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Original article

Bone morphological effects on post-implantation remodeling of maxillary anterior buccal bone: A clinical and biomechanical study

Nobuhiro Yoda DDS, PhD [a,*], Keke Zheng Graduate Student [b], Junning Chen PhD [c], Wei Li BE, ME, PhD [b], Michael Swain BSc, PhD [d], Keiichi Sasaki DDS, PhD [a], Qing Li BE, ME, ME(Res), PhD [b]

[a] Division of Advanced Prosthetic Dentistry, Tohoku University Graduate School of Dentistry, 4-1 Seiryo-machi, Aoba-ku, Sendai 980-8575, Japan
[b] School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, Australia
[c] Department of Biomaterials, Max Planck Institute of Colloids and Interface, Germany
[d] Department of Bioclinical Sciences, Faculty of Dentistry, Kuwait University, Kuwait

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ABSTRACT

Purpose: This study combines clinical investigation with finite element (FE) analysis to explore the effects of buccal bone thickness (BBT) on the morphological changes of buccal bone induced by the loaded implant.
Methods: One specific patient who had undergone an implant treatment in the anterior maxilla and experienced the buccal bone resorption on the implant was studied. Morphological changes of the bone were measured through a series of cone-beam computed tomography (CT) scans. A three-dimensional heterogeneous nonlinear FE model was constructed based on the CT images of this patient, and the *in-vivo* BBT changes are correlated to the FE *in-silico* mechanobiological stimuli; namely, von Mises equivalent stress, equivalent strain, and strain energy density. The anterior incisory bone region of this model was then varied systematically to simulate five different BBTs (0.5, 1.0, 1.5, 2.0, and 2.5 mm), and the optimal BBT was inversely determined to minimize the risk of resorption.
Results: Significant changes in BBTs were observed clinically after 6 month loading on the implant. The pattern of bone resorption fell into a strong correlation with the distribution of mechanobiological stimuli onsite. The initial BBT appeared to play a critical role in distributing mechanobiological stimuli, thereby determining subsequent variation in BBT. A minimum initial thickness of 1.5 mm might be suggested to reduce bone resorption.
Conclusions: This study revealed that the initial BBT can significantly affect mechanobiological responses, which consequentially determines the bone remodeling process. A sufficient initial BBT is considered essential to assure a long-term stability of implant treatment.

* Corresponding author.
E-mail addresses: nobuhiro.yoda.e2@tohoku.ac.jp, nyoda0730@gmail.com (N. Yoda).

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1. Introduction

Long-term stability is one of the most critical indicators to the success of dental implant treatment [1,2]. Other clinical indicators include the enhanced bone volume, health of peri-implant tissue and esthetic alignment with the natural teeth, etc. [3–5]. Especially in the anterior maxilla region, the buccal bone morphology around the implants is widely considered a primary feature in determining peri-implant tissue and soft-tissue esthetics [6–9]. Thickness of the buccal bone around the implant placed in the anterior maxilla is thus thought to be a critical factor for achieving a favorable outcome.

To date, several clinical findings concerning the bone volume reduction, especially the short-term morphological changes in the buccal bone around implant immediately placed into extraction sockets, have been reported in both animal [10–12] and human studies [13–15]. During the healing stage of immediately placed implant, marginal gaps between the implant and bone tissue are recognized to be closed with new bone formation, but this may be accompanied by bone resorption from the external ridge [13,14]. Clinically, it has been suggested that a minimum buccal bone thickness (BBT) of 2mm is required for maintaining a proper soft-tissue support on implant [6,7]. This threshold may be interpolated correctly from short-term observation during the bone healing periods after implant placement [16].

A major clinical challenge is that the BBT can continuously reduce over a long period of time even with an implant inserted in the healed maxillary anterior ridge [17]. The buccal bone on the implant may likely to resorb due to adverse remodeling activities induced by implant placement and functional loading, evidenced by the recent longitudinal computed tomography (CT) studies (7 years) [18,19]. Another case-series study revealed that none of the examined implants had complete buccal bone coverage after an average of 8.9 years in the non-bone grafted implant treatments [20]. Consequently, such bone resorption can lead to not only the instability of the implant, but also a high risk of soft tissue recession [6,21]. Unfortunately, there has been limited information available regarding the mechanism behind BBT reduction to recommend the required minimal BBT on the implant in the anterior maxillary for ongoing longitudinal stability, thereby preventing bone resorption under loading.

This study aimed to investigate bone morphological changes in the anterior maxilla after loading, where a patient-specific clinical case was investigated for ongoing time-dependent buccal bone reduction. A series of CT scans were acquired at different time points to measure morphological changes in bone, which was correlated to the mechanobiological stimuli obtained from three-dimensional (3D) patient-specific finite element (FE) analysis. Intrinsically, this study established an *in-silico* approach to exploring the effects of initial BBT on mechanobiological responses, thus estimating the potential bone remodeling outcomes in various bone morphologies. This new framework with both *in-vivo* clinical measurements and *in-silico* numerical modeling provides an effective tool for predicting the bone remodeling activities with different surgical options; thereby gaining new clinical and biomechanical insights into the minimal BBT required for preventing bone resorption.

