Acta Odontologica Scandinavica. 2015; 73: 312–320

informa healthcare

ORIGINAL ARTICLE

Comparing the influence of crestal cortical bone and sinus floor cortical bone in posterior maxilla bi-cortical dental implantation: A three-dimensional finite element analysis

XU YAN[1], XINWEN ZHANG[2], WEICHAO CHI[3], HONGJUN AI[1] & LIN WU[1]

[1]*Department of Prosthodontics,* [2]*Center of Implant Dentistry, School of Stomatology, China Medical University, Shenyang, PR China, and* [3]*School of Astronautics, Harbin Institute of Technology, Harbin, PR China*

Abstract

Objective. This study aimed to compare the influence of alveolar ridge cortical bone and sinus floor cortical bone in sinus areabi-cortical dental implantation by means of 3D finite element analysis. ***Materials and methods.*** Three-dimensional finite element (FE) models in a posterior maxillary region with sinus membrane and the same height of alveolar ridge of 10 mm were generated according to the anatomical data of the sinus area. They were either with fixed thickness of crestal cortical bone and variable thickness of sinus floor cortical bone or vice versa. Ten models were assumed to be under immediate loading or conventional loading. The standard implant model based on the Nobel Biocare implant system was created via computer-aided design software. All materials were assumed to be isotropic and linearly elastic. An inclined force of 129 N was applied. ***Results.*** Von Mises stress mainly concentrated on the surface of crestal cortical bone around the implant neck. For all the models, both the axial and buccolingual resonance frequencies of conventional loading were higher than those of immediate loading; however, the difference is less than 5%. ***Conclusion.*** The results showed that bi-cortical implant in sinus area increased the stability of the implant, especially for immediately loading implantation. The thickness of both crestal cortical bone and sinus floor cortical bone influenced implant micromotion and stress distribution; however, crestal cortical bone may be more important than sinus floor cortical bone.

Key Words: *finite element analysis, bi-cortical implant, stress distribution, resonance frequencies, sinus floor*

Introduction

The posterior region of the atrophic maxilla is characterized by thin cortical bone and low density trabecular bone. In many cases, the height of the bone in this region is insufficient to achieve high primary stability because of the presence of the sinus. Therefore, dental implants in this region show the highest rate of failure and surgical techniques have been proposed to increase their primary stability [1–3]. The most commonly used surgical methods are preparation of the site with tools one size smaller than the diameter of the implant [4], bone compression using an osteotome [5–7] and the use of bi-cortical fixation [8].

It is generally believed by implant dentists that longer implants give higher successful rates and better prognosis. For a certain height of alveolar ridge in atrophied posterior maxilla, some clinical researches have already shown that the implant should be long enough to provide sufficient retention force [9]. Since masticatory forces are light and fleeting, these forces are normally tolerated by the bone rather than evenly distributed throughout the interface of implant and bone [10]. Compared to implant length and width, bone type and cortical bone engagement may be a more important factor [11]. Okumura et al. [12] reported that the thickness of crestal cortical bone may heavily influence the stability of the implant. Some studies suggested that bi-cortical implant in the mandible may increase the initial stability and reduce the stress of the cortical bone around the implant neck [13,14]. However, in posterior maxilla area, it's not clear whether bi-cortical dental implant

Correspondence: Xu Yan, Department of Prosthodontics, School of Stomatology, China Medical University, Shenyang 110001, PR China. Tel: +8602483995567. Fax: +8602483995567. E-mail: xuyan1112014@yeah.net

(Received 8 May 2014; accepted 4 September 2014)

ISSN 0001-6357 print/ISSN 1502-3850 online
DOI: 10.3109/00016357.2014.967718

can be used and what is the influence of the thickness of the two layers of cortical bone, due to the thin layer of cortical bone in the sinus floor.

FEA (Finite element analysis) has been extensively used to analyze biomechanical performance of various clinical factors and to predict the outcome of implantation [15]. The distribution of forces in peri-implant bone of sinus area and maximum micro-motion have been investigated by 3D-finite element analysis in several studies [12,16,17], but none of these focus on bi-cortical dental implant. Sinus membrane trauma or exceeding micro-motion occurs frequently at the initial stage of implant installation because of the poor osseo-integration between implant and bone [18]. Both may lead to early failure of implantation. Several techniques can be used to measure primary implant stability to ensure a successful implantation [19]. Resonance frequency analysis (RFA) as a non-destructive measurement has been widely used in clinical practice in the recent years [20]. Resonance frequency as a kind of physical property can be simulated by finite element analysis which has been shown to be useful in biomechanical research of dental implantation [21,22].

In this study, we hypothesized that the thickness of crestal cortical bone and sinus floor cortical bone may influence implant micromotion and stress distribution differently. To test our hypothesis, the biomechanics performance of bi-cortical implant in sinus area (either immediate loading or conventional loading) were examined by 3D finite element analysis of maximum von Mises stress, stress distribution, implant displacement, as well as resonance frequency analysis.

