Original

Use of a laser displacement sensor with a non-contact electromagnetic vibration device for assessment of simulated periodontal tissue conditions

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Abstract: A non-contact electromagnetic vibration device (NEVD) was previously developed to monitor the condition of periodontal tissues by assessing mechanical parameters. This system requires placement of an accelerometer on the target tooth, to detect vibration. Using experimental tooth models, we evaluated the performance of an NEVD system with a laser displacement sensor (LDS), which does not need an accelerometer. Simulated teeth (poly-acetal rods) were submerged at various depths in simulated bone (polyurethane or polyurethane foam) containing simulated periodontal ligament (tissue conditioner). Then, mechanical parameters (resonant frequency, elastic modulus, and viscosity coefficient) were assessed using the NEVD with the following detection methods: Group 1, measurement with an accelerometer; Group 2, measurement with an LDS in the presence of the accelerometer; and Group 3, measurement with an LDS in the absence of the accelerometer. Statistical analyses were performed using

nonparametric methods ($n = 5$) ($P < 0.05$). The three mechanical parameters significantly increased with increasing depth. In addition, the mechanical parameters significantly differed between the polyurethane and polyurethane foam models. Although Groups 1 and 2 did not significantly differ, most all mechanical parameters in Group 3 were significantly larger and more distinguishable than those in Groups 1 and 2. The LDS was more accurate in measuring mechanical parameters and better able to differentiate periodontal tissue conditions. (J Oral Sci 58, 93-99, 2016)

Keywords: experimental model; laser displacement sensor; mechanical parameter; vibration device; resonant frequency.

Introduction

The Periotest is a diagnostic device that reliably measures tooth mobility (1-3). Tooth mobility is measured by analyzing the contact times between a tapping rod and the target tooth surface and is reported as Periotest values (PTVs) from -8 to +50 (1,2). Because of its cost effectiveness and ease of use, the Periotest is routinely used in the daily clinical practice of periodontics (4), prosthodontics (5), implantology (6), and traumatology (7).

Periodontal tissue, particularly the periodontal liga-

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Fig. 1 Design of the experimental tooth models for the three different submerged depths.

ment, has elastic and viscous properties (8-10). These properties present challenges during analysis of periodontal tissue, since Hooke's law of elasticity cannot be applied to the behavior of periodontal tissue (11). Therefore, PTVs that express only the contact time of a tapping rod might be insufficient for evaluating the overall condition of periodontal tissue. Additionally, application of the Periotest is limited by the confined intraoral environment. The manufacturer's instructions for measuring PTVs suggest that the handpiece should be held at the correct angle and position to the target tooth, because the reading from the Periotest is considerably affected by tapping direction and position (7,12,13). However, these recommendations are difficult to implement when assessing posterior teeth (11).

To accurately evaluate overall periodontal tissue condition, we previously developed a non-contact electromagnetic vibration device (NEVD) (14-16). This device analyzes both tooth mobility and periodontal tissue conditions using mechanical parameters (resonant frequency, elastic modulus, and viscosity coefficient) by measuring the vibration of the tooth. As previously described, the NEVD accurately assessed bottom thickness and qualitative changes in a simulated periodontal ligament and alveolar bone in an experimental tooth model (14,16). In addition, the NEVD was able to monitor both periodontal tissue condition and implant stability, using the same mechanical parameters (15). Although the evidence indicates that the NEVD is useful for assessing periodontal tissue conditions, it requires attachment of an accelerometer to the target tooth, to detect vibration. The total mass of the simulated tooth is thus increased by the presence of the accelerometer, and the mechanical parameters of the NEVD may be influenced by the mass of accelerometer. Therefore, refinement of the NEVD system might increase measurement accuracy in the assessment of periodontal tissue conditions.

