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Resonance frequency assessment of dental implant stability with various bone qualities: a numerical approach

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Abstract: Resonance frequency analysis (RFA) has been used by several investigators to assess the boundary conditions of dental implants. The goal of the current study was to determine the vibrating behavior of a dental implant under various surrounding bone conditions. A 3D finite element (FE) model of a cylinder-type titanium implant was developed. In this model, the implant was embedded into a cubic section of bone. The model was first validated using a series of modal testing experiments. The effects of bony conditions on the resonance frequencies of the implant were computed with different bone types and bone densities. Our results show that the resonance frequency of the implant with type III surrounding bone decreased linearly ($r = -0.996$, $P < 0.01$) from 17.9 kHz (without loss in bone density) to 0.6 kHz (90% loss in bone density) when the bone densities were decreased. On the other hand, without bone loss, the highest resonance frequency value (36.1 kHz) was found when the implant was placed into type I surrounding bone. In contrast, the resonance frequency of the implant with type IV bone quality was found to be 9.9 kHz, which is almost four-fold less than that found in the type I model. These results suggest that RFA could serve as a non-invasive diagnostic tool for detecting the stability of dental implants during the healing stages and in subsequent routine follow-up care after treatment.

The development of effective and durable dental implants has become increasingly important in oral rehabilitation along with the rapid increase in the number of dental implants installed. However, implant treatments still fail frequently. An important cause of implant failure is marginal bone transformation that leads to loosening of the dental implant. The height and quality of marginal bone are also important factors affecting the success rate of implant treatment (Kirsch & Mentage 1986; Albrektsson & Sennerby 1991; Adell 1983), and are the traditional basis for diagnosis and treatment. However, specific methods to obtain an accurate and effective assessment of stability of a implant have not been standardized.

Clinically, radiographic observation is the main technique used for bone assessment. However, it is unable to detect bone loss of less than 30% (Wong & Saha 1983), and its use often results in various kinds of human errors in the evaluation of bone-implant interfaces (Sundén et al. 1995; Elias et al. 1996). In addition, because X-radiation may impose health hazards, it is not suitable for long-term follow-up or early prevention and diagnosis.

In recent years, Periotest® (Siemens AG, Bensheim, Germany) has also been used to measure stability and to detect

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stability problems of dental implants. However, many studies have indicated that the Periotest® is not an ideal tool to study implant-bone interface conditions. In addition, the Periotest® is incapable of providing sensitive responses to minor changes in the implant-bone interface (Williams & Williams 1997; Meredith et al. 1996a). Therefore, its clinical usage in implant stability assessment is still limited.

Resonance frequency (RF) is an important parameter of a vibrating structure that is related to the stiffness and density of the vibrated object (Thomson 1988). RF can be used as a parameter in determining the boundary conditions of a structure. The technique for resonance frequency measurement is non-invasive and non-destructive. Therefore, in addition to the use of RF in the examination of industrial materials, it is also widely used in biomedical research, including the determination of bone density, the stability of orthopedic implants (Lowet et al. 1993, 1996), the assessment of bone healing after fracture (Lewis 1975; Sonstegard & Mathews 1976; Christensen & Ammitzboll 1986; Lowet et al. 1996), and in diagnosis in the joints of long bones (Hight 1980; Van der Perre et al. 1983; Cornelissen et al. 1986).

In previous research in oral rehabilitation, the use of vibration theory has proven to be a feasible method for determining the health condition and mechanical role of periodontal ligaments (Lee et al. 2000; Okazaki et al. 1996), and in stability assessment of dental implants (Kaneko 1987, 1989, 1991).

In order to evaluate the relationships between resonance frequency of an implant and its surrounding conditions, Meredith et al. used a sinusoidal force to vibrate a cantilever beam that was attached to an implant both in *in vivo* and *in vitro* conditions. Their results show that resonance frequency analysis (RFA) is a useful tool in analyzing the degree of osseointegration (Meredith et al. 1996a, 1997; Sennerby & Meredith 1998; Friberg et al. 1999; Rasmusson et al. 1999). In our previous study, the vibration behaviors of dental implants were analyzed using a non-contact modal testing method. The results demonstrated that the resonance frequency of an implant was linearly related to its boundary height and boundary contact characteristics (Huang et al. 2000). Although this technique has been shown to be a useful tool for implant stability examination, many factors, including bone density and bone type, which can affect resonance frequency of an implant, were not investigated and their effects remain unclear. To clearly determine the effect of surrounding bone quality on the resonance frequency of a dental implant, the finite element method (FEM) was applied using a numerical approach.

Finite element (FE) modeling not only can simulate complex geometric shapes and material properties, but also can simulate various boundary conditions which are difficult to replicate in experiments. As a result, it has gradually become an important tool in biomedical research. FEM has been used in analyzing vibration behavior in orthopedics (Van der Perre et al. 1983; Hobatho et al. 1991; Lowet et al. 1996) and in research on neurotrauma (Willinger et al. 1995; Kumaresan & Radhakrishnan 1996). However, the techniques used in these studies are rarely applied in RFA of dental implants. Williams & Williams (1997) reported the first study to use modal testing experiments together with FEM in the analysis of implant stability problems. Recently, Lee et al. (2000) also reported that FEM could serve as a tool to aid in the accuracy of RFA in periodontal problems. In the present study, a 3D FE model of dental implant with marginal bone was established. The vi-

