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Measurement of pulp blood flow rates in maxillary anterior teeth using ultrasound Doppler flowmetry

Y.-W. Cho[1] & S.-H. Park[2]

[1]Department of Conservative Dentistry, College of Dentistry, Yonsei University, Seodaemun-Gu, Seoul; and [2]Department of Conservative Dentistry, Oral Science Research Center, College of Dentistry, Yonsei University, Seodaemun-Gu, Seoul, South Korea

Abstract

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Aim To measure pulp blood flow rates of clinically normal maxillary anterior teeth of healthy adults using ultrasound Doppler flowmetry (UDF).

Methodology A total of 359 anterior teeth from 63 patients (mean age, 29.8 years; range, 22–52 years; 26 females and 36 males) were included. The data were collected according to tooth type (three groups: central incisors, lateral incisors and canines). An MM-D-K (Minimax, Moscow, Russia) ultrasound Doppler imaging instrument was used to measure pulp blood flow. Differences between the tooth types were analysed with one-way ANOVA and a Bonferroni correction at the 95% confidence level.

Results The mean average linear velocities during the systolic period (Vams) of the central incisors, lateral incisors and canines were 0.58, 0.58 and 0.52 cm s^{-1}, respectively. There were no significant differences in the mean Vams between the tooth types ($P > 0.05$).

Conclusions Within the limitations of this study, the pulp blood velocities of clinically normal, maxillary anterior teeth of healthy adults were between 0.5 and 0.6 cm s^{-1}. There were no significant differences in mean blood flow rates between maxillary central incisors, lateral incisors and canines.

Keywords: pulp blood flow, pulp vitality, ultrasound Doppler, vital teeth.

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Introduction

Several methods are used to assess the status of the pulp, including thermal (cold or hot) tests (Gopikrishna *et al.* 2007), electric pulp tests (EPT) (Gopikrishna *et al.* 2007, Karayilmaz & Kirzioglu 2011), laser Doppler flowmetry (LDF) (Kimura *et al.* 2000, Karayilmaz & Kirzioglu 2011), ultrasound Doppler flowmetry (UDF) (Thierfelder *et al.* 1978, Chandler 1988, Yoon *et al.* 2010, 2012) and pulse oximetry (Radhakrishnan *et al.* 2002, Jafarzadeh & Rosenberg 2009, Karayilmaz & Kirzioglu 2011). Although thermal test and EPT are commonly used, these two methods are indirect methods of assessing the sensibility of the pulp nerves. These tests rely on subjective responses of patients and have low reliability when sensibility is affected by extrinsic factors (Gopikrishna *et al.* 2007, Yoon *et al.* 2010). Evaluation of pulp blood supply is more reliable for direct pulp vitality testing (Fratkin *et al.* 1999, Radhakrishnan *et al.* 2002, Jafarzadeh & Rosenberg 2009), particularly in teeth with immature root apices or following temporary or permanent loss of sensory function due to trauma or orthognathic surgery (Radhakrishnan *et al.* 2002, Jafarzadeh & Rosenberg 2009, Yoon *et al.* 2010).

Experimental trials to evaluate pulp blood flow have been conducted. Methods such as radioisotope clearance tests (Hock *et al.* 1980, Kim *et al.* 1983) and H_2 gas desaturation tests (Aukland *et al.* 1964, Tonder &

Correspondence: Sung-Ho Park, Department of Conservative Dentistry, Oral Science Research Center, College of Dentistry, Yonsei University, 50 Yonsei-Ro, Seodaemun-Gu, Seoul 120-752, South Korea (Tel: +82-2-2228-3147, Fax: +82-2-313-7575, e-mail: sunghopark@yuhs.ac).

Aukland 1975) are clinically unacceptable due to their invasiveness. LDF and pulse oximetry are noninvasive, quantitative and objective because they do not rely on patient responses, are not painful and are easily accepted by sensitive patients after trauma (Radhakrishnan *et al.* 2002, Emshoff *et al.* 2004, Strobl *et al.* 2004).

Laser Doppler flowmetry is affected by the testing environment and clinical technique due to the sensitivity of the laser beam used (Odor *et al.* 1996a,b). In situations in which the pulp chamber is filled with necrotic debris (untreated) or is filled with gutta-percha or composite resin (root canal treated), the same negative recordings will be obtained if an instrument accurately detects pulp blood flow because there is no vital tissue in either case. However, the results of LDF will be different due to differences in the optical properties of the crown (Jafarzadeh 2009). LDF is also sensitive to the position, holding and fixation method of the probe (Cotti *et al.* 2003, Rajendran & Sundaresan 2007) and noise and vibration from the external environment (Vongsavan & Matthews 1993).

