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Article

The Combination Effects of Age-Related Bone Mechanical Property, Cortical Bone Thickness and Incisal Relationship on Biomechanical Performance of Narrow Diameter Implant Placed in Atrophic Anterior Maxilla: Finite Element Analysis

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Abstract. Atrophic anterior maxilla edentulous space could pose a significant challenge to successful osseointegrated implant due to inadequate labio-palatal dimensions. The load transferring to surrounding bone is a key factor for the long-term success of implant treatment. Thus, the aim of this study was to evaluate the influence of bone quality change in age-related bone mechanical property (AMP), cortical bone thickness (CBT) and incisal relationship (ICR) on the biomechanical performance of narrow diameter implant placed in atrophic anterior maxilla via finite element method. Three-dimensional models of a narrow diameter implant and an anterior maxillary bone were constructed. Eighteen different clinical situations including two CBTs [thin (0.5 mm) and thick (1.0 mm)], three AMPs [young, middle and old ages] under three ICRs [a low overbite (LO), a mean overbite (MO), a high overbite (HO)] were studied under the loading of 50.1 N. From the results, it is crucial to consider the critical situations of narrow diameter implant placed in atrophic anterior maxilla where the combination of the thin CBT, old age-AMP and HO-ICR clinical situation which induce surrounding bone resorption and implant damage.

Keywords: Narrow diameter implant, atrophic anterior maxilla, age-related bone mechanical property, cortical bone thickness, incisal relationship, biomechanical performance.

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1. Introduction

Currently, osseointegrated implant is intended to replace the missing tooth. It is a successful treatment modality, although the previous study reported that implants placed in the anterior mandible had a high survival rate, however the lower survival rates were observed in the anterior maxilla [1]. According to biomechanical aspect, load transferring to surrounding bone is a key factor for the long-term success of implant treatment. Thus, the important factors for a successful of a treatment are implant characteristics, such as an implant diameter, a quality of surrounding bone and a direction of loading that could affect biomechanical behaviors of osseointegrated dental implants, especially in the anterior maxilla.

Atrophic anterior maxilla edentulous space could pose a significant challenge to successful osseointegrated implant due to inadequate labio-palatal dimensions. Bone availability is usually a limiting factor in planning dental implant treatments. Bone resorption in the apico-occlusal and labio-palatal direction will also affect the implant selection. Tooth extraction commonly caused the alveolar bone to decrease in bone quantity and a change in bone morphology. The reduction of alveolar bone quantity following tooth extraction may influence the treatment outcome of osseointegrated implant. Clinically, standard diameter dental implants ensure an adequate bone to implant contact, which is inadequate for edentulous ridges that require bone augmentation. Considering the increased expense and surgical complication of bone augmentation, an alternative approach in clinical conditions of a limited amount of available alveolar bone width is to use narrow diameter implants. Sierra-Sánchez et al. [2] suggested that a narrow-diameter implant is generally taken to have a diameter from 3.0 to 3.5 mm.

According to bone structural, the cortical bone thickness (CBT) of surrounding bone is an important factor that affects bone resorption, which leads to implant stability. A high strain concentration in crestal cortical bone around the neck of implant would lead to the progression of crestal cortical bone loss and implant instability. The age-related bone mechanical property (AMP) also affects the magnitude of strain in the bone. Theoretically, the osseointegrated implant acts like a column elastically supported by the crestal cortical bone. Because of the relation of the upper and lower incisors when they are in contact, the load direction is not in the long axis of an implant. According to the incisal relationship (ICR), Steadman [3] demonstrated that, the direction of loading force varies due to different forms of overbite (low, mean, high). Clinically, the incisor classification is simpler and reliable. Katz [4] suggested that classification aids in the diagnosis and treatment planning of malocclusions by orienting the clinician to the type and the magnitude of the problems, possible mechanical solutions to the problems and also facilitates communication between clinicians. There is insufficient evidence to set a threshold for a minimal bone thickness to ensure an optimal biomechanical performance, although it has been suggested that it is crucial to have a labial bone plate of at least 1.0 mm. Because the loads of the anterior maxilla are in the outward direction, this labial bone has a special role in enduring the loads.

