Tilted or Parallel Implant Placement in the Completely Edentulous Mandible? A Three-Dimensional Finite Element Analysis

Roshanak Baghai Naini, DDS, MS[1]/Saied Nokar, DDS, MS[1]/
Hasti Borghei, DDS[2]/Marzieh Alikhasi, DDS, MS[1]

Purpose: *According to the so-called All-on-Four protocol, four dental implants are placed in the interforaminal region of the edentulous mandible to support full-arch fixed prostheses. In this design, the posterior implants are tilted distally to a maximum of 45 degrees. The purpose of this finite element study was to evaluate the stress concentration in peri-implant bone during two loading conditions and to compare this design with another design in which the four implants are placed parallel to each other and perpendicular to the occlusal plane.* ***Materials and Methods:*** *Three-dimensional finite element models consisted of mandibular bone, four dental implants inserted in two different configurations—with the distal implants tilted (model A) or four parallel implants (model S)—and hybrid superstructures. Two loading conditions (178 N/central incisors or 300 N/left first molar) were considered, and von Mises stress values were determined.* ***Results:*** *During anterior loading, higher stress concentrations were detected in the peri-implant bone of all four implants in model A. During posterior loading, lower stress concentrations were observed around the anterior implants of model A; however, the tilted posterior implants were subjected to higher stresses in every condition.* ***Conclusions:*** *Application of either of these designs was successful in reducing peri-implant stress in one loading condition. However, neither design demonstrated better performance in both loading conditions; therefore, within the limitations of this study, neither design demonstrated clearly superior performance.* INT J ORAL MAXILLOFAC IMPLANTS 2011;26:776–781

Key words: *All-on-Four, edentulous mandible, finite element analysis, tilted implant*

The proximity of dental implants to anatomic structures such as the maxillary sinus or the inferior alveolar nerve often prevents placement of long (> 10 mm) implants in the posterior areas of the resorbed maxilla and mandible.[1] According to the original Brånemark protocol, five to six implants should be placed in the interforaminal region of the mandible to support a fixed dental prosthesis.[2–5]

[1]Assistant Professor, Department of Prosthodontics and Dental Research Center, Department of Prosthodontics and Dental Research Center, Faculty of Dentistry, Tehran University of Medical Sciences, Tehran, Iran.
[2]Private Practice, Tehran, Iran.

Correspondence to: Dr Roshanak Baghai Naini, Department of Prosthodontics, Faculty of Dentistry, Tehran University of Medical Sciences, Ghods Ave, Enghelab St, Tehran, Iran. Fax: +9821-88516041. Email: robaghai@yahoo.com

Some researchers have suggested that tilted implants be placed in the interforaminal region to obtain adequate primary stability, optimize the anteroposterior spread of implants, and reduce the length of cantilevers.[6] This led to the development of the "All-on-Four" protocol, which uses four dental implants in the interforaminal region, with the posterior implants being tilted distally to avoid encroachment on the inferior alveolar neurovascular bundle.[6] In this manner, the cantilever length is reduced and the anteroposterior spread of implants is more favorable. Bone resorption and higher stress concentrations have been reported in the cortical bone around excessively inclined implants[7–10]; conversely, other studies have reported lower stress concentrations at the crestal region of tilted implants.[11] Clinical studies have demonstrated similar survival rates for straight and tilted implants.[12–15]

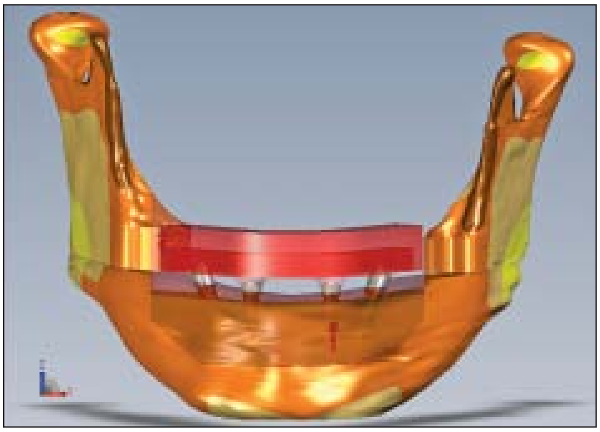

Fig 1 Three-dimensional FE model of human mandible incorporating four dental implants supporting a one-piece superstructure. The posterior implants are tilted distally in the so-called All-on-Four configuration.

