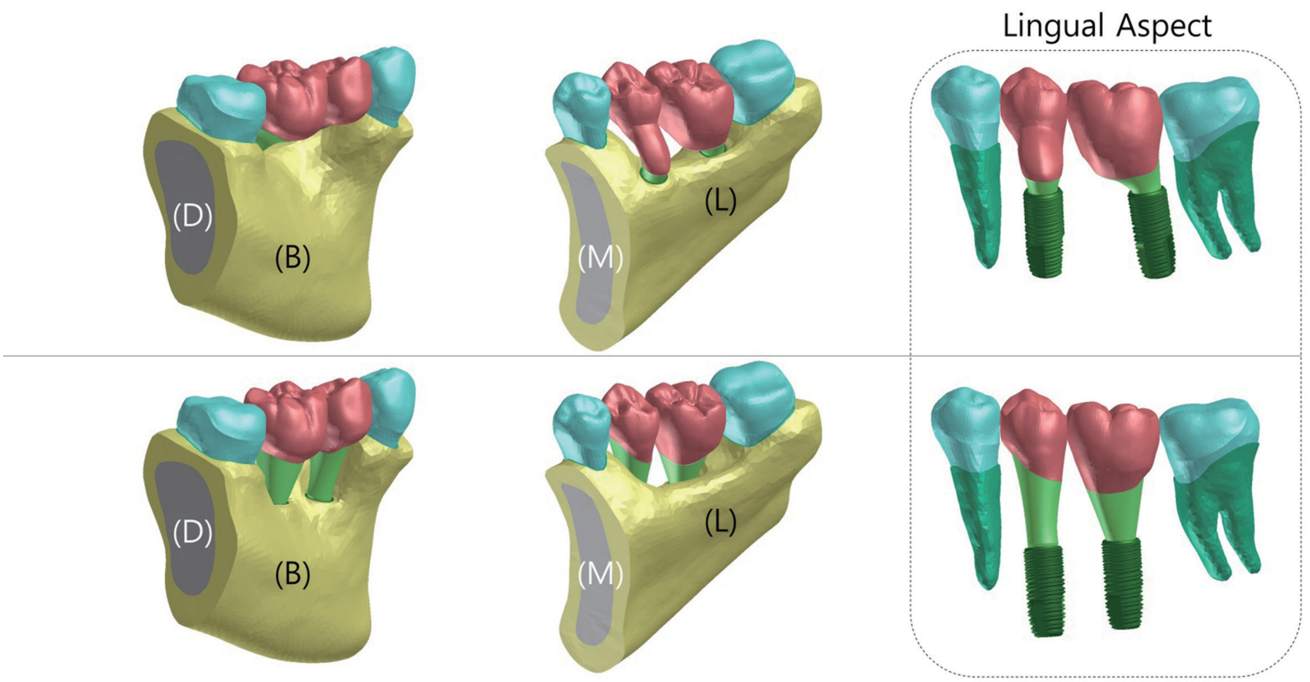

Fig. 2. Two models used in this study. Top: Model CP2 - two 4 mm diameter implants placed based on the bone quantity. Bottom: Model PD2 - two 4 mm diameter prosthetic-driven implants. (M): mesial, (D): distal, (B): buccal, (L): lingual.

bone were considered orthotropic materials whose properties change depending on the direction, unlike the isotropic materials whose properties are the same in all directions. The titanium for the implant fixtures, abutments, and abutment screws was considered an isotropic elastoplastic material by including the elastic modulus, tangent modulus, yield stress, and poisson's ratio as its material properties. All other materials, including gold for crowns, self-cure resin cement, dentin, and periodontal ligaments, were considered isotropic elastic materials. Material properties are listed in Table 2. Osseointegration was assumed to be 100%.[3,25,26] The contact between the implant components was set to a frictional contact with friction co-

Table 2. Material properties used in the study

Material	Elastic modulus (GPa)	Poisson's ratio	Shear modulus (GPa)	Tangent modulus (GPa)	Yield stress (GPa)
Cortical Bone*	E_1 (26.6) E_2 (17.9) E_3 (12.5)	v_{12} (0.28) v_{13} (0.21) v_{23} (0.19)	G_{23} (7.1) G_{31} (5.3) G_{12} (4.5)		
Cancellous Bone †	E_1 (1.148) E_2 (0.210) E_3 (1.148)	v_{12} (0.055) v_{13} (0.322) v_{23} (0.010)	G_{23} (0.068) G_{31} (0.434) G_{12} (0.068)		
Titanium (Ti-6Al-4V)	103 ‡	0.3 §		0.25 ‡	0.932 ‡
Dentin	20 ¶	0.31 §			
PDL	2.7×10^{-3} **	0.45 §			
Gold Alloy	100 ††	0.3 §			
Resin Cement	6 ‡‡	0.28***			