Ultrasound Doppler flowmetry has been used in the medical field as a noninvasive and radiation-free technique for the assessment of blood flow in microvascular systems. UDF shares the same 'Doppler principle' with LDF. The difference between UDF and LDF is the source; LDF is an 'optical' measurement method that uses a laser beam as a source (Jafarzadeh 2009), whereas UDF uses ultrasound rather than a laser beam. When the UDF probe emits the ultrasonic wave to a moving red blood cell, the cell reflects the incident wave. Therefore, the frequency of the reflected wave is altered according to the Doppler principle. This frequency shift is detected and analysed by the UDF machine. The UDF monitor shows real-time wave patterns within given time periods, and the UDF unit calculates the blood flow rate, pulsation index and circulation index (Yoon *et al.* 2010, Jamieson *et al.* 2014). Furthermore, the examiner can listen to pulsation sounds in real time (Yoon *et al.* 2010).

Ultrasound has also recently been applied to dentistry. Several studies have shown that ultrasound Doppler can be successfully used in the differential diagnosis of periapical granulomas and cysts based on the detection of the microvascularity of the lesion (Cotti *et al.* 2003) and can be used in follow-up evaluations of the healing of periapical lesions after root canal treatment (Rajendran & Sundaresan 2007). The authors of these studies concluded that UDF offers sufficient information about microvascularity. Recently, Yoon *et al.* (2010) evaluated blood flow in root filled teeth and contralateral teeth with healthy pulps using UDF and illustrated the potential of examining pulp blood flow with UDF (Yoon *et al.* 2010). Additionally, Yoon *et al.* (2012) reported that blood flow changes before and after infiltration anaesthesia can be measured using UDF (Yoon *et al.* 2012). Information about normal pulp blood flow rates of teeth with healthy pulps measured by UDF is required for the clinical application of UDF. The purpose of this article was to measure the pulp blood flow rates of clinically normal, maxillary anterior teeth of healthy adults using UDF.

Materials and methods

Subjects

A total of 359 anterior teeth from 63 patients (mean age, 29.8 years; range 22–52 years; 26 females and 36 males) were included. The data were collected according to tooth type (three groups: central incisors, lateral incisors and canines). Patients with systemic cardiovascular disease were excluded.

The inclusion criteria for the teeth were as follows: (i) no caries or restoration; (ii) no history of orthodontic treatment or trauma; (iii) clinically normal responses to thermal and EPT (Gentle Pulse Analog Pulp Vitality Tester; Parkell Inc., Edgewood, NY, USA), no sensitive response to percussion on and tooth mobility within the normal range; and (iv) normal periradicular state on a periapical radiograph.

This study was approved by the ethics committee of the dental hospital at Yonsei University (2-2010-0002).

Apparatus

An MM-D-K (Minimax, Moscow, Russia) ultrasound Doppler imaging instrument with a 20-MHz probe was used to measure pulp blood flow. The tip diameter of the 20-MHz probe was approximately 2.5 mm, and the entire length of the probe was approximately 20 cm (Fig 1). An ultrasound gel (Pro-gel II; Dayo Medical, Seoul, Korea) was applied as a coupling agent.

Procedures

All procedures were performed by a single examiner to eliminate interexaminer error. The study was explained to the patient, and informed consent was

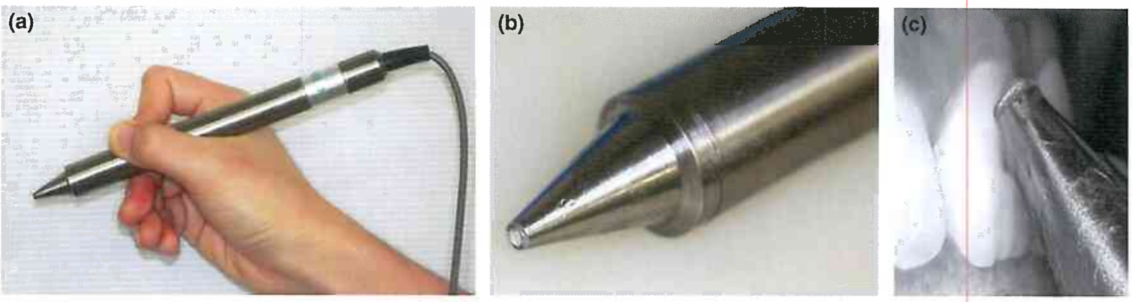

Figure 1 Ultrasonic probe of the Minimax Doppler machine. (a) Picture of ultrasonic probe held in a hand. (b) Tip of the ultrasonic probe. (c) Measurement position.

obtained. The patient was allowed to rest for more than 10 min prior to the measurements to ensure relaxation. Each patient was placed in a semisupine position. After drying the tooth surface, the ultrasound gel was applied to the cervical area of the tooth, and a probe was placed at a 60-degree angle to the labial surface. The blood flow measurements were performed with a 20-MHz probe. Because the examiner could hear the pulsating sounds in real time, the probe was hand-held at the site of maximal pulsation. The probe position was fixed at the site of the most clear pulsating sound for 8 s so that the wave pattern was recorded clearly.

