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Measuring tooth mobility with a no-contact vibration device

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Background and Objective: Mechanical parameters obtained from the frequency response at tooth vibration informs of various periodontal tissue conditions. An electromagnetic vibration device was investigated for measuring tooth mobility using mechanical parameters obtained from the frequency response characteristics of an experimental tooth model. This electromagnetic vibration device was able to assess the overall condition of periodontal tissue associated with the alteration of each parameter. In this study, reliability and effects of bottom thicknesses of simulated periodontal ligament relative to mechanical parameters were analysed.

Material and Methods: Measurement of tooth vibration was performed by an electromagnetic vibration device on experimental tooth models with different bottom thicknesses of simulated periodontal ligament. Using an electromagnetic vibration device, the mechanical parameters resonant frequency, elastic modulus and coefficient of viscosity were calculated from the frequency response characteristics derived from tooth vibration by an electromagnetic force. Variation of those parameters was investigated under four different experimental conditions and the implications of the results were discussed.

Results: An electromagnetic vibration device clearly detected three mechanical parameters in all experimental conditions. The resonant frequency and the elastic modulus decreased with increasing bottom thickness. However, no significant difference in the coefficient of viscosity was observed among the experimental conditions.

Conclusion: Assessment of tooth mobility using mechanical parameters of an electromagnetic vibration device reproduced fine details of various simulated periodontal ligament conditions. Variation in the parameters resonant frequency, elastic modulus and coefficient of viscosity might be useful in evaluating changes of components in periodontal tissues.

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Information on periodontal tissue conditions is important in clinical diagnosis, treatment planning and prognosis management. Radiographic examination, gingival tissue examination, tooth mobility, percussion and masticatory pressure are widely used to evaluate periodontal tissue conditions (1,2). In particular, a measure of tooth mobility is important for evaluating the function of periodontal tissues precisely. Miller's method (3) is in routine clinical use, but this method does not evaluate tooth mobility objectively because it depends on the operator's tactile sense.

In 1983, Schulte *et al.* (4) introduced a new diagnosis device, marketed commercially as Periotest® (5), to assess tooth mobility objectively. Periotest® measures the acceleration of a rod applying an impact load to the target tooth, which allows the detection of tooth mobility but does not reflect the overall periodontal tissue condition. Therefore, a new device for evaluating periodontal tissue conditions, including tooth mobility, using a vibration system similar to Periotest®, was investigated (6). This new device uses a metal rod to apply an impact load to the target tooth by repetitive motion along its long axis between the contact and static positions. This new method makes use of three parameters: the damped natural frequency; elastic modulus (spring constant); and coefficient of viscosity (viscous resistance). These parameters are obtained from the response wave at the vibrating tooth and are typical parameters used in the dynamic model. This vibration system revealed that these three parameters are precisely related to the condition of the periodontal tissues. However, this vibrationsystem is still not suitable for clinical application because the cheek, tongue and location of the target tooth in a narrow oral cavity can interfere with accurate measurement, and the increased impulse force used to improve the measurement accuracy can induce tooth pain.

To resolve those problems, we developed a new electromagnetic vibrating device called the no-contact vibration device, which utilizes the force generated by an alternating sine wave to vibrate the tooth without contact. The present study investigated the mechanical parameters obtained from the frequency response characteristics of a tooth vibrated using an electromagnetic force and established an objective evaluation method based on the relationships of the mechanical parameters.

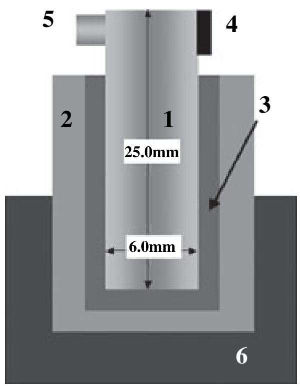

Fig. 1. Experimental tooth model.