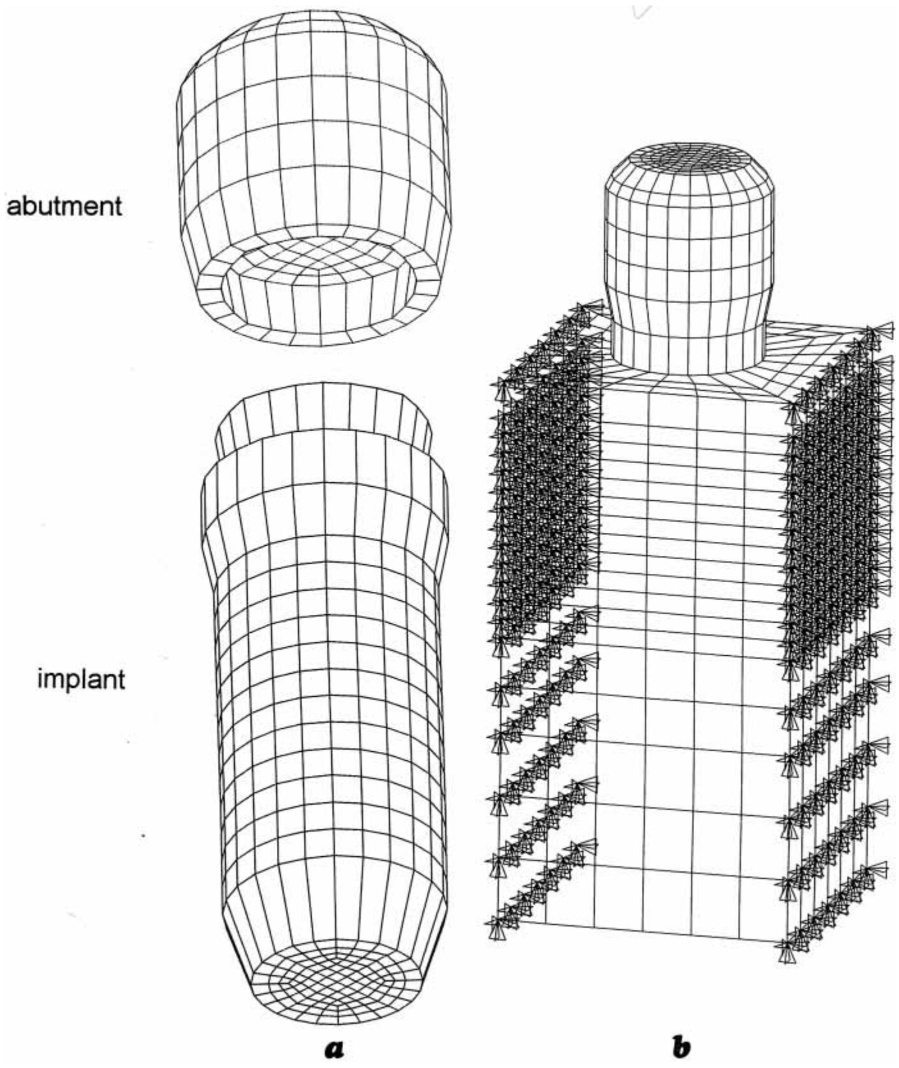

Fig. 1. The 3D finite element model used in this study. The figure shows an implant and the abutment (a). The implant was embedded into a bone block (b). The triangular symbols denote the boundary conditions.