E_1 is the elastic modulus in the mesiodistal axis. E_2 is the elastic modulus in the superoinferior axis. E_3 is the elastic modulus in the buccolingual axis. v_{xy} is the poisson's ratio for strain in the y-direction when loaded in the x-direction.
List of references: * [42], † [43,44], ‡ [45], § [46], ¶ [47], ** [24], † † [48], ‡ ‡ [49], *** [50]

efficient of 0.3.[27,28] Tetrahedral elements were used in the models. A symmetric segment to segment contact based on Coulomb friction model was used. However, to simplify the simulation, one exclusion from the contact condition was made, which was the implant-screw tied threads. The number of elements and nodes for each model is provided along with models details in Table 1.

Loads and Boundary Conditions: The terminal nodes in the mesial and distal sides of each model were constrained in all directions. A static load was applied and was set to 262 N as this value is the peak value of a chewing cycle.[29] The load was distributed on the occlusal surface of the prosthesis and directed buccally at seventy-five degrees to the occlusal surface. Screw preload was applied to the titanium abutment screws at 466.4 N as determined through experimentation.[30]

Analysis: Analysis was achieved by using finite element analysis package (Visual performance, ESI group, Paris, France) and screening of the results was performed by a viewing program (Visual viewer, ESI group, Paris, France). Maximum von Mises stress values in the bone and implant components were compared as well as maximum von Mises strain values in the bone. In addition, volumes of the bone undergoing specified ranges of stress and strain were provided to help understand the distribution. Furthermore, the maximum equivalent plastic strain was calculated along with the volumes of plastically deformed titanium per implant component.

RESULTS

The highest maximum von Mises stress in each model was concentrated in the premolar abutment for CP2 with a recorded value of 1,091 MPa and in the molar implant for PD2 with a recorded value of 1,085 MPa.

For the cortical bone, CP2 exhibited a lower maximum von Mises stress but a similar maximum von Mises strain (Fig. 3). Regardless of the model, the highest von Mises stresses and strains were mainly located around necks of the implants as shown in Fig. 4. For the cancellous bone, the maximum von Mises stress and strain in PD2 were higher in value (Fig. 3) and located at the apex of the premolar implant unlike in CP2 as shown in Fig. 4. Volume calculation of the bone undergoing specified ranges of stress and strain revealed that CP2 presented lower volumes of cortical and cancellous bone undergoing the high stress and strain ranges as shown in Table 3 and Table 4.

CP2 implant components exhibited overall slightly higher maximum von Mises stresses and higher maximum equivalent plastic strains. CP2 premolar abutment recorded a noticeably high value of maximum equivalent plastic strain (Fig. 5). The locations of the maximum von Mises stresses and maximum equivalent plastic strains were at the implant-abutment interfaces and in the necks of the abutment-screws. Locations of the maximum equivalent plastic strains are shown in Fig. 6. The volumes of the plastically deformed material per implant component have shown that CP2 has presented a noticeably higher deformation in the abutments as shown in Fig. 7.

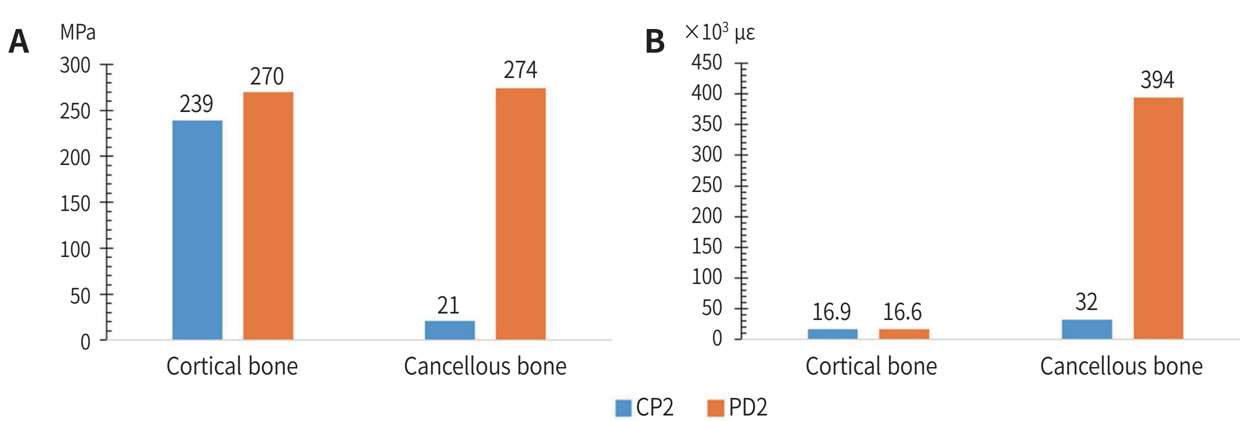

Fig. 3. Maximum von Mises stress and maximum von Mises strain in cortical and cancellous bone in two models. A: Maximum von Mises stress (MPa). B: Maximum von Mises strain (MPa).