Materials and methods

Implant system

The standard implant with a diameter of 4.0 mm and a length of 10.0 mm was modeled (the shape and structure was according to Nobel Biocare implant system) and placed in the three-dimensional finite element models of the sinus area. In order to simplify the analysis, the model of the implant and the abutment was modeled as a unit.

Sinus geometric modeling

Three-dimensional CAD models of posterior maxilla with 0.3 mm thick [23] sinus membrane, 10 mm height of alveolar ridge with different thickness of the crestal cortical bone and sinus floor cortical bone were generated using computer-aided design software (SolidWorks 2012, Fukuoka, Japan). The geometry of the maxilla was defined by a bucco-palatal section according to the anatomical aspects of the sinus area [24–27]. The first five models (Model 1–1 to Model 1–5) were constructed with the same thickness of crestal cortical bone of 1 mm and variable thickness (0.5 mm interval) of sinus floor cortical bone from 0–2 mm. The second five models (Model 2–1 to Model 2–5) were constructed with the same thickness of sinus floor cortical bone of 1 mm and variable thickness (0.5 mm interval) of crestal cortical bone from 0–2 mm. Models 1–1 and 2–1 were control models without sinus floor cortical bone and crestal cortical bone, respectively. Models 1–2 and 2–2 were the same with 1 mm crestal cortical bone and 1 mm sinus floor cortical bone according to the design of the study. For all the models, the implant apex just broke through the sinus floor cortical bone, which meant the upper surface of the sinus floor cortical bone and the apical surface of implant were in the same level.

Material properties

The material properties of different kinds of tissues as well as implants in the models were assumed to be homogeneous, isotropic and linearly elastic. Young's modulus, Poisson's ratio and Mass density of materials used in the analysis were taken from the literature [28–30], as shown in Table I.

Interface conditions

All the models were presumed to be in two kinds of interface conditions. One represented ideal osseo-integration for traditional loading, with 100% union between the implants and maxilla; while the other one represented a frictional interface before osseous integration on the implant–bone interface. Thus, we have in total four groups which are named as follows: Group 1: SC & IL (variable sinus floor cortical bone & immediate loading); Group 2: SC & CL (variable sinus floor cortical bone & conventional loading); Group 3: CC & IL (variable crestal cortical bone & immediate loading); Group 4: CC & CL (variable crestal cortical bone & conventional loading). To obtain initial stability for the situation of immediate loading after implantation, it was modeled using non-linear frictional contact elements, which allowed minor displacements between implant and

Table I. Material properties ascribed to materials used in the models.

Material	Young's modulus (MPa)	Poisson's ratio	Mass density (g/cm^3)
Titanium implant [28]	103 400	0.35	4.5
Cortical bone [28]	13 700	0.3	2.0
Cancellous bone (D3) [28]	1 370	0.3	1.0
Sinus membrane [29,30]	58	0.45	1.0

bone. Under these conditions, the contact zone transfers pressure and tangential forces (i.e. friction), but no tension. The friction coefficient was set to 0.3 between implant and bone [31].

Loading and boundary conditions

An average force of 129 N [32] inclined posteriorly 30° relative to the implant axis and 30° away from the sagittal plane was dispersed on the top of the implant abutment. Ansys14.5 software (ANSYS, Inc., Harbin, China) was used for FE analysis. All models were constrained in all directions at the nodes on the mesial and distal bone surfaces, the top of the simulated sinus, sinus walls and sinus membrane. These models were meshed with 4-nodes-tetrahedral elements and 8-nodes-hexahedron elements and composed of elements varying from 56 737–110 059 and nodes ranging from 139 651–383 770 (Figure 1). The von Mises stress values were measured in all kinds of implant surrounding tissues along the tissue–implant interface. To assess the distribution of stresses, maximum von Mises stresses were visualized with stress contour plots. The biomechanical effects were also analyzed by comparing the maximum displacement of the implant neck and apex. Buccolingual and axial resonance frequencies of the implant were also analyzed.

Results

Stress distribution and maximum von Mises stress

Cortical bone of alveolar ridge and sinus floor.. When implants were loaded with inclined force, von Mises stress mainly concentrated on the surface of crestal cortical bone around the implant neck for all the 10 models, regardless of immediate loading and

Figure 1. Finite element model of sinus area bi-cortical dental implantation with bone containing nodes and elements. Sample Model 1–2 with 1 mm thickness crestal cortical bone and 1 mm sinus floor cortical bone and standard implant bi-cortical implantation in the sinus area.

conventional loading. Stress distributions in crestal cortical bone of Model 1–2 and Model 2–2 are shown as examples in Figure 2.

The maximum von Mises stress of crestal cortical bone and sinus floor cortical bone of different loading opportunity and model groups were summarized in Table II. Generally, the maximum von Mises stress of sinus floor cortical bone under immediate loading was much higher than that of conventional loading for all the models. More specifically, for Group 1 and Group 2 (fixed crestal cortical bone and increasing sinus floor cortical bone), maximum von Mises stress of crestal cortical bone was decreasing as the thickness of sinus cortical bone increased for both immediate and conventional loading. However, for maximum von Mises stress of sinus floor cortical bone, the stress was the highest when the sinus floor cortical bone thickness was 1 mm (Model 1–3), the same thickness as the crestal cortical bone. For Groups 3 and 4 (fixed sinus cortical bone and increasing crestal cortical bone), the trend of maximum von Mises stress in crestal/sinus floor cortical bone was more or less the same with Groups 1 and 2, except for crestal cortical bone stress under conventional loading, which increased with thicker crestal cortical bone.

