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Tooth Movement Sensor for Clinical Use

Hisao Oka, Kiyotaka Yasuhara, Keiji Saratani[1], Takeki Nakanishi[1], Mitsuhiro Tatsuta[1], Takayoshi Kawazoe[1] and Kazuaki Hirai[2]

Faculty of Engineering, Okayama University
3-1-1 Tsushima-naka, Okayama-shi, Okayama 700, Japan
[1]Dept. of Fixed Prosthodontics, Osaka Dental University
1-5-17 Otemae, Chuo-ku, Osaka 540, Japan
[2]Megacera, Inc. 7-5 Harajuku, Hidaka City, Saitama 350-12, Japan

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The examination of tooth mobility is important in estimating the condition of the periodontium. The authors previously reported on a transducer for measuring the stiffness of the human skin, and have applied its principle to the measurement of tooth mobility. The tooth movement sensor developed is built into a simple and portable "T-M (tooth mobility) tester". In this tester, a sinusoidal vibration is applied to the tooth crown, the acceleration response is detected, and the *MI* (mobility index) corresponding to the tooth movement is obtained. The measurement conditions, such as the contact preload on the tooth crown and the actuating direction of the measuring probe, are also studied. The tooth mobility of artificial tooth models and the diurnal variation in physiological tooth mobility are also measured.

1. Introduction

The examination of tooth mobility is very important in estimating the condition of the periodontium in prosthodontics, orthodontics and periodontics. A manual examination of tooth mobility, which is performed by moving the tooth with fingers or hand-held dental instruments, is carried out regularly in dental clinics. The classifications made on the scale of M0 to M3 through a manual mobility examination[(1)] by trained dentists correspond to the degree of tooth movement, but their interpretation requires skill and experience.

In 1951, Mühlemann reported a method for measuring horizontal tooth mobility.[2] His Periodontometer comprised an intraorally attached dial indicator for recording tooth displacement and a hand-held dynamometer for applying loads. In clinical practice, however, it is time-consuming to set up the instruments.

PERIOTEST™ was designed at Tübingen University to quantitatively measure the periodontal function.[3] An electrically controlled rod percusses the tooth and then recoils. Periodontal structural changes in bone and/or soft tissue influence the contact time per impact between the rod and the tooth. Although the PERIOTEST™ value correlates well with the tooth mobility, it does not represent the measured contact time, but is based on a numerical scale from –8 to +50 set up according to a mathematical calculation. The force of the impact rod on the tooth is sometimes strong and can cause pain.

We have previously reported on an automatic diagnosis system for tooth mobility, for objectively determining tooth mobility in clinical practice, by applying a small random vibration (30 – 1000 Hz) onto the labial crown of a tooth.[4] The system is composed of a measuring probe with a vibrator and an impedance head, and a data analysis unit which requires a personal computer, but is fairly large because of the requirement for a personal computer.

In a previous study, the authors developed a new transducer for measuring skin stiffness.[5] The transducer utilizes bi-morph piezoelectric ceramics, and is therefore small, light, and convenient. The authors applied the transducer to a sensor system for measuring tooth movement.[6] The tooth movement sensor is incorporated into the tooth mobility (T-M) tester. The tester is characterized by its portable size and rapid measurement. The measured value is proposed as the index of the tooth mobility, which is called the mobility index (*MI*). The clinical practicality of the tester is examined by using artificial tooth models, and the mobility of maxillary and mandibular teeth and the diurnal variation in physiological tooth mobility are measured.

2. Design of T-M Tester

2.1 *Biomechanical mobility of teeth*

A manual examination of tooth mobility is performed and classifications are made using the M0 – M3 scale.[7] M0 indicates no perceptible movement and a healthy and clinically firm tooth. M1 refers to barely perceptible movement of a healthy lower incisor, M2 an increasing degree of movement, and M3 a degree of mobility indicative of a hopeless prognosis. A tooth that can be depressed is classified as M3. The readings of experienced dentists are very similar.

