Comparative analysis of stress patterns between mono-cortical and bi-cortical mini-screws: A three dimensional finite element analysis

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Objective : Evaluation of stress/strain field that develops at the mini-screw and bone interface using different diameter, length and insertion angle of the mini-screw so as to facilitate optimization of mini-screw for optimal anchorage.

Materials and methods : 3D finite element model of maxillary bone (both cortical and cancellous) and mini-screws were generated on a computer to evaluate stress values at bone and mini-screw interface with varying the angle of insertion, length and diameter. Mini-screws having diameter of 1.6 mm and 2 mm were used. The length of miniscrews was fixed at 8 mm, 10 mm and 12 mm. These were inserted at 4 different insertion angles of 45^0, 60^0, 75^0 and 90^0.

Results : Comparison of the maximum von Mises stress in the cortical and cancellous bone showed that stress/strain field that develops at the mini-screw and bone interface decreased with increase in diameter, length and insertion angle of the mini-screw.

Conclusion : Wider bi-cortical mini-screws should be preferred over mono-cortical mini-screws and should be placed as perpendicular to the bone as possible for better and enhanced stability.

Key words: Mini-screw, Finite Element Analysis, Mono-cortical, Bi-cortical

Introduction of absolute anchorage devices such as mini-screws are a boon in clinical orthodontics as the control undesired tooth movement of the anchorage units thereby preventing the anchorage loss. Various studies have revealed that the stability and success of the mini-screws are affected by age [1], sex [2], craniofacial skeletal pattern [3], site and side of application, mini-screw design feature (like diameter, length and shape) [4-7] insertion torque [8], insertion angle [9], quality and quantity of the cortical bone [10,11]thickness and mobility of the soft tissue [12].

Most of the previous studies on mini-screw stability were done to investigate the influence of diameter and length when mini-screws were used mono-cortically [4, 5, 7, 12-14]. Very few studies have been undertaken to investigate the influence of diameter, length and insertion angle using bi-cortical mini-screws. Studies using bi-cortical mini-screw have focused on their anchorage potential alone [15, 16].

Finite element analysis (FEA) is used to study stresses and strain in the field of engineering and also it is practically useful to simulate situations in the maxillofacial region by elucidating stresses caused by various internal and external forces [17]. Therefore the present study was undertaken using FEA to evaluate the stress/strain field that develops at the mini-screw and bone interface using different diameter, length and insertion angle of the mini-screw so as to facilitate optimization of mini-screw design for optimal anchorage.

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MATERIALS AND METHODS

A 3D finite element model of solid bone measuring 10 mm diameter, 11 mm length and 1.5 mm layer of dense cortical bone [18] surrounding a core of cancellous bone was generated on a computer using Pro/Engineer software (Parametric Technology Corporation, Needham, MA, USA) to simplify the complex geometry of posterior maxilla. Cortical and cancellous bones were modelled having different physical properties [19]. The elastic properties of bone model were obtained from the literature [2]. The entire assembly was then exported for analysis with ANSYS Workbench (ANSYS 12.1v, Inc, USA) through a bi-directional understandable translated system called initial graphics exchange specification (IGES).

Mini-screws (T- Bio Tech Co. Ltd, Korea) were scanned by a structured light scanning technique and a solid mini-screw model was reconstructed by a reverse engineering programme (Ideas Siemens, Germany). After incorporating the material properties (Table no. 1) and anatomic specifications of the mini-screws into the software (ANSYS 12.1v ANSYS Inc, USA) the model of mini-screw was generated.

Twenty four solid bone models simulating the posterior maxilla were developed and six mini-screw models were developed having diameter of 1.6 mm, 2 mm and length of 8 mm, 10 mm and 12 mm. Each mini-screw was inserted at 4 different insertion angles of 45^0, 60^0, 75^0 and 90^0. A simulating force equivalent to a retraction force of 300 grams (to simulate the anterior teeth retraction) was loaded horizontally (i.e. mesio-distally) to the head of the mini-screw to analyze the magnitude of stress using ANSYS Workbench (ANSYS 12.1v, Inc, USA) a 3D finite element analysis program. An assessment of the stress on the bone and mini-screw interface elements was performed by using von Mises equivalent stress contour at outer cortical and cancellous bone. Stress values at bone and mini-screw interface with varying the angle of insertion, length and diameter of mini-screw were observed.