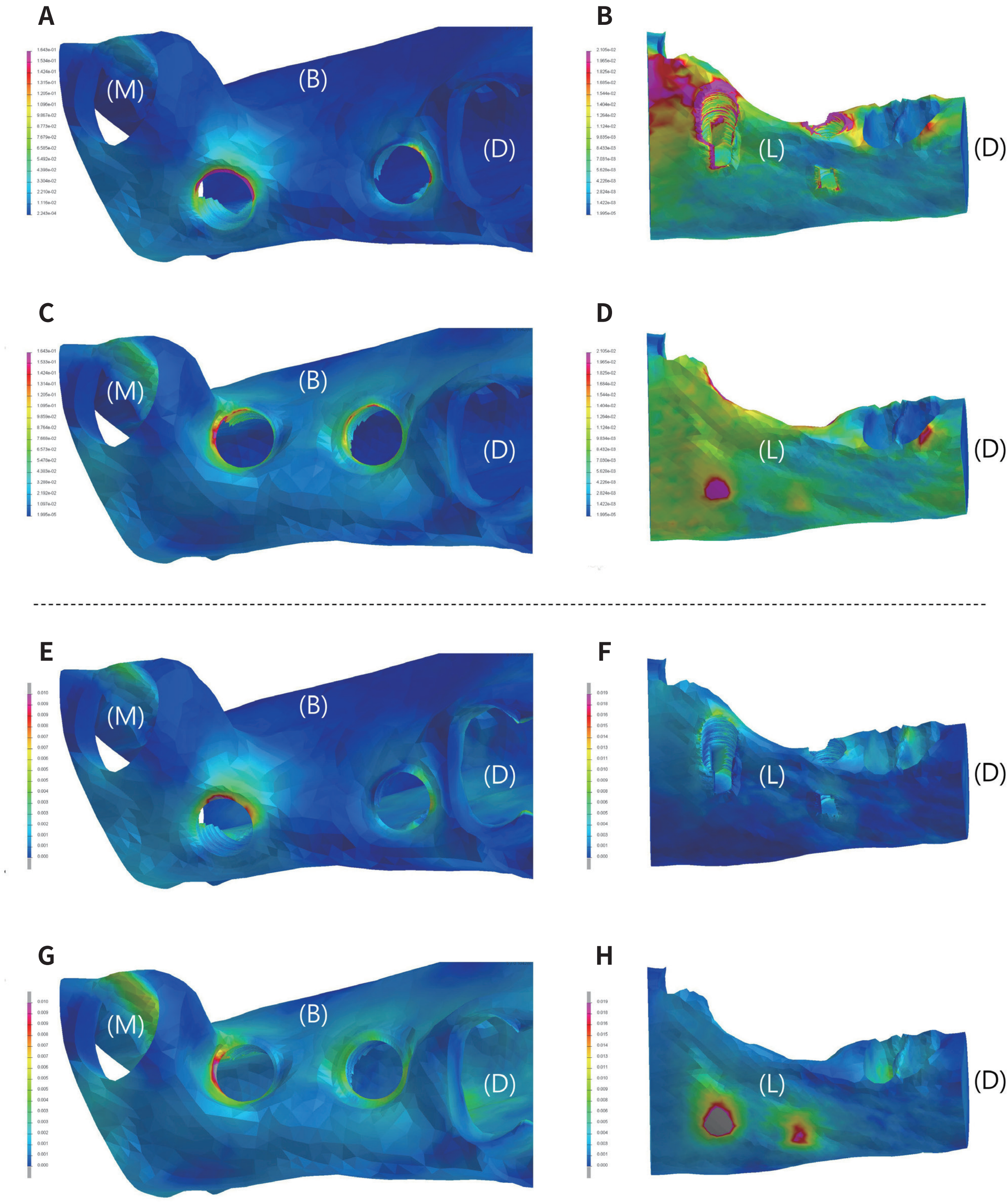

Fig. 4. Locations of maximum von Mises stress and strain in cortical and cancellous bone in two models. Locations of maximum von Mises stress (A - D); A: Model CP2 cortical bone, B: Model CP2 cancellous bone, C: Model PD2 cortical bone, D: Model PD2 cancellous bone. Locations of maximum von Mises strain (E-H); E: Model CP2 cortical bone. F: Model CP2 cancellous bone. G: Model PD2 cortical bone. H: Model PD2 cancellous bone. (B): buccal, (L): lingual, (M): mesial, (D): distal.