The four spectra[4] of the maxillary incisors diagnosed clinically as M0 – M3 are obtained by the automatic diagnosis system and shown in Fig. 1. The mechanical mobility of the periodontium expresses the tooth movability. Figure 1 shows that the four spectra are very different from each other around 100 – 500 Hz. Hence, it is possible to evaluate the tooth mobility with a high sensitivity by comparing the magnitudes of the mechanical mobility in this frequency region.

The mechanical properties of the temporo-mandibular joint also influence the tooth mobility of the mandible. The mechanical mobility spectra of the mandibular central incisor are shown in Fig. 2, corresponding to the open-mouth position. The effects of the

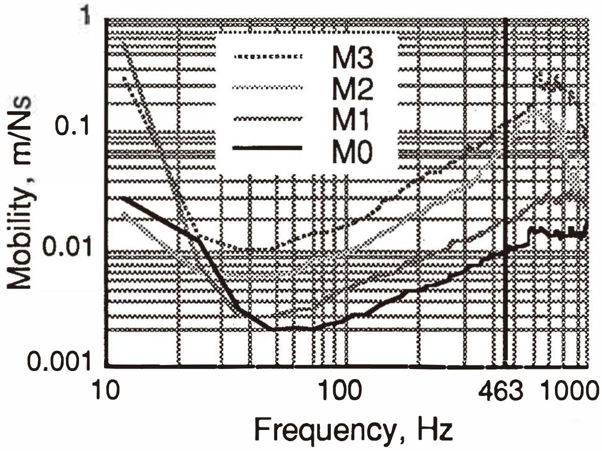

Fig. 1. Biomechanical mobility spectra of maxillary incisors (M0 – M3).

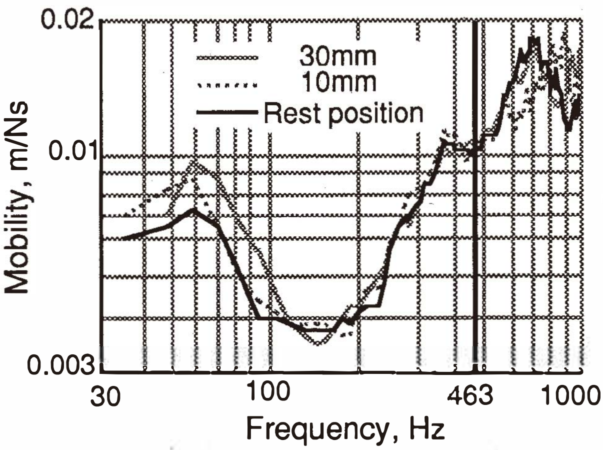

Fig. 2. Mechanical mobility spectra of mandibular central incisor with open-mouth position.

mechanical properties of the temporo-mandibular joint are found in the spectral region around 40 – 300 Hz.[8,9] There is almost no difference, however, in the mobility spectral region around 300 – 500 Hz. Hence, it is possible to evaluate the tooth mobility of not only the maxillary teeth but also the mandibular teeth by comparing the magnitudes of mechanical mobility around 300 – 500 Hz. The developed T-M tester applies a 463 Hz sinusoidal vibration on the tooth crown, and the acceleration is detected at the driving point of the tooth.

2.2 *Mobility index*

In the developed T-M tester, a single sinusoidal vibration is applied onto the tooth surface and the acceleration is detected at the driving point. The biomechanical mobility (a reciprocal of mechanical impedance) λ of the periodontium is defined as $\lambda = V/F = A/2\pi fF$ by the vibrating velocity V, force F, acceleration A and vibrating frequency f. The mobility index of tooth movement is defined as $MI = KA = K2\pi fF\lambda$ (K: proportional constant). When F and f are constants, the MI is proportional to λ. Since the biomechanical mobility of the periodontium is typical of tooth movability, it is possible to evaluate the tooth mobility using the MI. The MI is therefore proposed as a new index of tooth mobility but is a dimensionless quantity.

