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A novel laser Doppler flowmeter for pulpal blood flow measurements

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ABSTRACT

We have proposed and experimentally demonstrated a new configuration of laser Doppler flowmetry for dental pulpal blood flow measurements. To date, the vitality of a tooth can be determined only by subjective thermal or electric tests, which are of questionable reliability and may induce pain in patient. Non-invasive techniques for determining pulpal vascular reactions to injury, treatment, and medication are in great demand. The laser Doppler flowmetry technique is non-invasive; however, clinical studies have shown that when used to measure pulpal blood flow the conventional back-scattering Doppler method suffers from low signal-to-noise ratio (SNR) and unreliable flux readings rendering it impossible to calibrate. A simplified theoretical model indicates that by using a forward scattered geometry the detected signal has a much higher SNR and can be calibrated. The forward scattered signal is readily detectable due to the fact that teeth are relatively thin organs with moderate optical loss. A preliminary experiment comparing forward scattered detection with conventional back-scattered detection was carried out using an extracted human molar. The results validated the findings of the simple theoretical model and clearly showed the utility of the forward scattering geometry. The back-scattering method had readings that fluctuated by as much as 187% in response to small changes in sensor position relative to the tooth. The forward scattered method had consistent readings (within 10%) that were independent of the sensor position, a signal-to-noise ratio that was at least 5.6 times higher than the back-scattering method, and a linear response to flow rate.

Keywords: Laser Doppler Velocimetry, Back-, forward-scattering, Inflammation, Pulp, Noninvasive, Necrosis, Vitality.

1. INTRODUCTION

Determination of the dental pulpal health status is one of the basic criteria for dental treatment planning and monitoring. Accurate pulpal diagnosis is mandatory if treatment is to be optimized with regard to pain control, damage limitation, healing, restoration, and cost/benefit.

Presently, the two most commonly used clinical techniques are electrical and thermal pulp tests. Validity of the electrical pulp testing technique is often impaired by the presence of large restorations or crowns. In multi-rooted teeth, the vitality status of each canal may be different, resulting in a response that is often not indicative of the true condition of the pulp. Thermal tests are subject to similar limitations and both types of tests are often unpleasant for the patient. Moreover, they measure reactivity of nerves to stimulation. Yet positive reaction of the nerve supply to stimulus does not necessarily equate to a normal, healthy pulp. It has been shown that a considerable loss of blood supply may occur before sufficient degeneration of the nerve supply occurs to affect electrical or thermal test results. The nerve tissues, being highly resistant to inflammation, may remain reactive to such vitality tests long after degeneration of surrounding tissues.

In contrast, alteration in the pulpal microcirculatory function is one of the first signs related to inflammation or necrosis[1]. Since it is vascularity rather than innervation which determines pulpal vitality, diagnostic instruments should be developed that assess pulpal blood flow (PBF) rather than pulpal innervation. Of the various existing techniques, including Xe-washout[2] and radio-labeled microsphere techniques, have been applied to measuring PBF, but to date, none have been appropriate for clinical applications in man. Several attempts at using conventional LDF, which employs a back-scattering geometry, for PBF measurements have been reported[1,2]. These reports have demonstrated a great potential for LDF in dental applications. However, due to the back-scattering configuration used, the conventional LDF is inherently incapable of quantifying flow rate. Because of great variations in tooth size, shape and optical characteristics, the signal varies enormously, giving rise to very significant variations in the measurements obtained. This problem is further amplified by the very low SNR in these LDFs, causing unreliable measurements. Conventional LDF measurements applied to pulpal blood flow are severely limited because: 1) the readings vary enormously depending on the site and angulation of the probe in relation to the pulpal and periodontal tissues, 2) the readings have no correlation between measurements obtained at different points in time or at different locations in the mouth owing to the extreme localization-dependence of the technique, and 3) the measurements are simply unit-less flux readings, affected by the differences in the anatomical configuration of each tooth.