Table 3. Volume of bone (%) undergoing specified stress range (MPa)

Bone	Model	275 - 220	220 - 165	165 - 110	110 - 55	55 - 0
Cortical (%)	CP2	0.00006	0.0007	0.0025	0.3218	99.96
	PD2	0.00012	0.0007	0.0070	0.1570	99.84
Cancellous (%)	CP2	0	0	0	0	100
	PD2	0.00004	0.000004	0.00009	0.001	99.97

Table 4. Volume of bone (%) undergoing specified strain range (με)

Model	Strain (×10³ με) in Cortical Bone		Strain (×10³ με) in Cancellous Bone		
	17 - 8	8 - 0	394 - 32	32 - 16	16 - 0
CP2	0.0036	99.9964	0	0.0002	99.9998
PD2	0.0058	99.9942	0.0559	0.6259	99.3182

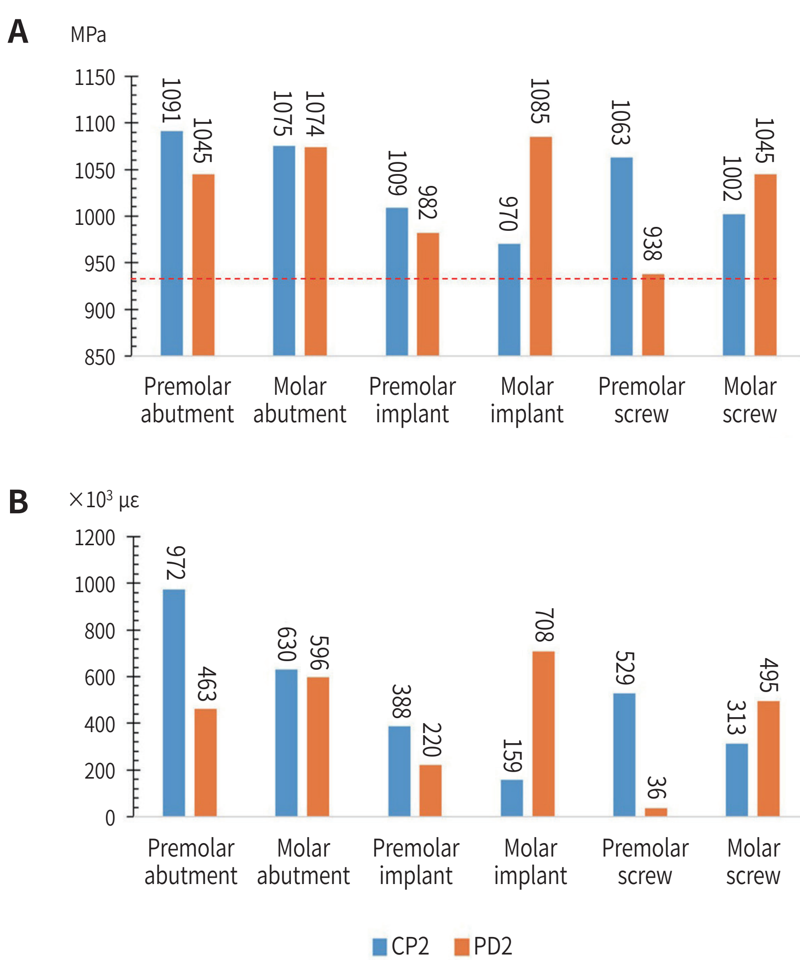

Fig. 5. Maximum von Mises stress and maximum equivalent plastic strain in implants components of two models. A: Maximum von Mises stress (MPa), B: Maximum equivalent plastic strain (×10³ με). The dashed red line refers to the yield stress at 932 MPa.