2.3 *Measuring probe and tooth mobility tester*

The schematic of the originally developed tooth movement sensor of measuring probe is shown in Fig. 3. The vibrating tip is made of aluminum and the head is covered with diamond powder in order to prevent the tip from slipping on the tooth surface. The tooth movement sensor is equipped with a set of bimorph piezoelectric ceramics (PZT). The ceramic disk is 25.5 mm in diameter and 100 μm thick, and its fringe is fixed with a holding ring. The piezoelectric strain constant of ceramic is -360×10^{-12} m / V in d_{31}. The surface of the ceramic is covered with a moisture-proof coat. The shim between the two ceramics is made of Be-Cu and is 100 μm thick. One ceramic is utilized for actuating, and the other is for detecting acceleration. The actuating element has an air chamber with a small aperture, which adjusts the resonance frequency of the sensor. Figure 4 shows a mechanical mobility spectrum of the designed sensor and it has a resonance frequency of 463 Hz. When the resonance frequency is utilized as the actuating frequency, the mechanical mobility of the sensor and the acceleration response are highest. The displacement amplitude at 463 Hz is 10 μm. When the sensor is in contact with the tooth crown, the

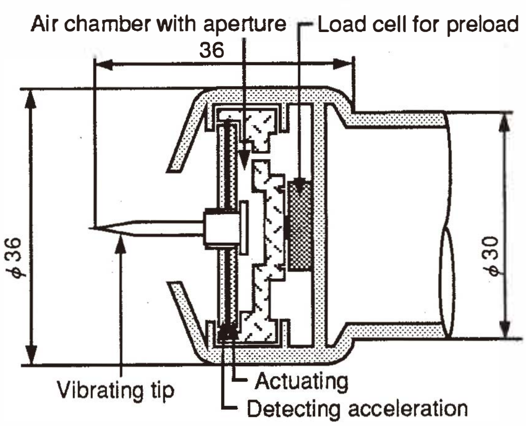

Fig. 3. Measuring probe of tooth mobility (T-M) tester.

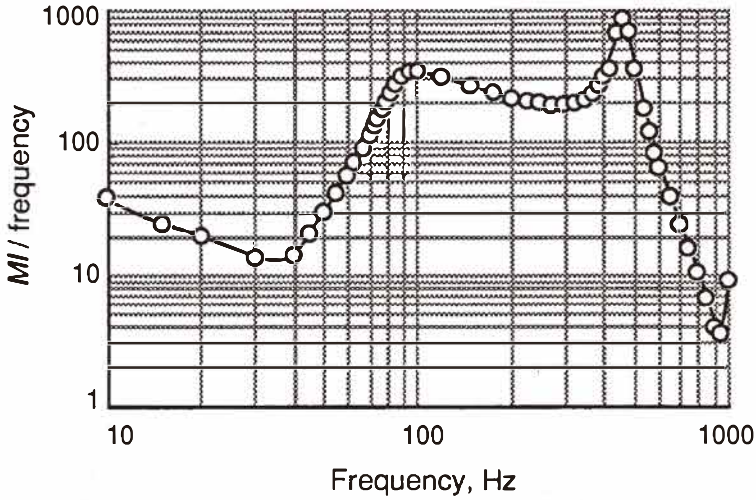

Fig. 4. Mechanical impedance spectrum of measuring probe.

acceleration response changes and the mechanical resonance curve of the sensor is different from the resonance curve shown in Fig. 4. Hence, it is possible to measure the tooth mobility with high accuracy and reliability.

A block diagram of the T-M tester is shown in Fig. 5. Its measurement principle is based on the same as that of the stiffness meter.[6] A sinusoidal vibration is applied to the tooth crown using a measuring probe, and the acceleration response is detected. When the contact preload on the tooth matches an initial set value, for example 50 ± 5 gf (gram-force), the acceleration is automatically measured. The preload is monitored using a preload level meter. A buzzer indicates the beginning/end of the measurement. The