Laser displacement sensors (LDS) are used in high-resolution measurement of target objects (17,18). The sensor head comprises the laser transmitter and laser receiver. The laser transmitter emits the laser beam to the target object. The beam reflects off the surface and is detected by the laser receiver. The controller, which is connected to the sensor head, continuously detects the distance between the sensor and object (Bánlaki P et al. Proceeding of IFFK 2013 paper 28, 141-150, 2013). Therefore, the LDS does not require an accelerometer or mechanical contact to monitor the vibration characteristics of the target object (Bosch T et al. Proceedings of 13th IEEE Instrumentation and Measurement Technology Conference, 648-653, 1996).

This study assessed the use of an LDS with the NEVD in experimental tooth models containing several degrees of simulated bone destruction and two types of bone quality.

Materials and Methods

Experimental tooth model

A cylindrical rod made of polyacetal (diameter $\times$ length: 6.0 $\times$ 25.0 mm, mass: 1.59 g), a tissue conditioner designed for functional impression (Shofu Tissue Conditioner II; Shofu Inc., Kyoto, Japan), and a block of polyurethane or polyurethane foam (Nissin Dental Products Inc., Kyoto, Japan) were used to simulate the tooth, periodontal ligament, and alveolar bone, respectively. Experimental tooth models were developed using procedures modified from a previous method (16). Briefly, simulated teeth (polyacetal) were submerged to a depth of 5.0, 10.0, or 15.0 mm in simulated bones (polyurethane or polyurethane foam) containing simulated periodontal ligaments (tissue conditioner) with a thickness of 0.5 mm (Fig. 1). All experimental models were placed in a thermo-hygrostat room (temperature: 23 $\pm$ 1°C; relative humidity: 50 $\pm$ 5%). The models were maintained under these conditions

Fig. 2 Schematic representation of the experimental design for the NEVD system with the LDS.

for 1 h before each measurement.

Periotest measurement

To verify the reliability of the experimental tooth models in this study, PTVs for all experimental conditions were measured using the Periotest device (Gulden Messtechnik, Bad Bensheim, Germany) according to the manufacturer's instructions. In each condition, five experimental tooth models were used to assess PTVs ($n = 5$). The data are expressed as the median (minimum / maximum) for PTVs.

NEVD system

The NEVD system comprised three components: a vibrator, a detector, and an analyzer, as previously described (16). In brief, the vibrator consisted of a ferrite disk magnet (maximum magnetic flux: 130 mT, mass: 0.19 g, diameter: 5.2 mm) (PIP Co., Ltd., Osaka, Japan), an electromagnetic vibration device, and a sensor amplifier (Toshiba TA7252AP Audio Amplifier Kit; Akizuki Denshi Tsusho Co., Ltd., Tokyo, Japan). The ferrite disk magnet was attached by an adhesive (cyanoacrylate; Toagousei Co., Ltd., Tokyo, Japan) to the lateral surface at the top of the simulated tooth. The ferrite disk magnet received an electrical force generated by an alternating magnetic field produced by the electromagnetic vibration device. The electromagnetic vibration device consisted of a ferrite rod wrapped with enamel wire (diameter: 5.0 mm) 720 times to form a coil.

Methods for detecting vibration of simulated teeth

Three detection methods were used to assess the vibration of simulated teeth in the NEVD system: Group 1 under-

Fig. 3 Frequency-response characteristics and formulae for calculation of the mechanical parameters. f_1 and f_2 are the frequencies at $1/\sqrt{2}$ times the maximum amplitude of the resonant frequency (f_n).

went conventional measurement of tooth vibration, using an accelerometer (mass: 0.40 g) (NP-3211; Ono Sokki Co., Ltd., Tokyo, Japan) attached to the simulated tooth (16); Group 2 underwent measurement of tooth vibration using the LDS in the presence of an accelerometer attached to the simulated tooth; and Group 3 underwent measurement of tooth vibration using the LDS without an accelerometer.