Material and methods

Experimental tooth model

The experimental tooth model consisted of a 6.0 × 25.0 mm cylindrical rod ($\phi \times L$) made of Polyacetal, a polyether rubber impression material (Examixfine Injection Type; GC, Tokyo, Japan), and plaster (Densite; Shofu, Tokyo, Japan)(Fig. 1). In addition, polyether rubber impression material and plaster were used to simulate periodontal ligament and alveolar bone, respectively.

Experimental tooth models were constructed with four different bottom thicknesses (0.5, 1.0, 3.0 and 5.0 mm), based on Maeda (6), in order to compare the results obtained from contact and no-contact vibration devices (Fig. 2).

Experimental device (no-contact vibration device)

A schematic diagram of the experimental device is shown in Fig. 3. The experimental device consists of three components: the vibrator; the detector; and the analyser.

Vibrator —The vibrator consisted of a disk magnet (ϕ 4 mm, 0.19 g, 80 mT; Pip Fujimoto, Osaka, Japan) and the electromagnetic vibration device. The disk magnet was attached to the lateral surface at the top of cylindrical rod by an adhesive (cyanoacrylate; Toagosei, Tokyo, Japan). The disk magnet receives the electrical force generated by the alternating magnetic field produced by the electromagnetic vibration device. The electromagnetic vibrating device consists of a ferrite rod (7.0 × 60.0 mm $\phi \times L$) wound with enamel wire (ϕ = 5 mm) 720 times to form a coil. The tip of the ferrite rod is conical.

Detector — The vibrations were detected with acceleration sensors that weigh 0.4 g (NP-601; Ono Sokki, Tokyo, Japan). The acceleration sensors were attached to the top of cylindrical rod, as shown in Fig. 1. The output signal from the acceleration sensor was amplified using a 30-dB sensor amplifier (PS-022; Ono Sokki) and input to the fast Fourier transformation (FFT) analyser.

Analyser — The FFT analyser was used to measure the vibrations. The frequency response characteristics of the experimental tooth model (i.e. the

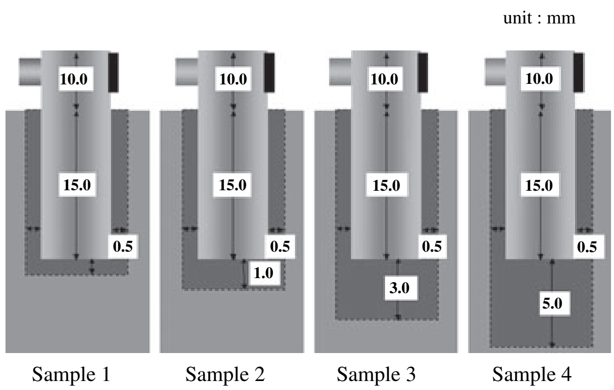

Fig. 2. Experimental tooth models with four different bottom thicknesses. The values are shown in mm.

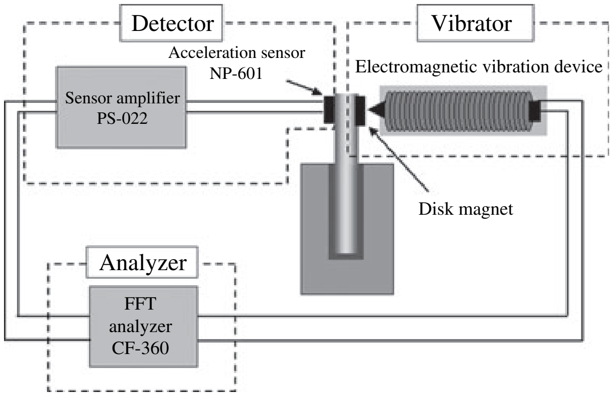

Fig. 3. Components of the experimental device. FFT, fast Fourier transformation.

ratio between the output of a sweep generator and the input of an acceleration sensor) were calculated by the FFT analyser. Measurements were made over a frequency range of 5 kHz, with a frequency resolution of 12.5 Hz and an 80-ms capture time. With these settings, 64 measurements were made at each frequency. The average value of each frequency was used as the measurement value.