2. Materials and methods

2.1. Patient condition and treatment

A 52-year-old healthy female patient, who experienced the buccal bone resorption on the implant after loading, was recruited. The patient was diagnosed with tooth root fracture of her maxillary right incisor at the Dental Implant Center, Tohoku University Hospital in Japan. As a result of the treatment consultation, the patient chose to replace the fractured tooth with the dental implant restoration. The initial cone-beam (CB) CT scan (3D Accuitomo, MORITA Corp., Kyoto, Japan) was performed at a standardized exposure of 90kV and 35mA and with slice width of 0.25mm before tooth extraction (Scan-1), and then flap-less tooth extraction was undertaken. The SimPlant software (Materialise Dental, Leuven, Belgium) was used for 3D surgical planning with the position and orientation of implant placement. The planning results were transferred to the surgery and implemented by means of a stereolithographic surgical guide system (SurgiGuide, Materialise Dental). An implant (Osseospeed TX 3.5S, DENTSPLY Implants, Mölndal, Sweden), with 3.5mm diameter and 13.0mm length, was inserted after a healing period of 8 week post extraction stabilization [4]. The implant showed good primary stability after placement with an insertion torque $\geq$20Ncm. The second CBCT scan (Scan-2) was performed at the same setting in 6 months after implant placement, along with installation of a temporary crown for loading. The third CBCT scan (Scan-3) was performed 12 months after the implant placement (*i.e.* 6 months with loading) during the follow-up examination. After the final restoration, the patient was recalled every 3 months for prosthetic and oral hygiene examinations.

The research protocol for this study was approved by the research ethics committee of Tohoku University Graduate School of Dentistry (Reference Number 26-34). The patient has given written consents for utilizing the image data and publishing these case details after full explanation of the procedure, risks and benefits.

2.2. Image processing and analysis

The CBCT data were processed with medical image viewer software (EV Insite S, PSP, Tokyo, Japan), which allows the detection and alignment of anatomic landmarks between the different cross-sectional examinations. The buccal-palatal cross-sectional images were selected for dimensional comparison across the implant by the multiple planar reconstruction (MPR) technique [22]. BBT was measured in terms of the thickness between the outer surface of cortical bone and implant-bone interface. The lines parallel to the implant platform were placed at 1, 2, 4, 6, 8, and 12mm apical to the implant platform (Fig. 1), to measure the distances from the implant surface (thread peaks) to the outline of the buccal bone. In this study, the bone morphological changes,

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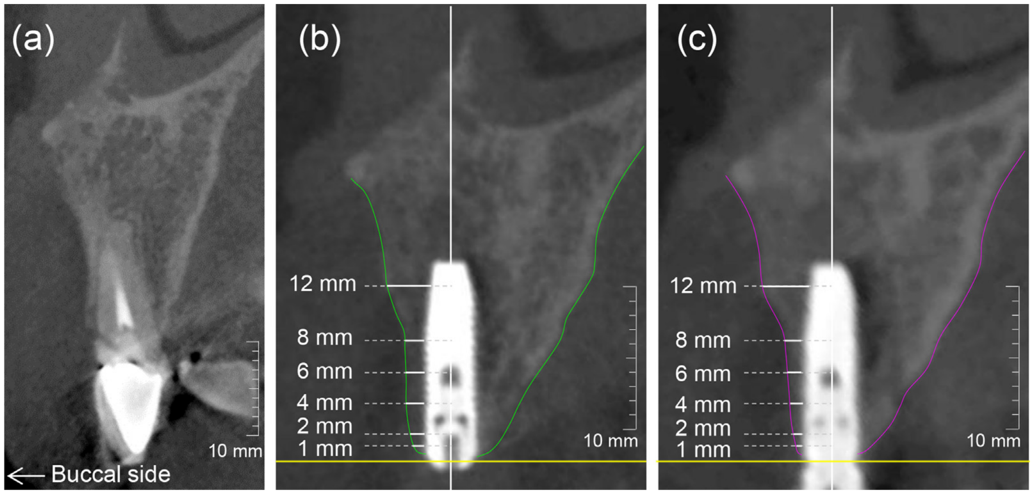

Fig. 1 – 2D sectional images of CBCT.
(a) Initial consultation (Scan-1), (b) 6 months after implantation (Scan 2), and (c) 6 months after loading (Scan-3); Six measurements were set at 1, 2, 4, 6, 8, 12 mm from implant platform (yellow line in (b and c)). Solid line: bone outer surface (green line (b) and purple line (c)).

particularly between the second and the third scans, were evaluated quantitatively.