Cancellous bone.. Von Mises stress mainly concentrated on the threads of the implant in the cancellous bone for all the models. In Model 2–1, the von Mises stresses were 23.39 MPa and 26.33 MPa for immediate loading and conventional loading separately, which were much higher than the other models because of the absence of crestal cortical bone. Other results are showed in Figure 3. Compared to the highest von Mises stress model of each group, the maximum von Mises stress decreased by 26.2% (Group 1), 35.9% (Group 2), 10.1% (Group 3) and 42.4% (Group 4).

Implant displacement

Maximum displacement of both the neck and apex of the implant was analyzed and the results are showed in Figures 4A (Implant neck) and B (Implant apex). The implant displacements of immediate loading of all the 10 models are shown in Figure 5. As the thickness of the two layers of cortical bone increased, the decrease of maximum displacements of implant necks were not so obvious (SC & IL: 12.6%, CC & IL: 10.6%), but it appeared to have more influence for the stability of implant apex (SC & IL: 67.7%, CC & IL: 40.3%). For conventional loading, the decrease of implant neck maximum displacement was much more obvious, especially the thickness of the cortical bone increased from 0 mm to 0.5 mm (Figure 4A). For implant apex, the effect of crestal/sinus floor cortical

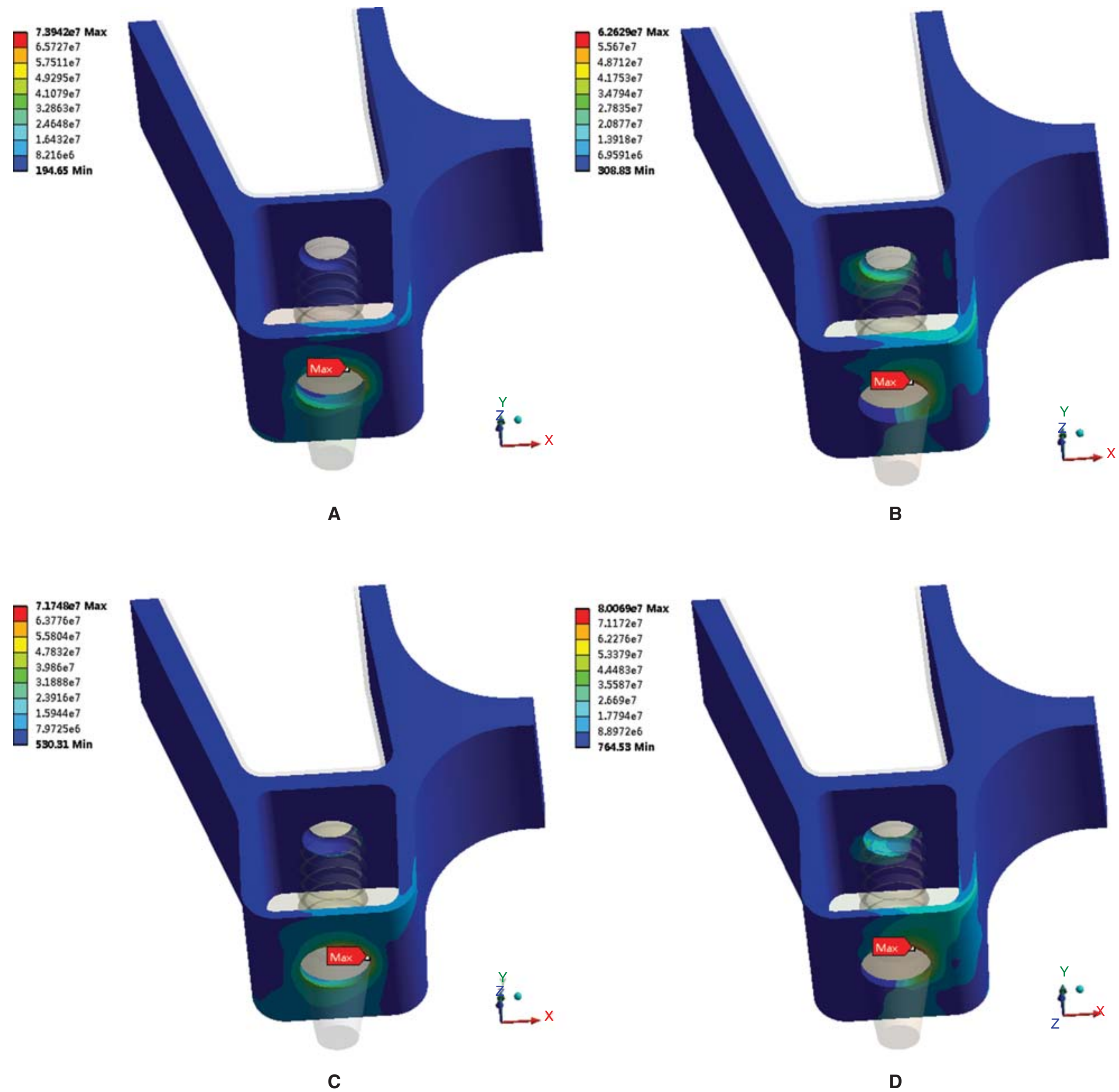

Figure 2. Stress distribution in crestal cortical bones. Model 1–2 with conventional loading (A), Model 1–2 with immediate loading (B), Model 2–2 with conventional loading (C) and Model 2–2 with immediate loading (D) are taken as examples. In all conditions, maximum von Mises stress is concentrated in the crestal cortical bone surface around the implant neck.

bone thickness increasing was almost the same (SC & CL: 57.2%, CC & CL: 51.4%) (Figure 4B).

Implant resonance frequencies

Next, the first order bending mode along implant longitudinal axial and the second order bending mode of buccolingual direction were observed. Figure 6 presents the two vibrational modes of the implant-bone system. Figures 7A (Axial resonance frequencies of implant) and B (Buccolingual resonance frequencies of implant) showed the results of implant resonance frequencies of immediate loading. For implant axial resonance frequencies, an increase of any kind of the cortical bone increased the axial resonance frequencies. When the cortical bone thickness was less than 1 mm, the influence of crestal cortical bone and sinus floor cortical bone were more or less the same. The implant axial resonance frequencies increased rapidly as the crestal cortical bone was more than 1 mm and continued to increase. For implant buccolingual resonance frequencies, the increase of any kind of the cortical bone also increased the buccolingual resonance frequencies. When the cortical bone thickness was less than 1 mm, with the decrease of crestal cortical bone thickness, buccolingual resonance frequencies decreased rapidly compared to the sinus floor cortical bone groups.

