Original Article

A Characteristic Analysis of the Pulse Transit Time to Dental Pulp: An Attempt at a New Approach to Dental Pulp Diagnoses Based on the Microcirculatory System

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Keywords : Pulse transit time (PTT), Transmitted-light plethysmography (TLP), Dental pulp viability, Blood pressure, Vascular elasticity

Abstract :
Objectives: This study examined the characteristics of healthy teeth by analyzing the pulse transit time (PTT) and factors influencing the PTT of teeth to diagnose dental pulp using transmitted-light plethysmography (TLP).
Design: The PTT was measured in 58 healthy maxillary central incisors in 34 healthy subjects. The PTT values in earlobes (ears), fingertips, and toes were also measured for comparison purposes. In addition, the optical density of the teeth was measured. Data were analyzed using a one-way analysis of variance followed by Dunnett's test. Pearson's correlation was performed to determine the relationship between the tooth PTT and mean blood pressure, systolic blood pressure, diastolic blood pressure, and heart rate.
Results: The average PTT of toes was significantly longer than the other three measurement sites, including the teeth. Additionally, the toes had a significantly longer average PTT among subjects in their 20s than in other age groups. There were no significant differences in the average PTT by age at the measurement sites of the teeth, ears, and fingertips, but the average PTT for the teeth and ears tended to decrease with age. The PTT of the teeth negatively correlated with the heart rate and tended to decrease with an increasing heart rate. Furthermore, the PTT of the teeth in females was significantly longer than in males.
Discussion: The average PTT of the toes was significantly longer than that at other measurement sites, possibly due to the distance from the measurement site to the heart. The average PTT of teeth tended to decrease with age, but there were no significant differences by age. The decrease in the pre-ejection period (PEP) with an increasing heart rate might have been due to the decrease in the PTT with an increasing heart rate. The loss of vascular elasticity caused by progressive atherosclerosis increases the pulse wave velocity (PWV) and decreases the PTT of teeth. Finally, the gender difference in the average PTT of teeth might have been due to the blood pressure and presence of female hormones.
Conclusion: We found that the PTT of teeth was influenced by the heart rate and elasticity of the systemic blood vessels. The PTT is useful for evaluating the blood flow in teeth and is promising for future applications in the diagnosis of dental pulp, such as in cases of chronic caries and trauma to teeth.

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Introduction

In the clinical practice of dentistry, sensitivity testing depending on the patient's response plays an important role in determining the vitality of traumatized teeth[1). However, there are concerns with sensitivity testing regarding the influence of the patient's subjectivity, especially in pediatric cases. In our previous study, we have reported that Transmitted-light plethysmography (TLP) was assumed to be an alternative pulp diagnostic method by detecting the microcirculation in dental pulp.

TLP is a non-invasive optical method of assessing the microcirculation in dental pulp[2)]. It is one of the photoplethysmography (PPG) technology, which can detect blood volume changes in the microvascular bed of tissue[3-5)]. TLP utilizes a light-emitting diode (LED) and matched photodiode (PD). In detail, an objective tooth is irradiated by an LED on the lingual side, and the transmitted light is then detected by the PD on the labial side. The transmitted light varies depending on the pulsatile blood volume change, which is converted to electric signals by the PD. These changes are then expressed as a pulse waveform. We found that the amplitudes of TLP pulse waves gradually changed during the prognosis of dental trauma[6)]. This means that TLP can not only distinguish the presence or absence of pulpal blood flow but also detect certain information from the dental pulp itself. Data on the blood flow in the dental pulp obtained via TLP are thus more objective than sensitivity testing for making diagnoses.

The time taken for the pulse wave to travel from the heart (left ventricle) to the periphery is defined as the pulse transit time (PTT)[7)]. The PTT is often calculated as the time between the R-peak on an electrocardiogram (ECG) and the onset of the peripheral pulse wave detected via a PPG sensor placed at the periphery[8)]. The PTT is expected to be useful for assessing vascular conditions noninvasively in clinical practice. A previous study in subarachnoid hemorrhaging patients suggested using the PTT instead of invasive arterial blood pressure monitoring to check cerebrovascular reactivity[9)]. However, another study conducted in subjects with varying ages[10)] showed that the PTT at the ear, finger, and toe decreased with age. This decrease in the PTT was thought to have been due to a rise in arterial stiffness, which increases with age. We hypothesized that the PTT could also be used to assess the microcirculation of blood in the dental pulp and TLP could be used as a peripheral PPG sensor with an ECG to calculate the PTT of teeth. However, to our knowledge, no study has applied the PTT to the field of dentistry.

This study was therefore conducted to examine the characteristics of healthy teeth by analyzing the PTT and identify factors that might influence the PTT of teeth in order to develop a method of diagnosing the dental pulp.

2. Materials and methods

2.1. Subjects and selected teeth

The human experiments in this study were approved by the Ethics Committee of the Faculty of Dentistry, Graduate School of Tokyo Medical and Dental University (No. D2016-063).