A literature review reported that placement of narrow diameter implants offers survival rates similar to the placement with implants of greater diameter [5-6]. However, researchers suggested that further studies are needed, with longer follow-up periods, in order to verify these reports [2, 7]. The important factors for the long-term failure of a dental implant have been focused on the biomechanical complications. Major problem leading to such failures may be lack of understanding of biomechanical behavior. The ability to predict the biomechanical behavior of implant components and supporting bone is important for a predictable treatment result. Finite element method (FEM) is an effective computational tool that has been adapted from the engineering arena to the medical field. Wattanutchariya et al. [8] analyzed the effect of combine loading on hydroxyapatite-bioactive glass plate that fixed to the humerus bone by FEM. Pakawan et al. [9] used FEM to studied the constitutive models and compressive performance of polydimethylsiloxane micropillar sheets that can be applied as superhydrophobic films for coating on medical devices as antifouling surfaces. Tarapoom and Puttapitukporn [10] evaluated the accuracy of finite element models and influence of human tibia structures and material properties on the stress distribution in human tibia. The FEM has been used widely in the prediction of biomechanical performance of dental implant systems [11]. In addition, it has been applied to orthodontics field. For example, Cho et al. [12] used FEM to explore the influence of internal implant-abutment engagement systems on the stress distribution in the abutment, the implant and the bone surrounding the implant. Hudieb et al. [13] utilized FEM to study the effect of an implant placement with a first thread above the crestal cortical bone on bone stress and bone strain. Joshi et al. [14] employed FEM to analyze the influence of the bar heights of mandibular supported overdenture on the bone stress distribution. Toniollo et al. [15] used FEM to compare the stress distribution of the ordinary prosthesis supported by three implants and pontic prosthesis supported by two implants. Shinya et al. [16] investigated the difference of strain and stress distribution in the bone in case of the dental implants that made of titanium and fiber-reinforced composite by FEM. Zhou et al. [17] applied FEM to study the influence of the distance between the mini implant and the tooth root on the biomechanical behavior of the bone. Fongsamootr and Suttakul [18] used FEM to study the effect of a periodontal ligament on the movement of tooth and stress distribution in a surrounding bone. Therefore, the aim of this study was to investigate the combination effects of CBT, AMP and ICR on the biomechanical performance of narrow diameter implant placed in atrophic anterior maxilla by finite element analysis.

2. Materials and Methods

A three-dimensional (3-D) model of an edentulous anterior maxilla bone section and a crown were created from 3-D scan data of artificial models, which consisted of a trabecular bone surrounded by a cortical bone. The thicknesses of the cortical bone were modeled as 1.0 mm (thick CBT) and 0.5 mm (thin CBT). Three-dimensional

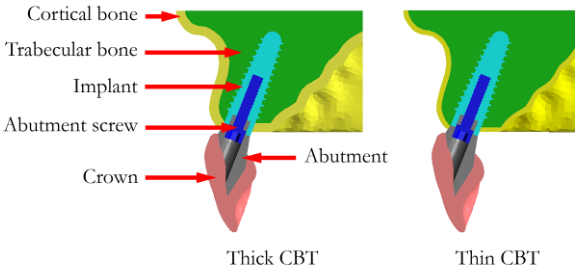

Fig. 1. Labio-palatal section of 3-D models of a narrow diameter implant placed in atrophic anterior maxilla.

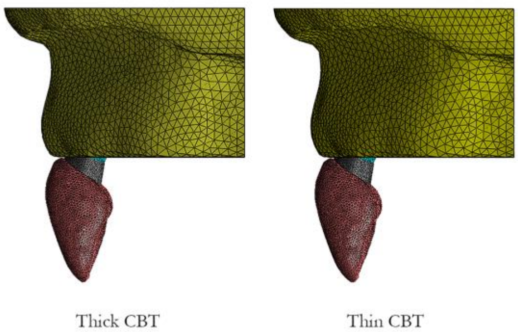

Fig. 2. Finite element models of a narrow diameter implant placed in atrophic anterior maxilla.