2.3. *Finite element modeling*

Case-specific finite element (FE) models were created for this patient based on Scan-2. The CBCT images were imported into ScanIP Ver. 4.3 (Simpleware Ltd, Exeter, UK) for segmentation. The segmented masks (bone, individual tooth and periodontal ligament (PDL)) were further processed in Rhinoceros 4.0 (Robert McNeel & Associates, Seattle, USA) to create parametric models with non-uniform rational B-spline (NURBS). Following development of the maxilla model with dentition, the implant with abutment and screw was modeled according to the manufacturing specifications in Solidworks 2013 (SolidWorks Corp, Waltham, MA, USA) (Fig. 2a). The superstructure was modeled based upon the native tooth profile. Those components were assembled and virtually inserted into the maxilla model in Rhinoceros 4.0 as guided by the CBCT images (Fig. 2b). An assumption of complete implant-bone contact, implying 100% osseointegration, was made [23–25]. The various contacts between implant components, such as implant body, screw, abutment, and superstructure were also assumed to be perfectly bonded. The final assemblies were exported to ABAQUS 6.9.2 (Dassault Systèmes, Tokyo, Japan) for FE meshing (Fig. 2c). The final meshes contain 431,156 degrees of freedom using 10-node quadratic tetrahedral elements with hybrid formulation (C3D10H). To ensure the numerical accuracy, a mesh convergence test was carried out as done previously [26].

In this patient-specific FE model, BBT was approximately 0.5 mm measured at the implant platform area. By using virtual topographical modification, four different BBTs were offset based on this baseline model to replicate bone grafting in the buccal bone region by using a smooth offsetting procedure, with an increment of 0.5 mm to the initial model from 0.5 to 2.5 mm in Rhinoceros. The specific buccal bone region was determined as the rectangular area covered between the length of dental implant and the breadth of the intra-implant-tooth distance (the green square-shaped area in Fig. 2c).

Although linear elastic and homogenous material models have been widely used to describe bone in most of previous FE studies, such assumptions may not adequately replicate the nature of this complex mineralized tissue and its responses to mechanical loading. In this study, maxillary bone was characterized with site-specific material properties, as per localized Hounsfield Unit, in order to more precisely reflect the anatomical variation in density and modulus, which can affect biomechanical responses (Fig. 2d). Teeth and dental implants were assumed to be linear elastic. All the material properties adopted in this study are summarized in Table 1.

A masticatory force was set to be 38.3N. This value was obtained from the measured force *in vivo* by crushing a peanut through a single implant-supported crown at the maxillary incisor region using an in-house built apparatus [31]. The load transfer angle was set as 65° to the long axis of the implant, as measured between the upper and the lower incisor tooth axes in the cast model of the patient (Fig. 2e).

Regions of interests (ROIs) were placed at the entire peri-implant area concerned. A special section for measurement of the stimuli distribution in the buccal bone surface area was also drawn from the implant platform to implant apex area (the red curve in Fig. 2e). Full kinematic constraints were applied to the lateral and upper-sectioned planes of the maxillary bone (Fig. 2f). For the implant-supported restoration, the implant screw threads were assumed to be fully bonded with surrounding bone in complete osseointegration [23–25,32].

Several different mechanobiological stimuli have been adopted in the previous studies on bone remodeling [23,24,33]. In this paper, we considered three common stimuli estimations; namely von Mises equivalent stress

Table 1 – Material properties adopted in FE modelling.

Materials	Young's modulus (MPa)	Poisson's ratio
Bone [27,28]	Heterogeneous	0.30
PDL [29]	Hyperelastic (Marlow)	0.45
Teeth [29]	20,000	0.20
Titanium (implant, abutment, screw) [30]	110,000	0.35
Ceramic crown [25]	140,000	0.28