Ultrasound Doppler flowmetry: parameters for pulp blood flow measurement

The measurement parameters are listed in Table 1. Under these parameters, the linear velocities (Vas, Vam and Vakd) are more meaningful than the volume velocities (Qas and Qam). Volume velocities, which are determined by the cardiac output volume, are similar regardless of vessel diameter or type (e.g. these velocities are similar between the aorta, the arterioles and the capillaries) (Riva *et al.* 1985, Jamieson *et al.* 2014). By definition, the maximum linear velocity during the systolic period (Vas) and the minimum linear velocity during the diastolic period (Vakd) are more strongly affected by blood pressure than are the average velocity values. Thus, in this study, the average linear velocities during the systolic period (Vams) were analysed.

Statistical analyses

The raw data were statistically analysed using SPSS v21.0 software (IBM Corp., Somers, NY, USA). The Vam values of the central incisors, lateral incisors and canines were compared with a one-way ANOVA and a Bonferroni correction at the 95% confidence level.

Results

The mean average linear velocities during the systolic period (Vams) of the central incisor, lateral incisor and canine were 0.58, 0.58 and 0.52 cm s^{-1}, respectively (Table 2). All teeth in this study exhibited pulsed waveforms and pulsating sounds that were characteristic of arterioles in teeth with healthy pulp (Fig. 2).

There were no significant differences in the mean Vams between the central incisors, lateral incisors and canines ($P > 0.05$).

Discussion

Laser Doppler flowmetry requires a zero-point setting and calibration using a Brownian motion medium prior to each measurement and demonstrates the relative blood flow rate in perfusion units or flux units (Chen & Abbott 2011, Chen *et al.* 2012). In contrast, UDF does not require a zero-point setting or calibration procedure; thus, UDF can reveal the absolute velocity value in cm s^{-1} or mm s^{-1}.

In UDF, the quality of the acquired image and the penetration depth of the ultrasonic wave are influenced by the frequency of the probe (Berson *et al.* 1999). Low-frequency probes (i.e. those that utilize frequencies below 10 MHz) provide sufficient penetration to depths exceeding 2 cm. However, low-frequency probes create low-quality images and cannot detect small vessels with low flow rates (Berson *et al.* 1999). In contrast, high-frequency probes (i.e. probes that utilized frequencies above 50 MHz) provide high-quality images and sensitive detection of

Table 1 Ultrasound Doppler flowmetry parameters

Parameter	Definition
Vas (cm s^{-1})	Maximum linear velocity during the systolic period
Vam (cm s^{-1})	Average linear velocity during the systolic period
Vakd (cm s^{-1})	Minimum linear velocity during the diastolic period
Qas (ml min^{-1})	Maximum volume velocity during the systolic period
Qam (ml min^{-1})	Average volume velocity during the systolic period
PI	Pulsation index: resilience of the blood vessel
RI	Resistance index: circulation resistance

Table 2 Sample sizes, mean Vams and standard deviations of the measured samples

Tooth type	*n*	Mean Vam (cm s^{-1})	Standard deviation
Central incisor	119	0.58	0.49
Lateral incisor	120	0.58	0.47
Canine	120	0.52	0.41
	359	0.56	

small vessels with low flow rates but only provide shallow penetration depths of <1 mm. Thus, the versatility of high-frequency probes is limited, and technical difficulties are associated with their use (Christopher *et al.* 1996, 1997).

A 20-MHz probe was used in the present study. Twenty-megahertz probes are known to produce images of limited resolution (80 μm axially and 250 μm laterally) (Berson *et al.* 1999). The present study aimed to measure pulp blood flow rates and not to study images; thus, image resolution was not relevant to this study. Twenty-megahertz probes can detect blood flow rates as deep as 0.8 cm and low flow rates below 0.05 cm s^{-1} (Berson *et al.* 1999); thus, the 20-MHz probe was useful for the evaluation of small arterioles and venules in the oral–maxillofacial region.

Blood flow rates were greater in vessels with larger diameters. In a study of blood flow rates that utilized triplex ultrasonography, the mean blood flow rate of the common carotid artery, which has a diameter of 5.4–7.5 mm, was found to be 48.2 cm s^{-1} (minimum 29.0 cm s^{-1}, maximum 67.0 cm s^{-1}), whilst the mean blood flow rate of the vertebral artery, which has a diameter of 2.3–3.8 mm, was found to be 31.4 cm s^{-1} (minimum 17.4 cm s^{-1}, maximum 45.4 cm s^{-1}) (Owolabi *et al.* 2014). Moreover, in another study that used a duplex colour Doppler imager, the authors concluded that there was a positive and linear correlation between vessel diameter and blood flow rate (Stoner *et al.* 2004).