The subjects were 34 adults (26-59 years old, mean ± SD; 38.0 ± 9.5, male; n=13, female; n=21) who were clinical staff members and graduate school students of Tokyo Medical and Dental University. All subjects had no underlying disease and no history of long-term medication. The selection criteria for teeth were healthy maxillary central incisors without dental caries, restorations, periodontal disease, or a history of trauma. The response of electric pulp vitality testing of all the subjects' teeth were confirmed using A Sybron Endo vitality scanner TM (model 2006; Sybron Endo Dental Specialties, Glendora, CA, USA).

Informed consent was obtained after explaining the purpose and methodology of the study to all subjects.

2.2. ECG measurements and PPG of peripheral tissues

Prior to the measurement of the tooth plethysmogram (TLP), an alginate impression of the subjects' teeth was taken, and individual acrylic resin caps for each tooth were prepared (Fig. 1(a)). Two holes were made in the cap to hold a 525-nm green LED (φ3 mm OSPG 3131P, Optosupply International, Hong Kong) on the palatal side of the tooth and a photodiode (HPS 304AL; Kodenshi Corp., Tokyo, Japan) on the labial side of the tooth. The LED and photodiode were connected to the prototype TLP system (J.Morita Corp., Kyoto, Japan).

To obtain ECG measurements, electrodes were attached to each subject's right wrist and both ankles (PL3508 PowerLab 8/35; AD Instruments, Sydney, Australia). In addition, photoelectric pulse wave sensors for the ear lobe, fingertip, and toe (IR Plethysmograph-Ear Clip II MLT1060EC, Finger Clip MLT1020FC, and Velcro Strap MLT1020PPG, respectively; AD Instruments) were attached to the subjects to record their photoplethysmograms.

After recording the systolic and diastolic blood pressure with a digital sphygmomanometer (HEM-7511 T; Omron, Kyoto, Japan) at the upper arm, photoplethysmograms of the peripheral tissues (earlobe, fingertip, toe), TLP, and ECG were recorded in a supine position for 90 seconds (Fig. 1(b)). All photoplethysmograms and ECGs of each subject were recorded simultaneously, and the heart rate was automatically calculated from the ECG data of 60 pulses using a signal processing software program (LabChart; AD Instruments, Sydney, Australia).

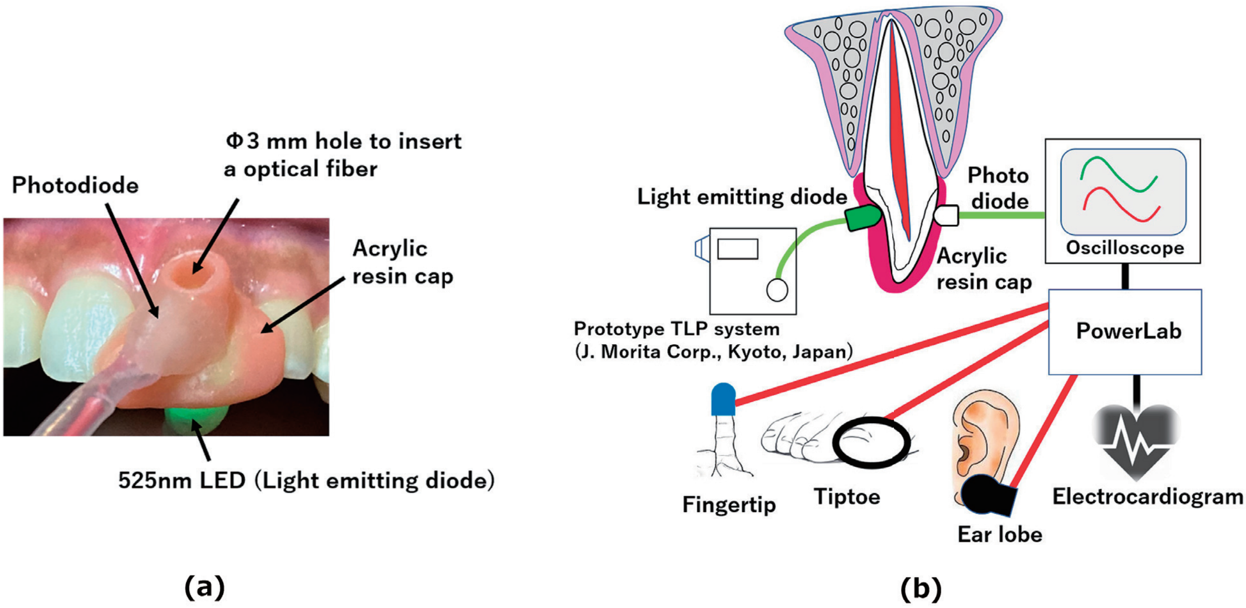

Fig. 1　(a) An individual acrylic resin cap for the TLP measurements.
(b) A schematic diagram of the PPG (Photoplethysmography) measurement system.