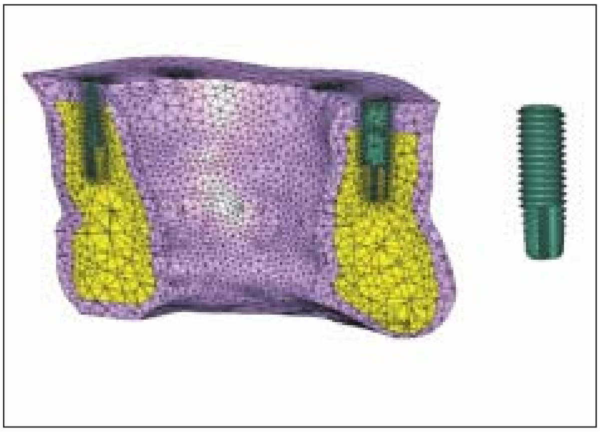

Fig 2 Views of the meshed models. *(Left)* Peri-implant bone; *(right)* Nobel Biocare implant.

The purpose of the present study was to employ three-dimensional (3D) finite element analysis (FEA) to analyze the stress and strain distribution in peri-implant bone of the edentulous mandible when four implants are placed either according to the All-on-Four scheme or parallel to each other to support a fixed mandibular prosthesis.

Table 1 Mechanical Properties Assigned to the Framework and Implants

	Modulus of elasticity (Pa)	Poisson ratio
Ti (implant)[1]	1.17×10^{11}	0.33
Ti (framework)[16]	1.10×10^{11}	0.3
Acrylic resin	2.7×10^{3}	0.35

MATERIALS AND METHODS

A 3D model of the human mandible was simulated from computed tomographic scan data of a cadaver. The images were acquired at small slice intervals (0.5-mm increments). The slices were assembled and a 3D model was constructed by means of modeling software (Mimics, Materialise; SolidWorks 2007, SolidWorks).

Cortical bone of various thicknesses (1 to 1.5 mm) was defined around the cancellous core. A 3D model of a dental implant (Brånemark MKIII Groovy, Nobel Biocare) was created from measurement data provided by a coordinate measuring machine (Microscribe MX System, Immersion). Straight abutments (multiunit abutment, Nobel Biocare) and angulated abutments (30-degree multiunit abutment, Nobel Biocare) were also measured by a coordinate measuring machine) and simulated in SolidWorks 2007.

Two models were created. In each model, four dental implants with a length of 13.5 mm and diameter of 4 mm were placed in the interforaminal region. In the All-on-Four model (model A), the posterior implants were inserted just anterior to the foramina and were tilted distally by about 30 degrees relative to the occlusal plane (Fig 1). In the other model (model S), the posterior implants were parallel to the anterior implants and were inserted in the first premolar region. In both models, the anterior implants were placed in the lateral incisor positions. A superstructure was simulated to include mesiodistal dimensions of incisors, canines, premolars, and first molars. A hybrid superstructure with a titanium frame and an acrylic resin covering was modeled; it was 10 mm high. The cantilevers were 10.5 mm and 17 mm long in models A and S, respectively.

The constructed model was exported to into FEA software (ABAQUS 6.7/1) for analysis. Models were meshed by tetrahedral elements. In both models, mesh sensitivity analysis was performed. The final mesh in model A consisted of approximately 479,565 elements and 885,089 nodes and model S was composed of 479,071 elements and 872,329 nodes (Fig 2).

Prior to the analysis, boundary conditions were determined to define the relationships between elements. The mechanical properties assigned to structural elements of the models are listed in Table 1.[16] In most previous FEA studies the mechanical properties of cortical and cancellous bones were assumed to be isotropic.[17,18] However, to improve the accuracy of calculations, the anisotropic properties of these bones should be taken into consideration.[19,20] In the present study, cortical and cancellous bone was assumed to be transversely isotropic (Table 2).[19]

Table 2 Anisotropic Material Properties of Bone Assigned to the Model[19]

Property	Cancellous bone	Cortical bone
E_X (MPa)	1,148	12,600
E_Y (MPa)	210	12,600
E_Z (MPa)	1,148	19,400
ν_{yx}	0.010	0.300
ν_{zy}	0.055	0.390
ν_{zx}	0.322	0.390
ν_{xy}	0.055	0.300
ν_{yz}	0.010	0.253
ν_{xz}	0.322	0.253

E = modulus of elasticity; ν = Poisson ratio.