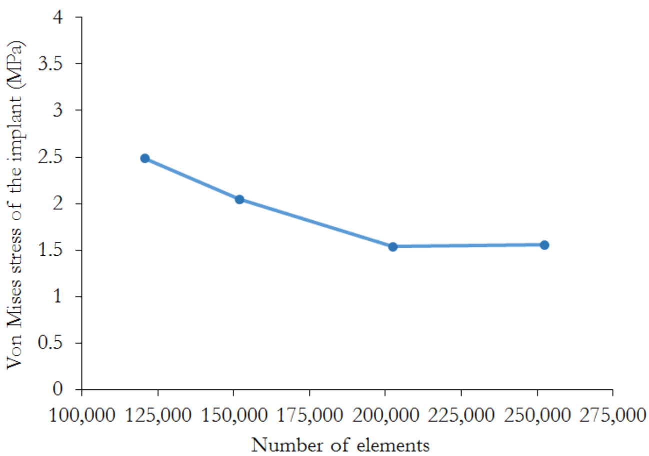

Fig. 3. Von Mises stress and the number of elements in convergence testing.

CAD models of a generic narrow diameter implant size 3.2×10 mm, an abutment, an abutment screw and a crown were created. All components were aligned to their position as shown in Fig. 1. The stereolithography (STL) files that were triangulated surfaces of 3-D models were imported to mesh generation software MSC.Patran (MSC software). According to an STL-based meshing, which can fit to free-form geometry, therefore, the element type used in this study was 4-node tetrahedral as shown in Fig. 2. The simulation was performed in finite element software MSC.Marc-Mentat (MSC software). Because the FEM is an approximate method, the number of elements can affect the accuracy of the results. However, the finer mesh increases the computational time of the computer. In order to determine the appropriate number of elements, a convergence test for the element quality of four different number of elements of a thin CBT model was performed as shown in Fig. 3. The relation between the von Mises stress of the implant and the number of elements showed that the appropriate number of elements was that started from 250,000 elements. Table 1 shows the number of elements and nodes used in this study. The difference of AMP was modeled by varying the Young's modulus according to study of Martens [19] which reported the Young's modulus of the cortical bone and trabecular bone for the age of 29, 47 and 77 that represent young age, middle age and old age people, respectively, as shown in Table 2. Geng et al. [11] have reported constant Poisson's ratio although different types of bone. The material properties of zirconia crown and titanium alloy of implant, abutment and abutment screw were taken from literature [20-21] as shown in Table 3.

Table 1. Numbers of elements and nodes used in this study.

Models	Elements	Nodes
Model with CBT of 0.5 mm	252,384	59,614
Model with CBT of 1.0 mm	261,214	60,889

Table 2. Material properties of cortical and trabecular bone used in this study.

Materials	Young's modulus (MPa) [19]	Poisson's ratio [11]
Cortical bone (young age)	18,100	0.3
Cortical bone (middle age)	17,100	0.3
Cortical bone (old age)	16,800	0.3
Trabecular bone (young age)	517	0.3
Trabecular bone (middle age)	262	0.3
Trabecular bone (old age)	163	0.3

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Table 3. Material properties of zirconia and titanium alloy.

Materials	Young's modulus (MPa)	Poisson's ratio
Zirconia [20]	210,000	0.3
Titanium alloy [21]	110,000	0.28

For the boundary conditions, a bite force of 50.1 N [22] that represented a chewing load was applied and the location and the direction of force were varied according to the study of Steadman [3] as indicated by the red arrows in Fig. 4. For a mean overbite (MO), the bite force was applied at a point below the cingulum of the crown with the angle of 87°. For a high overbite (HO), the bite force was applied at a point behind the cingulum of the crown with the angle of 80°. Finally, a low overbite (LO), the bite force was applied at a point anterior of the cingulum of the crown with the angle of 103° relative to a horizontal plane as shown in Fig. 4.