Table II. Maximum von Mises stress in crestal and sinus floor cortical bone of different models and loading opportunities.

	Immediate loading		Conventional loading	
Model No.	Crestal cortical bone (MPa)	Sinus floor cortical bone (MPa)	Crestal cortical bone (MPa)	Sinus floor cortical bone (MPa)
Model 1–1	76.24		98.83	
Model 1–2	62.63	41.03	73.94	9.19
Model 1–3	58.69	53.44	72.75	9.96
Model 1–4	57.22	42.46	70.41	9.20
Model 1–5	56.61	33.51	68.79	8.11
Model 2–1		23.39		36.75
Model 2–2	80.07	54.14	71.75	13.28
Model 2–3	58.69	53.44	72.75	9.96
Model 2–4	58.26	51.00	77.76	8.47
Model 2–5	56.76	50.18	85.43	7.01

The effect of two layers of cortical bone were more or less the same when cortical bone thickness was more than 1 mm. For all the models, both the axial and buccolingual resonance frequencies of conventional loading were a little higher than those of immediate loading, but the differences were no more than 5%, which is not statistically significant.

Discussion

Model

The models of posterior maxilla sinus area we used in this study were based on our previous studies about sinus lift without bone materials [33]. In order to study variable thickness of crestal and sinus floor cortical bone, we need to exclude the influences of anatomical variations of bone so that results of different models are comparable [34]. As suggested by Okumura et al. [35], the difference between the actual anatomical model of maxilla and the abstractive model is minimal in qualitative analysis. Thus, we decided not to use the actual anatomical model of maxilla provided by CBCT data. Instead, three-dimensional CAD models based on the same sketch, which is according to the anatomic data of the sinus area, has been developed to make the models more comparable in this study. For all the groups, we used one implant model in the fixed position excluding the influences of implant length/width, position and thread, etc., which was used in our previous study [33]. The only difference between groups was the thickness of crestal/sinus floor cortical bone, which are considered as the most important factors in this study.

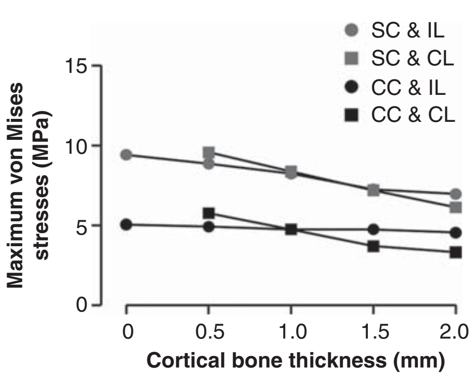

Figure 3. Maximum von Mises stress in cancellous bone for all the models of immediate/conventional loading except Model 2–1.