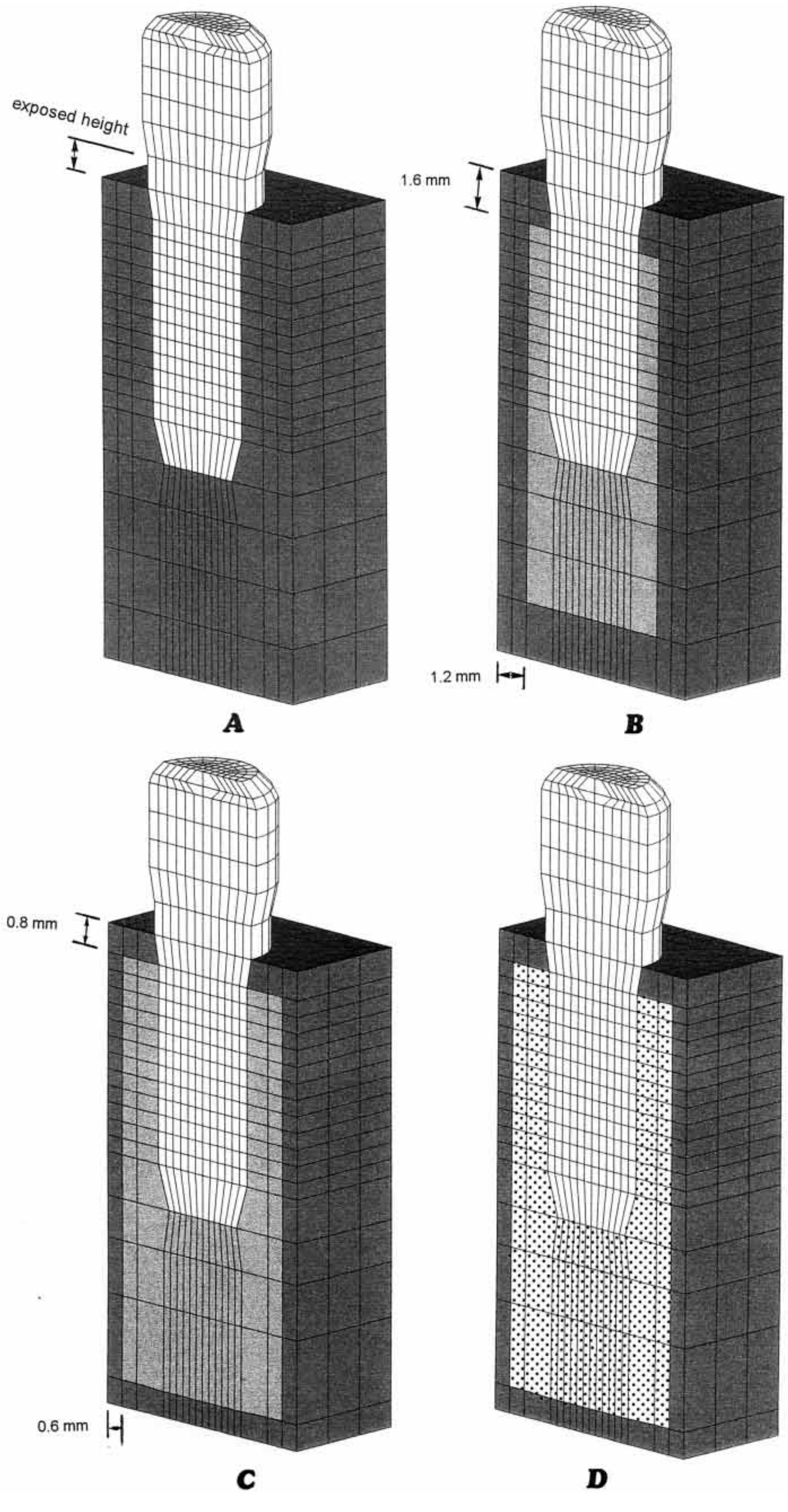

Fig. 2. Sagittal views of the four configurations of the model. A. Type I: the jaw is almost entirely comprised of compact bone. B. Type II: a thick layer of compact bone surrounds a core of dense trabecular bone. C. Type III: a thin layer of compact bone surrounds a core of dense trabecular bone. D. Type IV: a thin layer of compact bone surrounds a core of low-density trabecular bone. Elements with dark and light color represent compact bone and trabecular bone, respectively.

***Table 1.* Mechanical properties of the finite element model**

	Density (g/cm^3)	Elastic modulus (GPa)
Compact bone	2	10
Trabecular bone	1	0.25
Titanium	4.5	103

bratory properties, i.e. resonance frequencies, of the model were calculated and discussed for various bone heights and bone quality.

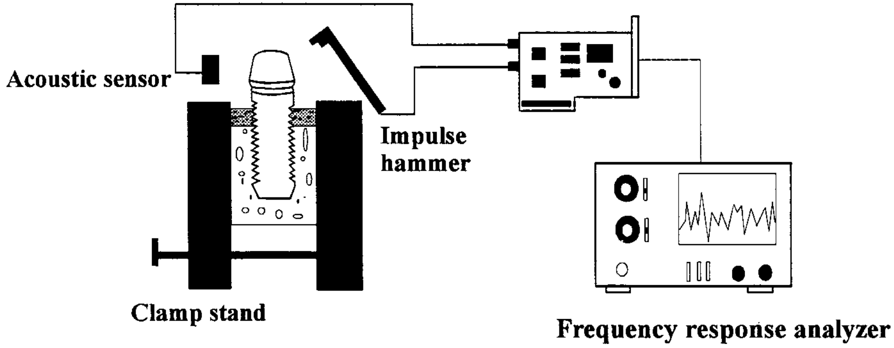

Fig. 3. The device set-up used for *in vitro* experiments in this study.

Material and methods

To determine the effects of different boundary conditions on the resonance frequency of a dental implant, a 3D FE model (Fig. 1a) of a dental implant (Brånemark System, Nobel Biocare AB, Goteborg, Sweden) with healing abutment was established. The fixture body was 3.75 mm in diameter and 10 mm in length. The healing abutment had a length of 3 mm. As shown in Fig. 1b, the implant was embedded into a bone block (10 mm×10 mm in cross-section and 15 mm in length with a compact bone of 2 mm thickness on the top side) with 0.8 mm exposed height. As shown in Fig. 2a, the term "exposed height" was defined as the distance from the upper bone surface to the cervical portion of the implant. According to the classification of Lekholm & Zarb (1985), four types of bone quality were simulated. In the type I model, the mechanical properties of the entire bone block were set as compact bone (Fig. 2a). In the type II model, a core of dense trabecular bone was covered by a thick layer of compact bone (with a width of 1.2–1.6 mm, Fig. 2b). The geometric configuration of the type III model was similar to the type II model, but the width of the compact bone was reduced to 0.6–0.8 mm (Fig. 2c). The type IV model had the same configuration as the type III model, however the density of trabecular bone was decreased by one-half (Fig. 2d). The thickness of compact bone set in our FE models were according to the previous study of Holmes & Loftus (1997).

Considering the actual conditions of resonance frequency measurement encountered in oral rehabilitation, the exciting force must be applied along the lingual-labial (frontal tooth) or lingual-buccal (posterior tooth) direction. Because alveolar bone cannot vibrate along the mesial-distal direction, the boundary conditions of this model were chosen to fix the mesial-distal side of the bone at all nodes. The entire model consists of 4586 nodes and 3996 hexahedral elements. The mechanical properties of the model were assumed to be homogeneous, isotropic and linearly elastic. The specific values of the properties were adopted from previous studies and are listed in Table 1 (Kamposiora et al. 1994; Van Zyl et al. 1995; Meijer et al. 1995; Park 1995a, 1995b). Because a stress analysis was not performed in this study, the FE model of the fixture body did not include the thread portion. The finite element analysis package, ANSYS (Rev.