In order to overcome the severe limitations of the conventional LDF technique for dental applications, we propose to use forward-scattering geometry that results in an increased signal-to-noise ratio and the ability to calibrate the sensor readings to actual blood flow rates. This new configuration provides a system that is significantly more reliable and accurate for dental applications. Thus, the proposed instrument can contribute clinically useful information and greatly improve the clinician's diagnostic capabilities to ensure optimal, cost-effective treatment. Here, we report some theoretical analysis and a preliminary experimental demonstration.

2. PRELIMINARY LDF EXPERIMENTS

2.1. Experimental Setup

Figure 1 shows a schematic diagram of the experimental setup.

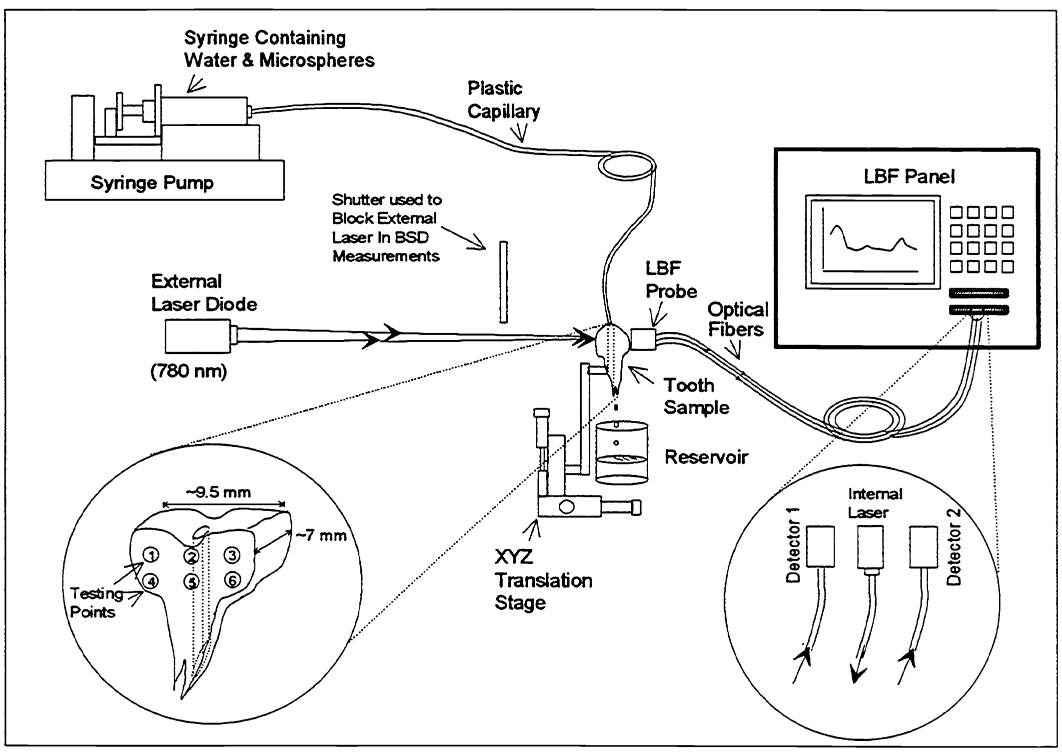

Figure 1. Experimental Setup.

The setup consisted of a laser blood flowmeter (LBF), Model MBF3D, Moore Instruments, England, an adult molar (~ 9.5x7 mm) as sample, a syringe pump (Model 22, Harvard Apparatus) used to provide desired flow rates, and a laser diode (Sharp LT024 MD) used as an external laser for forward-scattering detection (FSD). The sample tooth was vertically drilled with a 1.5 mm hole allowing water-microspheres to flow through. The sample tooth was mounted on an XYZ translation stage with which the tooth was able to be precisely moved to desired testing positions during the measurements. Polystyrene microspheres with 3.4 μm diameter (Cat. No. 7504A, Duke Scientific) were seeded in water as the testing liquid simulating human blood. The flow rate through the tooth was controlled by the syringe pump.