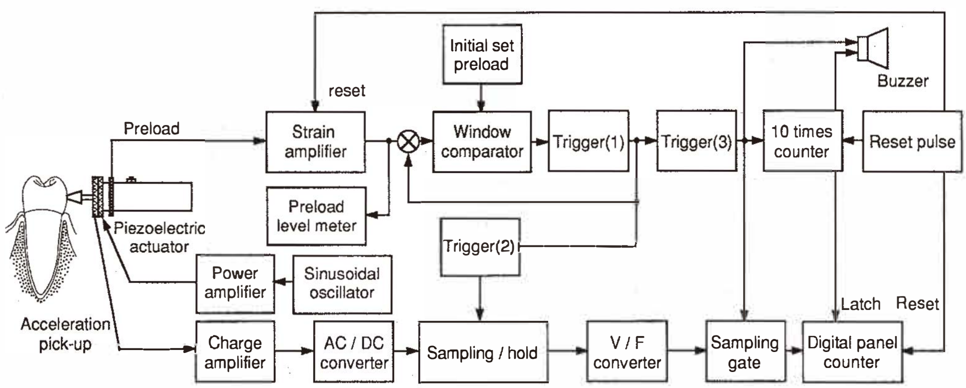

Fig. 5. Block diagram of T-M tester.

reading of the digital panel counter, after the sampling and processing of data are repeated 10 times, corresponds to the magnitude of mechanical mobility, i.e. the *MI*. When periodontal pathology advances and tooth movement becomes greater, the *MI* on the digital panel counter increases, corresponding to its biomechanical mobility.

A photograph of the T-M tester is shown in Fig. 6. A dentist places the measuring probe perpendicularly onto the tooth surface. The entire measuring time is about 10 s. When the *MI* of a central incisor with a healthy periodontium is measured 10 times, the reproducibility (variation = standard deviation/mean value) is about 6%.

3. Experimental Results

3.1 *Tooth models with different mountings*

A tooth model with four different mountings is shown in Fig. 7(a). The artificial periodontal ligaments are made of silicone impression material of thickness 0 (A), 0.28 (B), 0.56 (C) and 0.84 mm (D). The thickness of the material is varied on the assumption that it represents the width of the periodontal ligament space, which is one of the periodontal changes of the tooth support.(10) The changes in the *MI* and the viscoelastic coefficients as with the thickness of the material are shown in Table 1. The measuring points are at the incisal edge and the center of the tooth crown. The tooth mobility measured at the incisal edge should be larger than that at the center of the tooth crown, because of the rotation center of the tooth. The results conclude that the greater the tooth mobility, the higher the *MI*. Three viscoelastic coefficients of the periodontium, which are obtained from the mechanical mobility spectra measured using the automatic diagnosis system, are proposed by Noyes and Solt as shown in Fig. 7(b).(11)

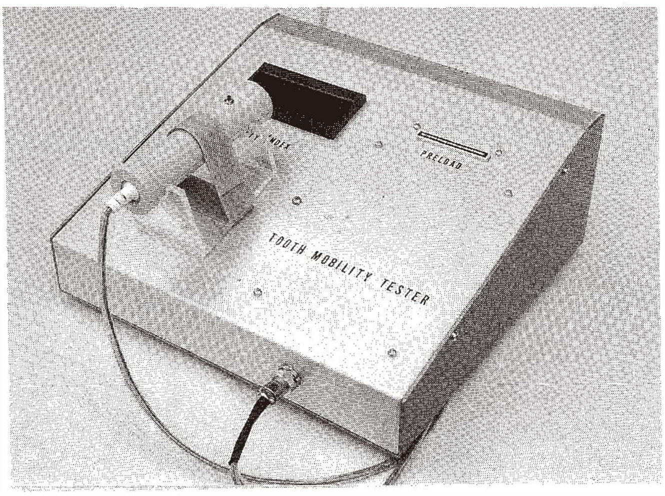

Fig. 6. Photograph of T-M tester.