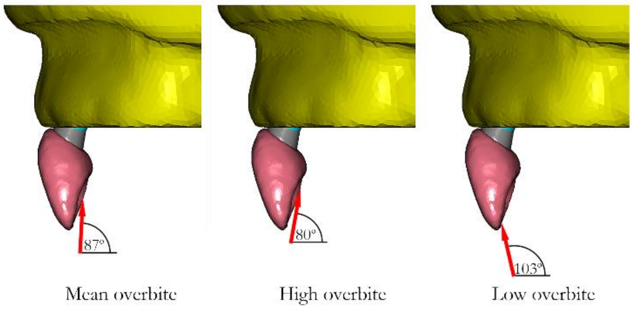

Fig. 4. Load direction of different ICRs.

Table 4. Analyzed cases in this study.

Case	Age	CBT (mm)	ICR
0.5-YM	Young	0.5	MO
0.5-YH	Young	0.5	HO
0.5-YL	Young	0.5	LO
1.0-YM	Young	1.0	MO
1.0-YH	Young	1.0	HO
1.0-YL	Young	1.0	LO
0.5-MM	Middle	0.5	MO
0.5-MH	Middle	0.5	HO
0.5-ML	Middle	0.5	LO
1.0-MM	Middle	1.0	MO
1.0-MH	Middle	1.0	HO
1.0-ML	Middle	1.0	LO
0.5-OM	Old	0.5	MO
0.5-OH	Old	0.5	HO
0.5-OL	Old	0.5	LO
1.0-OM	Old	1.0	MO
1.0-OH	Old	1.0	HO
1.0-OL	Old	1.0	LO

The displacements of all nodes at the top and the back of the maxilla were fixed. The interface between titanium alloy components and the bone were assumed osseointegrated. This situation was simulated using a glue contact condition of the MSC.Marc-Mentat software. This condition enables contact bodies to adhere together. The crown was assumed cemented to the abutment. The glue contact condition was applied to the interface between the crown and abutment as well. The contacts between titanium alloy components were modeled by a touch contact condition of the MSC.Marc-Mentat software. By this condition, adjacent contact bodies were able to slide and separate from each other. The touch contact was applied to the contacts among titanium alloy components to simulate their mechanical locks to each other and the frictional coefficient was assigned equal to zero to simplify the calculation. Therefore, 18 cases were analyzed as shown in Table 4. The stress in the implant, abutment screw, strain in the bone and the implant displacement were used to compare the biomechanical performance of the narrow diameter implant.

3. Results

The results of this study showed the combination effects of the CBT, AMP and ICR on biomechanical parameters consisted of the strain distribution pattern and the maximum strain exhibited in surrounding bone, the maximum stress in the implant and abutment screw and the implant displacement.

3.1. Strain Distribution in Surrounding Bone

Strain is a mechanical parameter that contributes to the adaptation of a bone around an implant subjected to an occlusal load. According to Frost's mechanostat theory, the magnitude of strain over 4,000 microstrain resulted in a resorption of a bone [23]. This causes a complication in a treatment by dental implantation. Since the labial bone play an important role in supporting an occlusal load, therefore the strain distribution pattern in the bone in a labio-palatal plane that passed through the center of the implant as shown in Fig. 5 was analyzed. From the strain distributions as shown in Fig. 6, it can be observed that the strain was concentrate at the labial side adjacent to the implant neck and tip of all CBTs, ICRs and AMPs. In overall, the thin CBT exhibited a larger

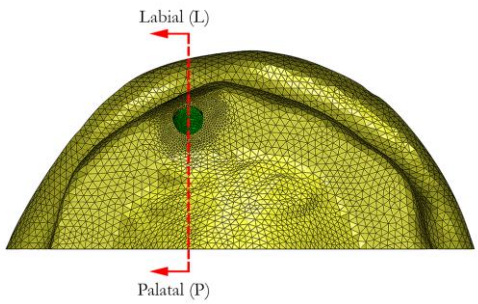

Fig. 5. Cutting plane for strain distribution in surrounding bone (labio-palatal plane).