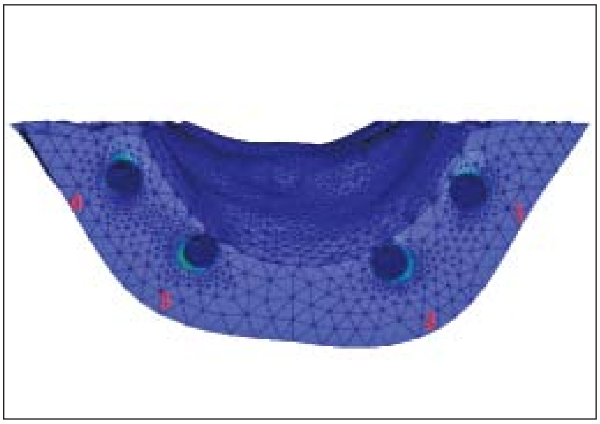

Fig 3 Stress distribution in the peri-implant bone of model A during anterior loading. The color range from blue to red indicates stress or strain concentration from low to high.

Table 3 Maximum Stress Values (MPa) in Peri-implant Bone During Anterior and Posterior Loading

	Implant no.			
Location of load	1	2	3	4
Anterior				
Model A	16.3	38.9	26.9	19.4
Model S	12.06	14.04	18.62	12.95
Posterior				
Model A	77.3	10.11	23.3	17.27
Model S	70.9	16.32	40.0	9.19

Each model was subjected to two loading conditions. First, a 300-N load was applied to the left first molar region (posterior loading). To decrease false stress concentrations in the area of load application, the load was divided into three 100-N force vectors and applied over an area with a diameter of 4 mm. For the second loading condition, a total load of 178 N was applied at the midline in the form of two force vectors of 89 N each (anterior loading).[10,21,22]

To simplify the analysis, data of the mandibular rami were not incorporated into the model, and the section was removed at a 45-degree angle at the gonial angle. The cross section was assumed as the restraint and the model was considered to be fixed in this area, so that any movement or rotation in this area was impossible. The implants were assumed to be 100% osseointegrated and node-to-node connection was considered at the bone-implant interface.

The stress analysis was performed using von Mises stress values, which summarized the effect of all six stress components with a unique value.

RESULTS

Validation of the models was performed by measuring the amount of displacement in different parts of the models. For convenience, each implant was given a number, beginning with 1 for the most distal implant on the left side (Fig 3).

During anterior loading in model A, maximum stress concentrations were detected in the distofacial cortical bone of the anterior implants (Fig 3). This finding was also observed in model S, in which the highest stress concentrations were seen in the distofacial cortical bone around the anterior implants. However, the values for maximum stress concentration on model A were considerably higher than those in model S. The maximum von Mises stress values detected in all implant sites during anterior loading are summarized in Table 3.

During posterior loading in model A, maximum stress concentrations were observed in the distobuccal cortical bone of the posterior implant on the left side (Fig 4). A dramatic increase in stress concentration was detected in the peri-implant bone of implant no. 3 (Table 3). Relatively similar findings with different stress values were detected in model S during posterior loading (Fig 4). Stress concentrations were comparatively higher around the tilted implants. However, for anterior implants, model S displayed higher stresses.

Considering strain distribution during anterior loading, maximum strain values were detected in the cancellous bone of the apical regions of the implants. In model A during anterior loading, the highest strain value (2,700 $\mu\varepsilon$) was found in the apical region of implant no. 1 (Fig 5); however, in model S, the highest strain (2,117 $\mu\varepsilon$) was detected around implant no. 3 (Fig 6).

