Portable Laser Doppler Flowmetry in Studying the Effect of Diabetes Mellitus on Cutaneous Microcirculation

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Abstract

Microcirculatory blood flow can be measured using laser Doppler flowmetry(LDF). However, the size and weight of the currently used system can be improved to make it light and portable. This paper describes a portable laser Doppler flowmetry(pLDF)system for taking real-time blood flow measurements in the dorsal foot of a diabetic. The system is comprised of a miniaturized probe, a fast digital signal processing(DSP) unit. The probe comprises an IR laser diode to illuminate tissue through an optical fiber and a photodetector, positioned 1 mm from the laser spot. The DSP uses the FFT based algorithm to estimate the laser Doppler power spectrum density. The pLDF unit is applied to the clinical evaluation of diabetes mellitus and a very high correlation was observed to exist between relative flow capacity(RFC) and occurrence of ulcer .

***Keywords*:** Laser Doppler, Microcirculation, RFC, DSP

Introduction

The laser Doppler flowmeter is a relatively new technique for measuring blood flow in a human body. This instrument was introduced about ten years ago, and the biological community is only now beginning to evaluate and understand the data obtained from its use.

The laser Doppler flowmeter is principally governed by the Doppler principle, the theory of modern radar systems and other ultrasonic flow or motion detection system used in medicine. The primary advantage of this application of this principle is that it does not require intravascular placement. The Doppler principle states that sound which emanates from an object in motion varies in frequency relative to a stationary observer in proportion to the speed of that object. Along with sound, this principle applies to all energy that travels as a wave, including light and other electromagnetic radiation. Here, laser light is focused on moving objects or particles and the shift in frequency of the backscattered light is a measure of their velocity but not their flow rate, as the vessel diameter is not know[5]. The regional flow velocities are measured in very small arterial beds, but cannot be measured by another method, like ultrasound.

In Fig.1, the skin is firstly illuminated with a narrow beam of laser light, which scatters as it moves through the transparent epidermis. The basal epidermis and upper dermis are also illuminated by some of the light that is scattered back to the surface. A spectral shift in the frequency of light does not occur since these tissues are not dynamic. Rays of light collide with moving red blood cells in the capillaries and the subpapillary plexus, and are shifted in frequency according to the velocity of the cells.

Backscattered components of both the shifted and unshifted light reflect back to the surface of the skin and are collected at a photodetector after passing through a limiting aperture. Constructive and destructive interference occurs in what is called a heterodyne process. Two waves of close frequencies are mixed to generate a beat frequency, which is the difference between the two frequencies. The unshifted light is the reference, while the difference between the frequencies of the shifted and unshifted components is the Doppler frequency shift.

Numerous of Doppler shifted frequencies arise due to the different angles and the actual different velocities at which the red cells move. Doppler shifted light readily mixes with other Doppler shifted light rather than the unshifted light, thereby generating another set of different frequencies, in a process called homodyning[5][6]. This process normally occurs in tissues with a higher percentage of red cells, however, heterodyning is responsible for most of the signal in most tissues.

The received spectrum of Doppler shifted frequencies is then converted into a value equivalent to blood flow within the sampled volume. Assuming constant flow geometry, Stem et al[2] concluded that the bandwidth of the spectrum of Doppler

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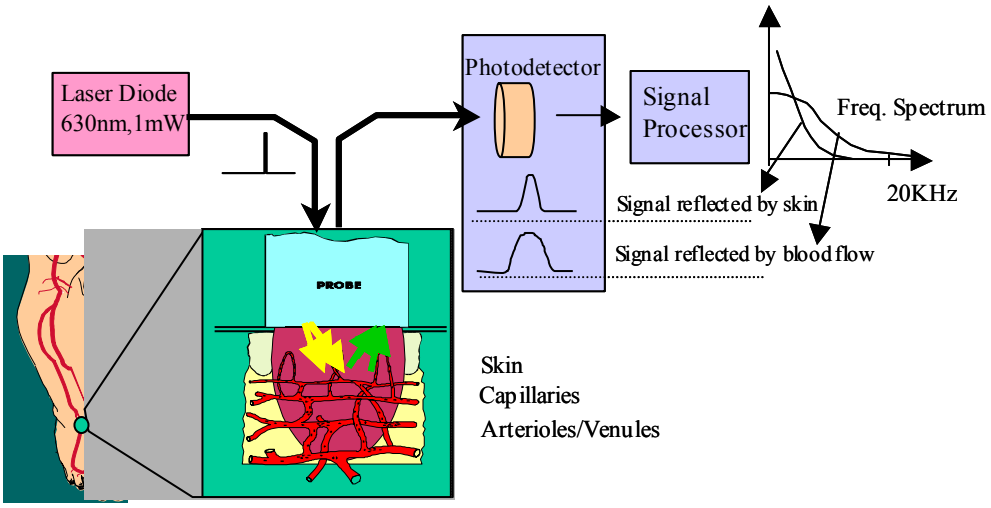