The LBF consisted of an electronic signal processor unit and a probe containing three optical fibers. One fiber (delivery fiber) in the probe was coupled to a laser inside the LDF housing (internal laser). This fiber was used to launch the internal laser beam into the sample for back-scattering detection (BSD) measurements. The other two fibers (receiving fibers) collected the back-scattered light signal. Both external and internal lasers had the same wavelength of 780 nm.

For system alignment, the external laser beam spot was positioned to overlap with the end of the delivery fiber in the LBF probe when the sample was not present. This alignment ensured that both methods were positioned on the same area on the tooth. Then, the sample tooth was placed at the position for measurements. To switch forward-scattering to back-scattering measurements, the external laser was blocked and the internal laser was switched on.

In BSD measurements, the laser beam emerging from the delivery fiber was launched onto the tooth. A portion of light captured by the two receiving fibers was reflected from the tooth surface and a portion was from light that penetrated into the tooth and was back-scattered by the enamel, dentin and microspheres in the water flow. The Doppler signal was generated by the coherent addition of the light scattered from the moving microspheres with the light scattered or reflected from the stationary tooth structure. The resulting frequency spectrum was analyzed by the LBF processor.

In FSD measurements, the internal laser was turned off, and only the external laser was used. The transmitted light beam, after being scattered by enamel, dentin, and the suspended microspheres in the water inside the tooth, emerged in a forward direction from the tooth. The emerging light was then partially captured by the two receiving fibers in the LBF probe. The Doppler signal resulted from the coherent addition of the forward scattered light from the moving microspheres and the remaining forward transmitted or scattered light. The frequency spectrum was processed by the LBF electronic processor. These tests were carried out over a flow range 0.1-0.8 ml/min controlled by the syringe pump.

2.2. Experimental Results

As expected, variable and inconsistent flux readings were obtained using BSD . This was due to two problems intrinsic to this technique as discussed previously: 1) variable optical coupling efficiency at the tooth surface; 2) incapability of calibration due to variable optical pathlength inside the tooth.

In contrast to these limitations, the FSD experiments were characterized by: 1) consistent flow rate readings independent of the testing spot locations; 2) linear response to flow rate; 3) higher sensitivity. Flux levels obtained in FSD were much higher than those obtained in back-scattering detection (BSD). Thus, these experiments demonstrated FSD has clear potential for calibrated and reliable pulpal blood flow (PBF) measurements.

a. Flow Rate Readings vs. Positions

To assess dependence of flow rate readings on measurement position on the tooth, a series of measurements using FSD and BSD was carried out at six different testing points along the sample tooth while holding the flow rate constant at 0.5 ml/min. Approximate locations of the six testing points on the sample tooth are schematically shown in the detailed part of the tooth in Figure 1. The results obtained using both FSD and BSD are shown in Figure 2 and

Table 1. Figure 2 shows histograms of flux readings for FSD and BSD techniques. It clearly demonstrates that FSD gave relatively consistent readings whereas the readings obtained from BSD were widely divergent. From Table 1, one can find that the readings varied only from 93 to 112 for FSD and varied from 0.48 to 1.8 for BSD. Thus, the measurement fluctuations ((maximum-minimum)/2 average) were as low as 9% for FSD and as high as 120% for BSD. In contrast, the consistent and position-independent flux readings obtained with FSD provided reliable flow rate information. A strong dependence of the flux readings on the testing position in the BSD measurements resulted in unreliable and meaningless information on the flow rate.