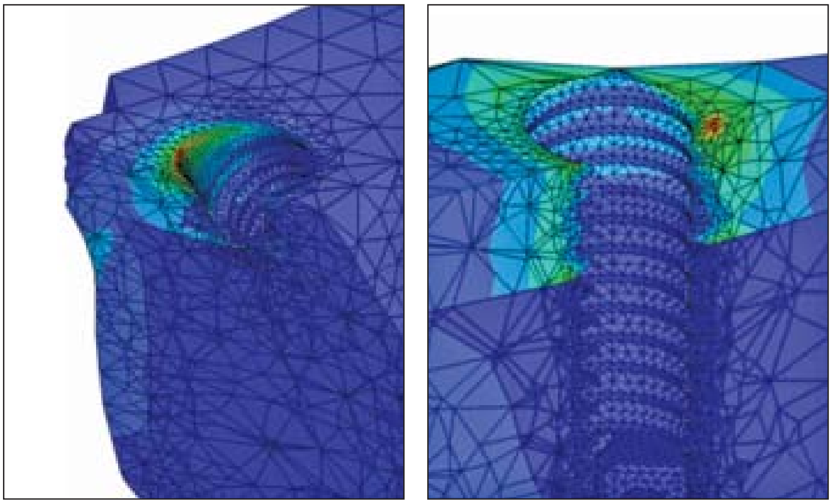

Fig 4 Von Mises stress distribution in a buccolingual cross section of peri-implant (no. 1) bone during posterior loading. *(Left)* Model A; *(right)* model S. The color range from blue to red indicates stress or strain concentration from low to high.

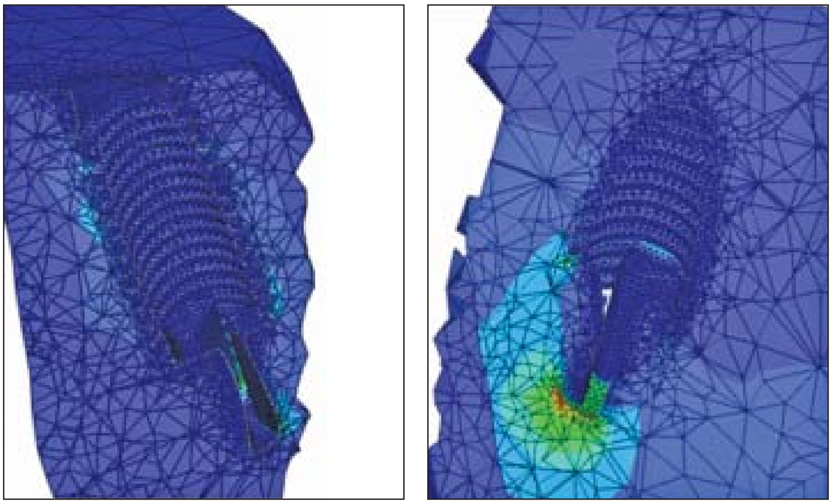

Fig 5 Strain distribution in a buccolingual cross section of peri-implant bone (at implant no. 1) in model A. *(Left)* Anterior loading; *(right)* posterior loading. The color range from blue to red indicates stress or strain concentration from low to high.

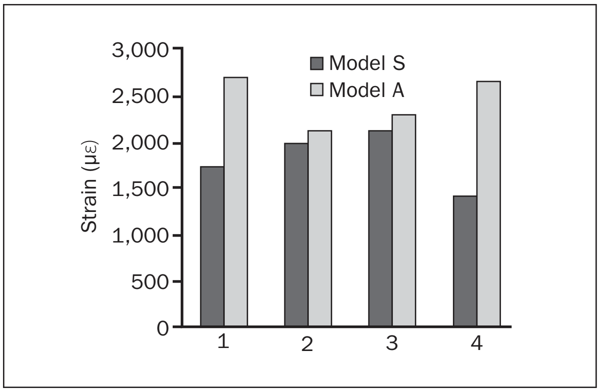

Fig 6 Strain values in models A and S during anterior loading.

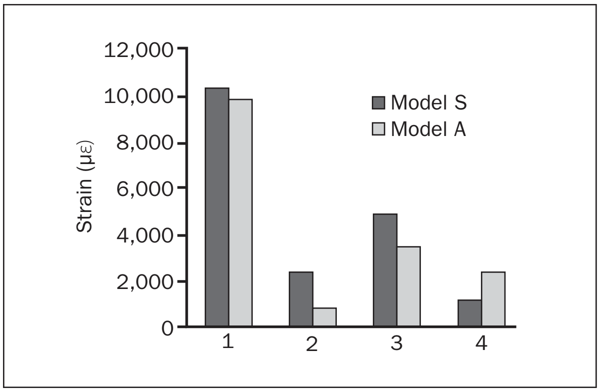

Fig 7 Strain values in models A and S during posterior loading.