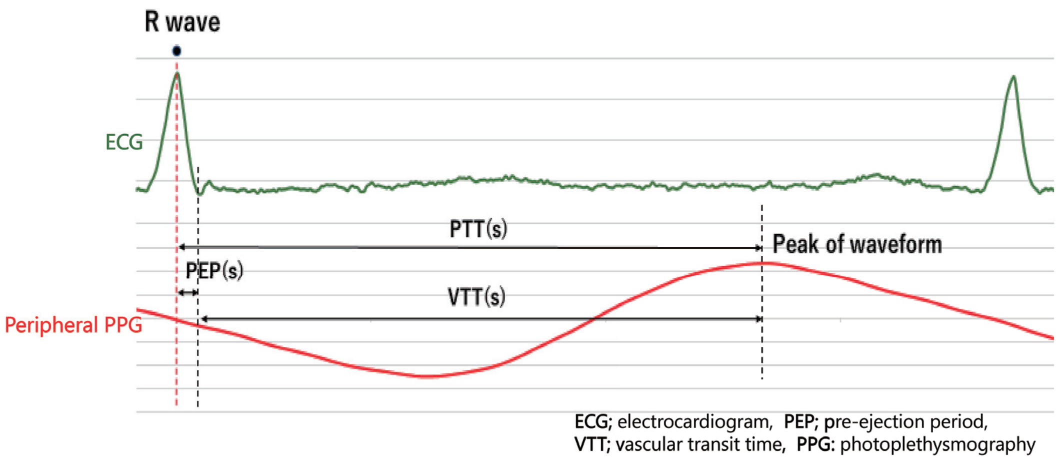

Fig. 2　Pulse transit time (PTT)

2.3. The PTT analysis

The PTT was determined as the pulse arrival time of the ECG R wave to peripheral tissues. The PTT is the sum of the pre-ejection period (PEP) and the vascular transit time (VTT) (Fig. 2). The landmarks of the ECG R peaks and photoplethysmogram peaks were automatically recognized by the LabChart software program, and the average PTT of 60 pulse waves was calculated.

2.4. Measurement of the optical density (OD)

The OD of each subject’s teeth was measured to assess the light attenuation level through the whole teeth. The same light-source LED and acrylic resin cap with TLP measurement were used to measure the transmitted light intensity. A third hole was made at the labial side of the acrylic resin cap (Fig. 1(a)) to insert the optical fiber of the spectrometer (Compact CCD Spectrometers CCS200/M; Thorlabs, Newton, NJ, USA). The incident and transmitted light intensity were detected, and the OD of the teeth was calculated using the following formula, where I_0 is the incident light intensity and It is the transmitted light intensity:

$$OD = \ln (I_0 / I_t).$$

Table 1 The Subject, blood pressure, and heart rate in each age group

	Subjects (n)	Age (years)	Gender		Teeth (n)	Ears (n)	Fingers (n)	Toes (n)	SBP (mmHg)	DBP (mmHg)	Heart rate (/min)
			Males(n)	Females(n)							
Age Group 20s-50s	34	38.0±9.5	13	21	58	34	34	34	119.12±14.72	80.15±12.03	72.59±11.50
Age Group 20s	10	27.8±1.2	2	8	17	10	10	10	109.30±5.98	72.60±4.48	69.60±10.67
Age Group 30s	10	34.9±3.2	6	4	14	10	10	10	122.80±13.82	81.44±7.03	77.00±12.11
Age Group 40s	9	44.9±2.9	4	5	17	9	9	9	120.67±17.88	81.00±17.57	69.11±11.72
Age Group 50s	5	56.0±2.2	1	4	10	5	5	5	128.60±11.45	89.40±8.71	76.00±6.45

value: mean± standard deviation SBP; systolic blood pressure, DBP; diastolic blood pressure

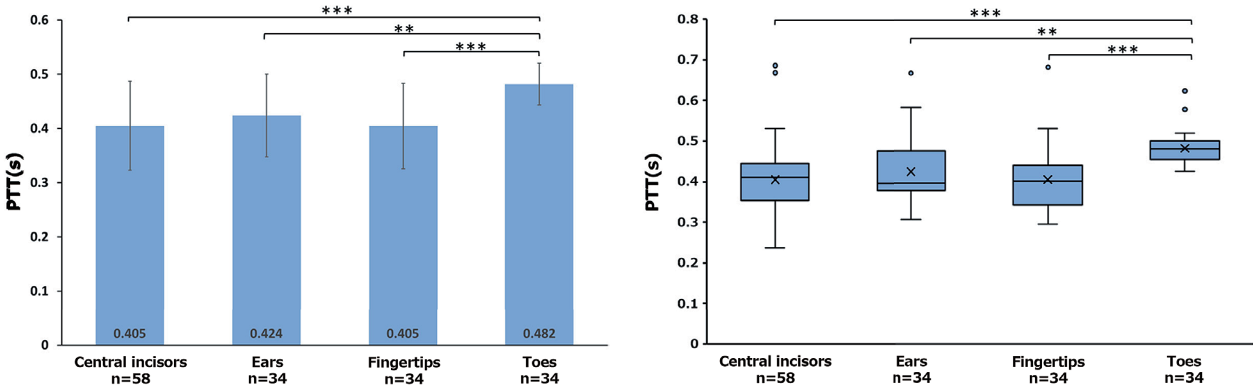

Fig. 3 The graph in the left side showed the mean±SD of the average PTT (Pulse transit time) according to the measuring points. The box plot in the right side showed the data distribution of PTT. It is composed of median value (horizontal line in the box), average value (cross mark), quartile, maximum and minimum values. The plots out of the box showed outliers. The asterisks indicate significant differences between the groups. (**p<0.01, ***p<0.001 Dunnet's method)