Measuring method

The distance between the disk magnet and the tip of the ferrite rod was kept at 1 mm in order to apply the electric force without contact. The ferrite rod was kept at right angles to the magnet disk. The power supply of the electromagnetic vibration device used FFT analyser with a built-in sweep generator (CF-360; Ono Sokki). The applied voltage was 10 Vp-p, and the frequency range was from 1 to 5 kHz.

The frequency response characteristics of experimental tooth models with four different bottom thicknesses were measured. Each parameter was calculated from the frequency response characteristics using the following formulas (Fig. 4) (7):

$$\zeta \cong \frac{f_2 - f_1}{2f_n} \qquad (eqn\ 1)$$

$$k = 4\pi^2 fn^2 m \qquad (eqn\ 2)$$

$$c = 2\zeta\sqrt{mk} \qquad (eqn\ 3)$$

where f_n is the resonant frequency (Hz), m is the mass (kg), ζ is the damping ratio (*O*), k is the elastic modulus (N/m^2) and c is the coefficient of viscosity (N·s/m^2). In equation 1, f_1 and f_2 are the frequencies at $1/\sqrt{2}$ times the maximum amplitude of the resonant frequency, and m is the total mass of the cylindrical rod, acceleration sensor and disk magnet (1.59×10^{-3} kg) in equations 2 and 3. The mass of the lead wire is negligible in this study because the wire was not tensed in measurement and its mass is small.

Results

The resonant frequency

The resonant frequency for each bottom thickness is shown in Fig. 5. The resonant frequency decreased with increasing bottom thickness. The maximum resonant frequency (2.01×10^3 Hz) occurred with a bottom thickness of 0.5 mm, and the minimum resonant frequency (1.76×10^3 Hz) was found at a bottom thickness of 5.0 mm. The regression analysis showed that the difference was statistically significant, and a negative correlation was observed in the correlation analysis.

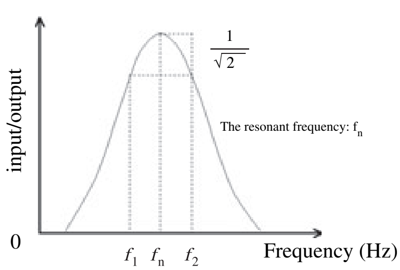

Fig. 4. Frequency response characteristics. f_1 and f_2 are the frequencies at $1/\sqrt{2}$ times the maximum amplitude of the resonant frequency (f_n).

The elastic modulus

The elastic modulus for each bottom thickness is shown in Fig. 6. The elastic modulus decreased with increasing bottom thickness. The maximum elastic modulus (1.60×10^5 N/m^2) occurred with a bottom thickness of 0.5 mm, and the minimum elastic modulus (1.24×10^5 N/m^2) was found at a bottom thickness of 5.0 mm. The regression analysis showed that the difference in the elastic modulus was statistically significant, and a negative correlation was observed in the correlation analysis.

The coefficient of viscosity

The coefficient of viscosity for the different bottom thicknesses is shown in Fig. 7. The coefficient of viscosity ranged from 0.462 to 0.531 N s/m^2 for bottom thicknesses of 0.5 to 5.0 mm, and from 0.46 to 1.26 N·s/m^2 for a bottom thickness of 5.0 mm. The regression analysis showed that the difference in the coefficient of viscosity was statistically significant, and a positive correlation was observed in the correlation analysis. In addition, there was no correlation in the range from 0.5 to 3.0 mm.

Discussion

Schulte *et al.* (4,5) developed a new measuring device for evaluating tooth mobility objectively. Their device provided a value based on the contact time between the tooth surface and the tip of a metal rod, which moved electrically with uniform motion. This method

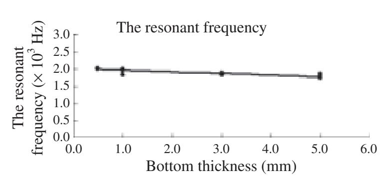

Fig. 5. Resonant frequencies at different bottom thicknesses.