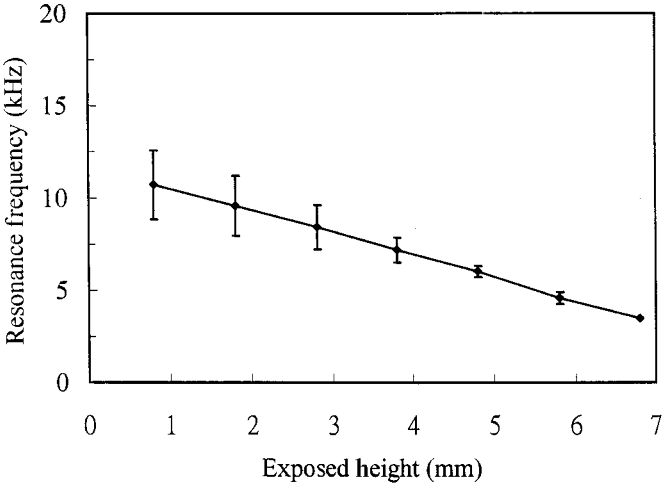

Fig. 4. Mean values of resonance frequency of the test implants obtained from *in vitro* modal testing experiments. The resonance frequencies decreased as a function of exposed height.

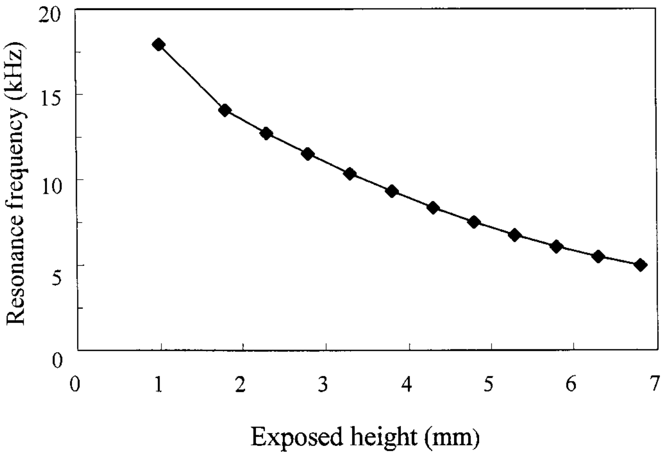

Fig. 5. The resonance frequencies under different marginal bone levels were calculated by the finite element method. The frequencies decreased linearly as the surrounding bone was reduced.

5.4, Swanson Analysis Systems Inc., Houston, PA, USA), was used on a personal computer for pre-processing and modal analysis.

To validate the reliability of the FE model, the resonance frequencies of actual dental implants were measured by a series of *in vitro* modal testing experiments. The implants were installed into cubic bone blocks, which were cut from the lumbar vertebrae of hogs for use as testing samples. These bone blocks had the same size as those of the FE model (10 mm×10 mm in cross-section, 15 mm in length). The exposed height after the implant was installed was also 0.8 mm. Seven testing samples were prepared. The density values of compact bone and trabecular bone of these specimens were 1.87±0.25 g/cm^3 and 1.13±0.11 g/cm^3, respectively.

As shown in Fig. 3, the testing samples were fixed by a clamping stand with a torque force of 20 N-cm, and lubricated with normal saline solution during the entire testing process. The implants were excited to vibrate by a transient force using an impulse force hammer (GK291C80, PCB Piezotronics, Buffalo, NY, USA). The vibration signal was recorded by a non-contact acoustic microphone (FM-10B, sensitivity 20 kHz, FC Electronics, Taipei, Taiwan). The recorded signals were then transferred into the computer through an A/D interface card (AD102 A, Prowave Engineering, Hsinchu, Taiwan). FFT software (SD200N, Signal Doctor, Prowave Engineering) was then used to determine the resonance frequency of the tested samples. The seven testing samples were tested with exposed height ranging from 0.8 mm to 6.8 mm in increments of 1 mm. Experimental data were derived from the average of 3 measurements, and the final data were obtained by averaging 5 experimental data results. For the FEM simulation, the resonance frequencies of the type III model were calculated from the same initial exposed height (0.8 mm), followed by increments of 0.5 mm until the exposed height reached a value of 6.8 mm.

After the reliability of the FE model was verified, two situations were simulated to assess the effects of surrounding bone. The first situation simulated different bone types, and evaluated their ef-