2.5. Statistical analyses

The subjects were classified into four groups based on their age in decades (20s-50s). Comparisons of the PTT and OD among age groups were analyzed using a one-way analysis of variance (ANOVA) followed by Dunnett's test. The comparison of the PTT among teeth, ear lobes, fingertips, and toes was also analyzed using a one-way ANOVA followed by Dunnett's test. To assess the influence of the blood pressure and heart rate on the PTT, Pearson's correlation coefficient was determined between the heart rate, systolic blood pressure, diastolic blood pressure, mean blood pressure, and PTT of the teeth. Comparisons of the PTT, OD, and blood pressure between males and females were statistically compared with Dunnett's test. P values less than 0.05 were considered statistically significant.

All statistical analyses were performed with the Easy R software program (version 1.55; Jichi Medical University Saitama Medical Center, Saitama, Japan).

3. Results

The subject groups, blood pressure, and heart rate in each age group are shown in Table 1.

3.1. PTT measurements of each peripheral tissue

As shown in Figure 3, the average PTT of the toes was significantly longer than at the other 3 measuring sites ($p<0.01$). There were no significant differences in the PTT among the teeth, ears, and fingers.

Figure 4 shows the mean±standard deviation (SD) of the average PTT by age group for the (a) toes, (b) teeth, (c) ears, and (d) fingers. The PTT of the toes of the subjects in their 20s was significantly longer than in other age groups (Fig. 4a). The PTT of the toes tended to decrease with age. There was no significant difference in the PTT at the other measuring sites among age groups. However, the PTT of the teeth (Fig. 4b) and ears (Fig. 4c) tended to decrease with age. Regarding the PTT of the fingers, no apparent relationship with increasing age was noted (Fig. 4d).

3.2. OD measurements of the teeth

There was no significant difference in the tooth OD among age groups (Fig. 5).

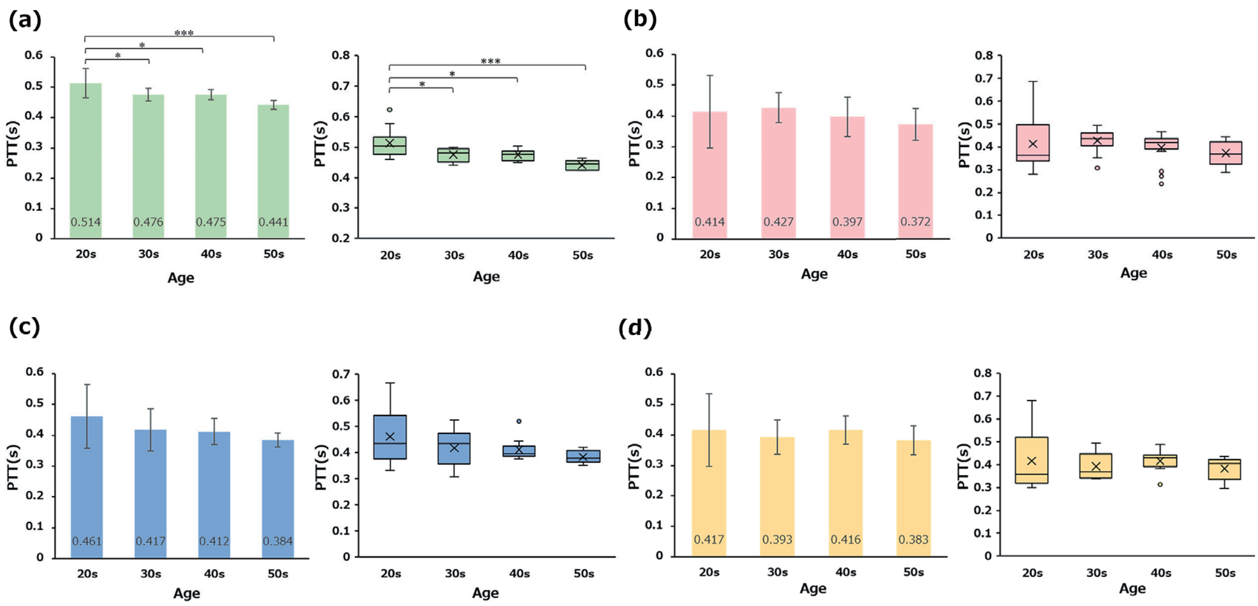

Fig. 4 The graphs in the left side showed the mean ± SD of the average PTT (pulse transit time) of the (a) toes, (b) teeth, (c) ears and (d) fingers by age group. The box plot in the right side showed the data distribution of PTT. It is composed of median value (horizontal line in the box), average value (cross mark), quartile, maximum and minimum values. The plots out of the box showed outliers.

