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Stress analysis of different wall thicknesses of implant fixture with various boundary levels

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The aim of the present work is to develop 3D finite element models of implant fixture with different wall thicknesses to predict maximum stress concentration sites and distribution contours after loading. A maximum lateral force of 150 N was applied to simulate horizontal occlusal forces. When the fixtures were constrained to simulate different boundary levels, the maximum equivalent stress (max EQV) was always located at the implant-bone interface. Max EQV increased when the wall thickness or boundary level was reduced to a certain extent. The fixture with a wall thickness of 0.97 mm demonstrated the smallest stress increase ratio when the boundary level was lowered. Our results indicated that both wall thickness and the boundary level played important roles in maintaining a well-distributed stress level within the fixture. The stress concentration decreased when the fixture wall became thicker, however, this effect was less significant when the surrounding bone level was reduced.

Introduction

Implant dentistry was introduced in the 1960s and has become increasingly popular due to high rates of success [1, 2]. Recently, treatments with implant-supported fixed and/or removable partial prostheses have been widely recommended for partially edentulous patients. Around one fourth of patients ages 45 to 69 would like to be treated with dental implants instead of removable partial dentures, and more than half of them preferred dental implants if they had lost only one or two teeth [3].

Both of the load applied on the implant and the load transferred to the bone are important when biomechanical concept of dental implants is considered. Mastication normally produces vertical and transverse forces, and exerts stress gradients in the implant as well as in the bone. Loads applied to the implant will be directly transmitted to the bone because of intimate contact at the implant–bone interface. Although a minimum amount of stress is necessary for bone remodelling [4], large amount of stress may exceed the limits that bone can tolerate, which subsequently lead to micro-damage and induce resorptive activities [5, 6]. The implant per se has to withstand stresses induced by intraoral forces. Increased or abnormal loading, as well as fatigue under physiological loads, can lead to fractures of certain implant components

Although clinically the success rate of dental implants is increasing, a high percentage of after-implantation problems, such as loosening and fractures, occur mainly in the first year, probably due to inadequate structural integrity. These problems are also complicated by cyclic fatigue, oral fluid invasion, and various occlusal patterns or overloading [7–12]. Fracture or loosening is most likely to occur in the retaining screw, followed by the abutment screw, then the fixture. As for fracture problems, however, it is difficult to predict which component will suffer fatigue and the resulting effects on the entire system.

Important aspects of implant design are related to biomechanics of implant systems and the different materials used for implants. Both parameters are complex issues, but more uncertainty and less factual information exist in the former one than the latter one [13]. Obviously, the relationship between the shapes of implants and stress distributions plays an important role in the integrity of implant systems.

Essentially, to prevent fracture, the structural diameters of retaining screws, abutment screws, and fixture should be carefully determined. Various diameters of the fixture body have been tested, and a wider one was suggested in clinical use to increase the contact surfaces between bone and implant and to reinforce implant stability [14]. However, an increase in fixture diameter is restricted by the finite thickness of the alveolar bone.

Wall thickness of the fixture is another significant factor influencing implant strength. Given a fixed outer diameter of the fixture, an increase of its inner diameter will weaken the structure. Conversely, a decrease of the inner diameter may reduce the diameter of the abutment screw. Thus, it is critical to achieve an ideal ratio of the diameters among different components in an implant system. However, very few studies have attempted to assess the influence of different wall thicknesses of the fixture on stress distribution and fracture resistance. On the other hand, a complex clinical variable, bone level around the implants, has not been reported systematically [15].

Finite element method (FEM) has been extensively used in biomechanical studies to analyze structural stress

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distribution of mechanical components. Because of increasing computing speed and progressively better programs, researchers can now more precisely calculate results and establish models [16]. Using an optimal design technique, the present study developed 3D finite element models of fixture bodies with different wall thicknesses. The same models with various boundary levels were also constructed to investigate different marginal bone conditions surrounding the fixture body.

Materials and methods

As shown in figure 1*a*, a 3D numerical model of the fixture body was developed using the FEM technique. The geometry of the computer model was based on standard shapes of the 3.75 × 10 mm pure titanium dental implant (Brånemark implant system®, Nobel Biocare AB, Göteborg, Sweden) with the inner and outer threads around the fixture body (figure 1*b*). A general purpose finite element software package, ANSYS® (Rev. 5.4, Swanson Analysis System, Houston, PA, USA), was executed on an NT-based personal computer for theoretical analysis. With the internal language of ANSYS (ANSYS Parametric Design Language), parametric control of the geometrical details was utilized to adjust the diameters of inner and outer threads without further remodelling.

