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Research Paper

Human pulpal blood flow in different root formation stages measured with transmitted-light plethysmography

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ABSTRACT

Objectives: To determine the pulp vitality after traumatic injury, dentists often use pulp sensitivity tests, which can be ambiguous in young permanent teeth with incomplete root formation. Transmitted-light plethysmography (TLP) is a non-invasive objective method that uses a 525-nm LED to detect blood volume change in the pulp. The present study aimed (1) to investigate pulpal blood flow with TLP and optical characteristics in healthy permanent maxillary incisors in different root formation stages, and (2) to assess the influences of body growth of the children and tooth color on the TLP amplitude.

Design: Seventy-eight fully erupted maxillary central incisors were divided into four groups, according to the root formation stages. Group 1: root with wide-open apex, Group 2: root completed in length with open apex, Group 3: root with half-closed apex, Group 4: root with complete formation. The TLP amplitude, optical density, electric pulp testing, and cervical tooth color measurements of each group were compared using a one-way analysis of variance followed by the Bonferroni method. The correlation between the weights/heights of children and TLP amplitudes was analyzed using Pearson coefficient.

Results: The TLP amplitude was significantly higher in Group 3 than in the other groups. The amplitude was correlated with the weights/heights of children, but not with the tooth color. Optical density and electric sensitivity increased with tooth maturation.

Conclusion: The amplitude of TLP and optical density may be affected by growth and development in children and indicate changes in the vascular dynamics of the pulp and hard tissue maturation during root formation stages.

1. Introduction

Pulp vitality tests are essential for the proper treatment and favorable prognosis of patients with traumatized teeth. In order to evaluate the pulp vitality, dentists often use sensitivity tests, such as electric and thermal tests. However, pulp vitality testing based only on the neuronal response is deficient, as this response greatly depends on a patient's subjective sensation (Ikeda & Suda, 1998). It may therefore not be suitable for diagnosing the developing teeth of children, due to possible false negative results (Otawa, Fujii, Kubota, & Machida, 1986).

Transmitted-light plethysmography (TLP) is a non-invasive and objective optical method that utilizes a single light-emitting diode (LED) to detect blood volume changes in the dental pulp (Ikawa, Horiuchi, & Ikawa, 1994; Kakino, Takagi, & Takatani, 2008; Schmitt, Webber, & Walker, 1991).

It has been reported that the TLP signal is less likely to be contaminated by the blood circulation of surrounding tissues than laser Doppler flowmetry (LDF) (Matthews, Ikawa, & Horiuchi, 1996). The TLP amplitude has a significant negative correlation with age in children, and the vital teeth had a significantly higher amplitude than the non-vital teeth with no pulse signal (Miwa, Ikawa, Iijima, Saito, & Takagi, 2002).

Our previous studies using an extracted tooth model have clarified that dentin thickness, pulp chamber size, LED wavelength, and blood concentration are substantial factors affecting the transmission of light through the teeth, and that changes in both the TLP amplitude and optical density (OD) are indicators of pulpal circulation (Kakino et al., 2007, 2008). Furthermore, the clinical application of TLP to

Abbreviations: TLP, transmitted-light plethysmography; LED, light emitting diode; EPT, electric pulp test; LDF, laser doppler flowmetry; OD, optical density; AC, alternating current; DC, direct current; PWV, pulse wave velocity; PTT, pulse transition time; C_A, arterial compliance

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traumatized teeth has shown that the TLP amplitude changes during the follow-up period, depending on the prognosis of the trauma (Kakino, 2010).

Dental trauma often occurs in growing children. There have been several studies on age-dependent changes in the pulpal blood supply using various non-invasive methods (Ikawa, Komatsu, Ikawa, Mayanagi, & Shimauchi, 2003; Komatsu, Ikawa, & Mayanagi, 2007; Miwa et al., 2002; Stella et al., 2015). However, throughout the root formation period, the pulpal chamber size vary in children of the same age (Moorrees, Fanning, & Elizabeth, 1963). To our knowledge, there are no clinical studies regarding pulpal blood supply changes in different root formation stages. In addition, discoloration often accompanies traumatized teeth. Although we were able to collect TLP pulse wave signals from discolored traumatized teeth (Kakino, 2010), the effects of tooth color on the TLP amplitude has not been studied yet. Furthermore, the processes of growth and development of the whole body vary from child to child, and the effects of these processes on the TLP amplitude have not been documented either. Without proper understanding of the normal condition in healthy teeth, diagnosing traumatized teeth will be difficult.

Thus, the aims of the present study were (1) to investigate pulpal blood flow with TLP and the optical characteristics in different root formation stages in healthy permanent maxillary central incisors and (2) to assess the influences of body growth of children and cervical tooth color on the TLP amplitude.