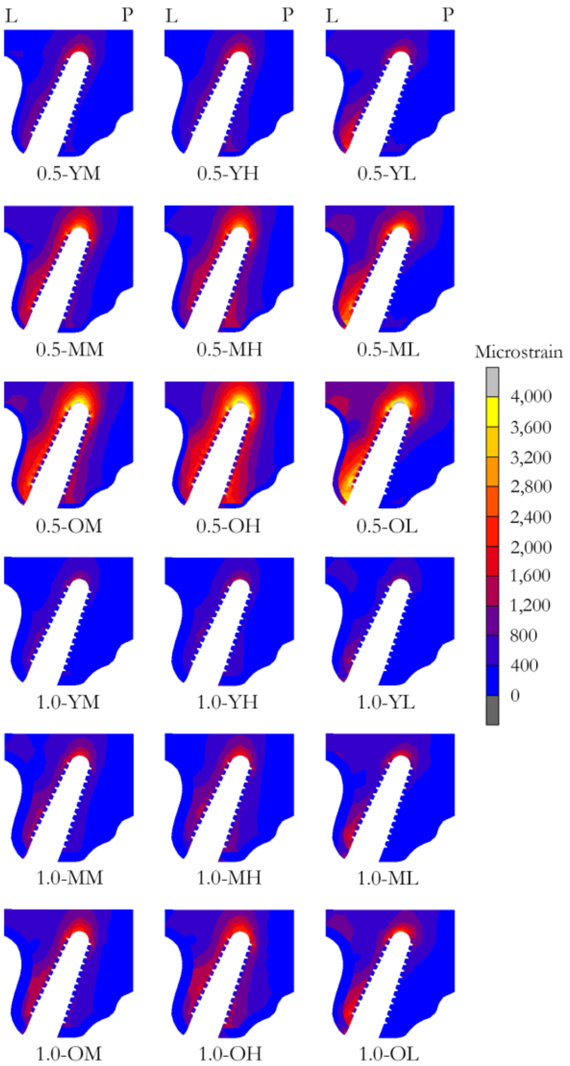

Fig. 6. Strain distribution in surrounding bone (labio-palatal plane).

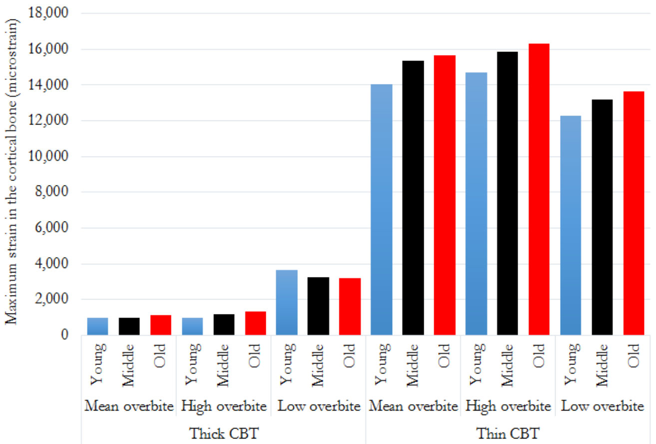

Fig. 7. Maximum strain values in the cortical bone.

area of high strain than the thick CBT. Moreover, for the thin CBT, the maximum strain in surrounding bone (Fig. 7) increased with age. Regarding the ICR, the highest of strain was the HO following by MO and LO, respectively. Therefore, in clinical situation, the thin CBT combine with the old age-AMP and the HO-ICR, biomechanical complication may occur leading to bone resorption.

3.2. Stress Distribution in Implant

The von Mises stress is a mechanical parameter for predicting a failure of the material. If the von Mises stress is greater than the yield strength of that material, a yielding occurs [24]. For the implant, the distribution pattern of the von Mises stresses was similar for all conditions, which the stress concentration were observed around the neck of implant as shown in Fig. 8. The maximum von Mises stress exhibited in the implant (Table 5) of the thin CBT models were clearly higher than the maximum von Mises stress seen for the thick CBT of all AMPs and ICRs clinical situations. Moreover, regarding the ICR, the highest of maximum von Mises stress of the thin CBT was the HO following by MO and LO, respectively. Therefore, in clinical situation, the thin CBT combine with the HO-ICR, an implant fracture may occurs.