Studies of the blood flow velocities in relatively small-diameter arterioles have been performed in ophthalmology. As measured using laser blood flowmeter, the mean blood flow velocity of retinal arterioles, which has a diameter of 85–129 μm, has been found to be 2.2–4.2 cm s^{-1} (Gilmore *et al.* 2005), and the mean blood flow velocity of conjunctival arterioles, which has a diameter of 6–12 μm, has been found to be 0.052–0.326 cm s^{-1} based on high-speed video microcinematography (Koutsiaris *et al.* 2010).

The targets of the UDF measurements in the present study were the pulp arterioles. The diameters of pulp arterioles have been reported to be 20–40 μm (Okamura *et al.* 1994) and 14–51 μm (Tomaszewska

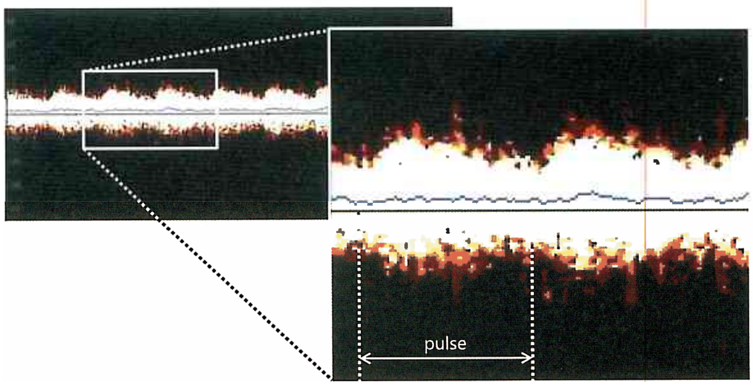

Figure 2 A characteristic pulsed waveform of an arteriole in a tooth with a vital pulp.

et al. 2013). Given the positive correlation between vessel diameter and flow rate, it can be deduced that the blood flow velocities of the pulp arterioles, which are 10–50 μm in diameter, were approximately 0.1–2.0 cm s^{-1}. In the present study, the blood flow velocities ranged from 0.44 to 0.67 cm s^{-1}. These findings are consistent with results reported in previous studies of 0.27–0.79 cm s^{-1} (Yoon *et al.* 2010, 2012) and 0.18–0.56 cm s^{-1} (Qu *et al.* 2014).

In this study, there were no significant differences in the mean blood flow velocities of the maxillary central incisors, lateral incisors and canines; however, the measured data had a relatively large standard deviation, which is consistent with other studies (Norer *et al.* 1999, Roy *et al.* 2008). Several predisposing factors, including vessel diameter and baseline blood pressure, might affect these values.

Vessel diameter and blood pressure might be the most critical factors that affect pulp blood flow velocity (Stoner *et al.* 2004, Owolabi *et al.* 2014). Vessel diameters are controlled by systemic and/or local factors of each patient and cannot be controlled by the examiner. Vessel diameters are also related to patient age, and the sample of this study consisted of young patients with a mean age 29.8 years. Blood pressure cannot be strictly controlled by the examiner, but the use of relaxation procedures prior to measurements can reduce blood pressure variation (Norer *et al.* 1999, Akpınar *et al.* 2004). In this study, the patients were provided with a sufficient amount of rest that exceeded 10 min prior to each measurement and were placed in the semisupine position during the measurement. Further studies of the relationship between blood pressure and blood flow rate using UDF are required.

Probe angle, probe position, probe design and the characteristics of the probe holder might also affect these results (Jafarzadeh 2009). These factors should be controlled and standardized in each study. In the present study, one experienced examiner measured all of the subjects using the same probe and techniques to eliminate variations between examiners.

The most useful application of UDF might be the longitudinal monitoring of the pulp status of traumatized or immature teeth, which generally require long-term evaluation. In such situations, the use of a repositioning stent (Yoon *et al.* 2012) for each patient might help to eliminate positioning variation due to the repetition of measurement for long time periods.

Prior to the clinical application of UDF, further studies of the sensitivity, specificity and discrepancies due to inter- and intra-examiner variations are needed.

Conclusions

Within the limitations of this study, the pulp blood velocities of clinically normal, maxillary anterior teeth of healthy adults were between 0.5 and 0.6 cm s^{-1}. There were no significant differences in mean blood flow rates between maxillary central incisors, lateral incisors and canines.

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