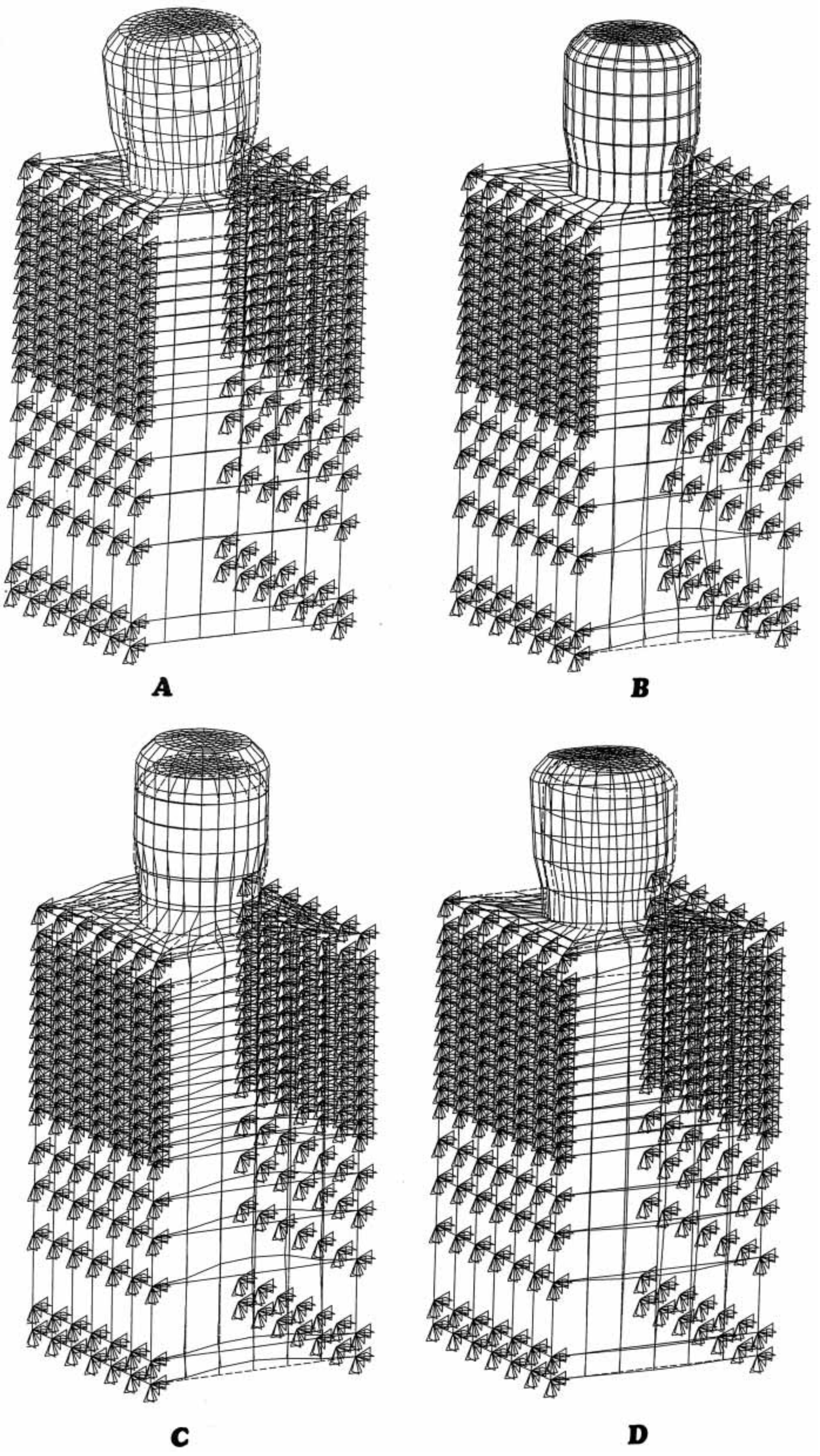

Fig. 6. The mode shapes of the vibrating implant. The first (a) and fourth (d) vibrational mode were bending modes, the second mode was a torsion vibration (b), and the third mode was an axial vibration (c).

fect on the resonance frequency of the dental implant. The second situation simulated continuous bone loss after implant treatment. In the first situation, the resonance frequencies and vibration mode shapes of the model were also computed with four different bone types.

In the second situation, to determine the effect of bone density on resonance frequency, the entire bone (both compact bone and trabecular bone) density in the type III model was altered from 100% to 10% in increments of 10%. Since resonance frequency is greatly affected by Young's modulus and density, there is a need to change these values simultaneously during the simulation. Carter & Hayes (1977) reported that a relationship exists between the Young's modulus and density of bone as follows:

$$E=C\text{ú}^{0.06}\rho^3 \quad (1)$$

Where E is the Young's Modulus (MPa), C a constant, ú the strain rate during testing, and ρ the bone density (g/cm^3). Since strain rate has a minimal effect on the value of E (Weinan et al. 1992), formula (1) can be simplified as:

$$E=C\rho^3 \quad (2)$$

Formula (2) has already been employed in various FE analyses concerning implant and interface bone generation and has been shown to be highly credible (Weinan et al. 1992). In the current study, the same formula was incorporated in the calculation of the Young's modulus of bone for each incremental decrease in the bone density. According to the material properties listed in Table 1, the constant C was calculated as 1250 for compact bone and 250 for trabecular bone.

Results

Fig. 4 shows the natural frequencies of the dental implant tested *in vitro* with various exposed heights. The highest RF value of the test implant (10.71±2.51 kHz) was obtained when the test implant had the minimum exposed height. In contrast, when the exposed height was increased to 6.8 mm, the resonance frequency of the test implant decreased to 3.48±0.32 kHz with an average decreasing ratio of 67.5%. As shown in Fig. 4, a significant linear relationship was present between resonance frequency and the exposed height, as follows: $Y=-1.2156\,X+11.752$ ($r=-0.999$, $P<0.001$), where X is the exposed height (mm) and Y is the corresponding resonance frequency in kHz.

To assess the validity of the FE model used in this study, the modal testing experiment described above was simulated with a type III FE model. The results are plotted in Fig. 5. A linear relationship, which can be expressed mathematically as follows: $Y=-2.06\,X+17.89$ ($r=-0.975$, $P<0.001$), was also found between the resonance frequency and the exposed height. The highest frequency was at 17.92 kHz when the exposed height was 0.8 mm, and the minimum frequency of 4.966 kHz was obtained when the exposed height was increased to 6.8 mm. A decreasing ratio of 72.3% was found when the exposed height was increased from 0.8 mm to 6.6 mm. The finding of similar qualitative results from the *in vitro* experiment and the numerical simulation demonstrates that the FE model is a reliable model for resonance frequency analysis.

To assess the vibration characteristics of the dental implant, the first four modes of natural frequencies and mode shapes were computed under the greatest values of the boundary conditions. Fig. 6 shows a plot of the mode shapes of the type III model. The first mode of the model (a) was a single bending mode; the second mode (b) was a torsional vibration; the third mode (c) vibrated along the longitudinal axis; and the fourth mode (d) was also a single bending mode vibrating along a direction orthogonal to the first mode. The corresponding frequency values were 17.92, 21.38, 23.88, and 38.41 kHz, respectively. Similar mode shapes were also obtained from the other three models.