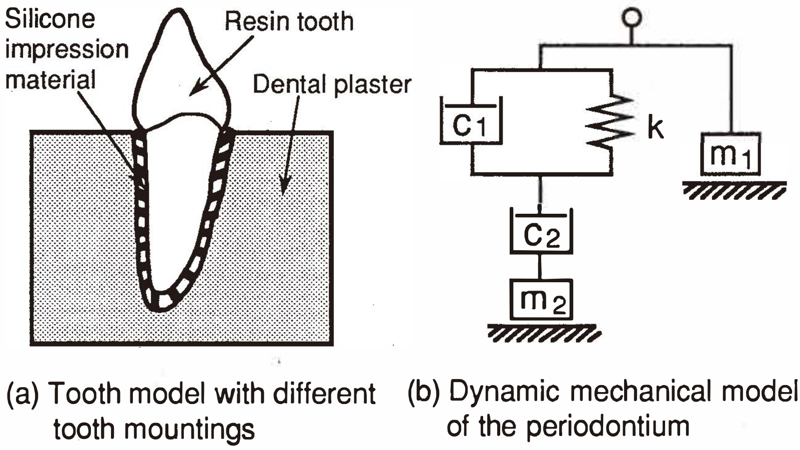

Fig. 7. Artificial tooth model and mechanical model of the periodontium. (a) Tooth model with different tooth mountings, (b) dynamic mechanical model of the periodontium.

Table 1
MI of tooth models with different periodontal spaces.

Periodontal space	Measuring point	*MI* ($\times 10^3$)	c_1, Ns/m	c_2, Ns/m	k, $\times 10^4$N/m
A	Incisal	7.75	33.0	325	17.0
(0 mm)	Central	7.10	44.5	486	19.8
B	Incisal	13.1	26.2	271	7.17
(0.28 mm)	Central	11.6	37.6	684	10.0
C	Incisal	18.5	10.5	100	2.65
(0.56 mm)	Central	15.3	15.3	141	4.15
D	Incisal	35.2	0.01	46.8	1.46
(0.84 mm)	Central	27.4	0.01	74.2	2.48

3.2 *Contact preload and vibrating direction*

In the measurement of tooth mobility, a static contact preload is horizontally applied to the tooth surface. The relationship between the *MI* of the B-model and that of the healthy incisor is shown in Fig. 8 with a horizontal preload of 20 – 100 gf. The *MI* decreases with an increase in the preload. When the preload increases, the change of *MI* in the case of the natural tooth is less than that in the case of the B-model. This is because the viscoelasticity of the natural periodontal ligament withstands the horizontal load to the tooth. Figure 8

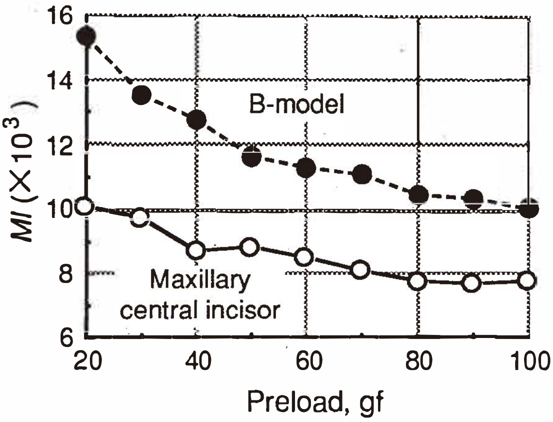

Fig. 8. Changes in the *MI* following an increase in contact preload onto tooth surface.

shows that the horizontal load applied in the bucco-lingual direction influences the viscoelasticity of periodontium. Using the T-M tester, the measurement is performed with the contact preload of 50 ± 5 gf.

The sinusoidal vibration is applied to the tooth crown in the lingual-labial direction, parallel to the occlusal plane. It has been claimed that horizontal or lateral loads induce a much larger displacement than axial loads.(7) The difference between the *MI* of the B-model and that of the healthy maxillary central incisor in the (a) gingival-incisal and (b) mesial-distal actuating directions is shown in Fig. 9. The transverse axis shows the angle of deviation from the median line (0 degree). Figure 9 shows that a difference in the actuating direction leads to a difference in the *MI* of the maxillary central incisor. The measuring probe should be held so as to reduce the resulting instability of the *MI* in the gingival-incisal direction.

4. Discussions

4.1 *MI of the human maxillary and mandibular teeth*

Although the measurement results for mobility of a single tooth have been frequently reported, the comparison of mobility betweem several teeth is not well documented.