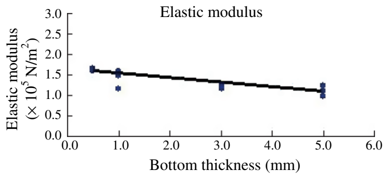

Fig. 6. Elastic modulus (k) at different bottom thicknesses. [Correction added after online publication on 30 August 2007: Figure 6 replaced].

is excellent for evaluating tooth mobility objectively compared with Miller's method (3), which is based on subjective tactile sensitivity. Nevertheless, because the Periotest® value reflects the displacement amplitude of the tooth on impact loading, the value does not reflect all periodontal tissue conditions.

Kurashima (8) investigated the relationship between the displacement of a natural tooth and the working load using an electric measuring instrument. The results suggested that periodontal tissues possess both elastic and viscous properties, and he reported that the tooth underwent natural vibration showing a resonance phenomenon when vibrated. Komatsu (9) derived an equation of motion from Yajima's dynamic model (10). He established a formula for the displacement of the tooth from the equation of motion. This theoretical study clarified what the damped natural frequency indicated objectively for tooth mobility under a load and suggested that it was a measure of the periodontal tissue conditions. Consequently, we developed an experimental vibration device (the contact vibration device) based on their theoretical concepts.

Maeda (6), Ikeda (11), Kamimoto (12) and Hayashi (13) investigated the mechanical characteristics of periodontal tissues quantitatively, using an experimental tooth model, with the contact vibration device. Maeda (6) studied this device in experimental tooth models with different bottom thicknesses, representing artificial periodontal ligament and root forms, and reported its reliability for the objective evaluation of periodontal tissue conditions using the damped natural frequency and mechanical parameters. In a study using a bifurcated tooth model, Ikeda (11) reported that how the mechanical parameters were influenced depended on the area of the root surface. In addition, Kamimoto (12) reported a relationship between the position of the detection sensor and the direction of the impact load. Hayashi (13) investigated the effects of the volume of the impulsive force on the results. The results of these studies showed that the contact vibration device could provide accurate information about various periodontal tissue conditions using the mechanical parameters.

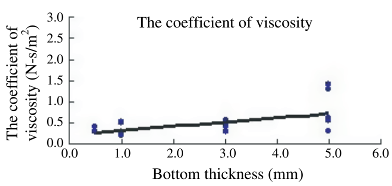

Fig. 7. Coefficient of viscosity at different bottom thicknesses. [Correction added after online publication on 30 August 2007: Figure 7 replaced].

Nevertheless, it was clear that the contact vibration device had shortcomings similar to those of the Periotest®. Specifically, the contact vibration device requires a horizontal position on the tooth surface to apply the impact load from the repeated uniform linear motion along the long axis of the metal rod. This requirement severely limits its use within the oral cavity, owing to interference from the cheek and tongue. Moreover, the strong impulsive force used caused pain, discomfort and physical damage to the tooth.

Continuously, Meredith *et al.* reported using sonic resonance frequency analysis to measure the stability value of the implant–tissue interface at implant placement and to determine the possibility of monitoring the change in tissue stiffness during the initial healing period and the subsequent follow-up period, indicating the level of osseointegration (14–16). They concluded that the resonance frequency rose with increase of osseointegration level. Thereafter, many studies in the field of dental implants have reported using this type of device, which is well known as the Ostell™ mentor (17,18), and recognized its clinical usefulness on the evaluation of implant stability. However, periodontal tissues have both elastic and viscous properties. Therefore, it is difficult to analyse the status of periodontal tissues using only the resonance frequency.

Therefore, in an attempt to resolve problems associated with the contact vibration device, Periotest® and the Ostell™ mentor, we developed a new vibration system using an electromagnetic force to produce no-contact vibration of the tooth.