Table no. 1: Material Properties of Mini-screw

Mechanical Properties	S.I Units
Tensile strength	1035 MPa
Yield strength	905 Mpa
Yield load	1156 Kg
Elongation	22 %
Overall length	14.2 mm
Mini-screw body length	12 mm
Head size	2.2 mm
External diameter	1.99mm

RESULT

The present study was aimed to evaluate the amount of stress/ strain field developing at mini-screw and bone interface with mini-screw diameter of 1.6mm and 2mm, and lengths of 8mm, 10mm and 12mm by varying the angle of insertion at 45^0, 60^0, 75^0 and 90^0. The difference of strain/stress magnitudes was compared to facilitate optimization of screw for optimal anchorage. A colour scale showing von Mises stress distribution with 9 stress values was used to evaluate quantitatively the stress distribution in the bone and the mini-screw interface (Fig 1, 2, 3). The scale for stress ranged from 0 MPa (blue) to the highest stress values (red). Red colour indicates areas with the highest stress and blue indicates areas with the lowest stress.

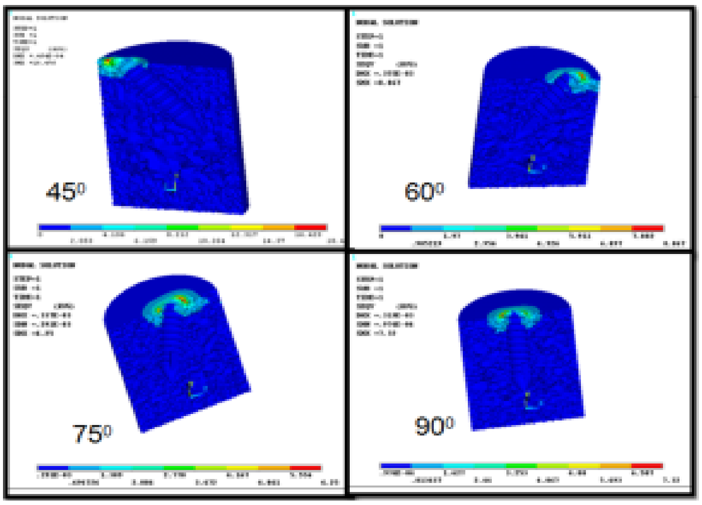

Fig 1.Bone model showing stress distribution on bone and the mini-screw interface at different angles of insertion.

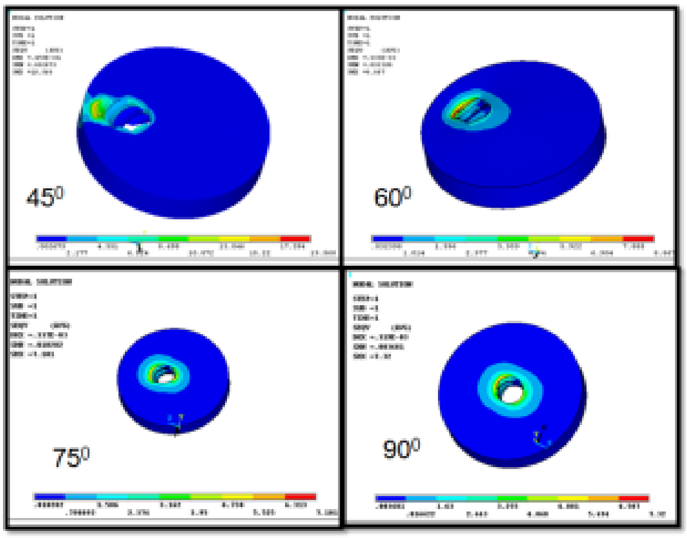

Fig 2. Cortical bone model showing stress distribution on bone and the mini-screw interface at different angles of insertion.