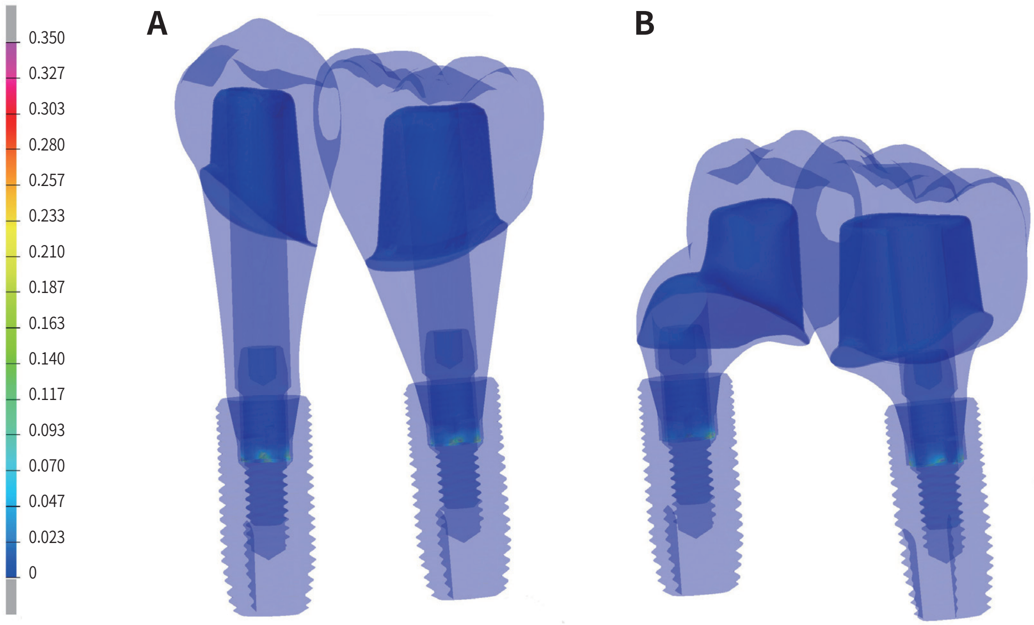

Fig. 6. Locations of maximum equivalent plastic strain in implants components of two models. A: Prosthesis of Model PD2. B: Prosthesis of Model CP2. Colors represent the occurring equivalent plastic strain in the components.

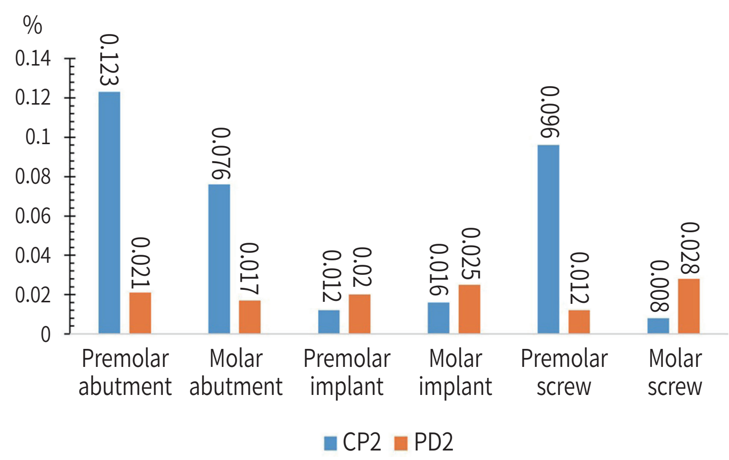

Fig. 7. Volume of plastically deformed material (%) per implant component.

DISCUSSION

The results of the highest maximum von Mises stress in each model showed that Model CP2 created higher maximum von Mises stress. The highest stress in CP2 was located at the abutment of the premolar implant, which had the longest buccal extension among the abutments in both models. Regarding the locations of peak von Mises stress and peak von Mises strain in the cortical bone, the results revealed that the highest von Mises stresses and strains were mainly concentrated around the neck of the implants, in correspondence with previous FEA studies.[31-33] For cancellous bone, the locations of the maximum von Mises stress and strain in Model CP2 were also at the neck of the implant. However, for Model PD2, they were at the apex of the premolar implant. As the cancellous bone covering the implant apex was thin, the distribution

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of the stress and strain from the implant apex was traced in the corresponding site in the cortical bone. The stress was 37 MPa and the strain was 2.3×10^3 $\mu\varepsilon$, which are relatively low values. Thus, it may be judged that the cancellous bone at this site was well supported with the cortical bone.

With respect to maximum von Mises stress values in bone, cantilevered prosthesis has been reported to exhibit higher peak stress in the bone when compared to noncantilevered prosthesis[3,34] and so do high crown-to-implant ratio prostheses when compared to lower crown-to-implant ratio prostheses.[35,36] In the present study, Model CP2 with the cantilevered prosthesis showed a lower peak stress in cortical bone compared to Model PD2, which had a shorter cantilever and a higher crown-to-implant ratio. That result is in accordance with a finite element study,[34] which studied a distal cantilever. In fact, the lengths of the cantilevers and the differences in crown-to-implant ratios of the models would significantly influence on the resulted stress values. Therefore, crown-to-implant ratios and buccal cantilever lengths for the models in the present study were measured and provided in Table 1. In the present study, CP2 exhibited a lower peak stress in the bone compared to PD2 but the results of von Mises strain in cortical bone have shown similar peak strain values. The non-proportional stress and strain relation in the bone might be caused by the assigned elastic modulus that was variable depending on direction. Volume calculation (Table 3 and Table 4), however, clarified that CP2 is presenting less volumes per specific stress and strain ranges.