To evaluate the influence of bone quality on the vibrational characteristics of implants, the RF values of the dental implant for various different bone types and bone densities were computed. Fig. 7 shows the results obtained from the simulations of the first situation, i.e. the simulation of different bone types and their effect on resonance frequency of

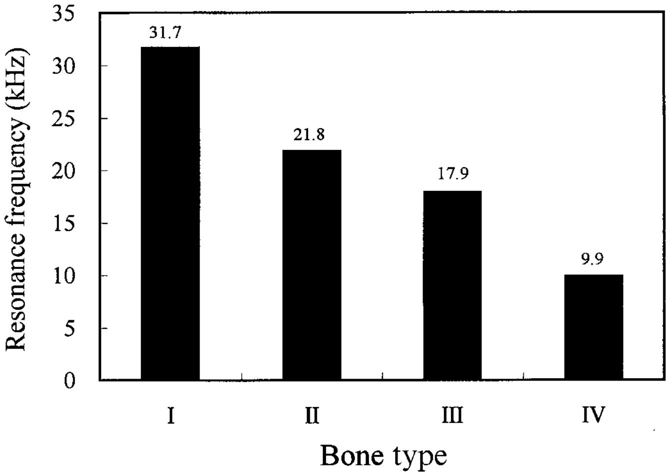

Fig. 7. Plot of the resonance frequency against different bone types. The resonance frequency decreased when the surrounding bone quality was lowered.

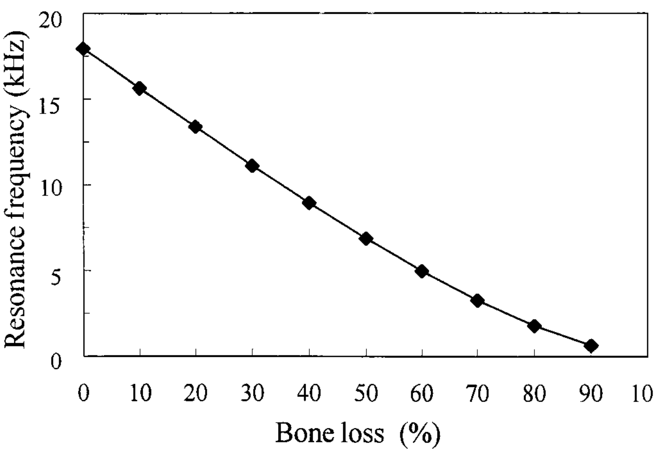

Fig. 8. Relationship between the natural frequency and the marginal bone density as assessed using finite element modeling. A high correlation was found between these two parameters.

the implant. The calculated frequencies decreased when the implant's surrounding bone quality was reduced. They were 31.7 kHz for the type I model, 21.83 kHz for the type II model, 17.9 kHz for the type III model, and 9.9 kHz for the type IV model. When the density of the surrounding bone in the type III model was reduced from 100% to 10%, the resonance frequency of the model also decreased from 17.92 kHz to 0.64 kHz. A significant linear relationship was found from the data plotted in Fig. 8 as follows: $Y=-0.2\ X+17.27$ ($r=-0.996$, $P<0.001$).

Discussion

In recent years, the use of FEM as an analysis tool in oral sciences has grown rapidly. However, there are various sources of error that can contribute to incorrect results (Moaveni 1999). To verify an FE model, experimental testing of the model may be the best way (Holmes & Loftus 1997; Moaveni 1999). In the present study, a series of modal testing experiments were carried out to test the model. Comparison of the data plotted in Fig. 4 and Fig. 5 revealed similar qualitative results. This demonstrates that the model used in this study is a credible model for resonance frequency analysis.

There are two basic types of stimuli used to determine the resonance frequency of a structure (Meredith 1998b; Nokes 1999). 1) The steady state test method, which is used to monitor the integrity of dental implants (Meredith et al. 1996b; Cawley et al. 1998). In this steady state, input consists of variable frequency cycles of pure sine waves. Then, the RF value is obtained simply by identifying the frequency at which the maximum response amplitude is obtained. 2) The impulse method, in which a transient force is applied by giving an impact with a hammer. The impulse will yield a response consistent with inputting a number of independent fundamental frequencies. The RF value of the tested structure can be analyzed by means of the Fast Fourier Transform. It is a relatively simple means to excite a structure into vibration (Ewins 1986) and the measurement of the RF value using this technique is very rapid and the apparatus is easy to set up (Meredith 1998a). This method is therefore used widely in vibration analysis in orthopedic research (Nokes 1999). The major disadvantage of the impulse method is the use of an accelerometer as a signal transducer because it should be attached firmly to the sample. In our previous work on *in vitro* studies, we used a sensitive piezoelectric microphone as a signal transducer, which had no contact with the tested samples. This methodology and instrument design has been proven to be reliable and sensitive (Huang et al. 2000). Although the FE simulation can calculate the resonance frequency values in continually changing bone, whether the minimum detectable change can be determined *in vivo* by using the impulse method is still unknown.