Concerning strain distribution during posterior loading, the highest strain concentrations in both models were seen in the apical region of implant no. 1 (9,850 and 10,300 με in models A and S, respectively) (Fig 7).

DISCUSSION

During anterior loading, maximum stress concentrations were detected at the distofacial aspects of the anterior implants and the distolingual aspects of the posterior implants. These observations could be a result of mandibular flexure, which causes contraction of the alveolar process in the anterior mandible and expansion in the posterior mandible. Since the rigid superstructure did not follow the deformation of the mandible, stress concentrations would be detected at the aforementioned sites. Moreover, the values for maximum stress concentration in model A were considerably higher than those seen for model S. These findings could be explained by considering the angulations of the posterior implants in model A and the formation of bending moments at these sites. Therefore, not only would the stress concentration in posterior implants be higher, but anterior implants would also be subjected to higher amounts of stress. Increases in stress concentration in the peri-implant bone at angulated implants have been observed in other photoelastic and finite element studies.[7–10]

Concerning posterior loading, higher stress concentrations around posterior implants in model A could be explained by considering their angulations and proximity to the loading area. This finding is in agreement with other studies.[23,24] There was a remarkable increase in stress values around implant no. 3 in both models. This might be a result of the fulcrum action of implants no. 2 and 4, which created a fulcrum line and magnified the stress on implant no. 3 because of the loading on implant no. 1. Relatively lower stress values in the peri-implant bone of the anterior implants in model A, in comparison to model S, were a result of the shorter cantilever in this model.

The increased stress values seen around angulated implants in this study were in disagreement with the findings of Zampelis et al[1] and Satoh et al.[25] However, the modeling and loading conditions in those studies were different. Decreased stress values around anterior implants during posterior loading in model A in comparison to model S were also observed in a previous study.[26] As mentioned in that study, the shortened length of the cantilever is responsible for lower stress values around anterior implants. However, in contrast, in the present study, decreasing the length of cantilever by tilting the posterior implant not only did not decrease the stress values around the tilted implants—it increased them by 9%.

Maximum strain values were detected in cancellous bone as a result of lower elastic modulus relative to cortical bone. During anterior loading, the maximum strain values in model S were detected around the anterior implants as a result of their proximity to the loading area; however, in model A, the maximum strain values were observed in the apical regions of the posterior tilted implants, and these values were comparatively higher.

It seems that, during anterior loading, tilting the posterior implants not only increases the stress and strain on the tilted implants, but it also decreases their load-bearing capacity and, as a consequence, stress and strain are increased on the anterior implants. However, during posterior loading on the cantilever area, decreasing the length of the cantilever might be beneficial for lowering the stress and strain values in anterior implants, even though the angled implants will be subjected to higher stresses.

Osseointegration was assumed to be 100%, and this was one of the limitations of the present study; higher stress values would be created by lower degrees of osseointegration. The application of vertical forces only, without inclusion of horizontal and oblique vectors of occlusal forces, was another limitation of the present study.

CONCLUSIONS

Based on this finite element analysis of a prosthesis supported by four implants, it appears that either design—one with the posterior implants tilted distally or one with parallel implants—exhibits stress concentration in a specific pattern. A shortened cantilever and the subsequent decrease in stress concentration around the anterior implants during posterior loading were advantages of the tilted posterior implant design; however, these advantages were created at the expense of tilting posterior implants and imposing higher stresses on them in every condition, which was accompanied by the formation of higher stresses during anterior loading around all implants.

ACKNOWLEDGMENT

This study was supported by a grant from the vice chancellor of Research and Dental Research Center of Tehran University of Medical Sciences.

REFERENCES

1. Zampelis A, Rangert B, Heijl L. Tilting of splinted implants for improved prosthodontic support: A two-dimensional finite element analysis. J Prosthet Dent 2007;97:S35–S43.
2. Misch CE. Dental Implant Prosthetics. St Louis: Mosby, 2005:254.
3. Vasconcellos DK, Bouino MA, Saad PA, Faloppa F. A new device in immediately loaded implant treatment in edentulous mandible. Int J Oral Maxillofac Implants 2006;21:615–622.
4. Eliasson A, Palmqvist S, Svenson B, Sondell K. Five year results with fixed complete-arch mandibular prostheses supported by 4 implants. Int J Oral Maxillofac Implants 2000;15:505–510.