The mobility of a tooth with a healthy periodontium is closely dependent on the height of the surrounding bone, the width of the periodontal ligament and the shape and the number of roots.(10) The *MI* of maxillary (○) and mandibular (●) teeth is shown in Fig. 10. The elastic coefficient (*k*) of maxillary (□) and mandibular (■) teeth is also measured by the automatic diagnosis system. The root length of the canine is the longest of the maxillary teeth in males. The root length decreases in the following order: central incisor, lateral incisor, and first premolar. The lateral area of the canine root is largest and

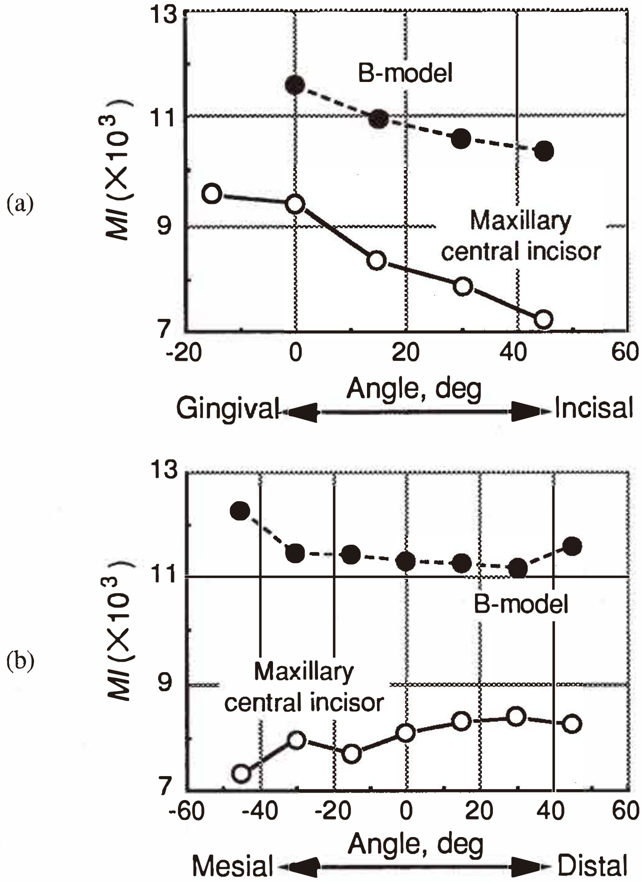

Fig. 9. Changes in the *MI* following a deviation in actuating direction. (a) Gingival-incisal direction, (b) mesial-distal direction.

decreases in the following order: first premolar, central incisor, and lateral incisor. The root length of the canine is longest in mandibular teeth and decreases in the following order: first premolar, lateral incisor, and central incisor. The lateral area of the canine root is largest and decreases in the following order: first premolar, lateral incisor, and central incisor. Figure 10 suggests a correlation between the *MI* and the length or lateral area of the tooth root, assuming that all the periodontium of maxillary and mandibular teeth is healthy.[12] Since the reciprocal of elastic coefficient k represents partially the tooth mobility or the *MI*, it is difficult to compare the *MI* with $1/k$ directly. The figure, however, shows a very similar tendency between the *MI* and the reciprocal of elastic coefficient k of maxillary and mandibular teeth.

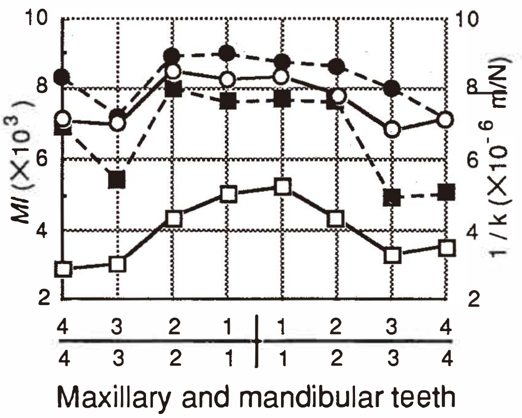

Fig. 10. *MI* and the elastic coefficient (k) of maxillaly and mandibular teeth. (*MI*: maxillary (○) and mandibular (●), $1/k$: maxillary (□) and mandibular (■)).

