

Real-time analysis of skin capillary-refill processes using blue LED

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ABSTRACT

A method for analysis of skin capillary-refill processes in real time by means of reflection photoplethysmography (PPG) contact probe operating in the blue ($438\text{nm} \pm 30\text{ nm}$) and infrared ($938\text{ nm} \pm 20\text{ nm}$) regions of spectrum is proposed. The corresponding prototype hardware and software for measurements have been developed and tested in laboratory. Real-time measurements of finger capillary refill kinetics by this technology have been taken and analyzed. Results demonstrated that both AC and DC components of the blue PPG biosignal are sensitive to capillary occlusion and refill.

Keywords: Skin capillary refill, photoplethysmography, optical perfusion diagnostics.

1. INTRODUCTION

Noninvasive real-time monitoring of peripheral perfusion is an important task to promote reliable diagnostics in a number of medical specialties [1]. For example, delay in capillary refill time may indicate to infant sepsis (>5 sec. instead of ~ 2 sec. for healthy infants) or other pediatric problems [2].

There is no exact method for capillary refill time calculations, so it is not strictly defined and vary by a subjective factor. The commonly used method for capillary refill time calculations is called "Capillary nail refill test". In this method capillary refill time is the duration required for natural color return to nail bed of a finger or toe after application of slight pressure which causes blanching [3]. As there is no technical equipment available to determine the exact "color return" point, it is usually done by visual approach, so the results are not strictly quantitative. Besides, the capillary refill time can vary with room temperature, human body temperature and human physical state.

The capillary refill time reflects the quality of peripheral vasomotor function. A few seconds (2 – 4) are considered to be a normal capillary refill time. Longer refill time may indicate to dehydration, shock, peripheral vascular disease or hypothermia, though it cannot be validated on its own and should be evaluated along with other signs and symptoms. Capillary refill time is typically tested during a routine cardiovascular assessment. It is not tested with suspected life-threatening disorders because other, more characteristic signs and symptoms appear earlier.

Recent multi-wavelength photoplethysmography (PPG) studies [4, 5] have demonstrated the possibility to characterize hemodynamics at different vascular depths by means of noninvasive optical technique. The depth selectivity was assured by proper selection of the working emission wavelength. The mean light penetration depth in skin at the 400 - 450 nm wavelength range is about 170 microns [7] which roughly corresponds to the thickness of human skin epidermal layer. The blue radiation therefore can reach only the upper skin capillaries, and the back-scattered PPG signal mainly reflects the capillary blood flow and its changes. Selective pressure-induced occlusion of the upper skin capillaries has been observed previously by analyzing the blue PPG signals [6, 7].

The purpose of this study was to create a device for simple, patient friendly non-invasive measurements of skin capillary refill kinetics. The previous device has been improved by adding infrared channel ($938\text{ nm} \pm 20\text{ nm}$, the mean penetration depth in skin ~1.5 mm) which helps to control the external pressure and to avoid occlusion of the deeper blood vessels.

2. METHOD AND EQUIPMENT

The measurement probe consisted of two light emitting diodes and photodiode, connected to the experimental medical device that read and processed the acquired signal. The probe cable length in current test conditions was 40 cm; it was not highly important because the transmitted signal is digital, so almost no affected by cable length.

Emission spectra of both LEDs (Fig. 1) were measured by the *Avantes* spectrometer AvaSpec-2048. Their central wavelengths and bandwidths appeared to be slightly different from the manufacturer's specifications.

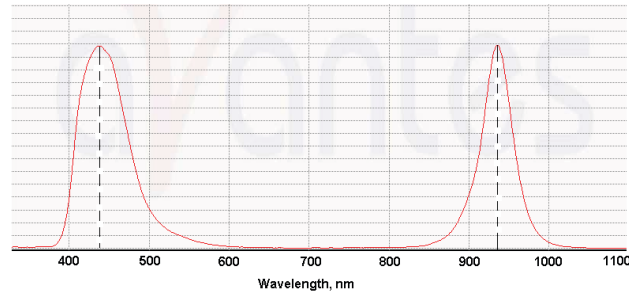


Fig.1. The measured spectra of the blue (438 nm) and infrared (938 nm) LED.

Block-diagram of the prototype device is presented on Figure 2. A standard pulse oximeter finger clip was redesigned to have two built-in LEDs (blue and infrared) and a photodiode with enhanced sensitivity in the blue spectral region. A blue LED (Everlight Electronics, mod. EL204UBD, diameter 3 mm) and an infrared LED (Everlight Electronics, mod. IR11-21C, surface mounted device 1206) were used as the light sources. The reflected PPG biosignals were detected by the blue-enhanced photodiode (Hamamatsu mod. S6931-01) placed 2 mm off the edge of the blue LED.