Figure1. Configuration of the pLDF measuring system

shifts is equivalent to the velocity of the red cells. The amplitude of the Doppler spectrum is also related the number of red cells in the sample volume, but not linearly.

Method

Processing signals

The photons in the tissue undergoes manyl collisions with static tissue elements(giving rised to the DC component) before interacting with moving red blood cells(giving rise to the AC component). Some of these frequency-shifted photons reach an optical detector after further scattering events with static tissue or other moving red blood cells, where they interface with non –Doppler-shifted light.Figures 2a and 2b presents the output signal of the detector and the relative power spectrum .The signal is analyzed by FFT to obtain the power spectrum. Periodograms are calculated using N-point fast Fourier transformations(FFT) to estimate the spectra of the signals. The spectrum broadens as flow increase, such that the bandwidth of the signal also increases.

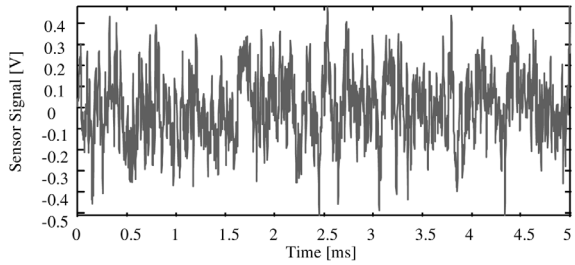
To calculate the RBC velocity, the power spectrum of the Doppler-shifted signal is integrated to get the scales linearly with RBC velocity concentration.

Integrating over the spectra area, the measured perfusion velocity can be estimated as,

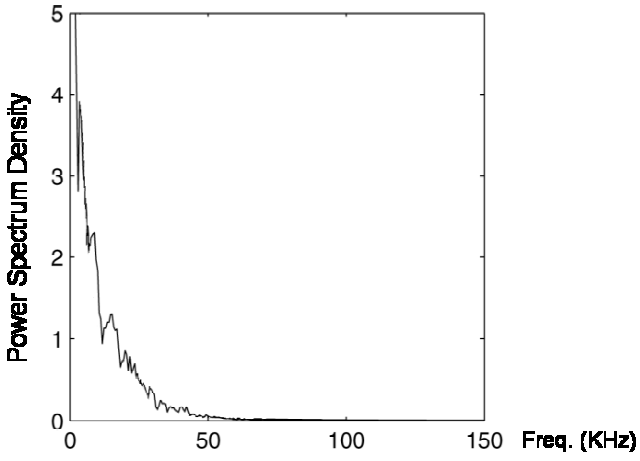
$$\textbf{pLDF Output} = \text{Measured perfusion} = \frac{\int_{20\,Hz}^{15\,kHz} \omega P(\omega)\, d\omega}{DC^2} \qquad (1)$$

Where, ω is the Doppler shift in angular frequency units (from 20Hz to 15K Hz). P(ω) is the optical power density at frequency ω .

Given the constraints of the laser Doppler signal bandwidth of 100KHz and the resulting rate 60 Hz real-time measurement of the dynamic flow signal, the signal processing algorithms can be implemented with very high-performance and expensive hardware.