A schematic representation of the experimental design for Group 3 is shown in Fig. 2. The LDS was placed 50 mm away from the simulated tooth. For optimal laser reflection, aluminum foil (5.0×5.0 mm) was attached to the lateral surface at the top of the simulated tooth. Vibration of the simulated tooth was detected by the LDS (repeatability: 0.025 μ m) (LK-H055; Keyence Corp., Osaka, Japan) equipped with a red laser diode (wavelength: 655 nm; power: 4.8 mW). The output signal from the LDS was input to a fast Fourier transformation (FFT) analyzer via a controller (LK-G5000; Keyence Corp.) connected to the LDS. The frequency response characteristics (i.e., the ratio between the output of a sweep generator and the input of the LDS) for the experimental tooth model were calculated by the FFT analyzer. With a frequency resolution of 12.5 Hz and an 80-ms capture time, the device yielded measurements over a frequency range of 5 kHz.

Calculation of mechanical parameters

Mechanical parameters were calculated as previously described (14) (Fig. 3). Five experimental tooth models were analyzed for each condition ($n = 5$). Data are expressed as the median (minimum / maximum) for mechanical parameter.

Table 1 PTVs

Submerged depth	Simulated bone quality	Median (minimum / maximum)
5.0 mm	Polyurethane	33 (32 / 37) ^{a,A}
	Polyurethane foam	37 (33 / 39) ^{a,A}
10.0 mm	Polyurethane	15 (12 / 18) ^{a,B}
	Polyurethane foam	19 (15 / 24) ^{a,B}
15.0 mm	Polyurethane	4 (1 / 6) ^{a,C}
	Polyurethane foam	7 (5 / 9) ^{a,C}

Identical lower-case letters for polyurethane and polyurethane foam values at the same submerged depth indicate that the values are not significantly different ($P > 0.05$).

Identical upper-case letters between submerged depths at the same bone quality indicate that the values are not significantly different ($P > 0.05$).

Table 2 Resonant frequency (kHz)

Submerged depth	Simulated bone quality	Group 1	Group 2	Group 3
		Median (minimum / maximum)		
5.0 mm	Polyurethane	0.46 (0.42 / 0.47) ^{a,A,I}	0.41 (0.38 / 0.43) ^{a,A,I}	0.49 (0.47 / 0.49) ^{a,A,II}
	Polyurethane foam	0.34 (0.31 / 0.35) ^{b,A,II}	0.31 (0.28 / 0.32) ^{b,A,I}	0.34 (0.33 / 0.34) ^{b,A,II}
10.0 mm	Polyurethane	0.97 (0.94 / 1.07) ^{a,B,I}	0.99 (0.97 / 1.04) ^{a,B,I}	1.37 (1.30 / 1.46) ^{a,B,II}
	Polyurethane foam	0.84 (0.81 / 0.89) ^{b,B,I}	0.78 (0.74 / 0.84) ^{b,B,I}	1.06 (1.01 / 1.10) ^{b,B,II}
15.0 mm	Polyurethane	1.87 (1.74 / 1.88) ^{a,C,I}	1.84 (1.83 / 1.91) ^{a,C,I}	2.91 (2.89 / 2.94) ^{a,C,II}
	Polyurethane foam	1.58 (1.57 / 1.63) ^{b,C,I}	1.56 (1.53 / 1.58) ^{b,C,I}	2.39 (2.19 / 2.41) ^{b,C,II}

Identical lower-case letters between polyurethane and polyurethane foam values at the same submerged depth indicate that the values within groups are not significantly different ($P > 0.05$).

Identical upper-case letters among submerged depths with the same bone quality indicate that the values within groups are not significantly different ($P > 0.05$).

Identical Roman numerals among groups with the same submerged depths and bone quality indicate that the values are not significantly different ($P > 0.05$).

Statistical analyses

Differences between PTVs at the various depths were assessed by using the Kruskal-Wallis and Steel-Dwass tests, as were differences between mechanical parameters in relation to depth and detection method. Differences in relation to type of simulated bone quality were assessed by using the Mann-Whitney *U*-test. A *P* value of <0.05 was considered to indicate statistical significance.