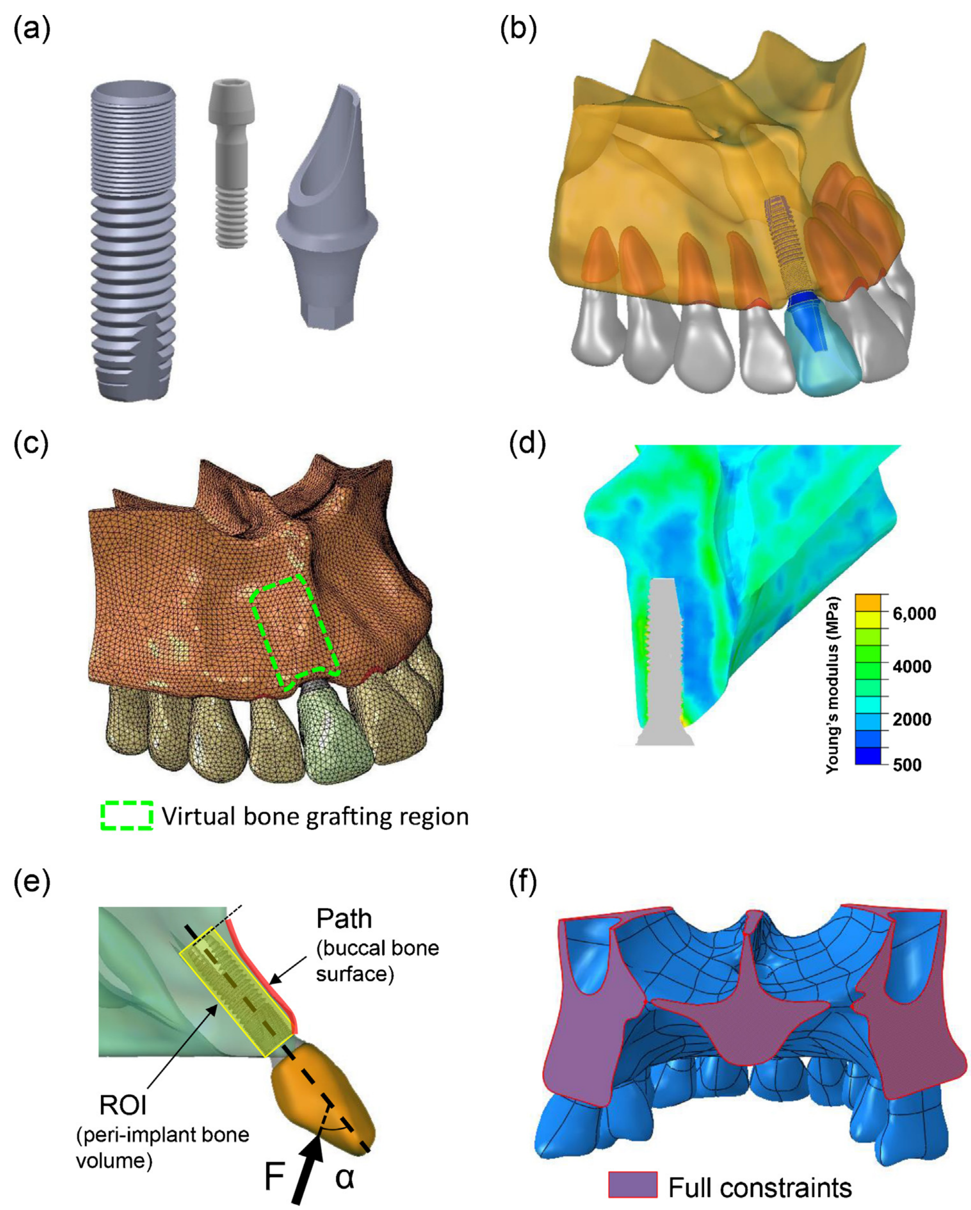

Fig. 2 – Process of FE model construction.
(a) Solid models of the implant, abutment and screw; (b) masks created for each individual component in ScanIP: virtual insertion of the implant in Solidworks; (c) final model meshed in ABAQUS; (d) site-specific material properties of osseous tissues assigned based on the Hounsfield Unit values from the CBCT data through a FORTRAN program in ABAQUS user subroutine; (e) region of interests (ROIs) in peri-implant and the path on the buccal bone surface, loading condition: F = 38.3 N, α = 65°; and (f) kinematic boundary conditions.

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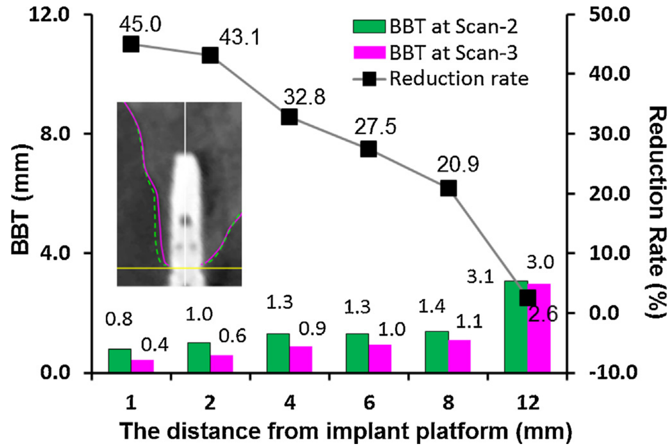

Fig. 3 – Horizontal dimensional changes in the buccal bone.
Horizontal bone dimensions (BBT) at 6 months after implant placement (green) and 6 month after loading (*i.e.* 12 months after implant placement) (pink) in this specific patient, as well as the corresponding reduction rates (black square dot in a curve).

(VMS) [34], equivalent strain (EQS) [35] and strain energy density (SED) [23,24]. The correlation of these biomechanical stimuli *in silico* with the different BBT measurements *in vivo* was evaluated to determine the effect of BBT on bone morphological change.