In the present study, finite element models of the fixture body were meshed with four-noded tetrahedron elements, and convergent studies were conducted to justify the mesh density. To evaluate effects of wall thickness on fixture bodies, the inner walls were given various thicknesses with possible magnitudes of 0.87 mm (Model I), 0.97 mm (Model II), 1.07 mm (Model III), and 1.17 mm (Model IV). Models I and IV are shown in figure 2 to represent the thinnest and thickest wall thicknesses of the fixture bodies. All of these models had a fixed outer diameter of 3.75 mm and length of 10 mm with slightly different numbers of nodes and elements in meshing with the finite element models (table 1).

Figure 1. Representative solid models of the fixture of 1.07 mm wall thickness (a) with outer threads only, and (b) with both inner and outer threads.

The material properties of the models were assumed to be homogeneous, isotropic, and linearly elastic. Young's modulus (110 GPa) and Poisson's ratio (0.33) of titanium alloy for the fixture bodies were adopted from previous studies [17, 18]. Due to the stress distributions in bone not being discussed in this study, the fixtures were rigidly constrained to simulated ideal osseointegration. To assess effects of marginal levels, the fixtures were simulated to embed into different marginal boundary levels with lengths of interface varying from 6 to 9 mm in increments of 1 mm.

Rugh and Smith [19] reported that maximum biting forces generally vary from 20.5 to 104.4 kg (244 N to 1245 N) as developed by the stomatognathic system. Under cusps of around 30°, the lateral force would be

Table 1. Numbers of nodes and elements used in the models of different wall thicknesses.

	Model I (0.87 mm)	Model II (0.97 mm)	Model III (1.07 mm)	Model IV (1.17 mm)
Nodes	3025	3263	3284	3462
Elements	11026	12470	12768	14073

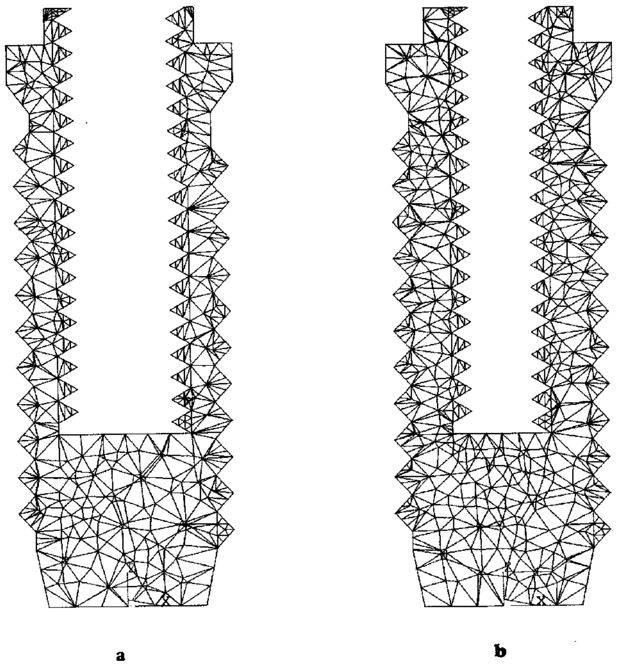

Figure 2. Sagittal sections of representative fixture models with wall thicknesses of (a) 0.87 mm and (b) 1.17 mm.

transmitted at half of the biting force. With an occlusal force of 300 N, the lateral force is then calculated as 150 N. Therefore, a maximum lateral force of 150 N was considered for a daily physical simulation of occlusal forces in this study. As demonstrated in figure 3, the forces were evenly distributed on the surface of the fixture collar in our simulations.

Von Mises stresses (equivalent stress [EQV]) within the four fixture models were calculated with different boundary levels, and the contours of stress distribution in implants were displayed for comparison.