Results

PTVs

The PTVs are shown in Table 1. The PTVs decreased linearly as depth increased, and ranged from Miller Class 0 to Miller Class III. Significant differences were observed in relation to depth of simulated teeth for both the polyurethane and polyurethane foam models. However, PTVs for the polyurethane and polyurethane foam models did not significantly differ at the same depth.

Mechanical parameters

The resonant frequencies of all subgroups are shown in Table 2. The resonant frequency increased curvilinearly as depth increased for simulated teeth in both the

polyurethane and polyurethane foam models. Resonant frequency significantly differed in relation to depth and was significantly higher for the polyurethane model than for the polyurethane foam model at all depths.

The elastic moduli of all subgroups are shown in Table 3. As was the case for resonant frequency, the elastic modulus increased curvilinearly with increasing depth in both the polyurethane and polyurethane foam models. Elastic modulus significantly differed in relation to depth and was significantly higher for the polyurethane model than for the polyurethane foam model at all depths.

The viscosity coefficients of all subgroups are shown in Table 4. Viscosity coefficient increased linearly with increasing depth for simulated teeth in the polyurethane and polyurethane foam models. Viscosity coefficient significantly differed in relation to depth and was significantly larger for the polyurethane models than for the polyurethane foam models at all depths.

No significant difference between Groups 1 and 2 was observed for any mechanical parameter in any experimental condition. However, the resonant frequency for Group 3 was significantly higher than those for Groups 1 and 2 at depths of 10 mm and 15 mm. Moreover, the

Table 3 Elastic modulus ($\times 10^5$ Pa)

Submerged depth	Simulated bone quality	Group 1	Group 2	Group 3
		Median (minimum / maximum)		
5.0 mm	Polyurethane	0.13 (0.11 / 0.14) ^{a,A,I}	0.11 (0.09 / 0.12) ^{a,A,I}	0.12 (0.10 / 0.12) ^{a,A,I}
	Polyurethane foam	0.07 (0.06 / 0.08) ^{b,A,I}	0.06 (0.05 / 0.06) ^{b,A,I}	0.05 (0.05 / 0.06) ^{b,A,I}
10.0 mm	Polyurethane	0.59 (0.56 / 0.72) ^{a,B,I}	0.61 (0.59 / 0.68) ^{a,B,I}	0.88 (0.79 / 1.00) ^{a,B,II}
	Polyurethane foam	0.44 (0.41 / 0.49) ^{b,B,I,II}	0.38 (0.35 / 0.44) ^{b,B,I}	0.53 (0.48 / 0.57) ^{b,B,II}
15.0 mm	Polyurethane	2.19 (1.91 / 2.22) ^{a,C,I}	2.12 (2.09 / 2.28) ^{a,C,I}	3.97 (3.92 / 4.07) ^{a,C,II}
	Polyurethane foam	1.56 (1.55 / 1.66) ^{b,C,I}	1.53 (1.47 / 1.56) ^{b,C,I}	2.68 (2.26 / 2.72) ^{b,C,II}

Identical lower-case letters between polyurethane and polyurethane foam values at the same submerged depths indicate that the values within groups are not significantly different ($P > 0.05$).

Identical upper-case letters among submerged depths with the same bone quality indicate that the values within groups are not significantly different ($P > 0.05$).

Identical Roman numerals among groups with the same submerged depths and bone quality indicate that the values are not significantly different ($P > 0.05$).

