Factors Influencing the Resonance Frequency of Dental Implants

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Purpose: Resonance frequency (RF) analysis has been used by several investigators to assess the boundary conditions of dental implants. However, a scientific investigation of the association between the structural condition of the alveolar bone and the dynamic behavior of dental implants has not yet been reported. The aim of this study was to assess the factors influencing the RF of dental implants using an in vitro modal analysis.

Materials and Methods: Resonant vibration within implants was induced by an impulse-force hammer. The induced vibration signal was subsequently detected using an acoustic microphone and analyzed by fast Fourier transform. The resultant data were further analyzed to test the statistical effects of the embedding-material boundary height, thickness, and density on the RF values of the sample implants.

Results: Significant changes ($P < .05$) in RF values were revealed for implants embedded within a high-density block when decreasing boundary height reached 6, 5, and 4 mm, at respective thickness increments of 10, 15, and 20 mm. For analogous low-density samples, significant changes ($P < .05$) in RF values were found when respective decreasing boundary height reached 6, 4, and 3 mm.

Conclusions: Our findings indicate that boundary height, width, and density factors can influence the RF of dental implants and that a lower boundary density and greater boundary thickness can lead to more obvious RF changes.

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It is generally accepted that the initial stability of a dental implant together with the integrity of the osseointegration process postimplantation are 2 of the most important factors for implant survival. Due to the lack of an efficacious device for accurate measurement of healing at the bone-implant interface, however, assessment of these 2 factors has remained a challenge for dentists. A number of techniques have been used to monitor the osseointegration process, including histologic analysis[1-5] and electron microscopic evaluation[6] of samples from the bone-implant interface and removal torque testing.[2,3,7-9] Due to the problems inherent to this type of invasive testing, however, these methods are not suitable for long-term clinical evaluation of related problems, which are mostly associated with this critical interface. Alternatively, radiographic study has been one of the most common methods for monitoring implant status[10]; however, analysis of 2-dimensional images cannot provide accurate information of 3-dimensional structures. Recently, the Periotest (Simens AG, Bensheim, Germany), a noninvasive device, has been used for implant-stability assessment.[11,12] According to a report by Caulier et al,[13] however, the correlation of Periotest results with the status of peri-implant bone tissue was not significant.

During the past 5 years, a number of workers have performed frequency analyses of induced vibration in implants to assess the status of the bone-implant interface.[14-20] The results have shown that not only do

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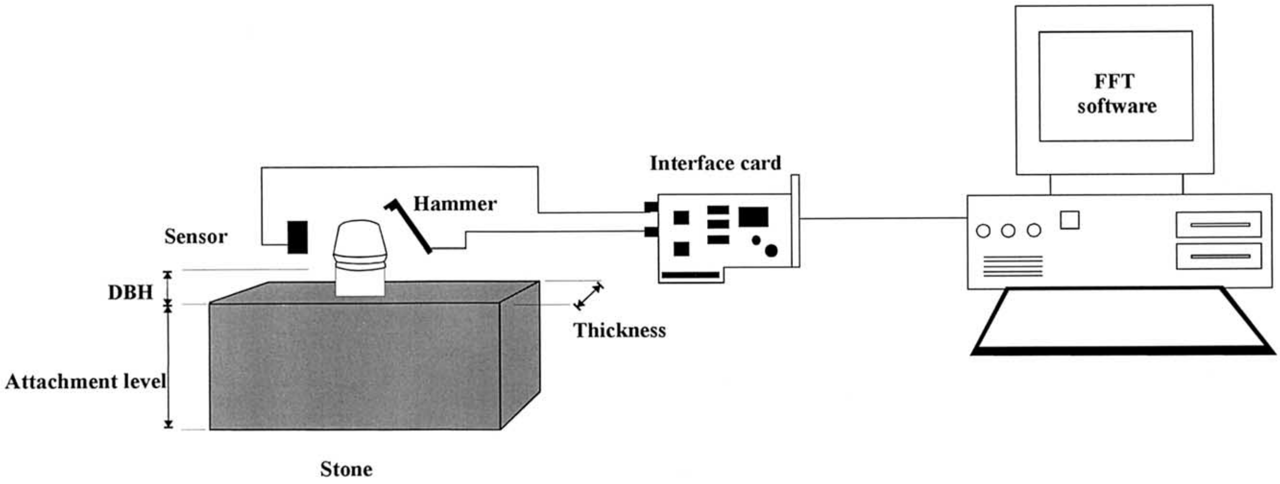

FIGURE 1. Schematic diagram of data acquisition system.