Results

When the fixtures were constrained to simulate different boundary levels, maximum equivalent stress (max EQV) was always located at the area of the implant-surrounding tissue interface. Figure 4 demonstrates the stress distribution contours of Model III (wall thickness of 1.07 mm) with an 8 mm marginal level. Similar stress distribution contours were found in all other models at different boundary levels. Max EQVs of the fixtures under different boundary conditions are listed in table 2. A linear relationship with negative slope between boundary level and max EQV within fixtures is noted in figure 5. Our results indicated that the amount of stress concentration significantly increased when the boundary level was lowered.

Figure 6 shows the relationship between boundary levels and max EQV increase ratios. The max EQV increase ratio (MEIR) is defined as the increase of max EQV when wall thickness decreases from a thicker to a thinner wall. When the wall thickness decreased from 1.17 to 0.87 mm at a boundary level of 9 mm, the max EQV significantly increased from 55.6 to 83.4 MPa (with a 50% increase, or an MEIR of 0.5). A similar phenomenon also occurred at a boundary level of 8 mm (with an MEIR of 0.3), as well as at a boundary level of 7 mm (with an MEIR of 0.22). It is noted, however, that at a boundary level of 6 mm (with 3 mm of marginal bone loss), the max EQV decreased from 221.6 (for 1.17 mm wall thickness) to 209.6 MPa (for 0.87 mm wall thickness) with an MEIR of −0.05. It was postulated that with 3 mm of marginal bone loss, the fixture may have been overloaded and subsequent failure might have been occurred [18, 20]. Due to the complex and nonlinear phenomena of fracture mechanisms, stress analysis at a boundary level of 6 mm was not included in the subsequent evaluation.

As listed in table 2, max EQV significantly increased when the boundary level decreased. However, a nonlinear relationship between MEIR and wall thickness is

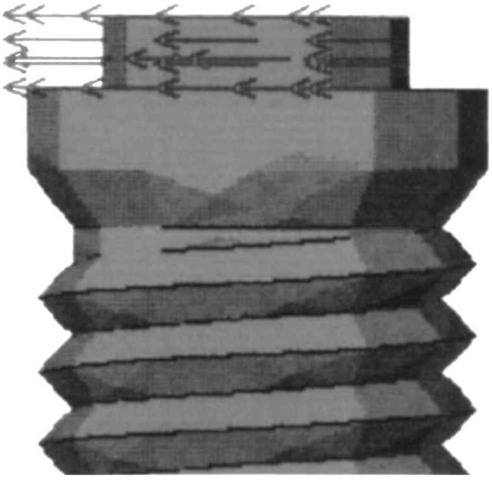

Figure 3. An average force of 150 N applied on the collar surface of the fixture body.

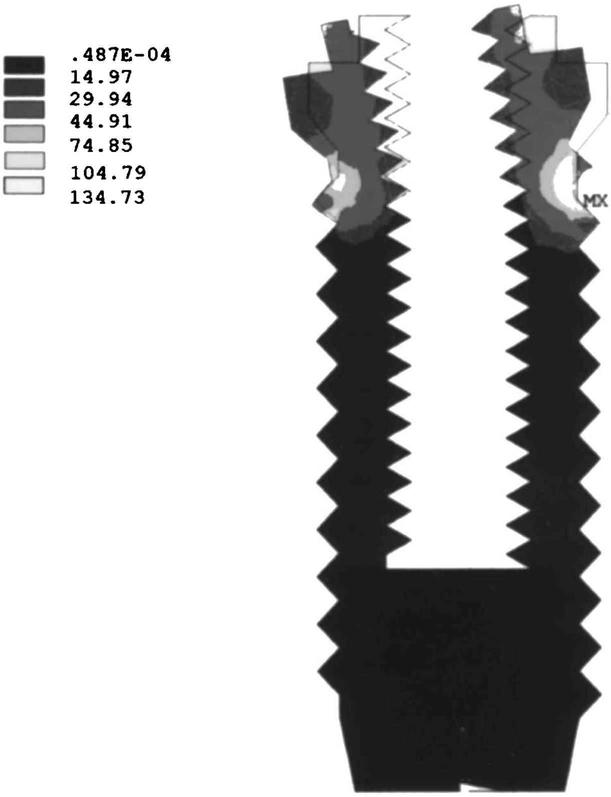

Figure 4. Representative sagittal stress distribution contour of sagittal section of the fixture model with a wall thickness of 1.07 mm and a boundary level of 8 mm. The portion with white colour shows a higher stress level.