The asterisks indicate significant differences among the groups. (*$p<0.05$, ***$p<0.001$ Dunnet's method)

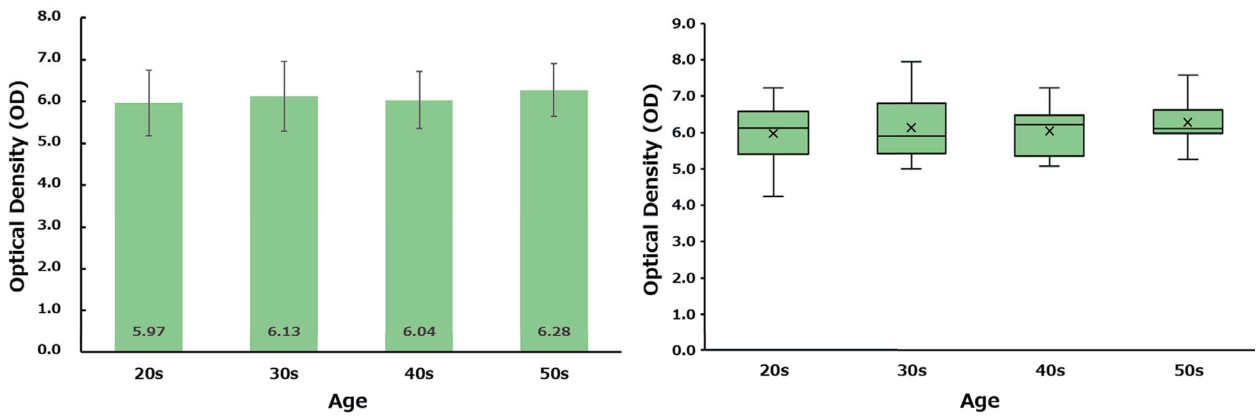

Fig. 5 The graph in the left side showed the mean ± SD of average OD (Optical density) of the subjects' teeth by age group. The box plot in the right side showed the data distribution of OD. It is composed of median value (horizontal line), average value (cross mark), quartile, maximum and minimum values. There was no significant difference among the different age groups.

3.3. Correlation between blood pressure, heart rate and PTT of the teeth

The PTT of the teeth had a significantly negative correlation with the heart rate, showing a Pearson's correlation coefficient of 0.387 ($p<0.01$) (Fig. 6a). There were no significant correlations among the mean blood pressure, systolic blood pressure, diastolic blood pressure, and PTT of the teeth (Fig. 6 b-d). Figure 7 shows the mean and diastolic blood pressure by age group. Both the mean and diastolic blood pressure of subjects in their 50s were significantly higher than in subjects in their 20s ($p<0.05$).

3.4. Comparisons of the PTT, OD, and blood pressure between the male and female groups

Figure 8 shows the mean ± SD of the (a) PTT of the teeth, (b) OD, (c) systolic blood pressure, and (d) mean blood pressure