3. Results

3.1. *Bone morphological changes*

The bone morphological changes after 6 month loading (*i.e.* between Scan-2 and Scan-3) are plotted in a bar chart as shown in Fig. 3. It is found that the decrease of BBT was substantial at all the measurement points after 6 months of loading, and the reduction was greatest at 1 mm from the implant platform but decreased gradually in the apical direction.

3.2. *Mechanobiological stimulus distributions on buccal bone surface*

As shown in Fig. 3, bone resorption was observed on the buccal bone surface area mainly from the implant platform to two thirds of the implant length, whereas little change in bone morphology appeared in other areas. To conduct a more quantitative comparison, Fig. 4a plotted the VMS, EQS, and SED values along the path on the outer surface of buccal bone as defined in Fig. 2e, and the corresponding *in-vivo* measurements of the initial BBT (Scan-2) were labeled. An inversely proportional relationship between the stimuli and initial BBT was obtained, *i.e.* the stimuli on the outer surface of buccal bone dropped quickly toward the apex of the implant with an increase in bone thickness.

More importantly, changes in BBT over 6 month loading are strongly associated with the distributions of mechanobiological stimuli on the buccal bone surface as plotted in Fig. 4b, implying that the status of mechanical stimulation on the outer surface of buccal bone appeared to be a primary determinant for surface remodeling activity in the bone.

3.3. *BBT effects on mechanobiological stimulus*

Since bone grafting can clinically provide a range of BBTs prior to implantation, five different BBTs (0.5, 1.0, 1.5, 2.0, and 2.5 mm) were virtually modeled in this study (upper row in Fig. 5a). SED distributions were shown in the lower row in Fig. 5a as an example to explore the changes in mechanobiological stimuli distribution. As BBT increased, the concentration of SED on the surface of buccal bone on implant platform decreased.

To compare the mechanobiological stimulus contours of buccal bone area in the different BBTs, the 2D sectional planes were selected (Fig. 5b). Although high values of VMS and SED were observed around the implant neck, their high values on the surface bone areas, which were correlating well with the clinical measurement of buccal bone resorption, gradually decreased as BBT increased. EQS was however observed to have higher values at the bone surface areas of the implant neck, which does not seem to be correlated well with the clinical bone resorption area.

To better evaluate the effect on the mechanobiological stimuli in the peri-implant region, the volume average of the VMS, EQS and SED were plotted against the corresponding BBTs in Fig. 6. These average values decrease monotonically with the increase in BBT. The regression analysis of those mechanobiological stimuli against the different BBTs showed a strong correlation (VMS: R^2=0.9852; EQS: R^2=0.9825; and SED: R^2=0.9882) in a power-law form as given in Eqs. (1)–(3) (where d denotes BBT in mm).

$$\sigma_{VMS} = f_{VMS}(d) = 1.6449d^{-0.209} \quad (1)$$

$$\varepsilon_{EQS} = f_{EQS}(d) = 0.00004d^{-0.209} \quad (2)$$

$$\sigma_{SED} = f_{SED}(d) = 0.0005d^{-0.293} \quad (3)$$

4. Discussion

Recent CT follow-ups revealed that more significant resorption occurred locally on the buccal bone on the implant placed in the anterior maxilla [18–20], leading to insufficient bone