Regarding implant components, maximum von Mises stress values were overall slightly higher in CP2, in consistence with what Zhong *et al*. reported for distal cantilever[37] and Park *et al*. reported for lingual cantilever.[38] However, the differences were not enough to conclude that CP2 exhibits noticeably higher stresses, which could be due to the higher crown-to-implant ratios in PD2. Therefore, analyzing the equivalent plastic strain has shown an importance. When the stress in the components has slightly surpassed the yield stress, a plastic strain has occurred. The little differences in stresses above the yield stress, which was 932 MPa, could lead to noticeably different plastic strain values as the stress-strain curve was bilinear. Therefore, the small differences in the peak stress values of implant components were amplified, revealing pronounced differences in peak plastic strain values. The maximum equivalent plastic strain values in CP2 were higher overall (Fig. 5). Furthermore, volume calculation of the plastically deformed titanium (Fig. 7) confirms the peak plastic strain results. Since the plastic strain refers to a permanent deformation occurring in the metal, the buccally-cantilevered prosthesis seems to be more prone to mechanical failure in accordance with clinical studies.[4,11,13] The deformed titanium volumes seem to be practically too small, but as cyclic fatigue was not analyzed, those volumes should remain theoretical. Since the plastic strain locations were at the implant-abutment interface right at the hex (Fig. 6), the simplest theoretical consequence might be a slight deformation in the hexes over time, which is known as a wear. A wear could also occur due to the micromovement that causes friction at the titanium-titanium interface. The micromovement in the parts was reported to increase as the load increased on a present cantilever.[39] Hence, *in-vitro* studies[40,41] have reported a wear in the material at the implant-abutment interface after undergoing a cyclic loading. Regarding the plastic deformation that occurred in the prosthetic screws, in the real situation, the prosthetic screws may undergo a plastic deformation causing screw loosening[6,8,11-13] or even screw fracture.[12] However, in this study, the contact condition for the screw threads was not ideal. The surfaces that were thought to be critical for the simulation were treated with contact condition to simplify the analysis. Ideally, all surfaces including screw thread have to be given a contact condition. The tied implant-screw threads might have influenced the results. This was a limitation for this study and a room for further research in this area.

Beside the mechanical complications that each prosthetic design has exhibited for this particular presentation, other possible clinical complications may occur. Lingualized implants in CP2 may cause tongue discomfort. In addition, the prosthetic design of CP2 could be hard to maintain and may cause food accumulation under the cantilever when gingival recession occurs. The interabutment space in PD2 could form a food trap, which is also hard to maintain. However, further clinical evidence is needed with respect to plaque control and discomfort levels.

CONCLUSION

Compared to bone quantity-based implant placement that creates a buccally cantilevered prosthesis, prosthetic-driven implant placement might biomechanically be more advantageous, despite the fact that a prosthetic-driven implant placement may create a higher crown-to-implant ratio.