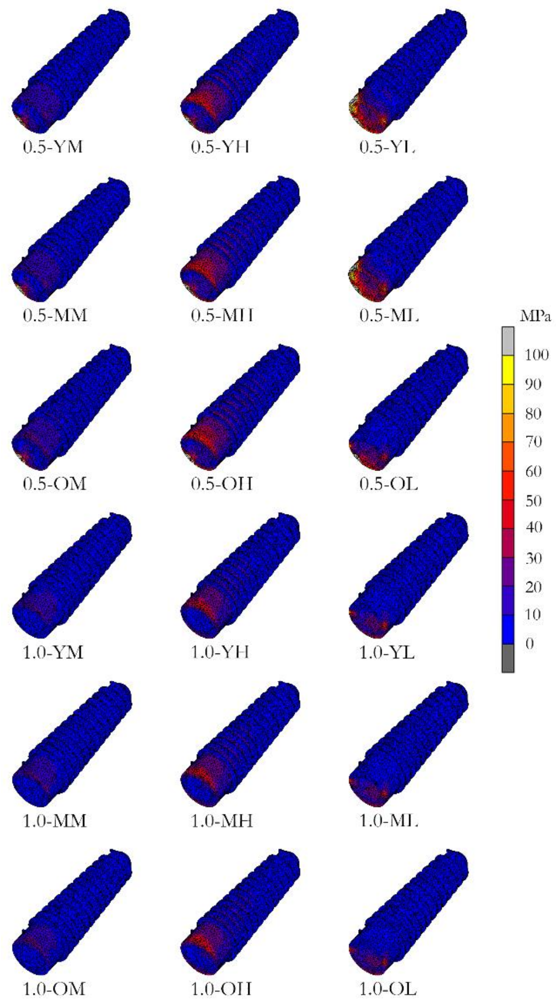

Fig. 8. Von Mises stress distribution in implants.

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Table 5. Maximum von Mises stress in implant, abutment screw and maximum implant displacement.

Case	Maximum stress in implant (MPa)	Maximum stress in abutment screw (MPa)	Maximum implant displacement (micron)
0.5-YM	547.71	206.46	4.59
0.5-YH	574.69	314.41	4.46
0.5-YL	504.75	169.93	8.40
1.0-YM	70.76	114.32	3.09
1.0-YH	51.31	91.43	3.30
1.0-YL	142.70	174.68	5.19
0.5-MM	571.82	210.47	6.84
0.5-MH	581.97	315.08	6.68
0.5-ML	503.46	173.34	11.10
1.0-MM	32.21	117.37	4.21
1.0-MH	57.95	94.44	4.45
1.0-ML	141.89	176.20	6.39
0.5-OM	572.89	213.51	8.83
0.5-OH	587.17	316.30	8.72
0.5-OL	512.00	171.67	13.20
1.0-OM	25.97	119.47	4.96
1.0-OH	61.48	95.68	5.30
1.0-OL	140.37	178.37	7.19

3.3. Stress Distribution in Abutment Screw

The von Mises stress distribution pattern and maximum von Mises stress of the abutment screw of this study are reported in Fig. 9 and Table 5. The von Mises stress were concentrated on the head of the screw for the MO and HO-ICRs of all ages while in the LO-ICR, the von Mises stress concentration also occurred at the neck just below the abutment screw head. The maximum von Mises stresses exhibited in the abutment screw of the thin CBT models (Table 5) were clearly higher than the maximum von Mises stresses seen for the thick CBT of all AMPs with the MO and HO-ICRs clinical situations. Moreover, regarding the ICR, the highest of maximum von Mises stress of the thin CBT was the HO following by MO and LO, respectively. Therefore, in clinical situation, the thin CBT combine with the LO-ICR, a neck of abutment screw fracture may occurs due to the stress concentration.