Stress distribution and maximum von Mises stress

There are three main directions of bite forces: occlusal, laterotrusion and protrusion [36]. Analysis of all three directions of forces are sometimes performed to study the stress distribution on implants [17,37]. To focus on the influence of cortical bone thickness on implants, we didn't go into details of bite force directions. Our results indicated that, for the bi-cortical implant in posterior maxilla area, no matter how the thickness of sinus floor cortical bone varies, the inclined occlusal force mainly relied on the crestal cortical bone around the neck of implant. Especially in the condition of conventional loading, the implant neck cortical bone absorbed most of the loading force when the implant and surrounding bone got osseointegration. The maximum von Mises stress of cancellous bone declined linearly as the cortical bone thickness increased. This applied to both the crestal cortical bone and sinus floor cortical bone. Furthermore, the thickness of crestal cortical bone should be thicker than 1 mm, otherwise the maximum von Mises stress will be much bigger for immediate loading. Our results of immediate loading were in line with Han et al.'s [38] data which indicated that the

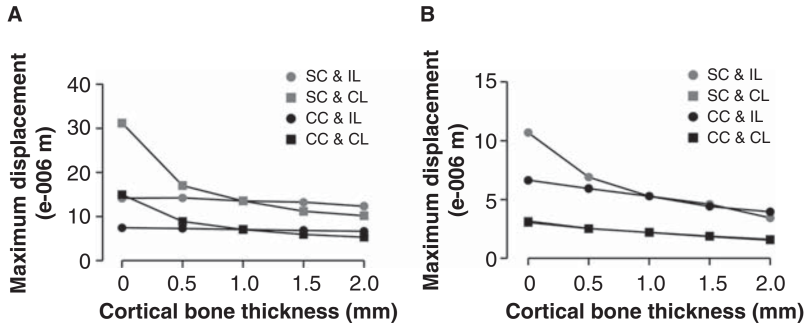

Figure 4. Maximum displacement of the implant: (A) neck; (B) Implant apex.

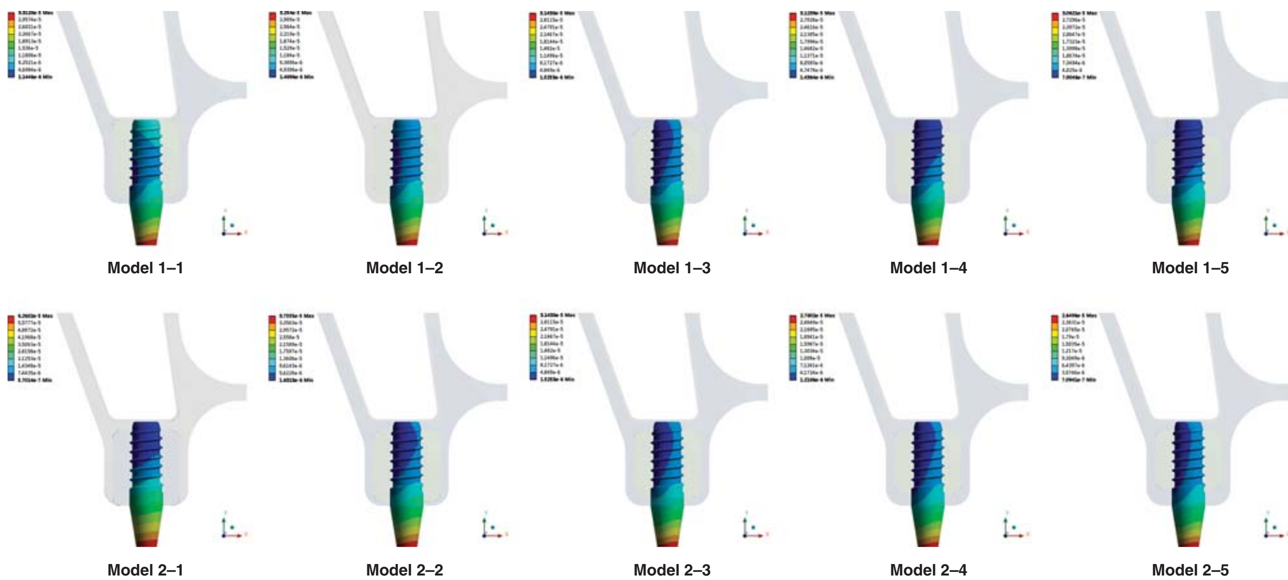

Figure 5. Implant displacement of immediate loading.

stresses were centralized at the crestal cortical bone of the implant cervix.

With the increasing thickness of sinus floor cortical bone, maximum von Mises stress of crestal cortical bone decreased. For immediate loading, sinus floor cortical bone can absorb more stress compared to conventional loading, but the effect is not much influenced by its thickness. The presence of sinus floor cortical bone in bi-cortical dental implantation is important for both immediate loading and conventional loading, but its thickness is not important since maximum von Mises stress was not reducing with increasing cortical bone of the implant neck. This result was beyond the traditional thinking that maximum stress of the peri-implant bone decreased as cortical bone thickness increased [39].