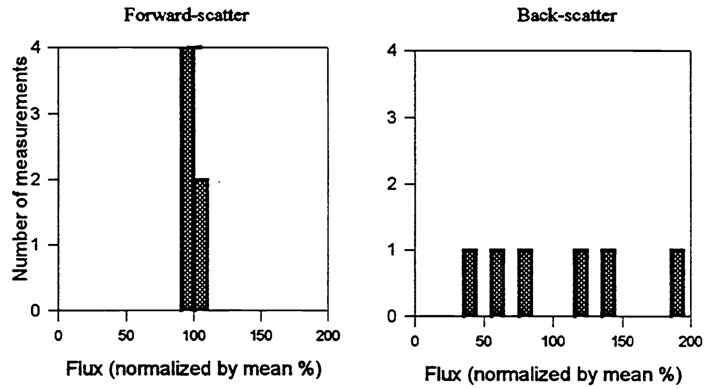

Figure 2. Histogram of flux measurements for forward-scatter and back-scatter methods. Forward scatter results in a narrow (RMS = 10%) while back-scatter method produces a wide distribution that appears almost random.

Table 1 Comparison of Forward- and Back-Scattering Measurements

	X_{max}	X_{min}	X_{max}/X_{min}	$\overline{X}$	σ_1 (%)	σ_2 (%)	σ_3 (%)	σ_4 (%)	σ_5 (%)	σ_6 (%)
FSD	112	93	120.4 %	102.7	0.68	9.1	9.1	8.9	0.68	9.1
BSD	1.8	0.48	375 %	1.38	27.5	65.2	43.5	87	30.4	17

where X_{max} and X_{min} are the measured maximum and minimum values, $\overline{X}$ is mean measured values, σ_j is the defined as $(X_j - \overline{X})/\overline{X}$.

b. Response of FSD and BSD to the Variable Flow rates

In this test, the flow rate was varied from 0.1 to 0.8 ml/min to assess the response of the flux readings to the flow rate changes in BSD and FSD measurements while holding the measurement position fixed. Both FSD and BSD show a linear relationship between the flux level and the flow rate. Typical measurement results obtained from both FSD and BSD at testing point 5 (see detailed tooth diagram in Figure 3) are shown in Figure 3. The linearity of FSD measurements were slightly better than that of BSD (see Figure 4 in detail).

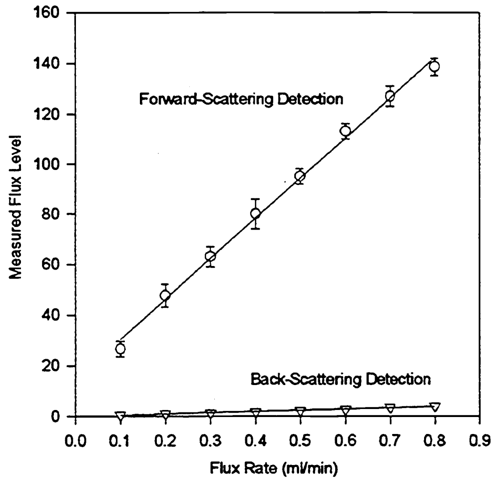

Figure 3. Flux Readings as a Function of the Flow Rates at test Point #5 for BSD and FSD.

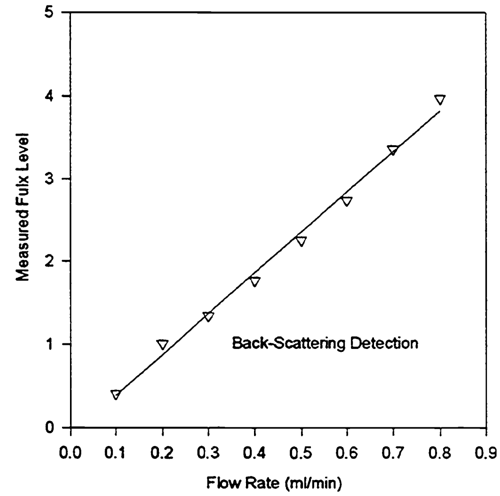

Figure 4. Flux Readings as a Function of the Flow Rates at test Point #5 for BSD.

c. Sensitivity

Typical measurement results for FSD and BSD are shown in Figures 5 and 6, respectively. A flux level of 65 was obtained for a flow rate of 0.3 ml/min in the FSD measurement (Figure 5), whereas a flux level of only 1.3 was obtained for the same flow rate in the BSD configuration (Figure 6). This is partially, but not entirely, due to the higher power of the laser used in the FSD tests. The laser power levels account for a factor of nine between the FSD and BSD measurements (2.7 mW for the FSD and 0.3 mW for the BSD). The flux level reading obtained by FSD remains 5.6 times higher than that obtained by BSD even after correcting for laser power. It should be also noted that the FSD detection was not optimized since the receiving fibers and the LBF signal processor were calibrated and optimized only for BSD. Thus, it is believed that the flux levels obtained by the FSD technique can be further increased if the receiving fibers and processing electronics are optimized.