A new approach for capturing of PPG signal by means of MCU-embedded 32 bit timer was used. The PPG signal was evaluated from the discharging time of photodiode [9]. Analog amplifiers and filters could be avoided this way. The measured data were sent to computer using USB connection for further data processing, imaging and storage.

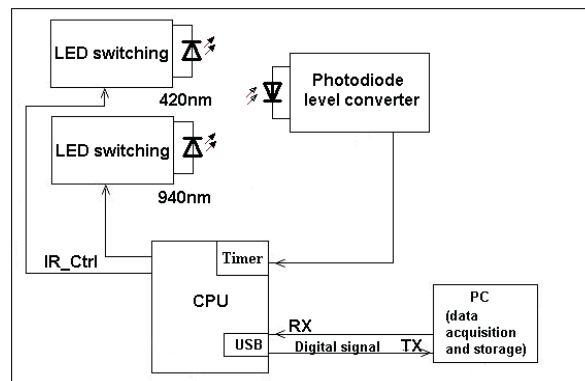


Fig. 2. Block diagram of the prototype device.

To obtain two photoplethysmography signals simultaneously using one photodiode, time division or switching technique was used. The light-emitting diodes were turned on and off alternately (Fig. 3). “A” waveform switched on the blue LED, and the logical “1” – high turned it off, because of the PNP junction transistor mounted in the sensor. “B” controlled the infrared LED. It was possible to switch the diodes without time gap. The blue LED was turned on immediately after switching off the infrared LED. Switching frequency was 500 Hz per channel. Since the skin remission and LED response times are very short (in the range of ns), they were not taken into account. Sampling rate was high enough

to observe and to measure the PPG signal transition processes. Resulting signals were perceived by the central processing unit (NXP, ARM7TDMI-S, LPC2148) running at 48 MHz.

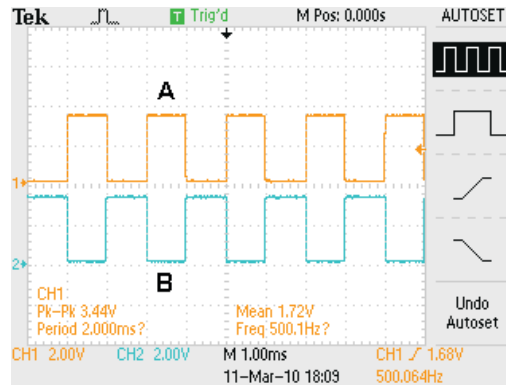


Fig. 3. Timing scheme of LED switchings.

Timer capture was done in hardware and therefore did not require software resources. Experimental device filtered acquired data using 128 sample FIR digital filter. It removed noise from electrical network and ambient light. The filter was designed in such a way that it did not influence PPG signal shape, amplitude and phase. It is important to mention, that this filter worked in real time with a constant time delay to actual signal. The filter could be disabled to obtain specific data for further analysis.

After a deeper capillary refill time research with the device made earlier [8], it was discovered that its complex analogue electric circuit had essential incompleteness, therefore some of the prior measurements and charts can be deficient or defective. As it can be seen from Figure 4, large signal spikes emerged due to analogue signal amplification and filtration in CRT measurement time. The basic reason for these inaccuracies is discharge of capacitors placed in analogue section of medical device. The capacitors store and release electric charge nearly the same way as photodiode in capillary refill time process, therefore any capacitor in CRT measurement process can affect its accuracy. We came to a conclusion that these uncertainties can decrease overall measurement accuracy. Therefore we concluded to scale down the analogue part as much as possible. Our new device has no external capacitors at all. The amplification and filtering has been done already with digital signal, so considerably improving the quality of acquired signal.

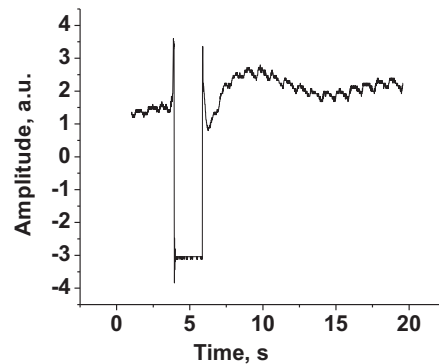


Fig. 4. Recapitalization waveform captured with blue LED in our recent device [8].

The PPG signal consists of two components – DC amplitude reflects the total skin microcirculation blood volume, and AC amplitude is directly proportional to the changes in signal during heartbeats. While the probe was compressed, all PPG pulsations disappeared, and the DC level decreased to zero at both channels. The fast de-compression of the probe caused gradual increase of the signal base (DC) level, and the capillary pulsations (AC) reappeared in few seconds.