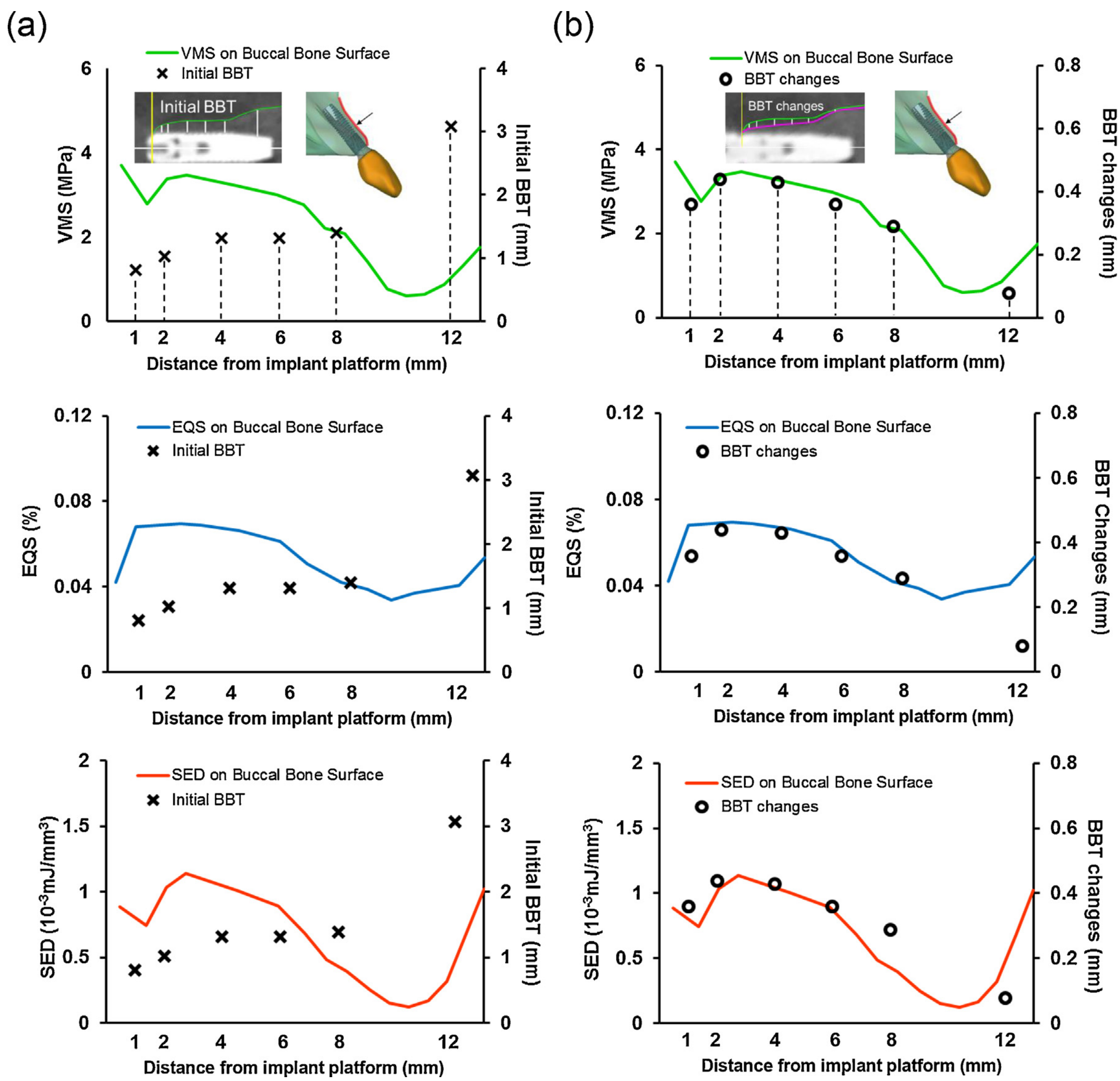

Fig. 4 – Correlation between BBT and mechanobiological stimuli on buccal bone surface.
(a) Correlation between the initial BBT and the mechanobiological stimulus distributions on the buccal bone surface, (b) correlation between the BBT changes during 6 months of loading and the mechanobiological stimulus distributions on the buccal bone surface.

volume to maintain the functionality and esthetics of an implant treatment. In contrast to other efforts dedicated to understanding of the bone-implant interface, little has been investigated as to the effects of BBT on the consequential buccal bone dimensional changes on an implant. This study provides some biomechanical insights into the time-dependent change in BBT post loading on implant.

4.1. *Correlation between in-vivo clinical measurements and in-silico biomechanical responses*

The BBT changes were measured using 2D sectional images of the CBCTs clinically obtained from a specific patient. The measurement of bone dimension was determined with reference to the existing criteria in literature, *i.e.* the BBT around implant [17,36]. In this patient, the buccal bone appeared to be mainly resorbed horizontally on the implant platform region and the resorption became less toward the apical region of the implant.

The FE model of the maxillary bone was characterized with site-specific material properties as per Hounsfield Unit [27,28,37], which enabled more realistic interpretation of peri-implant bone remodeling results. Quantitative comparison of the mechanobiological stimuli distribution on buccal bone surface with clinical measurement of the BBT changes showed good agreement (Fig. 4b), demonstrating the importance of biomechanical responses to bone surface remodeling. From a biomechanical perspective, latest CT imaging techniques and computational modeling methods demonstrated that the remodeling processes, independent apposition and resorption events, could be monitored clinically in a time-dependent fashion; and modeling and remodeling could be