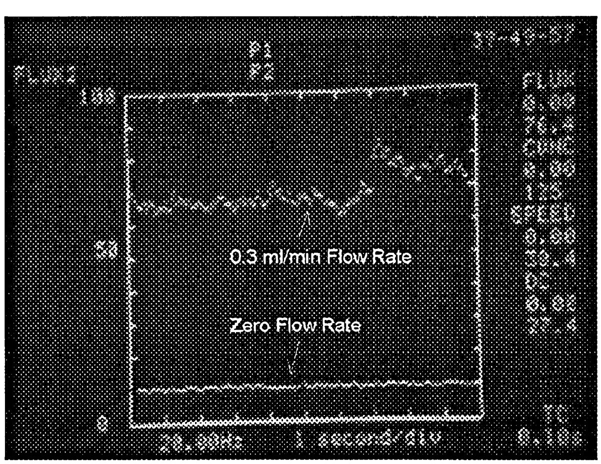

Figure 5. Flux Level Reading Obtained Using FSD for Flow Rates of Zero and 0.3 ml/min.

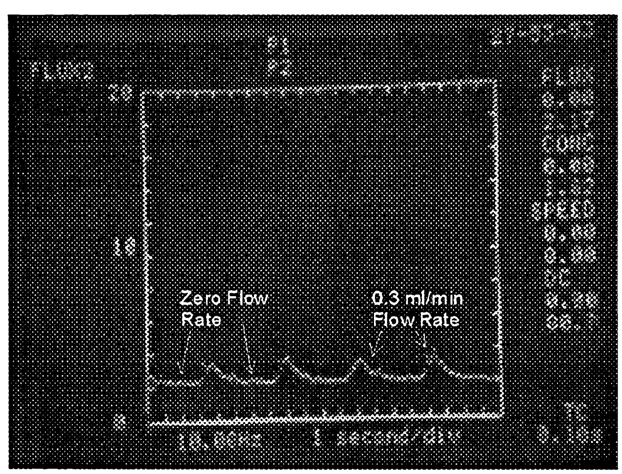

Figure 6. Flux Level Reading Obtained Using BSD for Flow Rates of Zero and 0.3 ml/min.

3. CONCLUSIONS

We have proposed and experimentally demonstrated a new LDF configuration for pulpal blood flow measurements. The novel LDF configuration employs a forward-scattering geometry instead of the conventional back-scattering geometry. Preliminary experimental results strongly validated our theoretical model and clearly showed that the forward scattering method had consistent readings (within 10%) independent of the sensor position, SNRs at least 5.6 times higher than the conventional technique and a linear response to flow rate. In contrast, the back-scattering method had readings that fluctuated by as much as 187% in response to small changes in test position. The new configuration provides a measurement system that has the potential to greatly improve existing dental diagnostic capabilities.

REFERENCES

1 E.R. Ingofsson, L. Tronstad, E.V. Hersh, and C.E. Riva, *"Efficacy of Laser Doppler Flowmetry in Determining Pulp Vitality of Human Teeth,"* Endon. Dent. Traumatol., **10**, 83 (1994).

2 S. Kim, M. Liu, K. Markowwitz, G. Bilotto, and J. Dörscher-Kim, *"Comparison of Pulp Blood Flow in Dog Canine Teeth Determined by the Laser Doppler and the ^{133}Xenon Washout Methods,"* Archs. Oral Biol., **35**, 41 (1990).