

NOVEL APPROACH TO LASER DOPPLER MEASUREMENT OF PULPAL BLOOD FLOW

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ABSTRACT

A modified laser Doppler flowmetry technique that significantly improves the performance of the current technique in measuring pulpal blood flow is described. A preliminary model demonstrates that, by using a forward-scattered geometry, the detected signal will have a much higher signal-to-noise ratio and calibration capacity. The forward-scattered signal is readily detectable because teeth are relatively thin organs with moderate optical loss. Preliminary experiments comparing forward-scattered detection with conventional back-scattered detection were carried out using an extracted, perfused human molar. The results showed that: (1) the existing back-scattering method produced readings that fluctuated by as much as 187% in response to small changes in sensor position relative to the tooth and (2) the forward-scattered method produced 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 that obtained by the back-scattering method, and a linear response to flow rate. The results validated the findings of the preliminary model and clearly showed the superiority of the forward-scattering geometry. © 1997 Society of Photo-Optical Instrumentation Engineers. [S1083-3668(97)00903-9]

Keywords laser Doppler flowmetry; back/forward-scattering; blood flow; pulp.

1 INTRODUCTION

Determination of pulpal health status is one of the basic criteria for planning and monitoring dental treatment. Accurate pulpal diagnosis is mandatory if treatment is to be optimized with regard to pain control, damage limitation, healing, restoration, and costs and benefits. Similarly, monitoring of treatment response by the clinician in a real-time, noninvasive fashion is necessary to tailor treatment to the response of the individual tooth.

At present, the two most commonly used clinical techniques are the electrical and thermal pulp tests. Accuracy of the electrical pulp testing technique is often impaired by the presence of large restorations or crowns. In multirooted teeth, the vitality status of each canal may be different, resulting in a response that is often not truly indicative of the condition of the pulp. An acutely abscessed tooth may give a positive response due to the presence of conductive residual pulpal elements. 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 a positive reaction of the nerve supply to a stimulus does not necessarily indicate a normal, healthy pulp. It has been shown that a considerable loss of blood supply may occur before sufficient degeneration of the nerve occurs to affect electrical or thermal test results. The nerve tissues, being highly re-

sistant to inflammation, may react positively to such vitality tests long after degeneration of the surrounding tissues.

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 that determines pulpal vitality, diagnostic instruments should be developed that assess pulpal blood flow (PBF) rather than pulpal innervation. Various techniques, including Xe-washout² and radiolabeled microsphere techniques,³ have been used to measure PBF, but to date none have been appropriate for clinical applications in man. Conventional laser Doppler flowmetry (LDF), which employs back-scattering detection (BSD) has been used for PBF measurements.⁴ These studies have demonstrated great potential for LDF in dental applications; however, due to the back-scattering detection configuration used, conventional LDF is problematic in several respects. Difficulties include (1) the large effect on measurements of probe site and angle in relation to the tooth surface; (2) a lack of correlation between measurements obtained at different times or on different teeth, owing to the extreme localization dependence of the BSD technique; and (3) an inherent incapability for quantifying flow rate: measurements are unitless flux readings, which are affected by differences in the anatomical configuration of each tooth. These problems are further amplified by the very low signal-

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to-noise (SNR) ratio in conventional LDF devices.

All currently available LDF devices use BSD, perhaps because of their medical origins and the fact that probe light would not travel well through the long optical path of a body organ such as a hand or a leg because of high optical absorption and diffusion. Yet the majority of the Doppler components in the detected signal are attributed to forward-scattering events within the individual red blood cells (RBC). The reasons are that (1) the probability of photon-RBC collision is very small since the moving scatters (RBCs) are so few compared with the stationary scatters (surrounding tissue matrix) and (2) the photon-scattering angle distribution of RBCs is sharply peaked in the forward direction (~ 6 deg)⁵ so that the number of photons forward-scattered by RBCs is about 1000 times greater than those back-scattered.^{6,7} The photons forward-scattered by RBCs can then be scattered back toward the detector by the surrounding stationary tissue matrix without further perturbation to the Doppler spectrum.

The purpose of the investigations described here is threefold: (1) obtaining an improved signal-to-noise ratio and sensitivity, (2) acquiring the ability to calibrate the flux measurement against a reference beam, and (3) obtaining consistent flux readings irrespective of probe location on the tooth.