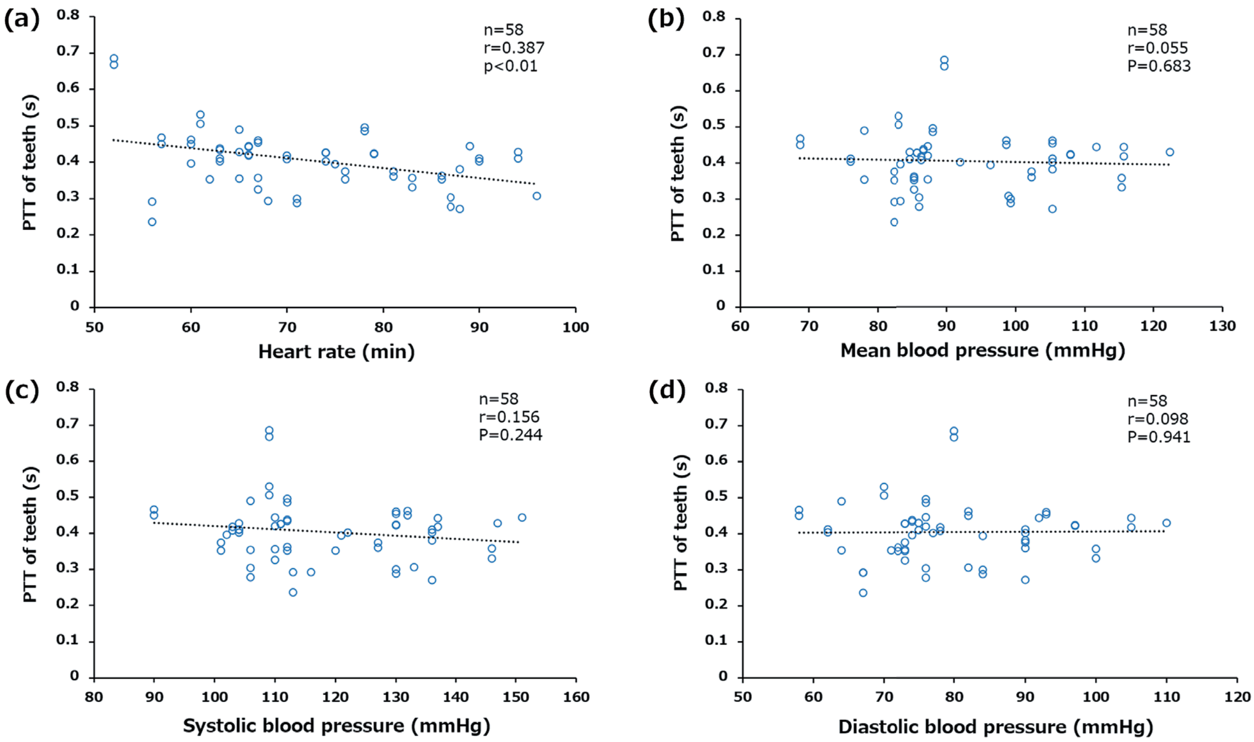

Fig. 6 The scattergram shows the correlations among such factors as the (a) heart rate, (b) mean blood pressure, (c) systolic blood pressure, and (d) diastolic blood pressure, and PTT (pulse transit time) of the teeth.

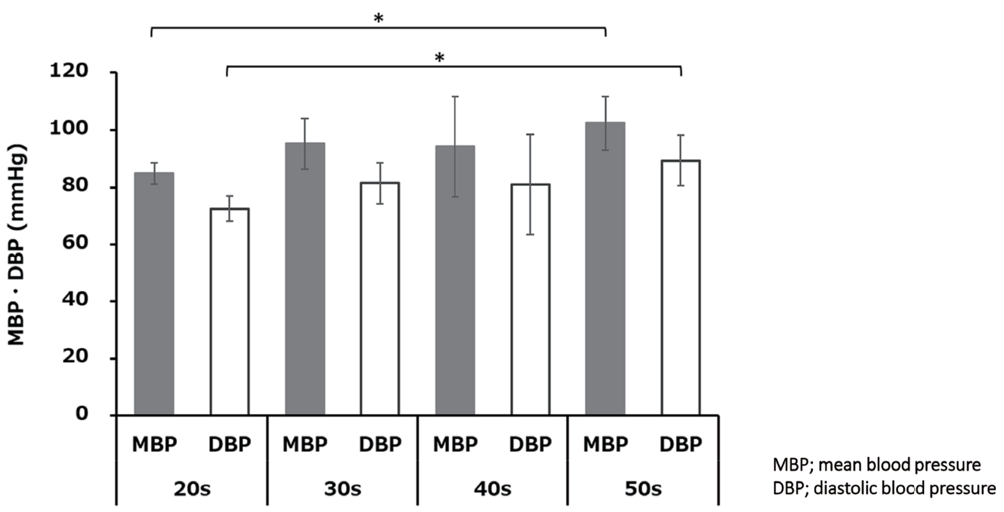

Fig. 7 The mean±SD of the mean and diastolic blood pressure by age group. The asterisks indicate significant differences among the groups. (*p<0.05 Dunnet's method)

in men and women. Significant differences between males and females were recognized with regard to the PTT, OD, systolic, and mean blood pressure ($p<0.05$).

4. Discussion

4.1. PTT of measuring sites and age groups

In the present study, the average PTT of the toes was significantly longer than that of the ears, fingers, and teeth, whereas there was no significant difference among the teeth,