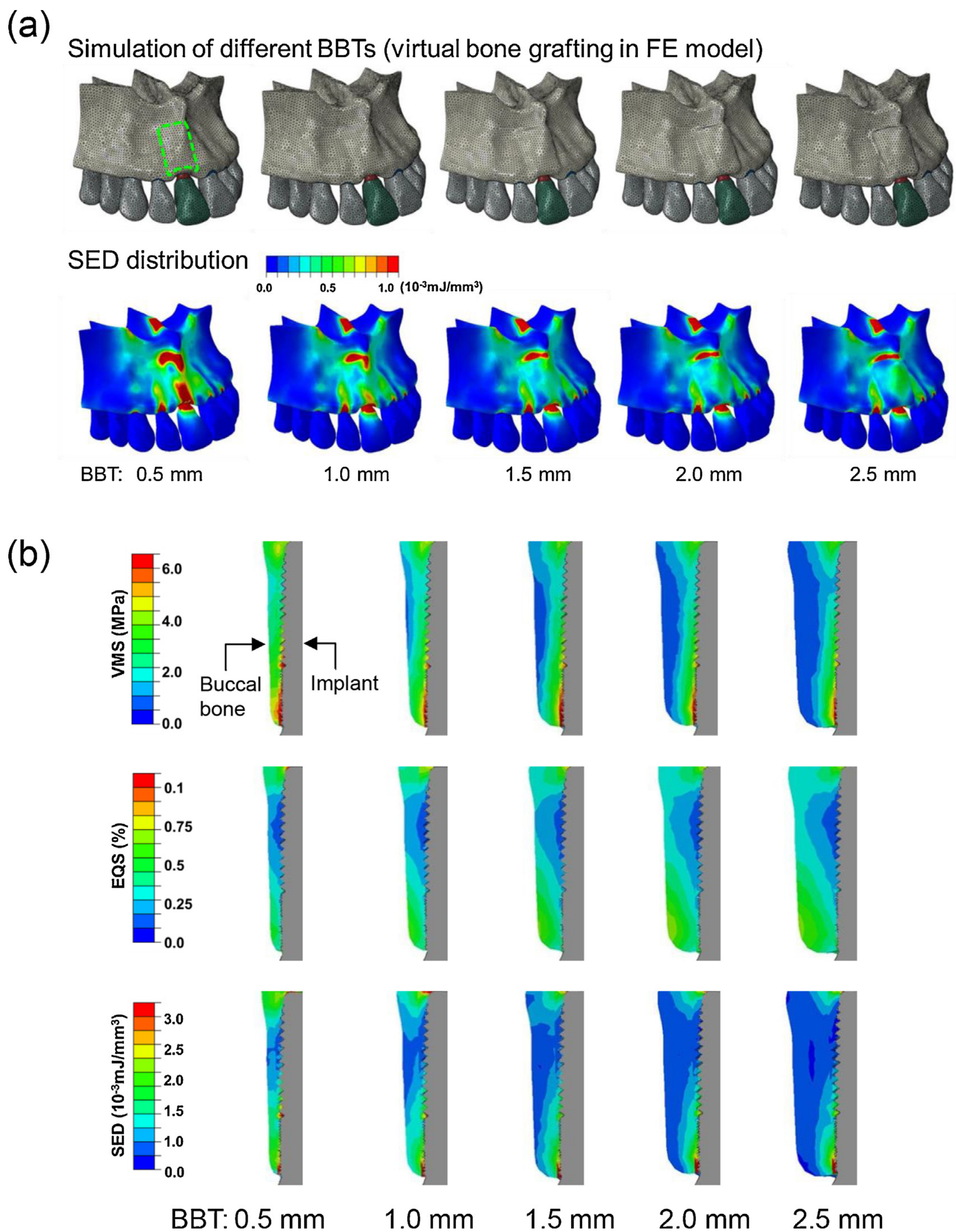

Fig. 5 – The mechanobiological stimuli in buccal bone area with different BBTs.
(a) FE models (upper row) and the examples of SED distribution (lower row) after virtual bone grafting. (b) Cross sectional images of buccal bone on implant for investigating the distribution of VMS, EQS, and SED in different BBTs.

distinguished on the bone surface [38]. This study thus focused more on the distribution and magnitudes of mechanobiological stimuli on the outer surface of buccal bone.

Veltri et al. showed through the clinical CBCT analysis of an anterior maxillary implant that buccal bone resorption occurred in the neck region of the implant (thin bone area) in most cases [20]. They also considered that the implants with the greatest interproximal remodeling were associated with a smaller buccal bone volume in the coronal portion and thinner bone, both buccally and marginally, which supports the findings obtained in our study. Interestingly, on the other hand, the buccal bone seems to be well preserved around a healthy natural tooth even with a thin thickness of 0.5–1.0 mm, commonly appearing in the majority of maxillary anterior teeth [39,40]. The soft tissue, especially the PDL, was believed to play an important role as a buffer in distributing the