implant resonance frequency (RF) values provide a meaningful clinical index for assessment of primary stability, but also RFs may constitute an important parameter for evaluating secondary stability. Additionally, because the technique is inherently noninvasive and nondestructive, it seems reasonable to suggest that the measurement is potentially a useful clinical tool for the prevention, diagnosis, and prediction of implant failure and for the facilitation of post-treatment maintenance of viable prostheses.[15] Recently, a new apparatus for resonance frequency analysis (RFA) of implants has been developed (Osstell; Integration Diagnostics, Göteborgsvägen, Sweden). Scientific investigations of the association of structural conditions of the alveolar bone with the dynamic behavior of dental implants have not yet been reported, however.

Thus, in this study, the influence of various factors, such as the height, width, and/or density of the alveolar bone, on the measured RF of an implant for various simulated boundary conditions was investigated using a modal testing technique. The results were then analyzed statistically.

Materials and Methods

Modal analysis was used to assess the frequency response of dental implants, with the RFs measured for a number of simulated boundary conditions. The fixture bodies of the test implants (Brånemark System; Nobel Biocare AB, Goteborg, Sweden) were 3.75 mm in diameter and 10 mm in length, with a 3-mm healing abutment. Before RF measurement, the test implants were embedded into gypsum blocks, which were used to simulate the mass effect of alveolar bone. To test the effects of boundary strength on the RF value of the implant, 2 types of gypsum were used, classifying the testing implants into 2 groups. Group I implants were embedded into a type I stone with a density of 1.90 g/cm^3. Type III stone, with a density of 1.45 g/cm^3, was used as the embedding material for the group II variants. Further, to test the influence of block width on the RF values of the implants, widths of 20, 15, 10, 8, and 6 mm were tested for each of the groups. The height and length of the stone blocks were fixed at 18 and 100 mm, respectively. Additionally, to evaluate the relationships for RF values and decreasing boundary height (DBH), the RF value for each of the tested implants was recorded with the DBH incrementally from 1 to 7 mm in 1-mm steps, resulting in progressive lessening in coverage of the implant. The stone ingredients were combined at a water/stone ratio of 0.3 in a vacuum mixer for 45 seconds, with 5 test samples prepared for each condition for RF measurements.

The test samples were fixed in a clamping stand with a torque force of 20 N-cm. Vibration of the implant was induced using a transient force produced by an impulse-force hammer (GK291C80; PCB Piezotronics, Buffalo, NY). The induced vibration signal was detected by a noncontacting acoustic microphone (FM-10B, 20-kHz sensitivity; FC Electronics, Taipei, Taiwan). The signals were then recorded and processed by computer after digital conversion by a 2-channel A/D interface card (AD102 A; Prowave Engineering, Hsinchu, Taiwan), and the RFs of the sample implants were determined using FFT software (SD200N, Signal Doctor; Prowave Engineering, Hsinchu, Taiwan) (Fig 1). Three induction trials were conducted for each sample, and results were averaged to reduce artifacts caused by noise and human error. Testing for each condition was repeated 5 times, once for every sample, and the mean and standard deviation were calculated for later comparison and discussion. One-way analysis of variance with Tukey's HSD test was used to test the association of

Table 1. RESONANCE FREQUENCIES (MEAN ± SD, KHZ) OF TESTED IMPLANTS FOR DECREASING BOUNDARY HEIGHTS (DBH) AND THICKNESS IN THE GROUP I AND II IMPLANTS