2 MATERIALS AND METHODS

2.1 EXPERIMENTAL SETUP

Figure 1 shows a schematic diagram of the experimental setup, which consisted of an LDF (Model

MBF3D, Moore Instruments, England), a freshly extracted adult molar ($\sim 9.5 \times 7$ mm), a syringe pump (Model 22, Harvard Apparatus, South Natick, Massachusetts) and a laser diode (Sharp LT024 MD, Japan) to be used as an external laser source for FSD. A 1.5-mm access hole to the pulp chamber of the sample tooth was vertically drilled from the occlusal surface to permit perfusion of the pulp chamber and root canal with a suspension of microspheres in water (see left inset on Figure 1). The sample tooth was mounted on an X-Y-Z translation stage, and then precisely moved to the desired testing positions. Polystyrene microspheres with a $3.4\text{-}\mu\text{m}$ diameter (Cat. No. 7504A, Duke Scientific, Palo Alto, California) were seeded into the water to simulate human blood. The concentration of polystyrene microspheres in the water was $\sim 3.7 \times 10^7$ /ml. Flow rate through the tooth was controlled by the syringe pump.

The LDF consisted of an electronic signal processor unit and a probe containing three optical fibers. One fiber in the probe was coupled with a laser inside the LDF housing (internal laser). This fiber delivered the laser beam to the sample for BSD measurements. The other two fibers received the scattering light signal. The external and the internal lasers emitted at a wavelength of 780 nm.

For system alignment, the external laser beam spot was aligned to overlap the fiber ends in the LDF probe when no sample tooth was present. This alignment was to ensure that both BSD and FSD detected the same area on the tooth. Then, the

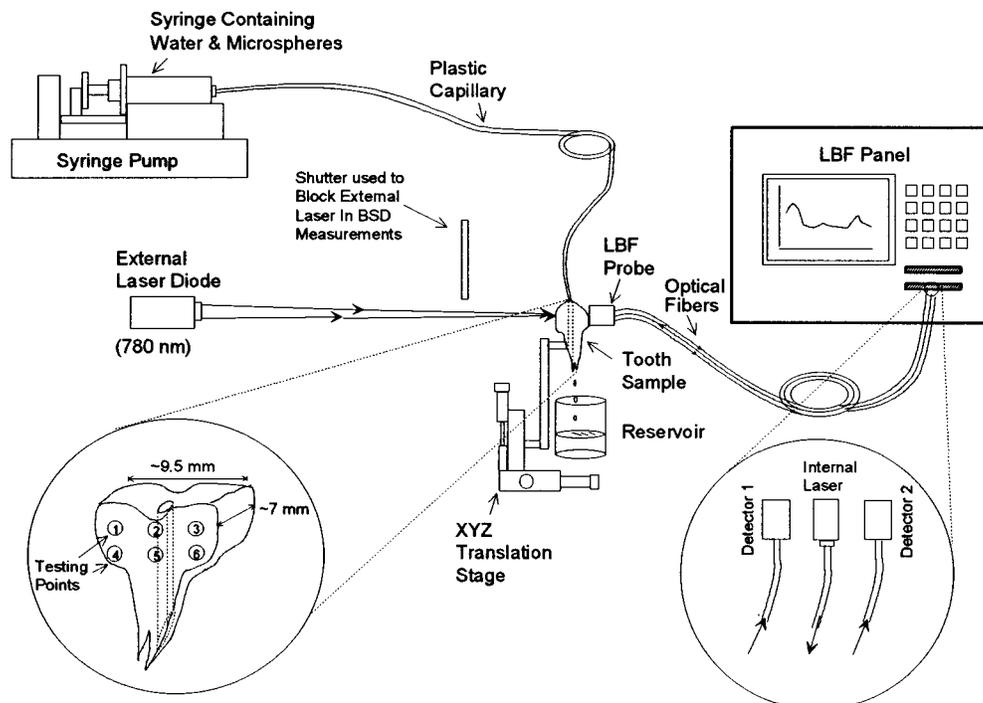


Fig. 1 Schematic diagram of experimental setup.

sample tooth was placed in position for measurements. To switch from FSD to BSD measurements, the external laser was blocked and the internal laser was turned on, or vice versa.

In BSD measurements, the laser beam emerged from the delivering fiber in the LDF probe onto the tooth. A portion of light captured by the two receiving fibers was reflected from the tooth surface and another portion stemmed 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 LDF 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 microspheres in 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 LDF probe and processed by the LDF electronic processor. 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 LDF electronic processor. Testing was carried out over a flow range of 0.1 to 0.8 ml/min controlled by the syringe pump.

To assess the influence of probe measurement position on the tooth on flow rate readings, a series of measurements using FSD and BSD was carried out at six different testing points along the sample tooth (Figure 1) while holding the flow rate constant at 0.5 ml/min.