(a)



(b)

Figure. 2 (a) Real LDF signal with AC and DC components, AC = Doppler raw signal magnitude, DC = Total light intensity caused by static tissue; (b).Estimated power spectrum density of real LDF signal

pLDF

Figure 3 presents the portable Laser Doppler Flowmeter system diagram. The laser output is connected through a lens

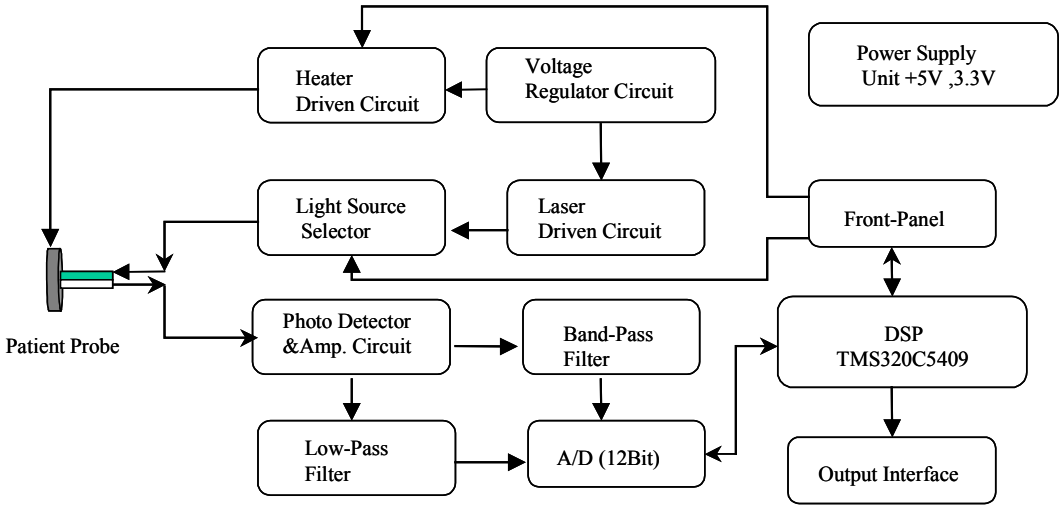


Figure 3. System diagram of pLDF

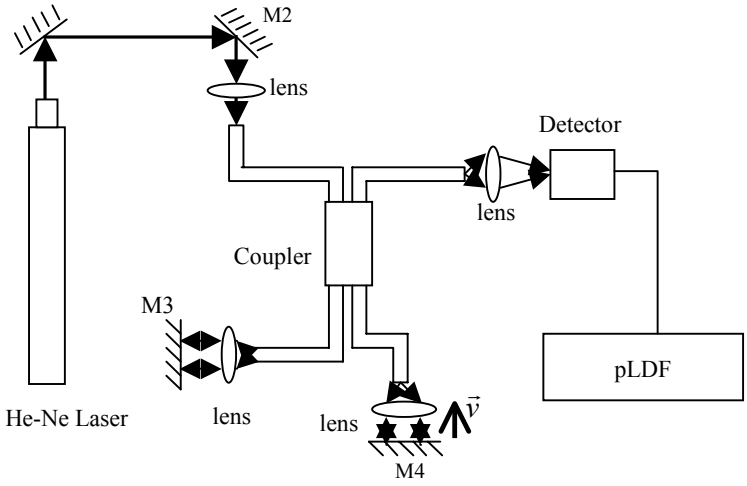


Figure 4. Testing environment for pLDF

into an ocular fiber that transmits light to the surface of the skin. The other end of the transmitting fiber, coupled with a receiving fiber, is contained in a probe to be used on the surface of the skin. Here, transmitting and receiving fibers are positioned in parallel, with their centers separated by 1 mm and encased in epoxy resin and a metal housing to maintain this separation. The exterior of the probe is designed for ease of use. However, a wider separation causes light to travel on a longer and deeper path through the skin between the transmitting and receiving fibers, causing the flow signal to come from deeper tissues[4][8][9].

The P.I.N. silicon photodiodes were used as a photo-detector as they do not need high-voltage power supplies, are smaller, and available at very reasonable prices.

The light source is a laser diode that emits at 1 mw at a wavelength of 835nm(or 630 nm). The diameter of the short fiber is 250 um. The detector circuit is an I/V converter with an adjustable amplifier and provides additional amplification up to a factor of 1000. The filter system provides a variable bandpass filter with minimal phase distortion. The passband is 20 Hz~ 100KHz. Real time measurements are made using a high-erformance DSP system, TMS320c5409 from Texas Instruments,which is built into the pLDF system. The pLDF also includes a 12 bit parallel A/D converter with a maximum sampling rate of 200 KHz and a corresponding anti-aliasing filter. Using the serial interface, the results of the implemented signal processing algorithms are sent to a PC, where they can be visualized online using another program.