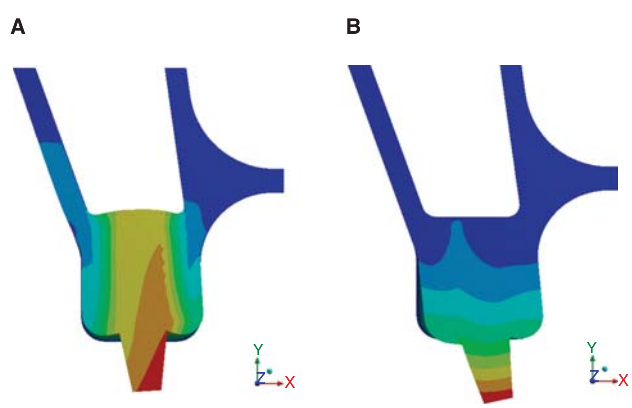

Figure 6. Vibrational modes of the bone-implant complex: (A) A mode; (B) Bending mode.

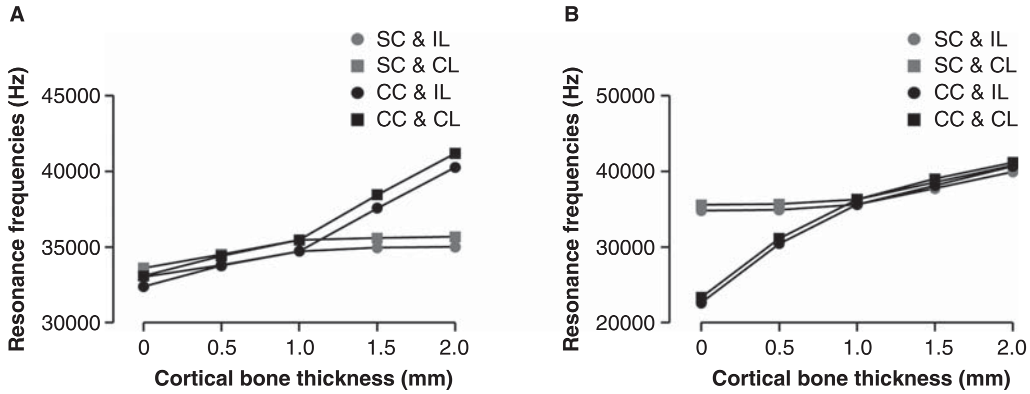

Figure 7. Implant resonance frequencies of immediate loading: (A) Axial resonance frequencies of implant; (B) Buccolingual resonance frequencies of implant.

Implant displacement

For immediate loading of inclined force, both the maximum displacements of the implant neck and apex were decreased slightly with increasing thickness of the crestal/sinus floor cortical bone. These results showed that the thickness of both layers of cortical bone was not the key factor for keeping the implant stable in the condition of immediate inclined loading. However, in the condition of conventional loading, the presence of crestal/sinus floor cortical bone and its thickness played important roles in the reduction of micromotion of implant, when the implant and surrounding bone got osseointegration. In the study of Chiang et al. [39], the micromotion level in full osseointegration was less than that in non-osseointegration and is also decreased as cortical bone thickness increases, the results of which were in agreement with our data.

Resonance frequencies analysis

It is generally accepted that primary stability is the most critical factor for successful implantation. As the immediate loading treatments are becoming more and more popular, primary stability attracted much more attention of the researchers and clinicians than it used to be. Primary stability is the result of mechanical engagement with the surrounding bone tissue and it has been thought that primary stability mainly depends on three major factors: (1) the implant bed condition such as bone quantity/quality and cortical bone thickness; (2) the mechanical characteristics of the fixture placed in the bone; and (3) the surgical techniques used to put fixture in the bone [40]. During the placement of an implant, primary stability can be measured with various parameters such as insertion and removal torque or by using RFA (Resonance frequencies analysis) or the Periotest. Some clinical and animal studies have shown that there is strong correlation between resonance frequencies value and cortical bone thickness, which suggests that cortical bone thickness plays a crucial role in the primary stability of implants [41,42].

In principal, there are several forms of resonance frequencies of implant. The most important forms for dental implantation are axial and buccolingual resonance frequencies. Axial and buccolingual resonance frequencies of implant reflect implant stability in vertical and horizontal directions, respectively. Our data demonstrated that both axial and buccolingual resonance frequencies increased with the increasing of crestal/sinus floor cortical bone thickness in bi-cortical dental implantation. The difference between immediate loading and conventional loading was less than 5% in bi-cortical dental implantation, regardless of loading opportunities. Based on our data, the difference between the immediate loading and conventional loading is not statistically significant. Bi-cortical implantation of immediate-loading can get resonance frequencies values nearly equal to conventional-loading. That means the implant is as stable in immediate loading as conventional loading for the same surgical technique of bi-cortical dental implantation. This results were in favor to Wang et al.'s [14] FEA study of bi-cortical implantation in the mandible. Based on this observation, we believe that the 3–6 month healing process in conventional loading may not benefit for osseointegration, in terms of RFA values, which means a case of low RFA value with immediate loading is very unlikely to have a higher RFA value with conventional loading after 3–6 months of healing. Clinically, this observation implies conventional loading may not have significant advantages over immediate loading, regarding osseointegration.