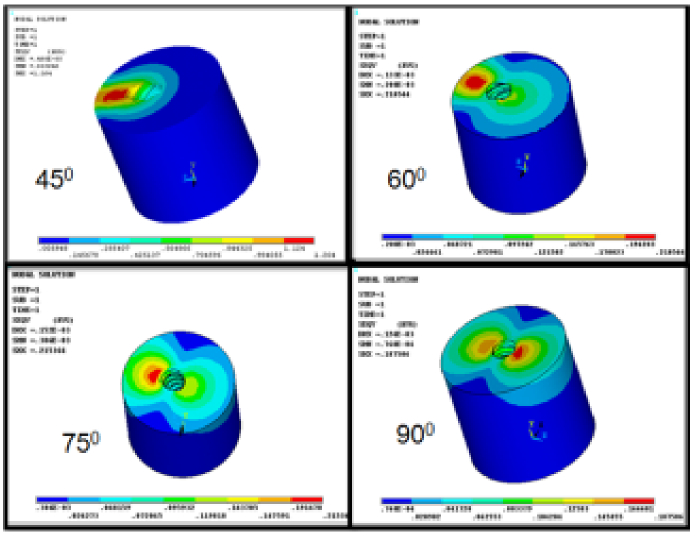

Fig 3. Cancellous bone model showing stress distribution on bone and the mini-screw interface at different angles of insertion.

The maximum von Mises stress values obtained from scale in cortical and cancellous bone and mini-screw interface was recorded and compared with the help of Table no 2, 3, 4 and 5. Results show that when the angle of insertion was increased from 45 degree to 90 degree there was a decrease in von Mises stress values at mini-screw and bone interface. The percentage decrease in von Mises stress values from 45 degree to 90 degree were observed, when the diameter of mini-screw was 1.6mm at length of 8mm, 10mm and 12 mm was 51.04% , 54.10% and 69.86% respectively. Similarly with the diameter of 2 mm, the percentage decrease in von Mises stress values was observed to be 52.04%, 53.88% and 67.39% at 8mm, 10mm and 12mm length respectively.

DISCUSSION

FEM is a technique capable of analyzing the biomechanical tissue response by providing the point-wise (nodal) displacements. The finite element analysis technique is reliable for stress analysis as shown by DeTolla DH et al [20]and Geng JP [21]. It is virtually impossible to measure stress accurately around bone and micro-screw interface in vivo. Hence, this study was done to evaluate

Table no. 2 Maximum von Mises stress values obtained for a mini-screw of 1.6 mm diameter in buccal cortical bone.

Mini-screw diameter = 1.6 mm, Maximum stress (MPa) in buccal cortical bone				
	45 Degree	**60 Degree**	**75 Degree**	**90 Degree**
8 mm	19.57	15.19	11.91	9.58
10 mm	14.03	9.58	7.29	6.44
12 mm	13.66	8.80	6.65	4.12

Table no. 3 Maximum von Mises stress values obtained for a mini-screw of 2 mm diameter in buccal cortical bone.

Mini-screw diameter = 2 mm, Maximum stress (MPa) in buccal cortical bone				
	45 Degree	**60 Degree**	**75 Degree**	**90 Degree**
8 mm	15.28	13.66	8.87	7.82
10 mm	13.66	8.87	7.10	6.30
12 mm	9.57	7.20	6.49	3.12

Table no. 4 Maximum von Mises stress values obtained for a mini-screw of 1.6 mm diameter in cancellous bone.

Mini-screw diameter = 1.6 mm, Maximum stress (MPa) in cancellous bone				
	45 Degree	**60 Degree**	**75 Degree**	**90 Degree**
8 mm	0.28	0.26	0.21	0.24
10 mm	0.24	0.23	0.17	0.20
12 mm	0.20	0.19	0.12	0.08

Table no. 5 Maximum von Mises stress values obtained for a mini-screw of 2 mm diameter in cancellous bone.

Mini-screw diameter = 2 mm, Maximum stress (MPa) in cancellous bone				
	45 Degree	**60 Degree**	**75 Degree**	**90 Degree**
8 mm	0.25	0.22	0.22	0.19
10 mm	0.23	0.21	0.21	0.19
12 mm	0.19	0.18	0.16	0.07

amount of stress/strain field developing at mini-screw and bone interface with varying diameter (1.6mm and 2mm), length (8mm, 10mm and 12mm) and angle of insertion (45^0, 60^0, 75^0 and 90^0) to facilitate optimization of mini-screw used as anchorage in orthodontic clinical setup.

Results of our study show that cortical bone takes up the maximum amount of stress out of overall stress transferred from mini-screw to bone. This is because the cortical bone has higher Young's modulus therefore it sustains higher load resistances and deformation than does cancellous bone. Secondly, the bending mode, as identified in the mini-screw stress, has more effect at the base support region, as justified by the concentrated high base stress in the entrance region of the cortex, than the rest of the embedded region, a straighter and less bent region. These results are best supported by previous finite element analysis studies by Moon CH [22] and Noble J [23] who showed that cortical thickness and density determines the overall load transfer from mini-screw to the bone, and the density of cancellous bone plays only a minor role in resisting this force.