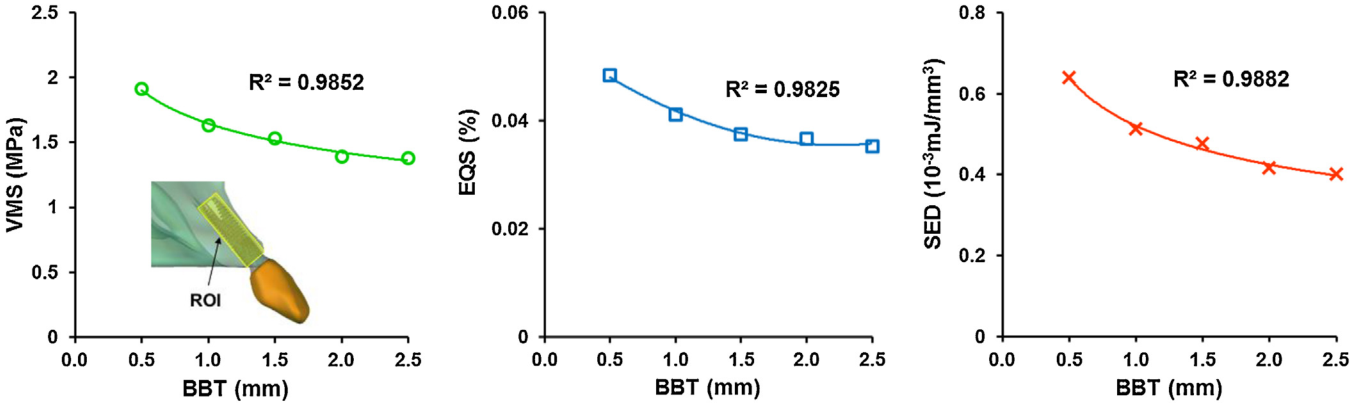

Fig. 6 – Volume average values of mechanobiological stimuli in peri-implant ROI with different BBTs.

mastication force [41], by preventing excessive stress induced by occlusal function from direct transfer to the buccal bone, rather than a hard-to-hard contact in the implant-bone interface [42]. Note that a sufficient blood circulation provided from PDL may contribute to the modeling and remodeling activity on the buccal bone region around the tooth. The absence of PDL may thus be one of the causes to the resorption on the buccal bone around the implant.

4.2. *Effect of BBT on the mechanobiological stimuli distribution*

In the present analysis, the average values of the mechanobiological stimuli in peri-implant ROI gradually decrease as BBT increases (Fig. 6). Thick BBT can contribute on the equilibrium of the stimuli distribution in peri-implant bone area. In addition, the mechanobiological stimuli on the outer surface of buccal bone were found to be lower in the thicker BBT, which suggested a significant role of BBT on the mechanobiological stimuli distribution (Fig. 5). Many biomechanical studies have demonstrated the effects of such mechanobiological stimuli on the peri-implant bone responses [23–25]. Therefore, the initial presence of sufficient buccal bone volume at implant placement can be one of the essential factors for preventing the bone from resorption under loading. The pre-implantation bone grafting can be recommended in the insufficient bone volume cases for long-term stability of buccal bone morphology.

4.3. *Clinical implication and limitations*

Based on the limited data, the distribution of mechanobiological stimuli on the buccal bone surface can be a critical factor for determining horizontal buccal bone remodeling. The VMS and SED contour were more spread out in the buccal rather than axial direction with over 1.5 mm BBT, which provides us with a biomechanical ground to determine the minimum initial BBT required. Considering the previous biomechanical literature, the SED appears to be best correlated with the clinical bone responses for the regions that concerned most with high risk of bone resorption [23,24]. Further, this study suggested the biomechanical benefits of pre-implantation bone grafting.

There are still inherent limitations in this patient-based study. First, while the specific patient was modeled to establish a conceptual assessment framework accounting for buccal bone responses here, all the interfaces between different tissues/materials were assumed to be fully bonded and osseointegrated completely. This assumption would have affected the transfer of occlusal load to the bone around an implant. Second, this study was based on the findings from only one patient and the follow-up period of this patient was only 1year after implant placement. A large scale of patient cases is certainly required to obtain the populated significance on this topic. Also, further follow up observations of this patient is still considered necessary to obtain more detailed longer term data of the biomechanical bone responses. Third, the physiological reduction in bone volume following tooth extraction may affect the measured BBT changes [43], though bone stability was clinically determined before loading and a strong association of changes in BBT with distributions of mechanobiological stimuli on the buccal bone surface was quantitatively observed (Fig. 4b). Fourth, the implant dimension, implant-abutment connection patterns and loading conditions, such as magnitude and direction, can all influence bone responses [44,45]. Although those factors were beyond the scope of this paper, further research is needed to more realistically clarify the biomechanical responses induced by the implant treatment.

5. Conclusions

This study presented clinical investigation into the morphology changes of buccal bone in a patient-specific case in the anterior maxillary incisor region. It combined the *in-vivo* clinical measurements with *in-silico* computational modeling to examine the effects of buccal bone thickness (BBT) on the bone remodeling. The 3D finite element analysis (FEA) results of different mechanobiological stimuli were quantitatively compared with the cone-beam computed tomography (CBCT) measurements over a one year period of clinical follow-up, in which the patient exhibited changes in BBT. A strong correlation was obtained between the mechanobiological stimuli on the surface of buccal bone area and the BBT changes. The FEA revealed that the increased BBT allowed stress distributing more evenly in the peri-implant region. Importantly, this patient-specific assessment approach provided us with a procedural tool to explore the minimal requirement of BBT around implant, thereby helping clinicians to optimize surgical plan for implantation involving the bone augmentation for maximizing clinical success and longevity of treatment.

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