3.4. Implant Displacement

The results as shown in Table 5 indicated that the AMP, CBT and ICR had an effect on the maximum implant displacement. The maximum of implant displacement was higher with the thin CBT than with the thick CBT. The maximum implant displacement trend was an increasing when the age increased. Regarding the ICR, the highest displacement occurred in the LO of all CBTs and AMPs. The highest of maximum displacement (13.20 micron) occurred on the clinical situation of the thin CBT, old age-AMP and LO-ICR.

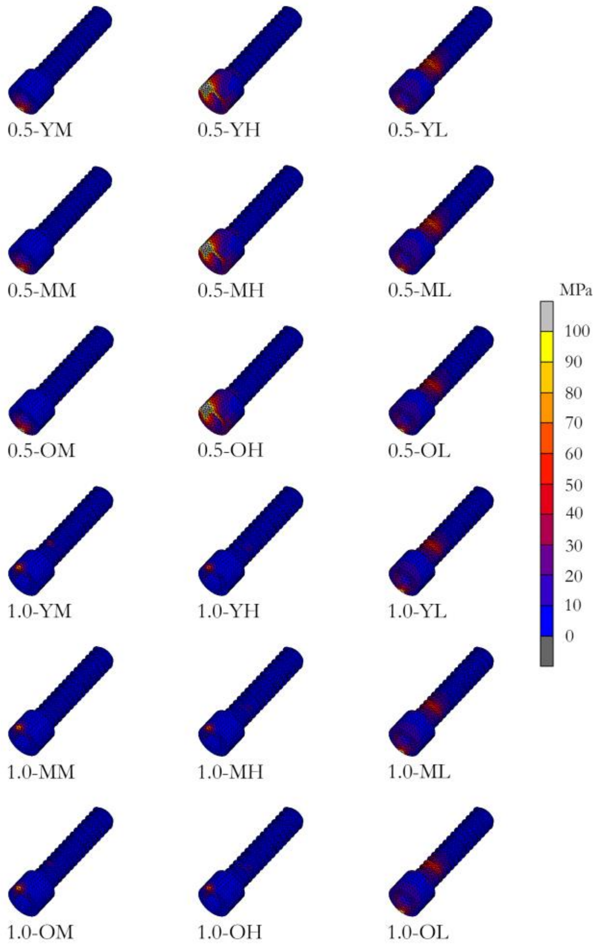

Fig. 9. Von Mises stress distribution in abutment screws.

4. Discussion

This study investigated the biomechanical performance of narrow diameter implant using finite element simulation to support the application of narrow diameter implant to anterior placement. In biomechanical aspect, load transferring to surrounding bone is important for the lasting success of osseointegrated implant [11]. Thus, excessive load on the implant may lead to bone resorption around the implant causing a failure of the anchored implant. Load transferred to the surrounding bone is affected by several biomechanical factors consisted of the loading, quantity and quality of the surrounding bone. In this study, the loading was analyzed by varying the location and direction of the load to represent the ICR of MO, HO and LO. The quantity and quality of the surrounding bone was considered by changing the CBT and the AMP, which, were reflected by the different thickness of the cortical bone and decreasing of the Young's modulus of the bone as the age increased, respectively.

From strain distribution in the surrounding bone (Fig. 6), because the load was not in an axial direction, the cortical bone acted like a fulcrum. Obviously, the present study showed that the strain was concentrated at the bone around an implant neck, similar to several previous studies [16, 25-26]. Furthermore, the strain on the labial side was higher than the palatal. This was more pronounced in case of the thin CBT. The result of this study demonstrated that, the strain exceeded 4,000 microstrain when the CBT was thin (Fig. 7). According to Frost's mechanostat theory, the strain over 4,000 microstrain is considered as a pathologic overload that caused bone resorption [23]. This implies the tendency of bone resorption when the cortical bone was thin and the ICR was HO. Regarding the AMP, the maximum strain in surrounding bone of the thin CBT increased with age. In addition, the area of high strain increased with age for both thin and thick CBTs (Fig. 6). It means that the strain increased when the Young's modulus decreased. This study suggested that the clinician must be aware when the clinical situation composed of the thin CBT, old age-AMP and HO-ICR, which biomechanical complication may occur leading to bone resorption.