5. Hatano N, Yamaguchi M, Suwa T, Watanabe K. A modified method of immediate loading using Brånemark implants in edentulous mandibles. Odontology 2003;91:37–42.
6. Malo P, Rangert B, Nobre M. All-on-four immediate-function concept with Brånemark system implants for completely edentulous mandibles: A retrospective clinical study. Clin Implant Dent Relat Res 2003;5(suppl 1):2–9.
7. Federick DR, Caputo AA. Effects of overdenture retention designs and implant orientation on load transfer characteristics. J Prosthet Dent 1996;76:624–632.
8. Watanabe F, Hata Y, Komatsu S, Fukuda H. Finite element analysis of the influence of implant inclination, loading position, and load direction on stress distribution. Odontology 2003;91:31–36.
9. Clelland NL, Gilat A. The effect of abutment angulation on stress transfer for an implant. J Prosthodont 1992;1:24–28.
10. Clelland NL, Lee JK, Bimbenet OC, Brantley WA. A three-dimensional finite element stress analysis of angled abutments for an implant placed in the anterior maxilla. J Prosthodont 1995;2:95–100.
11. Tuncelli B, Poyrazoglu E, Koyluoglu AM, Tezcan S. Comparison of load transfer by angulated, standard and inclined implant abutments. Eur J Prosthodont Restor Dent 1997;5:85–88.
12. Sethi A, Kaus T, Sochor P, Axmann-Krcmar D, Chanavaz M. Evolution of the concept of angulated abutments in implant dentistry: 14-year clinical data. Implant Dent 2002;11:41–51.
13. Balshi TJ, Ekfeldt A, Stenberg T, Vrielinck L. Three-year evaluation of Brånemark implants connected to angulated abutments. Int J Oral Maxillofac Implants 1997;12:53–58.
14. Sethi A, Kaus T, Sochor P. The use of angulated abutments in implant dentistry: Five-year clinical results of an ongoing prospective study. Int J Oral Maxillofac Implants 2000;15: 801–810.
15. Capelli M, Zuffetti F, Fabbro MD, Testori T. Immediate rehabilitation of the completely edentulous jaw with fixed prostheses supported by either upright or tilted implants: A multicenter clinical study. Int J Oral Maxillofac Implants 2007; 22:639–644.
16. Nanati AN, Carniel EL, Pavan PG. Investigation of bone inelastic response in interaction phenomena with dental implants. Dent Mater 2008;24:561–569.
17. Stegaroiu R, Sato T, Kusakari H, Miakawa 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.
18. Menicucci G, Mossolov A, Mozzati M, Lorenzetti M, Preti G. Tooth-implant connection: Some biomechanical aspects based on finite element analyses. Clin Oral Implants Res 2002;13:334–341.
19. 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;12:648–657.
20. Nokar S, Baghai Naini R. The effect of superstructure design on stress distribution in peri-implant bone during mandibular flexure. Int J Oral Maxillofac Implants 2010;25:31–37.
21. Saab XE, Griggs JA, Powers JM, Engelmeier RL. Effect of abutment angulation on the strain on the bone around an implant in the anterior maxilla: A finite element study. J Prosthet Dent 2007;97:85–92.
22. Ferrario VF, Sforza C, Serrao G, Dellavia C, Tarataglia GM. Single tooth bite forces in healthy young adults. J Oral Rehabil 2004;31:18–22.
23. Sertgoz A, Sungur G. FEA of the effect of cantilever and implant length on stress distribution in an implant-supported fixed prosthesis. J Prosthet Dent 1996;76:165–169.
24. Meijer HJA, Starmans FJM, Steen WHA, Bosman F. Loading condition of endosseous implants in an edentulous human mandible: A three-dimensional, finite element study. J Oral Rehabil 1996;23:757–763.
25. Satoh T, Maede Y, Komiyama Y. Biomechanical rationale for intentionally inclined implants in the posterior mandible using 3D finite element analysis. Int J Oral Maxillofac Implants 2005;20:533–539.
26. Bevilacqua M, Tealdo T, Pera F, Menini M, Mossolov A, Drago C. Three-dimensional finite element analysis of load transmission using different implant inclinations and cantilever lengths. Int J Prosthodont 2008;21:539–542.