REFERENCES

1. The Glossary of Prosthodontic Terms: Ninth Edition. J Prosthet Dent 2017;117:e1-105.
2. Hälg GA, Schmid J, Hämmerle CH. Bone level changes at implants supporting crowns or fixed partial dentures with or without cantilevers. Clin Oral Implants Res 2008;19:983-90.
3. Stegaroiu R, Sato T, Kusakari H, Miyakawa O. Influence of restoration type on stress distribution in bone around implants: a three-dimensional finite element analysis. Int J Oral Maxillofac Implants 1998;13:82-90.
4. Kim P, Ivanovski S, Latcham N, Mattheos N. The impact of cantilevers on biological and technical success outcomes of implant-supported fixed partial dentures. A retrospective cohort study. Clin Oral Implants Res 2014;25:175-84.
5. Romeo E, Lops D, Margutti E, Ghisolfi M, Chiapasco M, Vogel G. Implant-supported fixed cantilever prostheses in partially edentulous arches. A seven-year prospective study. Clin Oral Implants Res 2003;14:303-11.
6. Palmer RM, Howe LC, Palmer PJ, Wilson R. A prospective clinical trial of single Astra Tech 4.0 or 5.0 diameter implants used to support two-unit cantilever bridges: results after 3 years. Clin Oral Implants Res 2012;23:35-40.
7. Wennström J, Zurdo J, Karlsson S, Ekestubbe A, Gröndahl K, Lindhe J. Bone level change at implant-supported fixed partial dentures with and without cantilever extension after 5 years in function. J Clin Periodontol 2004;31:1077-83.
8. Maló P, de Araujo Nobre M, Lopes A. The prognosis of partial implant-supported fixed dental prostheses with cantilevers. A 5-year retrospective cohort study. Eur J Oral Implantol 2013;6:51-9.
9. Romeo E, Tomasi C, Finini I, Casentini P, Lops D. Implant-supported fixed cantilever prosthesis in partially edentulous jaws: a cohort prospective study. Clin Oral Implants Res 2009;20:1278-85.
10. Rosén A, Gynther G. Implant treatment without bone grafting in edentulous severely resorbed maxillas: a long-term follow-up study. J Oral Maxillofac Surg 2007;65:1010-6.
11. Zurdo J, Romão C, Wennström JL. Survival and complication rates of implant-supported fixed partial dentures with cantilevers: a systematic review. Clin Oral Implants Res 2009;20:59-66.
12. Romeo E, Storelli S. Systematic review of the survival rate and the biological, technical, and aesthetic complications of fixed dental prostheses with cantilevers on implants reported in longitudinal studies with a mean of 5 years follow-up. Clin Oral Implants Res 2012;23:39-49.
13. Brosky ME, Korioth TW, Hodges J. The anterior cantilever in the implant-supported screw-retained mandibular prosthesis. J Prosthet Dent 2003;89:244-9.
14. Schropp L, Wenzel A, Kostopoulos L, Karring T. Bone healing and soft tissue contour changes following single-tooth extraction: a clinical and radiographic 12-month prospective study. Int J Periodontics Restorative Dent 2003;23:313-23.
15. Tan WL, Wong TL, Wong MC, Lang NP. A systematic review of post-extractional alveolar hard and soft tissue dimensional changes in humans. Clin Oral Implants Res 2012;23:1-21.
16. Kim Y, Oh TJ, Misch CE, Wang HL. Occlusal considerations in implant therapy: clinical guidelines with biomechanical rationale. Clin Oral Implants Res 2005;16:26-35.
17. DeTolla DH, Andreana S, Patra A, Buhite R, Comella B. Role of the finite element model in dental implants. J Oral Implantol 2000;26:77-81.
18. Trivedi S. Finite element analysis: A boon to dentistry. J Oral Biol Craniofac Res 2014;4:200-3.
19. Brunski JB. Biomechanical factors affecting the bone-dental implant interface. Clin Mater 1992;10:153-201.
20. Robling AG, Castillo AB, Turner CH. Biomechanical and molecular regulation of bone remodeling. Annu