The fracture of the implant is one important caused of the long-term failure of the implant therapy. The maximum von Mises stress in the implant as shown in Table 5 were lower than the yield strength of titanium alloy that is 790 MPa [21]. Therefore, the implant can survive under function to support the loading of all ICRs and AMPs. However, in some clinical situations such as the thin CBT, HO-ICR and old age-AMP, which the von Mises stress value (587.17 MPa) was close to the yield strength, therefore, if the patients bite a hard diet, the failure of the implant may occur. In the clinical situation, cyclic loading occurred which generate fatigue and lead to an implant fracture, finally. From the simulation, the location of high stress concentration was the neck of the implant. It corresponded to the location of crack and fracture observed in the experimental studies by Velasco-Ortega et al. [27] and Pérez et al. [28]. Moreover, the different type of titanium and titanium alloy such as Ti-6Al-4V, Ti-Zr, all have an effect on biomechanical behavior of the implant. Alloying or cold working the titanium implant can improve the biomechanical behavior of the implant. Velasco-Ortega et al. [27] and Pérez et al. [28] suggested that some types of titanium such as commercially-pure titanium with 12% cold working or alloying with 15% Zr could increase fatigue limit of the implant. Therefore, the further study must concern many fracture causes, especially cyclic loading and mechanical property of different titanium types.

For the abutment screw (Fig. 9), because it was the smallest part of the implant system, therefore, the location of high von Mises stress was important for mechanical evaluation. The present study indicated that the LO-ICR produced high von Mises stress concentration at the neck just below the abutment screw head, which is the most fracture site of the abutment screw. This stress concentration site corresponded to the fracture of abutment screw as reported by Flanagan [29]. Although the maximum von Mises stress in the abutment screw was less than the yield strength of titanium alloy, the abutment screw may fail if the patients bite a hard diet, which generates a sudden overload. Therefore, in clinical practice, the LO-ICR was an important factor to consider.

In biomechanical point of view, the implant displacement is one of important factors for the long-term success of the treatment. Clinically, the implant is fixed to the bone by osseointegration process. It is a direct contact between the bone and the implant surface [30]. This process occurred by the biological activity of the bone cells. Because the bone composed of cortical and trabecular or spongy bone, which are deformable materials, it deforms with the implant when subjected to the occlusal load. Therefore, the glue contact was used to simulate the direct contact between the implant and bone in this biomechanical study. It differs from the contact in engineering fastener that the screw can experience a fretting damage and eventually screw loosening. However, Gao et al. [31] mentioned that fretting would occurred at the implant system as well as the implant-bone interface. The fretting damage of the bone-implant interface could be explained by the biological activity of bone cells. If the implant displacement is over 30 micron, the fretting damage cannot be handled by bone remodeling mechanism. It will become a bone resorption, leading to implant loosening. The micromotion of the implant less than this threshold is considered as safe. The present study showed that the AMP, CBT and ICR had an effect on the implant displacement, however, all simulations demonstrated that implant displacements were less than 30 micron. The clinical situation of the old age-AMP, thin CBT and LO-ICR had highest displacement (13.20 micron).

According to biomechanical consideration, although some individual factor does not have a direct effect on the biomechanical performance of long-term success of implant treatment, however, the combination factors may produce the biomechanical complication, which leading to long-term implant failure. The results of this study suggest that the clinician must be concern in the combination effects of the CBT, AMP and ICR when placed the implant in the atrophic anterior maxilla. The limitation of this study was homogeneous and isotropic material, complete osseointegration. Therefore, the application in clinical practice should be considered with this limitation.

5. Conclusions

In biomechanical point of view, this study suggested that in some clinical situations, there is a critical biomechanical complication from the combination effects of three investigation factors (CBT, AMP and ICR). It is crucial to consider the critical situations of narrow diameter implant placed in atrophic anterior maxilla where the combination of the thin CBT, old age-AMP which is the lowest Young's modulus and HO-ICR clinical situation which induce surrounding bone resorption and the implant damage. The neck of abutment screw fracture may cause by the LO-ICR.

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