The results of this study have shown that when the angle of insertion was increased from 45 degree to 90 degree there was a decrease in von Mises stress values at mini-screw and bone interface. The percentage decrease in von Mises stress values from 45 degree to 90 degree were observed, when the diameter of mini-screw was 1.6mm at length of 8mm, 10mm and 12 mm was 51.04% , 54.10% and 69.86% respectively. Similarly with the diameter of 2 mm, the percentage decrease in von Mises stress values was observed to be 52.04%, 53.88% and 67.39% at 8mm, 10mm and 12mm length respectively. The reason for the same may be attributed to a decrease in the insertion depth for the decreased angle of insertion and the longer distance the screw has to travel within the cortical bone. Similar results have been shown in a study by Zhang Y [24] who analyzed the influence of different tilted angles including 30^0, 40^0, 50^0, 60^0, 70^0, 80^0, and 90^0 on the biomechanical characteristics of orthodontic anchorage at the implant-bone interface. Results similar to our study was obtained by Jasmine F, ArifYezdani M, Tajir F, and Venu MR [9] who compared the maximum von Mises stress in the mini-screw, cortical and cancellous bone and showed that, as the insertion angle was increased from 30^0 to 90^0, there was decrease in stress values in both the cortical and the cancellous bone. Noble J, Karaiskos NE, Hassard TH, Hechter FJ and Wiltshire WA [23] found that removal of a temporary anchorage device that had been inserted at an angle exerted greater stress on the bone than when the mini-screw was placed perpendicular to the bone. This indicates that stress levels decrease as the insertion angle increases from 30^0 to 90^0. Moon CH, Lee DG, Lee HS, Im JS and Baek SH [22] reported that mini-screws should be inserted at 70^0 to 80^0 to the long axis of the teeth for better stability and success of the micro-implant in the posterior buccal region of the maxilla and the mandible.

So our study along with the above mentioned studies are in correlation that the mini-screw should be inserted as perpendicular to the bone as possible. The clinical implication obtained by the evaluation of stress pattern is to increase the angulation of the implant from 45^0 to 90^0 to keep the stress levels as low as possible to prevent failure of the mini-screw.

The results also showed that on increasing the length from 8mm to 12mm, a decrease in von Mises stress values was observed at mini-screw and bone interface. For diameter of 1.6mm, percentage decrease seen at angle of insertion of 45^0, 60^0, 75^0 and 90^0 were 30.20 %, 42.06%, 44.12% and 56.99% respectively. In case of diameter of 2mm the percentage decrease observed were 37.36%, 47.29%, 26.86% and 57.38% at 45^0, 60^0, 75^0 and 90^0 angle of insertion respectively. The reason for this can be attributed to the fact that as the length of mini-screw increases the ability of mini-screw to distribute applied stress increases over greater areas of the surrounding bone. The results of this study also indicated the marked decrease in stress for the mini-screw at length of 12 mm with diameter of 1.6 and 2mm respectively at an insertion angle of 90^0. This is probably because the mini-screw passes through the outer cortical bone as well as the inner cortical bone and becoming bi-cortical mini-screw, with an ability to distribute applied forces over greater areas of bone and to both outer and inner cortical bone than that of shorter mono-cortical miniscrew. Clinically, the advantage of using a longer bi-cortical mini-screw is its reduction in stress at cortical and mini-screw interface which are generated during force application using mini-screw as anchorage, which enhance the orthodontic mini-screw stability and its success. This might even enable the mini-screw to withstand higher forces as well. Also the previous study by Jiang L, Kong L, Li T, Gu Z, Hou R and Duan Y [25] showed that in combination with larger diameter and longest length mini-screw within safety range were the optimal biomechanical choices to be used for the maxillary posterior region. Morarend C et al [6] in their study also concluded that bi-cortical screws provide anchorage force resistance at least equal to larger diameter mono-cortical screw. Hence narrow bi-cortical screw is useful where there is insufficient room inter-proximally to place a larger diameter mono-cortical screw. This is especially true in the case of a patient with thin maxillary cortical bone; a bi-cortical screw might be the mini-screw of choice.