Table 4 Viscosity coefficient (Pa · s)

Submerged depth	Simulated bone quality	Group 1	Group 2	Group 3
		Median (minimum / maximum)		
5.0 mm	Polyurethane	2.69 (2.50 / 2.87) ^{a,A,I}	2.50 (2.37 / 2.62) ^{a,A,I}	3.27 (3.18 / 3.37) ^{a,A,II}
	Polyurethane foam	2.12 (2.00 / 2.25) ^{b,A,I}	1.87 (1.75 / 2.12) ^{b,A,I}	2.06 (1.96 / 2.15) ^{b,A,I}
10.0 mm	Polyurethane	4.13 (3.87 / 4.45) ^{a,B,I}	3.87 (3.61 / 4.28) ^{a,B,I}	6.36 (6.36 / 6.82) ^{a,B,II}
	Polyurethane foam	3.56 (3.53 / 3.88) ^{b,B,I}	3.54 (3.30 / 3.67) ^{b,B,I}	4.11 (4.02 / 4.20) ^{b,B,II}
15.0 mm	Polyurethane	7.80 (6.36 / 9.36) ^{a,C,I}	7.11 (6.49 / 8.49) ^{a,C,I}	8.04 (7.43 / 8.23) ^{a,C,I}
	Polyurethane foam	4.81 (4.44 / 5.31) ^{b,C,I,II}	4.74 (4.56 / 5.00) ^{b,C,I}	4.39 (4.34 / 4.63) ^{b,C,II}

Identical lower-case letters between polyurethane and polyurethane foam values at the same submerged depths indicate that the values within groups are not significantly different ($P > 0.05$).

Identical upper-case letters among submerged depths with the same bone quality indicate that the values within groups are not significantly different ($P > 0.05$).

Identical Roman numerals among groups with the same submerged depths and bone quality indicate that the values are not significantly different ($P > 0.05$).

elastic modulus and viscosity coefficient in Group 3 were significantly larger than those of the other groups at depths of 15 mm and 10 mm, respectively.

Discussion

An important function of periodontal tissue is to flexibly support the tooth. This flexibility can be observed as tooth mobility, even in healthy periodontal tissue (19,20), and the degree of tooth mobility is one way to identify periodontal disease (21). Traditionally, Miller's technique (2) has been used for this purpose, because of its simplicity and practicality in clinical settings. However, this method is subjective, as it depends on the clinician's tactile sense and experience. Tooth mobility should also be measured by objective methods. Moreover, it is important to objectively determine the mechanical condition of periodontal tissue (8-10). The NEVD was developed by using simulated tooth models and assesses these mechanical conditions (14-16). However, to detect vibration, an accelerometer must be attached to the target tooth. In the present study, we investigated the use of an LDS as an alternative to the accelerometer used with the

NEVD.

First, PTVs were measured to verify the reliability of the experimental tooth models. PTVs could be determined in all experimental conditions and significantly linearly decreased as depth increased. A previous study found that PTVs are associated with periodontal bone loss on radiography and with probing pocket depth (22). Thus, the present experimental tooth models were evaluated in order to simulate varying periodontal tissue conditions. Schulte and Lukas (2) compared PTVs with the standard classification by Miller's technique (i.e., Class 0 to III) (Table 5). On the basis of those results, we used depths of 5.0, 10.0, and 15.0 mm for simulated teeth in this study, to reflect Miller's mobility Class III (tooth mobility >1 mm), Class I (first distinguishable sign of movement), and Class 0 (no distinguishable sign of movement), respectively. Thus, these experimental tooth models are likely to accurately simulate several degrees of clinical bone destruction and can therefore be used to assess simulated tooth vibration.

Two types of simulated alveolar bone, polyurethane and polyurethane foam, were used to assess qualitative

Table 5 Corresponding Periotest values (PTVs) for Miller's mobility index Classes 0 to III (2)

Mobility index according to Miller's technique	PTV
Class 0	-8 to +9
Class I	10 to 19
Class II	20 to 29
Class III	30 to 50

changes in bone. PTVs did not differ between the polyurethane and polyurethane foam models. These findings are consistent with those of a previous study, which found no significant difference between polyurethane and polyurethane foam models when PTVs were measured using various conditions of simulated periodontal ligament (16). Those results were attributed to the fundamental function of the Periotest, which depends to some extent on tooth mobility but primarily reflects periodontal damping characteristics.