2.2 RESULTS

2.2.1 Sensitivity, Reproducibility, and Response of FSD and BSD to Variable Flow Rates

Figures 2 and 3 depict typical measurement results for FSD and BSD, respectively. A flux level of 65 was obtained for a flow rate of 0.3 ml/min in the FSD measurement (Figure 2), whereas a flux level of 1.28 was obtained for the same flow rate in the BSD configuration (Figure 3). The FSD reading was 50.4 times higher than that from the BSD. This effect was partially attributed to the higher power of the laser used in the FSD tests. The laser power levels account for a factor of 9 between the FSD and BSD measurements (2.7 mW for the FSD and 0.3 mW for the BSD); however, the flux level reading obtained by FSD remains 5.6 times higher than that obtained by BSD after correcting for laser power. It is reasonably believed that the signal level is linearly proportional to the collected signal power, which is linearly proportional to the laser power used in the experiments.

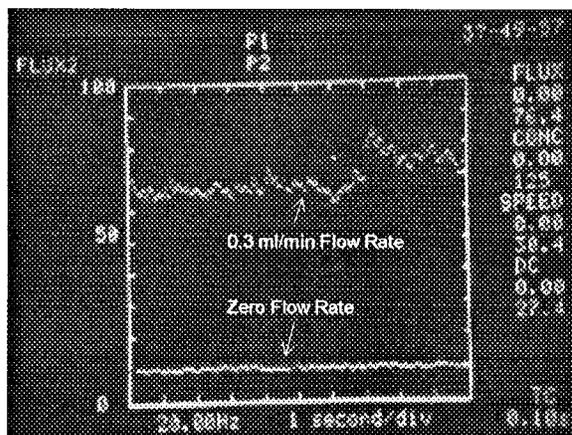


Fig. 2 Typical measurement results obtained from FSD.

During flow rates of 0.1 to 0.8 ml/min, FSD and BSD showed a linear relationship between flux measurements and flow rate. Typical measurement results obtained from both FSD and BSD at testing point 5 (see detailed tooth diagram in Figure 1) are shown in Figure 4. The linearity of FSD measurements was slightly better than that of BSD (see Figure 5).

2.2.2 Flux Readings versus Probe Positions

To assess the dependence of flux readings on the measurement position on the tooth, a series of measurements using FSD and BSD were carried out at six different testing points along the sample tooth while holding the flow rate constant at 0.5 ml/min. The results obtained using both FSD and BSD are summarized in Table 1 and Figure 6. FSD gave significantly more consistent readings whereas the readings obtained from BSD were widely divergent. Table 1 indicates that the readings varied from 93 to 112 for FSD and from 0.48 to 1.8 for BSD. Thus, the measurement fluctuation (rms deviation) was 6.5% for FSD and 52% for BSD, respectively, and the ratios of measured maximum and mini-

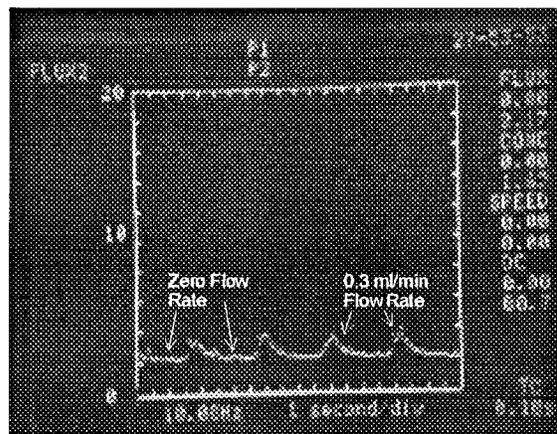


Fig. 3 Typical measurement results obtained from BSD.

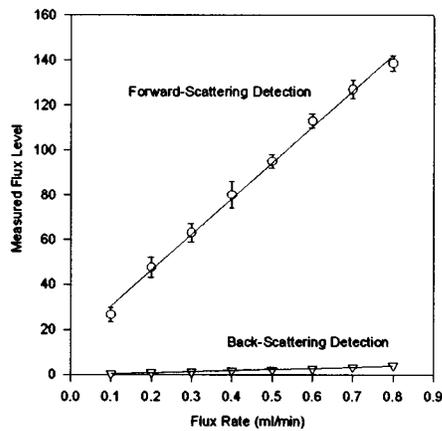


Fig. 4 Typical measurements obtained from FSD and BSD at testing point 5 on the tooth.

imum values were as low as 120% for FSD and as high as 375% for BSD. It should be noted that the rms deviation obtained from the BSD measurements was eight times higher than that from FSD measurements. These results indicated that BSD measurements demonstrated a strong dependence of flux readings on the testing positions. In contrast, consistent and position-independent flux readings were obtained with FSD.