Boundary Thickness (mm)	DBH (mm)							
	0	1	2	3	4	5	6	7
Group I								
6	11.83 ± 0.30	11.38 ± 0.13	11.12 ± 0.13	11.00 ± 0.10	10.84 ± 0.11	10.33 ± 0.12	9.42 ± 0.04	8.09 ± 0.04
8	12.56 ± 0.08	12.58 ± 0.07	12.28 ± 0.14	12.26 ± 0.08	12.03 ± 0.15	10.89 ± 0.11	9.93 ± 0.08	8.12 ± 0.15
10	14.59 ± 0.36	14.27 ± 0.06	14.03 ± 0.12	13.45 ± 0.08	12.06 ± 0.16	11.67 ± 0.19	9.75 ± 0.13*	8.13 ± 0.05*
15	17.66 ± 0.23	17.32 ± 0.09	17.03 ± 0.07	16.83 ± 0.08	14.38 ± 0.26	11.81 ± 0.13*	9.23 ± 0.04*	7.00 ± 0.27*
20	18.79 ± 0.06	18.61 ± 0.11	17.39 ± 0.13	16.71 ± 0.15	14.02 ± 0.11*	11.35 ± 0.18*	9.41 ± 0.06*	7.51 ± 0.03*
Group II								
6	8.96 ± 0.11	8.88 ± 0.10	8.84 ± 0.20	8.91 ± 0.14	8.73 ± 0.14	8.28 ± 0.06	7.03 ± 0.15	4.12 ± 0.21
8	11.20 ± 0.14	11.03 ± 0.09	11.03 ± 0.08	10.94 ± 0.14	10.69 ± 0.09	9.24 ± 0.11	7.96 ± 0.06	6.62 ± 0.13
10	11.61 ± 0.17	11.67 ± 0.16	11.64 ± 0.26	11.31 ± 0.23	10.61 ± 0.39	9.97 ± 0.06	8.43 ± 0.05*	6.64 ± 0.11*
15	16.95 ± 0.05	14.60 ± 0.21	14.59 ± 0.09	13.95 ± 0.23	12.30 ± 0.07*	10.25 ± 0.06*	8.47 ± 0.04*	6.77 ± 0.10*
20	17.01 ± 0.07	16.39 ± 0.16	14.29 ± 0.36	13.66 ± 0.04*	12.41 ± 0.11*	10.51 ± 0.04*	8.69 ± 0.08*	6.95 ± 0.02*

*$P < .05$.

the RF values and the boundary attachment level, for various boundary thicknesses, and the 2 block densities.

Results

Table 1 lists the RFs of dental implants tested for the simulated bony conditions, in vitro. The mean derived frequency ranges were from 7 to 19 kHz for group I implants (Table 1, group I) and from 4 to 17 kHz for group II analogs (Table 1, group II). Frequency ranges for the group I implants were higher than those of the analogous group II implants. By contrast, regardless of the boundary thickness of the tested implant, RF values decreased as DBH of the implants were increased.

Relationships between RF and DBH values at various thicknesses are plotted in Figures 2 and 3 for group I and II implants, respectively. For group I implants, significant differences ($P < .05$) in RF values were demonstrated at DBH of 6, 5, and 4 mm for boundary thicknesses of 10, 15, and 20 mm, respectively (Table 1, group I). Significant differences ($P < .05$) were also shown for analogous group II implants where respective DBH of the implants were 6, 4, and 3 mm (Table 1, group II).

Discussion

Clinical observations have indicated that after restorative superstructures have been established, physiologic responses to occlusal stress and associated inflammation may lead to changes in alveolar bone height and width. According to Ericsson et al,[2] alveolar recession of 3 mm is a critical threshold for assessment of the failure of a dental implant. Shillingburg et al[21] suggested an ideal crown-to-root ratio for restoration of 1:1; otherwise, the prosthesis may fail due to an unfavorable cantilever effect. An abutment with a length of 3 mm was used for the present study, giving a total length for our test implant (fixture and abutment) of 13 mm. When the DBH values of the

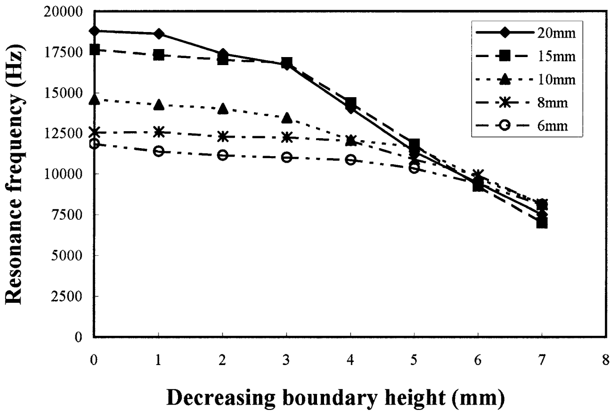

FIGURE 2. Plot of resonance frequency against decreasing boundary height at various simulated bony thicknesses for group I implants.