Analysis of mechanical parameters

The elastic modulus and coefficient of viscosity were derived from Yajima's dynamic model (10) (Fig. 8), which applied exciting forces.

The equation of motion in the dynamic model can be expressed as follows:

$$\mathrm{M}\ddot{\mathrm{x}} + \mathrm{c}\dot{\mathrm{x}} + \mathrm{kx} = \mathrm{Fm}\sin\omega t \qquad (eqn\ 4)$$

From the equation of motion, while considering the elastic and viscous friction forces, the displacement magnification factor, μ_D, is defined as:

$$\mu_D = \frac{1}{\sqrt{4\zeta^2 u^2 + (1-u^2)^2}} \qquad (eqn\ 5)$$

where u and ζ are the frequency ratio and damping ratio, respectively. The displacement magnification factor (μ_D) is the ratio of the displacement under static and dynamic forces, and depends on the frequency ratio.

The characteristic curve obtained when plotting the displacement magnification factor (μ_D) against the frequency ratio (u) is the resonance curve when a forced vibration is applied.

The displacement magnification factor (μ_{Dm}) at resonance can be expressed as $\mu_{Dm} \cong (1/2\zeta)$ for small values of the damping ratio (ζ). Therefore, μ_{Dm} at resonance is proportional to $(1/2\zeta)$. When the frequency ratio is u_1 and u_2, corresponding to $1/\sqrt{2}$ times μ_{Dm}, then ζ can be expressed as:

$$\zeta \cong \frac{u_2 - u_1}{2} \qquad (eqn\ 6)$$

Furthermore, when $u_1 = \omega_1/\omega_n$ and $u_2 = \omega_2/\omega_n$ are given, ζ equals:

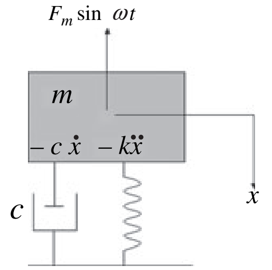

Fig. 8. Yajima's dynamic model. *c*, coefficient of viscosity; *k*, modulus of elastic; *m*, mass; X, variable; ωt, external force.

$$\zeta \cong \frac{f_2 - f_1}{2f_n} \qquad (eqn\ 7)$$

In addition, the elastic modulus can be expressed as $k = 4\pi^2 fn^2 m$ because the relationship $\omega_n^2 = k/m$ links ω_n and k. The elastic modulus can be obtained from the resonant frequency using the formulas described above. A relationship also exists between the damping ratio ζ and the coefficient of viscosity c, such that $c = 2\zeta\sqrt{mk}$, and c can be obtained from the damping ratio and elastic modulus. The elastic modulus and coefficient of viscosity can be derived from the damping ratio after calculating the resonant frequency obtained from the characteristics of the frequency response.

The present study determined the mechanical parameters from the resonant frequency and the characteristics of the frequency response using an experimental tooth model (Fig. 1) based on physiological theory.

The relationship between mechanical parameters and bottom thickness

The resonant frequency and elastic modulus decreased with increasing bottom thickness in the experimental tooth model (Figs 5 and 6), indicating that the increased bottom thickness resulted in greater tooth mobility as a result of the weak bone support. The increase in thickness can be understood as the serial elastic modulus in the mechanical model. If the serial elastic modulus is k_1, k_2,…k_n, then the combined elastic modulus, k_T, can be expressed as:

$$\frac{1}{k_T} = \frac{1}{k_1} + \frac{1}{k_2} + \cdots\cdots + \frac{1}{k_n} \qquad (eqn\ 8)$$

This equation shows that the combined elastic modulus, k_T, decreases as the number of elastic moduli (k_1, k_2,…k_n) increase. This explains why the elastic modulus in Fig. 6 decreased with increasing bottom thickness and why both the resonant frequency and elastic modulus decreased when the implant conditions became poor.