Added advantage of a bi-cortical over mono-cortical mini-screw is that bi-cortical mini-screw is longer in length and similar in diameter, so better implant stability can be achieved through bi-cortical stabilization. As the study by Ivanoff CJ, Sennerby L, and Lekholm U [26] demonstrated that removal torques for bi-cortically stabilized implants were twice the values for mini-screw with mono-cortical engagement in a study using rabbit tibiae. Freudenthaler JW, Haas R and Bantleon HP [27] showed that some load-distributing advantages can be achieved through bi-cortical stabilization of implants in the jaws by engagement of the lingual cortical plate.

During the conduct of this study it was also seen that when the diameter of the mini-screw was increased from 1.6 mm to 2mm, there was a decrease in the von Mises stress values at mini-screw and bone interface. For a mini screw of length 8 mm percentage decrease of von Mises stress observed were 21.92%, 10.07%, 25.44% and 23.59% at 45^0,60^0, 75^0 and 90^0 angle of insertion respectively. Similarly, for length of 12 mm, percentage decreases in stress values seen were 29.94%, 18.18%, 20.04% and 24.27% at 45^0,60^0, 75^0 and 90^0 angle of insertion. This could again be easily explained by the bending mode of the loaded mini-screw. Under bending, based on the second moment of inertia of a cylinder, the peak stress is inversely proportional to the third power of the diameter. Therefore, the mini-screw diameter was the dominant factor in governing the stress values of the structure among all investigated factors in our study. Increasing the mini-screw diameter was the most effective way to reduce the peak stress in cortical and cancellous bone as well. Earlier Lim JW, Kim WS, Kim IK, Son CY and Byun HI [28] had done a comparison of the maximum von Mises stresses in the cortical and cancellous and bone showed that as the diameter increases from 1.2mm to 2.0mm the stresses decreased. Miyawaki S et al [3] had done the comparisons between different type of screw; the type A screw with 1.0mm diameter, type B screw with a 1.5-mm diameter and the type C screw with a 2.3-mm diameter the success rate was 0 %, 83.9% and 85% respectively. Thus they concluded that the success rate increased with an increase in the diameter of the mini-screw. Other studies also found that wider mini-screws had better stability [16].

CONCLUSION

The following conclusions can be drawn from the study:

1. The comparison of the maximum von Mises stress in the cortical and cancellous bone showed that
   - (i) Stress values decreased with the increase in insertion angle from 45^0 to 90^0.
   - (ii) Stress values decreased with the increase in length from 8 to 12 mm. Hence the bi-cortical mini-screws provided better and enhanced stability than the mono-cortical mini-screws.
   - (iii) Stress values decreased with the increase in the diameter from 1.6 to 2 mm.
2. The wider bi-cortical mini-screw should be preferred over mono-cortical mini-screws and should be placed as perpendicular to the bone as possible for better and enhanced stability.

REFERENCES

1. Park HS. Clinical study on success rate of microscrew implants for orthodontic anchorage. Korea J Orthod. 2003;33: 151–156.
2. Dos Reis LM, Batalha JR, Munoz DR, Borelli A, Correa PH, Carvalho AB, and Jorgetti V. Brazilian normal static bone histomorphometry: effects of age, sex, and race. J Bone Miner Metab. 2007;25:400–406
3. Miyawaki S, Koyama I, Inoue M, Mishima K, Sugahara T,and Takano-Yamamoto T. Factors associated with the stability of titanium screws placed in the posterior region for orthodontic anchorage. Am J OrthodDentofacOrthop 2003;124:373–8.
4. Wilmes B, Rademacher C, Olthoff G,andDrescher D. Parameters affecting primary stability of orthodontic mini-implants. J OrofacOrthop 2006;67:162–74.
5. Song YY, Cha JY,and Hwang CJ. Mechanical characteristics of various orthodontic mini-screws in relation to artificial cortical bone thickness. Angle Orthod. 2007;77:979–985.
6. Morarend C,Qian F Steve D. Marshall, Southard A,Grosland MN ,and Morgan TA , McManus, and Southard TE . Effect of screw diameter on orthodontic skeletal anchorage. Am J OrthodDentofacialOrthop 2009;136:224-9
7. Kim JW, Baek SH, Kim TW, and Chang YI. Comparison of stability between cylindrical and conical type mini-implants. Angle Orthod. 2008;78:692–698.