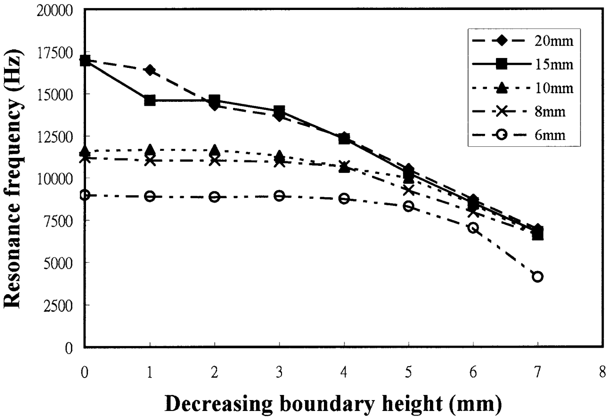

FIGURE 3. Plot of resonance frequency against decreasing boundary height at various simulated bony thicknesses for group II implants.

implants reached 3.5 mm, the height ratio of the exposed to embedded parts of the implant was 1:1. As shown in Figures 2 and 3, where the DBH value is greater than 3 mm, the decreasing RF value is more obvious, especially where the boundary thicknesses of the implant model are less than 15 mm. If we assume that 3 mm of alveolar bone loss is important in terms of prediction of the success of an implantation, then the feasibility and practicality of evaluation of the bone-implant boundary using RF measurement can also be proposed.

Within the oral cavity, one end of an implant is exposed to air while, under normal conditions, the other end is firmly constrained within the alveolar bone. Thus we can evaluate an implant's RF by applying the formula for a cantilevered beam as follows:[16,22]

$$f_n = \alpha \sqrt{\frac{EI}{\rho l^4}}$$

where f_n is the RF of the beam, l is the effective vibrational length of the beam, E is Young's modulus, I is the moment of inertia, ρ is the mass per unit effective vibrational length, and α is a constant related to boundary conditions. From the formula, it is clear that as the boundary density of the implant increases, the value of α will also increase with an associated tendency for the RF value to increase. In our simulation, 2 types of gypsum matrix of different densities were used as the embedding material. Our results show that the RF values for implants embedded within the higher-density matrix were greater than those for analogous lower-density variants (Table 1). Furthermore, previous studies have also shown associations between the boundary attachment level of implants and RF values, with lower values shown for DBH in comparison to healthy implants, due to the larger l value for the less-healthy variants.[15,23] Our measurements were also consistent with these results.

Furthermore, statistical analysis of our data revealed that boundary thickness is a factor influencing the measured RF values of dental implants in vitro. Kaneko[24] reported that pulsed oscillation testing, which applies a dynamic load to the implant itself, will induce vibration in the surrounding bone. Further, this induction effect has been confirmed by Lee et al,[25] with these researchers using the finite element method to analyze the RF values and vibration mode for natural teeth and surrounding bone. In this study, an impulse force was used to trigger implant vibration, and it was expected that resonance would be induced in the boundary material when the impulse force was applied. According to the formula expressed above, increased block thickness should be reflected in increased moment of inertia (*I*), resulting in an increased RF values for the tested sample.

Further, when the boundary attachment level was reduced by 3 mm, a significant difference was only shown for RF values of goup II implants with a 20-mm boundary thickness. A similar statistical effect was also noted when comparing RF values for implants of both tested groups with a 15-mm boundary thickness, as shown in Table 1. This suggests that greater sensitivity, in terms of RF value changes, may be shown for implants surrounded by lower-density stone as the boundary attachment level is lowered.

Additionally, a reduction of 3 to 4 mm in alveolar bone may lead to implant failure due to unfavorable stress concentrations.[26,27] Thus, when using RF measurements to provide an indicator of implant stability, it is important to evaluate the sensitivity to bony recession of 3 to 4 mm. We found that sensitivity to frequency changes increases with increasing boundary width, regardless of density. Therefore, we suggest that it is reasonable to conclude that the RF value of an implant is a useful indicator for implant status assessment, especially for patients with greater alveolar bone width.

The results of our simulation indicate that significant differences in RF values for reductions in boundary attachment level of 3 to 4 mm will only occur where the width of the investing material reaches 15 mm. This exceeds the typical measurement for alveolar bone, however. As described earlier, the sensitivity of RF values for implant-bone interface assessment is greater for implants surrounded by lower-density embedding material. Therefore, the sensitivity of this technique must be improved when applied in the oral cavity because the density of the cancellus bone (1.0 to 1.4 g/cm^3) is lower than that of the investing stones (1.90 g/cm^3 for type I stone and 1.45 g/cm^3 for type III stone) used in this study.[28,29]

Although useful data were obtained from this investigation, the quantitative results may have limited application because real bone tissue was not used and densities of the investing materials were not similar. Nonetheless, analysis of our findings provides useful qualitative conclusions regarding the significance of boundary-height, width, and density factors and their influence on dental implant RFs. Further evaluation of these boundary dimensions may lead to additional useful information on the effects of RF alterations. We hope that this study can serve as a useful reference for further, more advanced studies elaborating the RF characteristics of dental implants.

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