4.2 *MI of the healthy and pathological teeth*

In 3.1, the relationship between the *MI* and the tooth mobility is shown experimentally using four artificial tooth models. The relationship between the *MI* and the clinical tooth mobility of forty natural teeth in nine subjects (4 males and 5 females, age 26–71 yrs.) is shown in Fig. 11. The subjects were classified on the scale of M0 to M3 (M0: 15 teeth, M1: 14 teeth, M2: 8 teeth, M3: 3 teeth). The results of the measurements suggest an adequate correlation and support the possibility of clinical use.

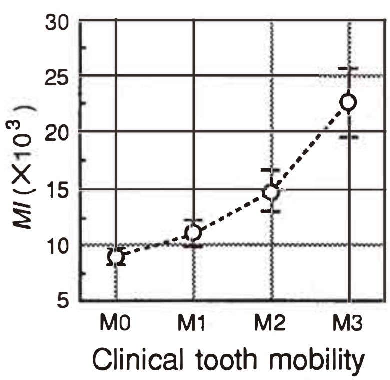

Fig. 11. *MI* of healthy and pathological teeth.

4.3 *Diurnal variation in physiological tooth mobility*

Slight tooth movements occur during mastication, but humans are not usually aware of them. The range of physiological tooth mobility varies among individuals and with time for each tooth.(13) The physiological tooth movement depends on many factors such as an occlusion, and a bio-physical state; *e.g.* peripheral blood and lymph circulation in small blood vessels and tissue fluid of the periodontal ligament.(14) The tooth movement is greatest upon waking up, possibly due to the slight extrusion of the tooth, caused by the absence of function during the night. The tooth movement diminishes during the day, possibly owing to the intrusion caused by pressure from chewing and swallowing. The diurnal variation in physiological tooth mobility of a healthy incisor during a 12-h period is shown in Fig. 12. During sleep, the *MI* is highest, since the occlusion is smallest. After waking up and having breakfast in the morning, the *MI* decreases. During the day, it hardly changes or slightly decreases and at night, it gradually increases. The *MI* decreases immediately after eating twice a day (hatched time period as shown in Fig. 12).

The 24-h variation in physiological tooth mobility without eating and sleeping is shown in Fig. 13. Because the subject did not eat or sleep during the day, the figure shows the highest *MI* at night.

5. Conclusions

A tooth movement sensor utilizing bi-morph piezoelectric ceramics was developed and incorporated into the T-M tester for clinical use. A new index of tooth mobility, *MI,* was proposed for the T-M tester. The tester is characterized by its portable size and rapid measurement. Using the T-M tester, it was possible to measure quantitatively not only the mobility of maxillary and mandibular teeth but also small variations in physiological tooth mobility.

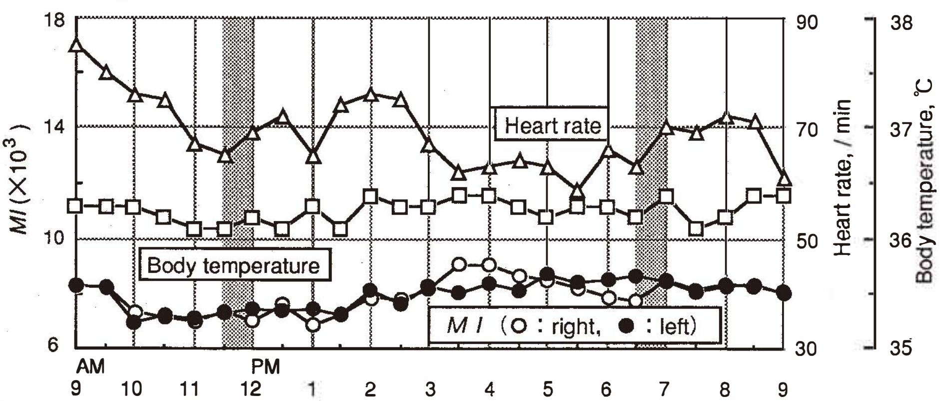

Fig. 12. Diurnal variation of physiological tooth mobility during a 12-h period.