The coefficient of viscosity increased uniformly for bottom thicknesses from 0.5 to 3.0 mm. This differs from the results for the resonant frequency and elastic modulus, and may have arisen from the lack of visco-elasticity of the polyether rubber impression material. In addition, the coefficient of viscosity had a range of values for the specimens with bottom thicknesses of 5.0 mm. This probably arose from air bubbles caught within the material while preparing the experimental tooth model.

Comparison of the contact and no-contact vibration devices

Maeda (6) reported little change in the resonant frequency and elastic modulus with increasing bottom thickness using the contact vibration device. By contrast, those parameters decreased with increasing bottom thickness using the no-contact vibration device. Furthermore, as shown in Table 1, the standard deviation of the elastic modulus was smaller with the no-contact vibration device than with the contact vibration device. Moreover, as shown in Table 2, the variation in the standard deviation of the coefficient of viscosity with the no-contact vibration device was smaller than that with the contact vibration device, except for a bottom thickness of 5.0 mm. It is thought that the stable results arose from the vibration stability with the no-contact vibration device. In addition, the no-contact vibration device appears to produce greater measurement accuracy owing to its frequency response characteristics compared with the contact vibration device.

Moreover, because this vibration system did not produce an impact load, mechanical tooth damage was absent and patient discomfort was minimized. In addition, the no-contact vibration device is more compact than the contact device because movement of the metal rod is not required. Thus, it may be easy to set the no-contact device to target teeth in the oral cavity, independently of the location of the teeth or of other organs (e.g. tongue and cheeks).However, more improvements of this device are needed to maintain consistency during clinical application.

Table 1. Elastic modulus of the no-contact and contact vibration devices

	Elastic modulus (k) (× 10^5 N/m^2)	
The bottom thickness (mm)	The no-contact vibration device	The contact vibration device
0.5	1.60 (0.02)	2.64 (0.26)
1.0	1.49 (0.10)	2.45 (0.22)
3.0	1.35 (0.03)	2.69 (0.22)
5.0	1.24 (0.05)	2.38 (0.21)

Results are expressed as mean (standard deviation). n = 5. [Correction added after online publication on 30 August 2007: Table 1 replaced]

Table 2. Coefficient of viscosity of the no-contact and contact vibration devices

	The coefficient of viscosity (c) (N·s/m^2)	
The bottom thickness (mm)	The no-contact vibration device	The contact vibration device
0.5	0.462 (0.03)	3.67 (0.45)
1.0	0.496 (0.07)	3.45 (0.30)
3.0	0.531 (0.07)	3.62 (0.27)
5.0	0.785 (0.36)	3.29 (0.38)

Results are expressed as mean (standard deviation). n = 5. [Correction added after online publication on 30 August 2007: Table 2 replaced].

For example, the use of an angled hand-piece, a holder for proper hand-piece positioning or a wireless acceleration sensor for measurements might be helpful to ensure that there is a precise distance from and angle to the tooth.

Conclusions

To establish an objective method for evaluating periodontal tissue conditions, this study investigated the relationship between the mechanical parameters obtained from the frequency response characteristics of a tooth measured using a newly developed no-contact vibration device. The following conclusions were obtained.

(i) The resonant frequency and elastic modulus obtained from the characteristics of the frequency response decreased with increasing bottom thickness.

(ii) The coefficient of viscosity ranged from 0.462 to 0.531 $N{\cdot}s/m^2$ for bottom thicknesses of 0.5 to 3.0 mm, respectively, and showed a range of values for a bottom thickness of 5.0 mm.

(iii) The standard deviation of the elastic modulus with the no-contact vibration device was smaller than with the contact vibration device.

(iv) The variation in the standard deviation of the coefficient of viscosity using the no-contact vibration device was smaller than with the contact vibration device, except for a bottom thickness of 5.0 mm.

In conclusion, the electromagnetic vibration system was more accurate than the contact vibration system. In addition, the resonant frequency, elastic modulus and coefficient of viscosity were able to contribute to the objective evaluation of various periodontal tissue conditions.

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