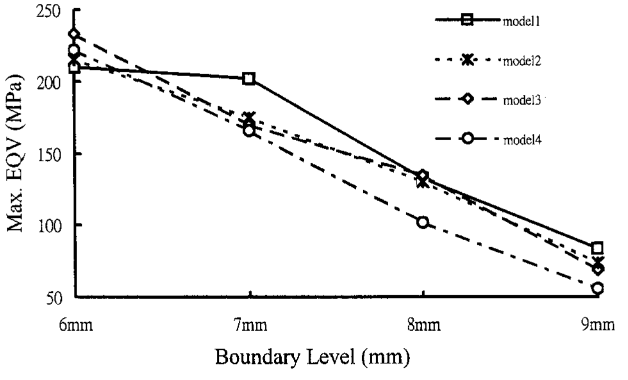

Figure 5. Relationship between max EQV and boundary level.

Table 2. Maximum equivalent stress (max EQV) (MPa) in all the models with different wall thicknesses under various boundary levels.

Boundary level	Model I (0.87 mm)	Model II (0.97 mm)	Model III (1.07 mm)	Model IV (1.17 mm)
6 mm	209.6	215.2	232.8	221.6
7 mm	202.0	174.7	169.7	165.8
8 mm	132.5	130.0	134.7	101.6
9 mm	83.4	73.7	68.7	55.6

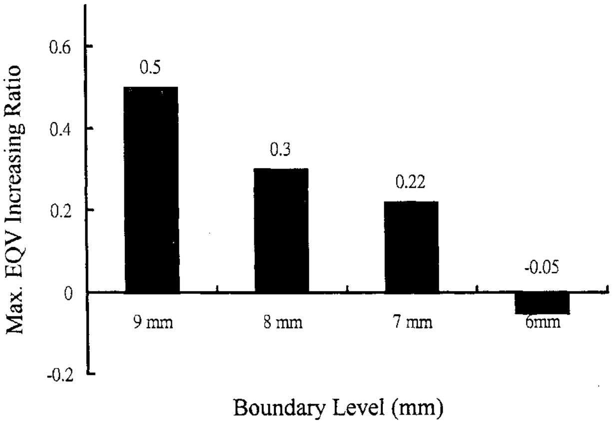

Figure 6. Relationship between max EQV increase ratios (MEIR) and boundary levels.

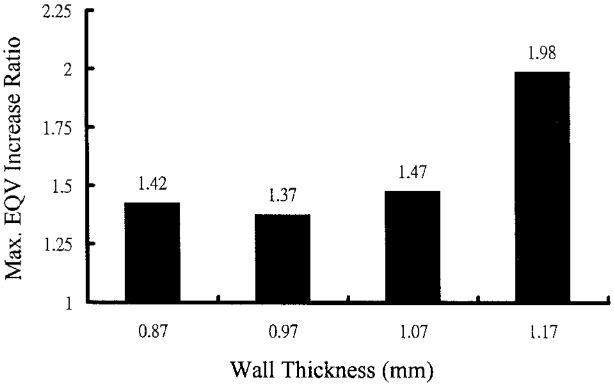

Figure 7. Relationship between max EQV increase ratios (MEIR) and wall thicknesses.

shown in figure 7. The MEIR, here, is defined as the increase of max EQV when boundary level decreases from a higher to a lower level. The fixture with 1.17 mm wall thickness showed the largest MEIR of 1.98 when boundary level decreased from 9 (55.6 MPa) to 7 mm (165.8 MPa). A similar trend was noted in all other models. The minimum MEIR (1.37) was found in the fixture body with a wall thickness of 0.97 mm.

Discussion

A key determinant of the success rate of an oral implant is the way mechanical loads are transmitted to the surrounding bone. These loads depend on the type of loading, bone-implant interface, length, diameter, shape of the implants, structure of the implant surface, superstructures, and quality of the surrounding bone, etc. Although osseointegration does exist between bone and dental implants, overloading or implant fractures may affect its integrity. Investigating stress distributions in major implant components of different shapes and sizes may help determine the best combination to retain or reinforce osseointegration. Within the limited width of the alveolar bone, it is critical to consider the relationship between wall thickness of the fixture body and diameter of the abutment screw, as well as that between the surrounding bone level and the fixture body. Finite element analysis, being considered as an appropriate method for internal stress analysis, was used in the present study. A static analysis is suitable to simulate clenching, grinding, and most mastication conditions. Since bruxism was reported to be one of the main factors potentially damaging bone and implants [7, 21, 22], static loads were sufficient for the purpose of this study.