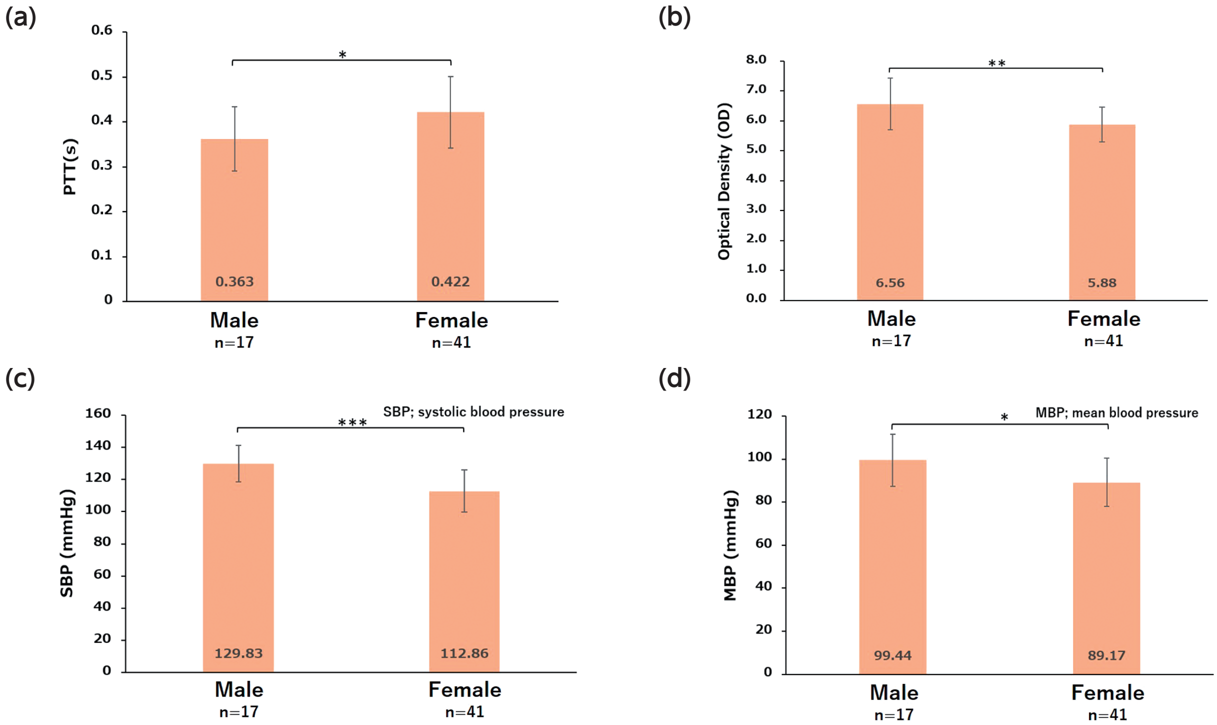

Fig. 8 The mean ± SD of the (a) PTT of the teeth, (b) OD, (c) systolic blood pressure (SBP), and (d) mean blood pressure (MBP) in male and female. The asterisks indicate significant differences between the groups. (*$p<0.05$, **$p<0.01$, ***$p<0.001$ Dunnet's method)

ears, and fingers. In the previous study of Allen et al[10], there were significant differences among the PTT values at all measuring sites (ears, fingers, and toes), and the PTT of the toes showed the largest values, followed by the fingers and then the ears[10]. Furthermore, the previous study designed for children between the ages of 5 and 12 years old reported that the lengths of the leg and arm were significantly correlated with the PTT at the toe and finger, respectively[7]. These results suggest that the PTT increases with distance from the measuring site to the heart.

The average PTT of the toes in our study was significantly longer due to the relatively substantial distance from the toe to the heart, which was greatest among all our measuring points. The inconsistency in the findings between the present and previous reports (i.e. the lack of significant differences between the teeth, ears, and fingers) might be due to differences in the study design, such as the number of subjects, age distribution, and measuring device used. To our knowledge, there have been no previous reports concerning the PTT of the teeth. The present study found no significant difference in the PTT between the teeth and ears, since both sites belong to the head and neck region.

In a comparison of the average PTT among different age groups, only the PTT of the toes showed significant differences by age. Although no significant differences among age groups were recognized in the average PTT of the teeth and ears, they tended to decrease with age. A previous study speculated that the decrease in the PTT with increasing age was due to an increase in the pulse wave velocity (PWV), which progressed with arteriosclerosis caused by aging[10]. The elevation of both the mean blood pressure and diastolic blood pressure is an index reflecting the progression of arteriosclerosis[11]. Generally, the health standard of the mean blood pressure is <100 mmHg in clinical practice[12], with a value ≥100 mmHg classified as cardiovascular disease, indicating that the patient may have progressive arteriosclerosis. In the present study, both the average mean blood pressure and diastolic blood pressure in the subjects in their 50s were significantly higher than in the subjects in their 20s. It was assumed that changes in the cardiovascular system, such as the progression of arteriosclerosis and loss of vascular elasticity with aging, alter the systemic blood pressure, which in turn increases the PTT with age.

Allen and Murray reported that the greatest reduction of PTT with increasing age appeared at the toes, compared to the fingers and ears[10]. As the toes were located farthest from the heart among all measuring sites, the distance for the pulse to travel was much longer than that for other peripheral tissues. The PTT of the toes tended to be susceptible to systemic vascular resistance and showed significant differences among age groups. Regarding the PTT of the teeth and ears, downward trends with age were noted; however, this difference was not significant. We speculated that since each peripheral tissue specimen had a specific characterization of its vascular system, there might have been some local factors which could have affected the PTT other than systemic vascular resistance. With regard to the dental pulp, the anatomical morphology of the dental pulp may influence the PTT of the tooth, as the microcirculatory systems are surrounded by hard tissues.

4.2. OD of age groups

On comparing the average OD among age groups, there was no significant difference in the present study. A previous report on OD that investigated the development of young permanent central upper incisors in children 6-17 years old showed that the OD of the teeth increased with root formation[13]. The light attenuation through the dentin layer is the dominant factor responsible for the increase in the OD[13]. The increase in dentin thickness and calcification with root development leads to a reduction in light transmission and a consequent increase in OD.