Rev Biomed Eng 2006;8:455-98.
21. Teixeira E, Sato Y, Akagawa Y, Shindoi N. A comparative evaluation of mandibular finite element models with different lengths and elements for implant biomechanics. J Oral Rehabil 1998;25:299-303.
22. Nejatidanesh F, Shakibamehr AH, Savabi O. Comparison of marginal and internal adaptation of CAD/CAM and conventional cement retained implant-supported single crowns. Implant Dent 2016;25:103-8.
23. Coolidge ED. The thickness of the human periodontal membrane. J Am Dent Assoc 1937;24:1260-70.
24. Mandel U, Dalgaard P, Viidik A. A biomechanical study of the human periodontal ligament. J Biomech 1986;19:637-45.
25. Chen XY, Zhang CY, Nie EM, Zhang MC. Treatment planning of implants when 3 mandibular posterior teeth are missing: a 3-dimensional finite element analysis. Implant Dent 2012;21:340-3.
26. Huang HL, Huang JS, Ko CC, Hsu JT, Chang CH, Chen MY. Effects of splinted prosthesis supported a wide implant or two implants: a three-dimensional finite element analysis. Clin Oral Implants Res 2005;16:466-72.
27. Saidin S, Abdul Kadir MR, Sulaiman E, Abu Kasim NH. Effects of different implant-abutment connections on micromotion and stress distribution: prediction of microgap formation. J Dent 2012;40:467-74.
28. Wu T, Liao W, Dai N, Tang C. Design of a custom angled abutment for dental implants using computer-aided design and nonlinear finite element analysis. J Biomech 2010;43:1941-6.
29. Gibbs CH, Mahan PE, Lundeen HC, Brehnan K, Walsh EK, Holbrook WB. Occlusal forces during chewing and swallowing as measured by sound transmission. J Prosthet Dent 1981;46:443-9.
30. Martin WC, Woody RD, Miller BH, Miller AW. Implant abutment screw rotations and preloads for four different screw materials and surfaces. J Prosthet Dent 2001;86:24-32.
31. Bölükbaşı N, Yeniyol S. Number and localization of the implants for the fixed prosthetic reconstructions: on the strain in the anterior maxillary region. Med Eng Phys 2015;37:431-45.
32. Gonda T, Yasuda D, Ikebe K, Maeda Y. Biomechanical factors associated with mandibular cantilevers: analysis with three-dimensional finite element models. Int J Oral Maxillofac Implants 2014;29:e275-82.
33. Sotto-Maior BS, Senna PM, da Silva WJ, Rocha EP, Del Bel Cury AA. Influence of crown-to-implant ratio, retention system, restorative material, and occlusal loading on stress concentrations in single short implants. Int J Oral Maxillofac Implants 2012;27:e13-8.
34. Cenkoglu BG, Balcioglu NB, Ozdemir T, Mijiritsky E. The effect of the length and distribution of implants for fixed prosthetic reconstructions in the atrophic posterior maxilla: a finite element analysis. Materials (Basel) 2019;12:2556.
35. Kitamura E, Stegaroiu R, Nomura S, Miyakawa O. Influence of marginal bone resorption on stress around an implant-a three-dimensional finite element analysis. J Oral Rehabil 2005;32:279-86.
36. Sayyedi A, Rashidpour M, Fayyaz A, Ahmadian N, Dehghan M, Faghani F, Fasihg P. Comparison of stress distribution in alveolar bone with different implant diameters and vertical cantilever length via the finite element method. J Long Term Eff Med Implants 2019;29:37-43.
37. Zhong J, Guazzato M, Chen J, Zhang Z, Sun G, Huo X, Liu X, Ahmad R, Li Q. Effect of different implant configurations on biomechanical behavior of full-arch implant-supported mandibular monolithic zirconia fixed prostheses. J Mech Behav Biomed 2020;102:103490.
38. Park JM, Kim HJ, Park EJ, Kim MR, Kim SJ. Three dimensional finite element analysis of the stress distribution around the mandibular posterior implant during non-working movement according to the amount of cantilever. J Adv Prosthodont 2014;6:361-71.
39. Cassel B, Dan L, Dan K. Deflections of an implant-supported cantilever beam subjected to vertically directed loads. In vitro measurements in three dimensions using an optoelectronic method. II Analysis of methodological errors. Clin Oral Implants Res 2011;22:645-50.
40. Stimmelmayr M, Edelhoff D, Güth JF, Erdelt K, Happe A, Beuer F. Wear at the titanium-titanium and the titanium-zirconia implant-abutment interface: a comparative in vitro study. Dent Mater 2012;28:1215-20.
41. Almeida PJ, Silva CL, Alves JL, Silva FS, Martins RC, Fernandes JS. Comparative analysis of the wear of titanium/titanium and titanium/zirconia interfaces in implant/abutment assemblies after thermocycling

and mechanical loading. Rev Port Estomatol Cir Maxilofac 2016;57:207-14.
42. Schwartz-Dabney C, Dechow P. Edentulation alters material properties of cortical bone in the human mandible. J Dent Res 2002;81:613-7.
43. O'Mahony AM, Williams JL, Katz JO, Spencer P. Anisotropic elastic properties of cancellous bone from a human edentulous mandible. Clin Oral Implants Res 2000;11:415-21.
44. O'Mahony AM, Williams JL, Spencer P. Anisotropic elasticity of cortical and cancellous bone in the posterior mandible increases peri-implant stress and strain under oblique loading. Clin Oral Implants Res 2001;12:648-57.
45. Dong L, Deshpande V, Wadley H. Mechanical response of Ti-6Al-4V octet-truss lattice structures. Int J Solids Struct 2015;60-61:107-24.
46. Geng JP, Tan KB, Liu GR. Application of finite element analysis in implant dentistry: a review of the literature. J Prosthet Dent 2001;85:585-98.
47. Xu HH, Smith DT, Jahanmir S, Romberg E, Kelly JR, Thompson VP, Rekow ED. Indentation damage and mechanical properties of human enamel and dentin. J Dent Res 1998;77:472-80.
48. Wataha JC. Alloys for prosthodontic restorations. J Prosthet Dent 2002;87:351-63.
49. Saskalauskaite E, Tam LE, McComb D. Flexural strength, elastic modulus, and pH profile of self-etch resin luting cements. J Prosthodont 2008;17:262-8.
50. Lanza A, Aversa R, Rengo S, Apicella D, Apicella A. 3D FEA of cemented steel, glass and carbon posts in a maxillary incisor. Dent Mater 2005;21:709-15.