2. Materials and methods

2.1. Subjects and selected teeth

This cross-sectional study was approved by the Ethics Committee of the Graduate School of Tokyo Medical and Dental University (No. 914). The subjects were 31 children aged 6–17 years who visited the pediatric dental clinic of the Dental Hospital, Tokyo Medical and Dental University, and 10 adult volunteers aged 25–36 years. Informed consent was obtained after explaining the purpose and methodology of the study to all participants and their guardians. The selection criteria for teeth were healthy, fully erupted maxillary central incisors without dental caries, restorations, periodontal disease, visible discoloration and a history of trauma. Subjects with systemic diseases, a history of orthodontic treatment and adults with smoking habits were excluded from the study.

2.2. Group classification

Intraoral radiographs of the subjects' teeth were taken to evaluate the root formation stages. The teeth were divided into four groups (G1–G4) according to their developmental stage (Fig. 1). The number of subjects, teeth, and mean age in each group are shown in Table 1.

2.3. Measurement of TLP and OD

A TLP system with a 525 nm green LED (prototype system, J. Morita Corp., Kyoto, Japan) was used to measure the pulpal blood flow of the maxillary central incisors. Fig. 2 shows the experimental setup of the present study. In the preceding pilot study we examined the effect of opaque black rubber dam on the signal from surrounding tissues in Group 4 teeth. There was no statistically significant difference between measurements with and without a rubber dam. Therefore, all measurements in the present study were done without any isolation. Prior to measurement, a silicone impression was taken to make an individual acrylic resin cap for each tooth. Two holes were made in the cap to hold an LED (Ø 3 mm OSPG 3131 P, OptoSupply International) on the palatal side of the tooth and a photodiode on the labial side. We used a typical Si-PIN photodiode with specifications of spectral sensitivity of 450–1110 nm, and a peak wavelength of 920 nm (HPS 304AL, Kodenshi Corp., Tokyo, Japan). The sensitivity at 525 nm was around 0.23 A/W (Fig. 3). Each measurement lasted 90 s, while the subjects were in the supine position, and finger plethysmogram was recorded simultaneously to obtain the heartbeat signals. An amplified transmitted light signal, *i.e.* TLP pulse waves (alternating current: AC) and transmitted light intensity (direct current: DC), appeared on the oscilloscope connected to a TLP system. The average amplitude of 30 wavelengths was measured using a signal processing software program (LabChart, AD Instruments Pty., Ltd., Australia). The ratio of the pulsatile (AC) and non-pulsatile (DC) transmitted light intensities was calculated as a percentage of the TLP amplitude as follows:

$$\text{TLP amplitude (\%)} = 100\ (\text{AC (V)}/\text{DC (V)})$$

For the OD measurement, the same light source LED and individual acrylic resin cap were used to obtain transmitted light from the exact same position as TLP measurement. A mini-spectrometer (model C10082CA, SpecEvaluation software; Hamamatsu Photonics K.K, Hamamatsu, Japan) was used to detect the incident and transmitted light intensities. The OD of the teeth was calculated using the following formula, where I_o is the incident light and I_t is the transmitted light:

$$OD = \ln (I_o/I_t)$$

2.4. Tooth color measurements

A Crystaleye Spectrophotometer® (Olympus Corp., Tokyo, Japan) was used to record the color of the cervical area on the labial surface. Since the LED and photodetector were positioned approximately 3 mm from the gingival margin, the color of the cervical area on the labial surface was recorded. The CIELAB color scale was applied to obtain L*a*b* parameter values, where L* is lightness (0 is black, 100 is pure white), a* is red (+a*) to green (−a*) hue, and b* is yellow (+b*) to blue (−b*) hue. A disposable mouth piece was used in each subject to fix the tooth position, and the device was calibrated before each measurement.

2.5. Electric pulp test (EPT)

A Sybron Endo vitality scanner ™ (model 2006; Sybron Endo Dental Specialties, Glendora, CA, USA) was used for electric pulp vitality testing. After the tooth had been isolated with cotton rolls and air dried, the electrode was placed on the labial center of the enamel surface. EPT values from 0 (no output) to 80 (maximum output) were recorded when each subject could perceive any sensation.

2.6. Body weight and height measurements

The body weight and height of the children were measured on the same day with optical measurements.

2.7. Statistical analyses

The comparisons of the TLP amplitude, OD values, EPT values, and tooth color indicators (L*, a*, and b*) between Groups 1 to 4 were analyzed using a one-way analysis of variance and the Bonferroni method. The Pearson correlation coefficient was calculated between tooth color, weight, height, and TLP amplitudes. P values less than 0.005 were considered statistically significant. All statistical analyses were performed using the SPSS software program, version 23.0 (IBM Corp., Armonk, NY, USA).

3. Results

Fig. 4 shows examples of tooth and finger plethysmograph recordings in each group as real-time monitoring. During the TLP