Conclusion

In conclusion, the results of this study demonstrated that bi-cortical implant in the sinus area increased the stability of the implant, especially for immediately loading implantation. The thickness of both crestal cortical bone and sinus floor cortical bone influenced micromotion and stress distribution of the implant; however, crestal cortical bone may play a more important role than sinus floor cortical bone.

Acknowledgment

This research was supported by the National High Technology Research and Development Program of China (863 Program, 2011AA030107) and Young Scholars foundation, School of Stomatology, China Medical University, Shenyang, China (grants K101593-12-34). The authors would like to thank the Regenerative Dentistry and Implant Center and Section of Removable Prosthodontics, Division of Oral Rehabilitation, the Faculty of Dental Science, Kyushu University, Fukuoka, Japan, for their support and allowing us to use their facilities.

***Declaration of interest*:** The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

References

[1] Ahn SJ, Leesungbok R, Lee SW, Heo YK, Kang KL. Differences in implant stability associated with various methods of preparation of the implant bed: an *in vitro* study. J Prosthet Dent 2012;107:366–72.

[2] Balshi TJ, Wolfinger GJ, Balshi SF 2nd. Analysis of 356 pterygomaxillary implants in edentulous arches for fixed prosthesis anchorage. Int J Oral Maxillofac Implants 1999; 14:398–406.

[3] Herrmann I, Lekholm U, Holm S, Kultje C. Evaluation of patient and implant characteristics as potential prognostic factors for oral implant failures. Int J Oral Maxillofac Implants 2005;20:220–30.

[4] Friberg B, Ekestubbe A, Sennerby L. Clinical outcome of Branemark System implants of various diameters: a retrospective study. Int J Oral Maxillofac Implants 2002;17: 671–7.

[5] Crespi R, Cappare P, Gherlone E. Osteotome sinus floor elevation and simultaneous implant placement in grafted biomaterial sockets: 3 years of followup. J Periodontol 2010;81:344–9.

[6] Nedir R, Bischof M, Vazquez L, Nurdin N, SzmuklerMoncler S, Bernard JP. Osteotome sinus floor elevation technique without grafting material: 3 year results of a prospective pilot study. Clin Oral Implants Res 2009;20: 701–7.

[7] Nedir R, Nurdin N, Szmukler-Moncler S, Bischof M. Placement of tapered implants using an osteotome sinus floor elevation technique without bone grafting: 1-year results. Int J Oral Maxillofac Implants 2009;24:727–33.

[8] Ivanoff CJ, Grondahl K, Bergstrom C, Lekholm U, Branemark PI. Influence of bicortical or monocortical anchorage on maxillary implant stability: a 15-year retrospective study of Branemark System implants. Int J Oral Maxillofac Implants 2000;15:103–10.

[9] Lee JH, Frias V, Lee KW, Wright RF. Effect of implant size and shape on implant success rates: a literature review. J Prosthet Dent 2005;94:377–81.

[10] Lum LB. A biomechanical rationale for the use of short implants. J Oral Implantol 1991;17:126–31.

[11] 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.

[12] Okumura N, Stegaroiu R, Kitamura E, Kurokawa K, Nomura S. Influence of maxillary cortical bone thickness, implant design and implant diameter on stress around implants: a three-dimensional finite element analysis. J Prosthodont Res 2010;54:133–42.

[13] Xiao JR, Li YQ, Guan SM, Kong L, Liu B, Li D. Effects of lateral cortical anchorage on the primary stability of implants subjected to controlled loads: an *in vitro* study. Br J Oral Maxillofac Surg 2012;50:161–5.

[14] Wang K, Li DH, Guo JF, Liu BL, Shi SQ. Effects of buccal bi-cortical anchorages on primary stability of dental implants: a numerical approach of natural frequency analysis. J Oral Rehabil 2009;36:284–91.

[15] Van Staden RC, Guan H, Loo YC. Application of the finite element method in dental implant research. Comput Methods Biomech Biomed Engin 2006;9:257–70.

[16] Li T, Yang X, Zhang D, Zhou H, Shao J, Ding Y, et al. Analysis of the biomechanical feasibility of a wide implant in moderately atrophic maxillary sinus region with finite element method. Oral Surg Oral Med Oral Pathol Oral Radiol 2012; 114:e1–8.

[17] Schuller-Gotzburg P, Entacher K, Petutschnigg A, Pomwenger W, Watzinger F. Sinus elevation with a cortical bone graft block: a patient-specific three-dimensional finite element study. Int J Oral Maxillofac Implants 2012;27:359–68.

[18] Gabbert O, Koob A, Schmitter M, Rammelsberg P. Implants placed in combination with an internal sinus lift without graft material: an analysis of short-term failure. J Clin Periodontol 2009;36:177–83.

[19] Tabassum A, Meijer GJ, Wolke JG, Jansen JA. Influence of the surgical technique and surface roughness on the primary stability of an implant in artificial bone with a density equivalent to maxillary bone: a laboratory study. Clin Oral Implants Res 2009;20:327–32.