3 DISCUSSION

3.1 SIGNAL-TO-NOISE RATIOS

Since the tooth is a relatively thin organ with a relatively low optical loss, a light beam can pass through it. Thus, the forward-scattering light signal is detectable. As shown in Figure 7, the optical path lengths for light beams back-scattered and forward-scattered from moving RBCs (see dotted lines in Figure 7) are nearly the same. Thus, photons escaping at the back and front of the tooth surfaces would travel the same path lengths and have the same absorption losses at identical light intensities. Although enamel and dentin are inhomogeneous tissues with some waveguidelike structures, especially in dentin tubules, which may affect forward- or back-scattering efficiency, strong forward-scattering peaks at ~ 5 deg in enamel and dentin were observed in the experiments.⁸ Therefore, the intensity of forward-scattered light is higher than that of back-scattered light in enamel and dentin.

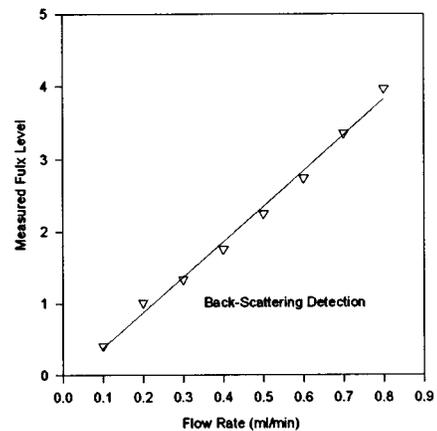


Fig. 5 Detail of typical measurements obtained from FSD and BSD at testing point 5 on the tooth.

These concepts were confirmed in our investigations: the FSD readings obtained were at least 5.6 times higher than the BSDs. Moreover, FSD detection was not optimized since the receiving fibers and the LDF signal processor were optimized only for BSD. Thus, it is believed that the flux measurements obtained by the FSD technique can be further improved if the receiving fibers and processing electronics are optimized.

3.2 DEPENDENCE OF MEASUREMENT VALUES UPON PROBE LOCATIONS ON TOOTH

The SNRs of LDF readings are proportional to a product of the reference and the signal intensities. A meaningful LDF reading should only relate to a correlation between the reference and signal intensities. Unfortunately, there is no such correlation in the BSD configuration for two major reasons, the influence of surface reflection and the influence of the location of the pulp.

3.2.1 Influence of Surface Reflection

The efficiency of light coupling into the tooth varies dramatically because of the great variations in tooth size and shape. In the back-scattered configuration, the receiving fiber is located very close to the light delivery fiber on the same side. The receiving fiber collects light beams back-scattered from inside the tooth that contain reference and signal beams (see Figure 7), and it may also collect some light directly

Table 1 Comparison of forward- and back-scattering measurements.

	\bar{X}	σ (%)	X_{\max}	X_{\min}	X_{\max}/X_{\min} (%)
Forward scattering detection	102.7	6.5	112	93	120.4
Backward scattering detection	1.38	52	1.8	0.48	375

Note: \bar{X} is the mean measured value, σ is the rms deviation, and X_{\max}/X_{\min} is the ratio of the measured maximum and minimum values.

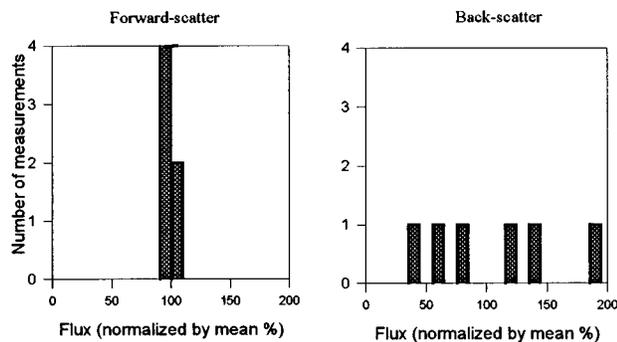


Fig. 6 Measurement results at six different testing points using (a) FSD and (b) BSD at a set flow rate of 0.5 ml/min.

reflected from the tooth surface. The collected reflection from the tooth surface may be much stronger than the back-scattered light escaping from the tooth interior, becoming the major contributor to the reference light for the LDF. Since the reflection from the tooth surface is dependent upon the coupling efficiency, the flux reading in the LDF is totally dependent upon the coupling conditions.