In this study the Von Mises stress (EQV) was chosen to display the computational results for comparison. Since all materials were considered to be linearly elastic, stresses in the model increased proportionally with the force applied. Knowing the EQV for unit loads, stresses generated by loads in the range of occlusal forces can be thus deduced. Computer simulation generally operates with simplifications and assumptions related to material properties, geometry, load, and interface conditions. For this reason, when applying the results to clinical practice, a qualitative comparison between models is recommended, rather than focusing on quantitative data from finite element analysis.

Ratios between stress values remain the same, regardless of the magnitude of the force, as long as the load applied allows only elastic deformation of the materials in the model. No attempt was made to use a particular biting force in matching the various occlusal loads reported [23]. It has been shown in the present study that max EQV always located at the fixture – boundary interface when lateral force from the occlusion was applied to the fixture body. These stress concentration patterns are essentially in accord with basic mechanical theories and investigations.

An increase in the diameter of abutment screw is expected to reinforce the mechanical strength of the implant system. However, the increase in the diameter of abutment screw will unavoidably reduce the wall thickness of the fixture body, which may lead to fracture of the fixture body under normal occlusal forces. Using finite element modelling, an optimal design technique was utilized to improve the reliability and durability of the implant system and to prevent inadequate design of individual components.

To reduce the maximum stress level within the abutment, the occlusal force should not be concentrated at the abutment or retaining screws. The loading should be guided from the prosthesis (cylinder included), abutment, fixture body, and then ultimately to the bone. This may induce large amounts of stress at the fixture-bone interface as illustrated in figure 4. According to basic mechanical theories, high stress concentrations must occur in the surrounding bone, which might lead to bone resorption [15]. Similar results were demonstrated in the present study.

The max EQV of all models increased significantly when boundary level around the implant decreased. This may be due to an increase of distance (moment arm) from the applied force to the supportive bone, and thus increases the bending moments upon the implant fixture. Figure 7 carries an important message regarding the relationship between MEIR and the wall thickness of the fixture body. The fixture with a wall thickness of 0.97 mm demonstrated the smallest magnitude of MEIR, indicating such a model may produce the lowest stress level when boundary level is lowered. This also explains why the wall thickness of 0.97 mm is more desirable for the fixture of an outer diameter of 3.75 mm.

Bending moments on a Brånemark implant rigidly connected to teeth have been examined in an *in vivo* study [24], and were measured at between 10 and 15 N-cm. It was hypothesized that 10 N-cm is required to withstand bending deflection to compensate for the initial intrusion of the fixture body. In the present study, a maximum lateral force of 150 N was used, and bending moments of up to 30 N-cm on the fixture-bone interface were applied.

When the marginal level decreased, bending moments on the fixture concomitantly increased. This may result in overloading of the fixture body and subsequent bone resorption. Figure 5 demonstrates the relationship between max EQV and boundary level: the lower the boundary level is, the higher the stress may be generated. These results conform to those findings of Gross and Laufer [15].

The wall thickness of the fixture body plays an important role in resisting overloading caused by normal or abnormal occlusal forces. As shown in table 2, max EQV decreased when wall thickness increased. Accordingly, less strain may be induced by the applied force, which resulted in greater structural strength of the implant system. However, as shown in figure 6, MEIR decreased when boundary level was lowered. This indicates that the wall-thickness effect decreases when surrounding tissue is destroyed. When boundary level was reduced to 6 mm, MEIR increased as a function of wall thickness. This may be due to the nonlinear properties of the fracture mechanism. In fact, implants may fail when the height of bone loss reached 3 mm [20].

The above results are essentially based on a standard shape of Brånemark fixture body and fixture bodies of other shapes were not conducted. The shape of the fixtures will be a very interesting subject for future studies. Within a restricted jawbone, different shapes in various implant components with different material properties will complicate the optimal design of an implant system. Thus, it is suggested that future studies may aim at a fixture design that will balance the resulting stresses and avoid bone absorption. At the same time, optimal design of the implant system can be achieved based on the proper size of the limited bone width.

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