[20] Chang PC, Lang NP, Giannobile WV. Evaluation of functional dynamics during osseointegration and regeneration associated with oral implants. Clin Oral Implants Res 2010; 21:1–12.

[21] Huang HM, Lee SY, Yeh CY, Lin CT. Resonance frequency assessment of dental implant stability with various bone qualities: a numerical approach. Clin Oral Implants Res 2002;13: 65–74.

[22] Pattijn V, Van Lierde C, Van der Perre G, Naert I, Vander Sloten J. The resonance frequencies and mode shapes of dental implants: rigid body behaviour versus bending behaviour. A numerical approach. J Biomech 2006;39:939–47.

[23] Pommer B, Unger E, Suto D, Hack N, Watzek G. Mechanical properties of the Schneiderian membrane *in vitro*. Clin Oral Implants Res 2009;20:633–7.

[24] Underwood AS. An inquiry into the anatomy and pathology of the maxillary sinus. J Anat Physiol 1910;44:354–69.

[25] Ulm CW, Solar P, Gsellmann B, Matejka M, Watzek G. The edentulous maxillary alveolar process in the region of the maxillary sinus–a study of physical dimension. Int J Oral Maxillofac Surg 1995;24:279–82.

[26] van den Bergh JP, ten Bruggenkate CM, Disch FJ, Tuinzing DB. Anatomical aspects of sinus floor elevations. Clin Oral Implants Res 2000;11:256–65.

[27] Gosau M, Rink D, Driemel O, Draenert FG. Maxillary sinus anatomy: a cadaveric study with clinical implications. Anat Rec (Hoboken) 2009;292:352–4.

[28] Ding X, Zhu XH, Liao SH, Zhang XH, Chen H. Implant-bone interface stress distribution in immediately loaded implants of different diameters: a three-dimensional finite element analysis. J Prosthodont 2009;18:393–402.
[29] Seoane J, Lopez-Nino J, Tomas I, Gonzalez-Mosquera A, Seoane-Romero J, Varela-Centelles P. Simulation for training in sinus floor elevation: new surgical bench model. Med Oral Patol Oral Cir Bucal 2012;17:e605–9.
[30] Huang C, Chen L, Wu D, Chen Y. Finite element simulations of the contact stress between rotary sinus lift kit and sinus membrane during lifting process. Life Sci J 2012;9:167–71.
[31] Mellal A, Wiskott HW, Botsis J, Scherrer SS, Belser UC. Stimulating effect of implant loading on surrounding bone. Comparison of three numerical models and validation by *in vivo* data. Clin Oral Implants Res 2004;15:239–48.
[32] Morneburg TR, Proschel PA. Measurement of masticatory forces and implant loads: a methodologic clinical study. Int J Prosthodont 2002;15:20–7.
[33] Yan X, Zhang X, Gao J, Matsushita Y, Koyano K, Jiang X, et al. Maxillary sinus augmentation without grafting material with simultaneous implant installation: a three-dimensional finite element analysis. Clin Implant Dent Relat 2014. doi: 10.1111/cid.12254.
[34] Akca K, Cehreli MC. Biomechanical consequences of progressive marginal bone loss around oral implants: a finite element stress analysis. Med Biol Eng Comput 2006;44:527–35.
[35] Okumura N, Stegaroiu R, Nishiyama H, Kurokawa K, Kitamura E, Hayashi T, et al. Finite element analysis of implant-embedded maxilla model from CT data: comparison with the conventional model. J Prosthodont Res 2011;55: 24–31.
[36] Mericske-Stern R, Venetz E, Fahrlander F, Burgin W. *In vivo* force measurements on maxillary implants supporting a fixed prosthesis or an overdenture: a pilot study. J Prosthet Dent 2000;84:535–47.
[37] Morneburg TR, Proschel PA. *In vivo* forces on implants influenced by occlusal scheme and food consistency. Int J Prosthodont 2003;16:481–6.
[38] Han XL, Liu ZW, Li YT. [Three dimensional finite element analysis of biomechanical distribution of dental implants with immediate loading]. Hua xi kou qiang yi xue za zhi. Huaxi kouqiang yixue zazhi. West China J Stomatol 2011;29: 121–4.
[39] I-Chiang C, Shyh-Yuan L, Ming-Chang W, Sun CW, Jiang CP. Finite element modelling of implant designs and cortical bone thickness on stress distribution in maxillary type IV bone. Comput Methods Biomech Biomed Engin 2014;17: 516–26.
[40] Sennerby L, Roos J. Surgical determinants of clinical success of osseointegrated oral implants: a review of the literature. Int J Prosthodont 1998;11:408–20.
[41] Su YY, Wilmes B, Honscheid R, Drescher D. Application of a wireless resonance frequency transducer to assess primary stability of orthodontic mini-implants: an *in vitro* study in pig ilia. Int J Oral Maxillofac Implants 2009;24:647–54.
[42] Roze J, Babu S, Saffarzadeh A, Gayet-Delacroix M, Hoornaert A, Layrolle P. Correlating implant stability to bone structure. Clin Oral Implants Res 2009;20:1140–5.