3.2.2 Influence of Pulp Location

As depicted in Figure 7, the signal beam is scattered by RBCs, and the probability of photon-RBC collision is small. Owing to relatively high scattering coefficients in enamel and dentin, even a very small change in optical path length causes significantly differing scattering losses for the penetrated beam before reaching the pulp for photon-RBC collision.

In contrast, for the FSD configuration, the receiving fiber is located on the opposite side of the tooth to collect only the transmitted light escaping from

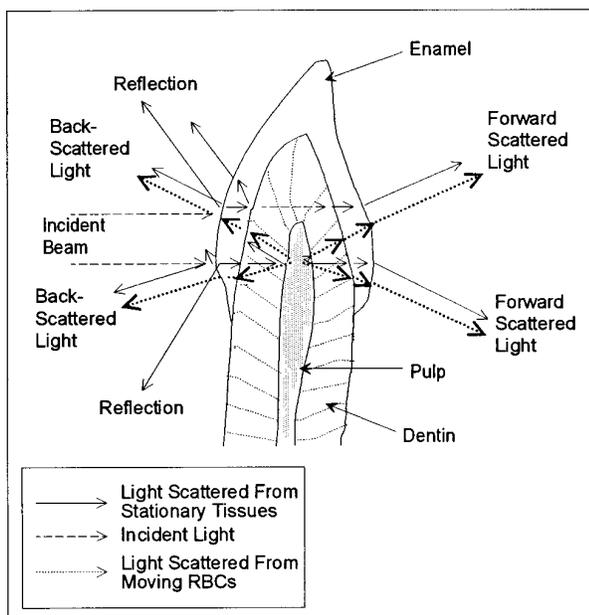


Fig. 7 Optical pathways of back-scattered and forward-scattered light.

the tooth surface (see Figure 7). The transmitted light contains signal and reference light beams. The reference beam scattered by stationary tissues and the signal beam scattered by RBCs and their product determine the LDF readings. Both signal and reference beams travel through the whole length of the tooth in order to escape from the opposite side of the tooth. Therefore, the ratio of the signal and reference beams is mostly determined by the probability of photon-RBC collision. Consequently in FSD, the signal and reference beams have an intrinsic interrelationship with each other, which is independent of coupling conditions. This reference-signal correlation provides a calibration base for flux measurement in FSD.

4 CONCLUSIONS

We have proposed and experimentally demonstrated a new LDF configuration for measuring pulpal blood flow. The novel LDF configuration employs forward-scattering detection instead of the back-scattering detection configuration used in existing LDF. Preliminary experimental results strongly validate our simplified model and demonstrate that FSD measurements are characterized by: (1) consistent flow-rate readings independent of the testing spot locations, (2) a linear response to flow rate, and (3) a higher sensitivity with increased signal strength and an improved signal-to-noise ratio that is at least 5.6 times higher than that obtained by the conventional technique. The new configuration provides a measurement system that has the potential to greatly improve existing dental diagnostic capabilities.

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REFERENCES

1. E. R. Ingólfsson, 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**, 83-87 (1994).
2. S. Kim, J. Dorscher-Kim, M. T. Liu, and H. O. Trowbridge, "Biphasic pulp blood-flow response to substance P in the dog as measured with a radio-labeled, microsphere injection method," *Archs. Oral Biol.* **33**(5), 305-309 (1988).
3. S. Kim, M. Liu, K. Markowitz, G. Bilotto, and J. Dorscher-Kim, "Comparison of pulp blood flow in dog canine teeth determined by the laser Doppler and the 133Xenon washout methods," *Archs. Oral Biol.* **35**, 411-413 (1990).
4. B. Gazelius, U. Lindh-Stromberg, H. Patterson, and P. A. Oberg, "Laser Doppler technique—a future diagnostic tool for tooth pulp vitality," *Internat. Endodon. J.* **26**, 8-9 (1993).
5. R. Bonner and R. Nossal, "Principles of laser-Doppler flowmetry," Chap. 2, in *Laser Doppler Blood Flowmetry*, P. A.

- Shepherd and P. A. Öberg, Eds., pp. 17–45 Boston, Kluwer Academic Publisher, 1990.
6. L. O. Reynolds, C. Johnson, and A. Ishimaru, "Diffuse reflectance from a finite blood medium: application to the modeling of fiber optic catheters," *Appl. Opt.* **15**, 2059–2067 (1976).
 7. J. M. Steinke and A. P. Shepherd, "Comparison of Mie theory and the light scattering of the red blood cells," *Appl. Opt.* **19**, 4027–4033 (1988).
 8. J. R. Zijp and J. J. ten Bosch, "Angular dependence of He-Ne laser light scattering by bovine and human dentine," *Archs. Oral Biol.* **36**, 283–289 (1991).