In this study, the utility of the LDS was determined by evaluating and comparing three mechanical parameters measured with the NEVD. For all detection methods, the resonant frequency significantly increased in each group as depth increased. Resonance is observed when the frequency stimulating the target object matches the natural frequency of the system. The resonant frequency is the frequency that exerts maximum amplitude in a vibrating object. Lee et al. (23) and Kojima and Fukui (24) found that lowering the attachment level of teeth significantly decreased natural frequencies, and their findings are supported by the present results. In addition, the elastic modulus and viscosity coefficient were assessed because periodontal tissue has elastic and viscous properties (8-10). These mechanical parameters significantly increased with increasing depths in all groups, similar to the results for the resonant frequency. The elastic modulus and viscosity coefficient in this study are believed to represent repulsion and resistance, respectively, in simulated periodontal tissue surrounding the simulated tooth. Therefore, changes in the mechanical parameters were caused by differences in vibrating conditions attributable to the depth of simulated teeth in the experimental models.

Additionally, values were significantly larger for the polyurethane model than for the polyurethane foam model under all experimental conditions, although the PTVs for the two models were not different. A previous report also found that the NEVD system could distinguish polyurethane foam from polyurethane in various simulated periodontal ligament conditions. The authors suggested that polyurethane was denser than polyure-

thane foam and that the porosity of polyurethane foam acted as a spring rather than as a damper (16). The present results can be explained similarly.

When comparing the three detection methods, no significant difference between Groups 1 and 2 was observed in any experimental condition. Thus, the LDS and conventional accelerometer were the same in detecting changes between depths of the simulated teeth. Because the utility of the LDS in NEVD was confirmed, we investigated measurements with the LDS only, in the absence of the accelerometer (Group 3). Interestingly, the resonant frequency in Group 3 was significantly higher than those in Groups 1 and 2 at depths of 10 and 15 mm. The elastic modulus and viscosity coefficient in Group 3 were significantly larger than those of the other groups at 15 mm and 10 mm, respectively. Additionally, the values for Group 3 clearly distinguished the different periodontal tissue conditions. An important characteristic of the LDS is that it can assess vibration of the target object without an accelerometer. Attachment of an accelerometer, which weighs approximately 0.40 g, increases the total mass of the simulated tooth (Groups 1 and 2) and may affect the mechanical parameters, as described by the formulas listed in Fig. 3. Thus, the higher values for mechanical parameters in Group 3, as compared with Groups 1 and 2, may be caused by the decrease in mass of the simulated tooth. Therefore, LDS data are likely to be more accurate, as they are based on the actual total mass of the simulated tooth. In addition, it is easier to distinguish the different periodontal tissue conditions with an LDS than with an accelerometer. Moreover, the NEVD might also provide superior clinical operability if an accelerometer no longer needs to be connected to the FFT analyzer by cables.

A recent study suggested that the Periotest is not appropriate for examination of teeth in the early post-injury period, because of discomfort from repetitive tapping (25). The peak value of the force delivered by the tapping rod varied between 18 N and 12 N for respective PTVs of -4 to +2 (26,27). In contrast, the magnetic flux density of the magnetic disk and electromagnet used in this study imparted 54.6 and 38.1 mT at the maximum value, respectively, as determined using a Gauss meter. The magnetic flux density of the magnetic disk was larger than that of the electromagnet; therefore, the force added to the simulated tooth in this study was estimated to be 9.8×10^{-3} N. When comparing these systems, the force added to the simulated tooth using the NEVD was much smaller than that of the Periotest, and it is expected that patients would feel no pain with this system, even during the early post-injury period.

In conclusion, the use of an LDS with the NEVD detected differences in relation to depth of simulated teeth and the quality of simulated bone in the present in vitro experimental tooth models. Additionally, as compared with the conventional accelerometer, the LDS yielded more accurate measurements of the mechanical parameters in simulated periodontal tissue conditions. Therefore, the LDS may be more useful than an accelerometer when combined with an NEVD for overall assessment of periodontal tissue conditions.

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