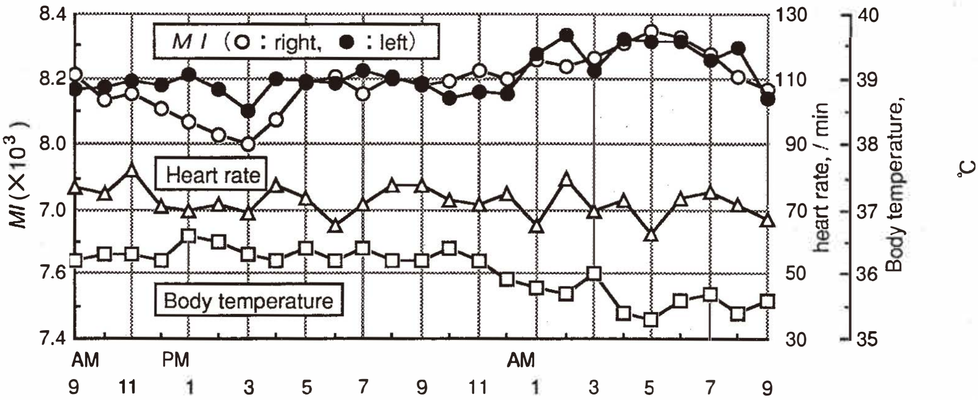

Fig. 13. Diurnal variation of physiological tooth mobility without eating and sleeping during a 24-h period.

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Hisao Oka received BE and ME degrees in Electrical Engineering from Okayama University, Japan in 1976 and 1978, respectively, and completed a DE degree in Biomechanical Property Measurement at Osaka University in 1988. He is presently an associate professor in the Department of Electrical and Electronic Engineering, Faculty of Engineering, Okayama University.

He is currently interested in measurements and applications of biomechanical properties.

Kiyotaka Yasuhara is presently an electronic technical officer in the Department of Electrical and Electronic Engineering, Faculty of Engineering, Okayama University.

His technical interest is low frequency instrumentation.

Keiji Saratani received his D. D. S. degree from Osaka Dental University, Osaka, Japan in 1980 and his Ph. D. there in 1984. He is presently a lecturer for the Department of Fixed Prosthodontics at Osaka Dental University. He is a member of the International Association for Dental Research and the Japan Society of Medical Electronics and Biological Engineering.

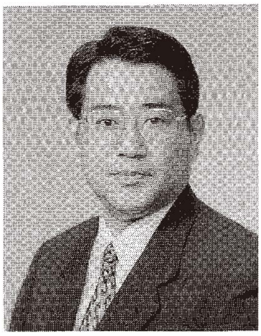
He is currently interested in dynamic analysis of tooth supporting structures.

Takeki Nakanishi received his D. D. S. degree from the Osaka Dental University, Osaka, Japan in 1991 and his Ph. D. degree from the same university in 1995. He is a part-time lecturer for the Department of Fixed Prosthodontics at Osaka Dental University.

He is a member of several professional organizations, including the International Association for Dental Research, the Japan Prosthodontic Society, the Japanese Society of Oral Implantology and the Japanese Society of Stomatognathic Function.

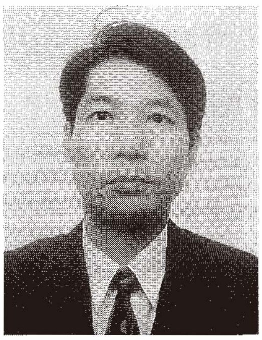
Mitsuhiro Tatsuta received his D. D. S. degree from the Osaka Dental University, Osaka, Japan in 1993. He is a graduate student majoring in Prosthodontics at Osaka Dental University.

He is a member of several professional organizations, including the International Association for Dental Research, the Japan Prosthodontic Society, the Japanese Society for Temporomandibular Joint and the Japan Society of Medical Electronics and Biological Engineering.



Takayoshi Kawazoe received his D. D. S. degree from Osaka Dental University, Osaka, Japan in 1966 and his Ph. D. there in 1970. He is presently a professor in the Department of Fixed Prosthodontics at Osaka Dental University. He is a member of the International Association for Dental Research and the Japan Society of Medical Electronics and Biological Engineering.

He is currently interested in the diagnosis of occlusion and temporomandibular joint disorders.



Kazuaki Hirai received his BE degree from Nippon University in 1970. He is currently a technical master in Megacera Inc.

He is interested in the development of a PZT ceramic condenser and actuator.