In the present study, all subjects' teeth were adult healthy teeth with complete root formation. Although the OD was expected to increase in adult teeth with aging due to pulp obliteration and calcification, no significant differences were recognized among age groups. The individual anatomical differences in the optical characteristics of the teeth with complete root formation stage may not have been obvious compared to those in the root formation stages. The present findings therefore indicate that individual differences in the adult teeth scarcely affect the PTT of the teeth.

4.3. Influence of blood pressure and heart rate on the PTT of the teeth

According to the present results, there was a significant negative correlation between the PTT of the teeth and the heart rate, with the PTT of the teeth decreasing as the heart rate increased (Fig. 6a). The PTT is the sum of the PEP and VTT[14]. As reported by Yousefian et al., the PEP decreases with increasing heart rate[15], which might lead to a decrease in the PTT of the teeth. In addition, the VTT is known as an index of vascular stiffness[14]. Regarding the effect of arteriosclerosis on the PTT, loss of elasticity in blood vessels would occur with arteriosclerosis progression, which might cause an increase in arterial blood pressure along with an increase in the PWV[16], resulting in a decrease in the PTT.

Regarding the effect of blood pressure on the PTT of the teeth, there was no significant correlation between the blood pressure and PTT. However, a previous study using adult rats with a pharmacologically controlled heart rate and blood pressure demonstrated that the PWV calculated from the PTT showed a high correlation with the heart rate in the high-diastolic blood pressure group[17]. Furthermore, in a previous clinical report, an elevated peripheral blood pressure was associated with an elevated heart rate in patients defined as "prehypertensive" or with a normal blood pressure[18]. Although there was no significant correlation between the PTT of the teeth and blood pressure in our study, we suspected that a blood pressure change might affect the PTT indirectly. According to the average blood pressure of the age groups in our study, both the diastolic blood pressure and mean blood pressure in the subjects in their 50s were significantly higher than in the subjects in their 20s (Fig. 7). These results suggest that vascular stiffness in the subjects in their 50s might be greater than that in other groups, and reducing the elasticity of systemic blood vessels tends to cause a reduction in the PTT of the teeth, ears, and toes with age.

4.4. Differences in the PTT by sex

According to our results, the average PTT of the teeth in females was significantly higher than in males. We considered several factors potentially responsible for this sex-based difference. The average OD in males was significantly higher than that in females. As described above, the dominant factor of light attenuation through the whole tooth was dentin thickness and calcification. The difference in anatomical tooth size, thickness, and calcification degree of the dentin between males and females may affect the attenuation level of subjects' teeth. The OD is the index for the light attenuation level of the teeth. Since the light transmission time through the tooth become longer with increasing OD, it is difficult to imagine the OD as a factor influencing the differences between males and females.

There were no significant differences in the average heart rates between males and females in our study. However, both the mean blood pressure and diastolic blood pressure were higher in males than in females. As mentioned above, the mean blood pressure may be used as an index reflecting arteriosclerosis progress. Regarding the relationship between the PWV and arteriosclerosis, Cheung et al. suggested that the progression of arteriosclerosis affected the PWV in children with polyarteritis nodosa, and their PWV was significantly greater than in healthy children[19]. Another study showed that the PWV in postmenopausal females receiving hormone replacement therapy (oral conjugated equine estrogen) was significantly lower than in postmenopausal females with no therapy, and the arterial stiffness in postmenopausal females receiving hormone replacement therapy was improved[20]. We therefore suspect that the difference in the PTT of the teeth between males and females in this study may have been related to difference in the blood pressure and presence of female hormones.

4.5. Potential applications of the PTT in dental diagnoses

This study was the first attempt to record the PTT of dental pulp. As a result, regarding the systemic factors affecting the PTT, our findings indicated that the PTT of a healthy tooth was affected by the heart rate and elasticity of systemic blood vessels. Our findings also suggested that the blood pressure affects the PTT indirectly. The PTT can also be affected by peripheral and local clinical conditions. For example, Kortekaas et al. reported that the PTT of the toes in subjects with lower limb peripheral arterial occlusive disease (PAOD) was associated with the grade of PAOD[14)]. In our previous study, the clinical measurement of traumatized young permanent teeth showed that the TLP amplitude changes during the follow-up period depended on the prognosis of the trauma[6)]. Furthermore, the assessment of pulpal circulation using TLP during the root development stages suggested that neuronal regulation of arteriolar vasoconstriction controlled by the sympathetic and sensory nervous system might affect the amplitude of TLP pulse waves[13)]. If the pathological changes in dental pulp caused by chronic caries and dental trauma do indeed affect pulpal circulation, the PTT of the teeth may be a useful indicator for quantitatively diagnosing dental pulp viability.

Further studies will be required to examine the PTT of the teeth under pathological conditions, such as in cases of chronic caries and dental trauma, in order to clarify its applicability for new dental pulp diagnoses.

COI statement

All authors declare that they have no conflicts of interest.

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