From a mechanical standpoint, an implant that is free to vibrate at one end and fixed at the other is a simple cantilever beam. The resonance frequency (f) of such a beam can be expressed as follows:

$$f = \alpha \sqrt{\frac{EI}{\rho l^4}} \qquad (3)$$

Where l is the effective vibrating length of the beam, ϱ the vibration mass per unit l, I the moment of inertia, and α is a constant related to the boundary conditions (Thomson 1988, Lowet et al. 1993; Meredith et al. 1996a). The sagittal section and length of dental implants with similar design are constant, and their Young's modulus and density are the same. Therefore, the resonance frequency of a dental implant with similar design would only be associated with its boundary conditions, such as the surrounding bone quality and effective vibrational length, i.e. exposed height. As shown in both Fig. 4 and Fig. 5, the resonance frequencies of the implant decreased linearly when the exposed heights were increased. These results are consistent with the findings of our previous study (Huang et al. 2000) and are in agreement with vibration theory. When the resonance frequency values obtained from experimental tests and computer simulation were compared, the results obtained from FEM simulation (decreased from 17.92 kHz to 4.97 kHz) were found to be slightly higher than those of the *in vitro* experiments (reduced from 10.71 kHz to 3.48 kHz). This is because the FE model used in this study assumes that a perfect attachment existed between the implant and the surrounding bone tissues. However, such a perfect interface rarely exists in actual clinical conditions, therefore an assumption of such a condition explains the overestimation of the value of the resonance frequency. On the other hand, in the *in vitro* experiments, no real integration process was performed after the test implants were placed into the bone block. Therefore, the resonance frequencies obtained from these experiments were probably underestimated. Based on these observations, we can expect that the real values of the resonance frequencies fall between the values obtained for FE modeling and those obtained in *in vitro* testing. Since the purpose of the current study was to qualitatively assess the effect of changes in bone quality on the resonance frequencies of a dental implant, the precise value of these resonance frequencies in the oral cavity remain to be determined in *in vivo* experiments.

Primary and secondary implant stability are two important factors influencing the survival of implants. Several attempts, such as cutting resistance technique and removal torque technique, have been used to determine the conditions of the implant-bone interface. However, the clinical usage of such techniques is still limited. Johansson & Strid (1994) used the cutting resistance of the taping process as a reference in determining the amount of time needed for osseointegration. They found that the smaller the contact area between implant and bone, the lesser the resistance to twisting forces. However, the cutting resistance method can only be used before the implant is installed, it cannot be used for a long-term assessment. Friberg et al. (1999) studied the correlation of bone's cutting resistance to the implant's resonance frequency *in vivo.* Their results show that various bone densities could be identified during implant placement using either the cutting torque technique or RFA. In this study, we computed the resonance frequencies of the implant model using various bone types as classified by Lekholm & Zarb (1985). Our results show that dental implant installed in type I bone has the highest resonance frequency. In contrast, the lowest resonance frequency was found in the type IV model (Fig. 7). These results imply that an implant with a lower interface restriction has a lower resonance frequency. Clinical studies conducted after implant installation have also shown that type IV bone has a much higher failure rate compared to the three other types (Jaffin & Berman 1991). The close similarity of the results obtained from clinical observation, cutting torque experiments and our numerical simulations indicates that the resonance frequency can be used as a parameter in the inspection and testing of an implant's marginal bone condition in the initial implantation stage.

Removal torque is a method used in the assessment of implant-bone interface status. However, performing the removal torque test before complete bone mineralization imposes damage on the surrounding soft tissue that will ultimately lead to implant failure. Therefore, the use of the removal torque in measuring the degree of osseointegration is highly restricted. From a mechanical standpoint, the removal torque technique measures the strength of the bone-implant interface in terms of shear, while the RFA is considered to measure the stability during bending (Rasmusson et al. 1999). However, shear stress between the bone-implant interface caused by a twisting force rarely occurs in daily life, while implant failure due to an excess bending moment caused by an abnormal occlusal force is relatively common. Lee et al. (2000) reported that it is appropriate to take the first natural frequency of the teeth as representative in the assessment of interface problems. As shown in Fig. 6(a), the first vibrational mode of the implant computed in this study is a single bending vibration. This finding indicates that the use of resonance frequency as a parameter for implant-bone interface assessment is reliable. On the other hand, when resonance frequencies were computed with various bone densities, we found a strong correlation between the resonance frequency and the surrounding bone density (Fig. 7). These findings indicate that the frequency technique may be able to ideally identify surrounding bony conditions and assess the stability of an implant after implantation treatment.

Although the RFA technique has numerous advantages in implant stability assessment including non-invasiveness, non-destructiveness, and instantaneous determination of results (Elias et al. 1996; Meredith 1998b), the sensitivity of this technique may be related to the performance of the devices. Kay et al. (1998) used the natural frequency (i.e. resonance frequency) to assess the stability between an external fixation pin and bone. He found that a slight decrease in bone quality, which may be detected radiographically, might not be enough to decrease the natural frequency of the pin. This may be due to the fact that an axial vibration mode was measured in their study. As shown in Fig. 6, the first vibration mode of an implant (17.92 kHz) is a single bending vibration, and the third mode is an axial vibration (23.88 kHz). Because of the damping effect of natural tissue, the higher-mode resonance frequencies of the implant were difficult to observe by the modal testing technique. In this study, owing to the bending vibration characteristics of the implant, we collected vibration signals by putting the microphone along the lingual-labial (frontal tooth) or lingual-buccal (posterior tooth) direction for measuring the first vibrational mode.

The height and density of the marginal bone are important factors affecting implant survival rate. The results of this study show that the resonance frequency of an implant was affected by its marginal bone characteristics including type, density and level. Thus, the resonance frequency may be useful as a parameter in future development of devices for assessing surrounding problems. On the other hand, numerical simulation can already offer reliable results in the analysis of the vibrational characteristics of a dental implant. The methodology used in this study may provide a useful reference for future study in resonance frequency analysis.