8. Lim SA, Cha JY,and Hwang CJ. Insertion torque of orthodontic miniscrews according to changes in shape, diameter and length. Angle Orthod. 2008;78:234–240.
9. Jasmine F, ArifYezdani M, Tajir F, and MuraliVenu R. Analysis of stress in bone and microimplants during en-masse retraction of maxillary and mandibular anterior teeth with different insertion angulations: A 3-dimensional finite element analysis study. Am J OrthodDentofacialOrthop 2012;141:71-80
10. Deguchi T, Nasu M, Murakami K, Yabuuchi T, Kamioka H,and Takano-Yamamoto T. Quantitative evaluation of cortical bone thickness with computed tomographic scanning for orthodontic implants. Am J OrthodDentofacialOrthop. 2006; 32. 129:721. e7–e12.
11. Kim HJ, Yun HS, Park HD, Kim DH,and Park YC. Soft-tissue and cortical-bone thickness at orthodontic implant sites. Am J OrthodDentofacialOrthop. 2006;130:177–182.
12. Freire JN, Silva NR, Gil JN, Magini RS,and Coelho PG. Histomorphologic and histomophometric evaluation of immediately and early loaded mini-implants for orthodontic anchorage. Am J OrthodDentofacOrthop 2007;131:704–9.
13. Tseng YC, Hsieh CH, Chen CH, Shen YS, Huang IY,and Chen CM. The application of mini-implants for orthodontic anchorage. Int J Oral Max Surg 2006;35:704–7.
14. Wilmes B, Ottenstreuer S, Su YY,andDrescher D. Impact of implant design on primary stability of orthodontic mini-implants. J OrofacOrthop 2008;69:42–50.
15. Wu JC, Huang J and Zhao SF .Bicortical head for mesial movement of posterior tooth in beagle dog. Am J orthodDentofacOrthop 2007 ;132:353-9
16 .Brettin TB, Grosland NM, Qian F, Southard KA, Stuntz TD, Morgan TA, Marshal SD, and Southard TD.BicorticalvsMonocortical Skeletal Anchorage. Am J OrthodDentofacOrthop 2008;134 :625-35
17. Dharmendra CH.To evaluate and recommend various types of forces for debonding orthdontic attachments based on a finite element analysis method. Orthod CyberJr . Nov 2010
18. Park HS . An anatomic study using CT images for implantations of micro-implant. Korea J orthod. 2002; 32(6): 435-41
19. Rho JY, Ashman RB, Turner CH, Young's modulus of trabecular and cortical bone material: ultrasonic and microtensile measurements, J. Biomech. 1993;26 (2) :111–119.
20. DeTolla DH, Andreana S,Patra A, Buhite R and Comella B. Role of the finite element model in dental implants. J Oral Implantol 2000;26: 77-81.
21. Geng JP, Tan KBC, and Liu GR. Application of finite element analysis in implant dentistry : A review of literature. J Prosthet Dent. 2001; 85: 585-98
22. Moon CH, Lee DG, Lee HS, Im JS &Baek SH. Factors associated with the success rate of orthodontic miniscrews placed in the upper and lower posterior buccal region. Angle Orthod 2008;78:101-6.
23. Noble J, Karaiskos NE, Hassard TH, Hechter FJ & Wiltshire WA. Stress on bone from placement and removal of orthodontic miniscrews at different angulations. J ClinOrthod 2009;43: 332-4.
24. Zhang Y, Zhang D, Feng CJ. A three-dimensional finite element analysis for the biomechanical characteristics of orthodontic anchorage micro-implant. Shanghai Kou Qiang Yi Xue 2005;14:281-3.
25. Jiang L, Kong L, Li T, Gu Z, Hou R and Duan Y. Optimal selections of orthodontic mini-implant diameter and length by biomechanical consideration: A three-dimensional finite element analysis. AdvEng Software. 2009; 40: 1124–1130
26. Ivanoff CJ, Sennerby L, Lekholm U. Influence of mono- and bicortical anchorage on the integration of titanium implants. A study in the rabbit tibia. Int J Oral MaxillofacSurg 1996;25:229-35.
27. Freudenthaler JW, Haas R, Bantleon HP. Bicortical titanium screws for critical orthodontic anchorage in the mandible: a preliminary report on clinical applications. Clin Oral Implants Res 2001;12:358-63.
28. Lim JW, Kim WS, Kim IK, Son CY, Byun HI. Three dimensional finite element method for stress distribution on the length and diameter of orthodontic miniscrew and cortical bone thickness. Korean J Orthod 2003;33:11-20.