Relative flow capacity

The criteria for classifying the occurrence of diabetic ulcer are based on the relative flow capacity parameter[1][3]. The procedure for measuring RFC is as follows[1]:

- ✓ Put the laser Doppler probe on the skin, measure the resting blood flow.
- ✓ Increase the skin temperature to 40°C, measure the hyperemic blood flow.
- ✓ RFC is the ratio of the change in flux to the hyperemic flux.

Table 1. Doppler shift measured by pLDF for different velocities of the mirror

Velocity of mirror M4	Measured by pLDF	Theoreticaly Doppler shift
0.055 mm/s	170 Hz	173.8306 Hz
0.065 mm/s	200 Hz	205.4362 Hz
0.095 mm/s	300 Hz	300.2528 Hz

Table 2.Blood flow measured in each group by LDF

	Group A (n=60)	Group B (n=60)	Group C (n=55)
Mean RF	86.7	80.9	96.4
Mean HF	315.8	204.1	171.4
Mean RFC	0.69	0.55	0.39

Mean RF: Mean resting flux Mean HF: Mean hyperemic flux

The RFC has been used to predict the healing of burns, and the classifying equitation is,

Predicted value=0.05(AHWA)+0.31(F100)+5.0(RFC)-2.3

where,

AHWA: Average hyperemic wave amplitude

F 1 0 0: Number of flux values above 100

R F C: Relative flow capicity, averagehyperemic flux divided by average hyperemicflux

The predicted outcome is based on the positive or negative values obtained from the discriminant function.

Results

pLDF Testing

A testing environment was designed using Michelson Interferometer, as shown in Fig. 4., to evaluate the performance of pLDF.

An He-Ne laser was used as a stabile coherent light source. The moving platform M4 (Newport, M-UTS20CC.1F) was driven by a stepping motor, and the moving particle was thus simulated at different velocities to determine its Doppler shift. Table 1 lists some results.

Clinical Experiment

Subjects: Thirty healthy persons as group A, 30 diabetic without ulcers as group B, 30 diabetic with ulcers as group C. Procedure: Laser Doppler Flowmetry was used to measure cutaneous flow in dorsal foot of each member of each group at rest condition. Then, the skin temperature was increase to 40℃ to measure the hyperemic flux.

Results: The experiment data is listed in Table 2 and the distribution of each group is shown in Fig. 5..

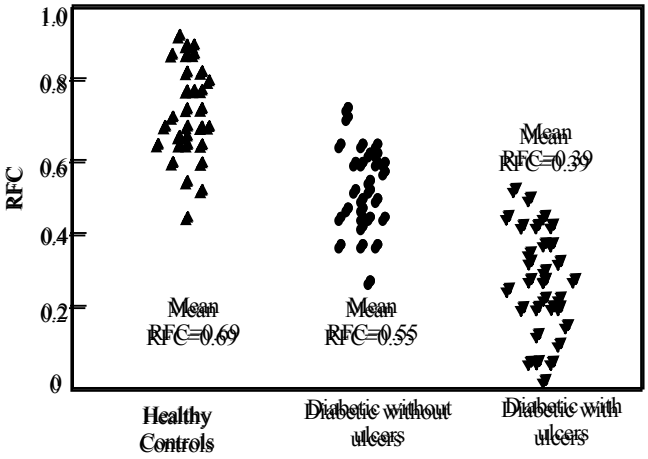


Figure 5. The RFC data distribution of each group in the experiment

- No significant differences among the resting cutaneous flows in the three groups.
- Cutaneous blood flow in healthy foot increases significantly over that of the diabetic foot following heating.
- Compatible with clinical findings that the diabetic foot becomes more badly ulcer.
- Significant differences among the three groups.
- RFC may be used to predict the occurrence of an ulcer in a diabetic foot.

Conclusion

A new portable Laser Doppler flowmeter was presented. It uses the RFC parameter classification to identify the occurrence of a diabetic ulcer. All algorithms were built in a single DSP unit to perform real-time measurement. The LDF enables blood flow in capillaries to be measured and thus skin areas, developing of diabetic ulcers to be examined. The advantage of pLDF is that the measurements are made online, the use of the RFC parameters makes the classify occurrence of diabetic ulcer is became more significant.

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