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Résumé

L'analyse par fréquence de résonance (RFA) a été utilisée par de nombreux chercheurs afin de déterminer les conditions d'attache des implants dentaires. Le but de l'étude présente a été de déterminer le comportement vibratoire d'un implant dentaire sous diverses conditions de l'os avoisinant. Un modèle d'éléments fini en trois dimensions (FE) d'un implant de type cylindrique a été développé. L'implant était placé dans un cube d'os. Le modèle a d'abord été évalué en subissant une série de tests. Les effets des conditions de l'os sur les fréquences de résonance de l'implant ont été enregistrés par ordinateur avec différents types d'os et de densité osseuse. La fréquence de résonance de l'implant dans de l'os de type III diminuait linéairement ($r=-0.996$, $P<0.01$) de 17.9 kHz (sans perte de densité osseuse) à 0.6 kHz (avec 90% de perte de densité osseuse) lorsque les densités osseuses étaient diminuées. D'autre part, sans perte osseuse, la plus haute valeur de fréquence de résonnance (36.1 kHz) a été mesurée lorsque l'implant a été placé dans de l'os de type I. Par contre, la fréquence de résonnance de l'implant dans de l'os de type IV était de 9.9 kHz c.à-d. presque quatre fois inférieure à celle trouvée dans le modèle de type I. RFA pourrait servir d'outil de diagnostic non-invasif pour déterminer la stabilité des implants dentaires durant les étapes de guérison et dans les suivis de routine subséquents.

Zusammenfassung

Die Resonanzfrequenzanalyse (RFA) wurde von verschiedenen Forschern zur Untersuchung der Gewebekonditionen um dentale Implantate verwendet. Das Ziel der vorliegenden Studie war es, das Vibrationsverhalten eines dentalen Implantats in unterschiedlichen Knochenumgebungen zu bestimmen. Es wurde ein 3D finite element (FE) model eines zylindrischen Titanimplantats entwickelt. In diesem Modell wurde das Implantat in einen kubischen Knochenschnitt eingebettet. Zuerst wurde das Modell mittels einer Serie von Testexperimenten bestätigt. Der Einfluss der Knochenkonditionen auf die Resonanzfrequenzen des Implantates wurde bei verschiedenen Knochentypen und Knochendichten aufgezeichnet. Unsere Resultate zeigen, dass die Resonanzfrequenz des Implantats in Knochen des Typs III linerar ($r=-0.996$, $P<0.01$) von 17.9 kHz (ohne Verlust an Knochendichte) auf 0.6 kHz (90% Verlust an Knochendichte) abnimmt, wenn die Knochendichten reduziert werden. Ohne Knochenverlust andererseits wurde der höchste Wert für die Resonanzfrequenz (36.1 kHz) gefunden, wenn das Implantat in Knochen des Typ I gesetzt wurde. Im Gegensatz dazu betrug die Resonanzfrequenz des Implantats im Knochen des Typ IV 9.9 kHz, was fast viermal weniger ist als das Resultat im Typ I Modell. Diese Resultate lassen vermuten, dass die RFA als nützliches nichtinvasives diagnostisches Hilfsmittel zur Aufzeichnung der Stabilität von dentalen Implantaten während der Einheilphase und in den darauffolgenden Routineuntersuchungen nach Behandlungsabschluss dienen kann.

Resumen

El análisis de la frecuencia de resonancia (RFA) ha sido usado por varios investigadores para valorar las condiciones limite de los implantes dentales. La meta del presente estudio fue determinar el comportamiento vibratorio de un implante dental bajo diversas condiciones de hueso circundante. Se desarrolló un modelo 3D de elemento finito (FE) de un implante de titanio de tipo cilíndrico. En este modelo el implante se embebió en una sección cúbica de hueso. El modelo fue primero validado usando una serie de experimentos modales de prueba. Los efectos de las condiciones óseas en las frecuencias de resonancia del implante se computaron con diferentes tipos de hueso y densidades óseas. Nuestros resultados muestran que la frecuencia de resonancia del implante con hueso circundante tipo III disminuyó linealmente ($r=-0.996$, $P=-0.01$) desde 17.9 kHz (sin perdida de densidad ósea) hasta 0.6 kHz (90% de perdida de densidad ósea) cuando las densidades óseas decrecieron. Por otro lado, sin perdida ósea, el valor mas alto de frequencia de resonancia (36.1 kHz) se encontró cuando el implante se colocó en torno a hueso tipo I. En contraste, la frecuencia de resonancia del implante con calidad de hueso tipo IV apareció como 9.9 kHz, lo cual es cuatro veces menos que aquel encontrado en el modelo tipo I. Estos resultados sugieren que la RFA pudiera servir como una herramienta diagnóstica no invasiva para detectar la estabilidad de los implantes dentales durante las fases de cicatrización y en el subsiguiente seguimiento de mantenimiento tras el tratamiento.

要旨

共鳴周波数分析（RFA）は歯牙インプラントの境界条件を評価するために数人の研究者によって用いられてきている。本研究は、周辺の骨の様々な条件下で、歯牙インプラントの振動の挙動を検討した。シリンダー型チタン製インプラントの三次元有限要素（FE）モデルを開発した。同モデルでは、インプラントは立方体の骨片に包まれていた。まずこのモデルを一連のモーダル試験実験によって検証した。異なる骨質や骨密度について、骨の条件がインプラントの共鳴周波数に及ぼす影響を計算した。その結果、タイプ３の骨においては、インプラントの共鳴周波数は骨密度の減少につれて１７．９ｋＨｚ（骨密度の喪失なし）から０．６ｋＨｚ（９０％の骨密度喪失）に直線的に減少した（ｒ＝－０．９９６、ｐ＜０．０１）。他方骨喪失が無い場合では、インプラントをタイプ１の骨に埋入した時に、最高の共鳴周波数（３６．１ｋＨｚ）が得られた。これとは対照的に、タイプ４の骨質ではインプラントの共鳴周波数は９．９ｋＨｚであり、タイプ１のモデルのほぼ４分の１であった。これらの結果は、ＲＦＡは治癒期間及びその後の定期的追跡検査のための、歯牙インプラントの安定性を評価するための非侵襲的なツールとして使用できることを示唆している。

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