As the experimental medical device for capillary refill time (CRT) was developed, the problem of data interpretation emerged. As already mentioned, there is no clear way how to calculate the CRT, so we developed two methods that could be helpful in CRT calculation and lead to a more objective result.

The simplest method is “Direct current linearization” method that determines the CRT by linear approximation. As it can be seen in Figure 5, the DC component is almost constant during short time intervals (~6 seconds), so, by altering component linearization, straight and marginally horizontal line can be obtained. This line is being used as a baseline for CRT calculation. To calculate the CRT, two main values should be cleared up – the start point value and the end point value of the CRT process in the time scale. The start point has a clear definition, as this is the point in time scale, when applied pressure is taken off. Using “Direct current linearization” method, the end point value of the CRT process is established by finding the point at which the acquired data crosses the direct current baseline. The CRT is calculated by subtracting the start point value from the end point value.

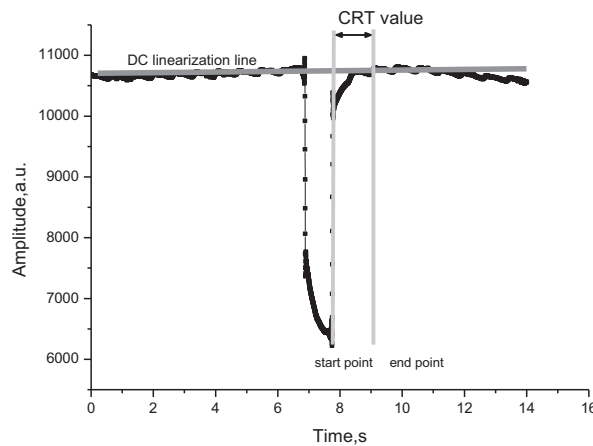


Fig. 5. “Direct current linearization” method.

Another approach is used in the “Dynamics of capillary refill process” method. The basic idea is to obtain the best exponential fit to the measured capillary refill process. As it can be seen from Figure 6, the capillary refill process makes rapid changes in direct current amplitude. Exponential function

$$y = y_0 - A \cdot \exp\left[-\frac{t}{T}\right] \quad (1)$$

is used to describe these changes. Parameter “ y_0 ” describes offset (distance form ground level to main signal). Parameter “ A ” determines the position of the given exponential function towards X-axis. It could have some practical value, but future research is required to clarify the accurate interpretation of this parameter. Fitting of the exponential function with the measured data is done in OriginPro 8 software using Simplex iterations and no weighting.

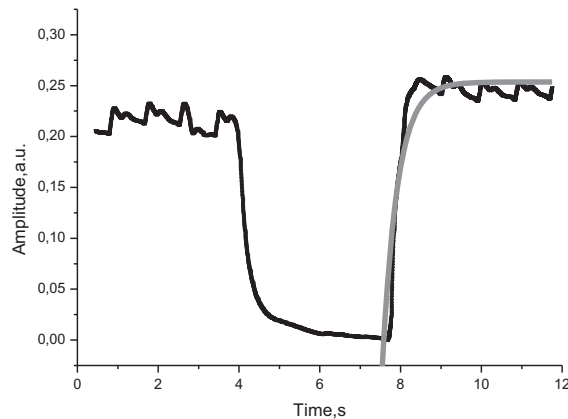


Fig. 6. Recapitalization time - exponential function model.

The following measurement protocol was used:

- 1) Person was in sitting position.
- 2) The right hand was placed on the table and the measurement probe was attached to the index finger. Patient was asked to relax and to take the most comfortable position, so his/her hand was lying freely on the desk.
- 3) The probe was adjusted until expected pulse signal appeared on the screen.
- 4) When a stable pulse signal was acquired, the actual capillary refill measurement was performed, by applying an external pressure on the sensor until complete disappearance of pulsations, and further renewal of pulsations after the external pressure was removed.

These measurements were taken by the same researcher to provide possibly evenly measurement conditions. The laboratory lighting was turned off during the measurements to avoid the background noise. The PPG measurements were taken from fingertips of 7 volunteers, 21 - 27 years old. 8 measurement cycles with compression-decompression were performed for each volunteer. All volunteers in this research were healthy with no blood vessel diseases.

3. RESULTS OF THE MEASUREMENTS

The new device was tested on a group of volunteers using the measurement protocol described above. The blue PPG signal fully disappeared in result of capillary occlusion and re-appeared after the probe release within few seconds, reflecting the kinetics of capillary refill process in real time. To verify that the external pressure caused only capillary occlusion and did not influence the deeper blood vessels, 938 nm reference PPG signals were recorded in parallel (Fig. 7d). Essential differences in capillary refill kinetics recorded for different subjects have been observed.

The measurements confirmed that capillary refill time is highly dependent on finger compression force, as well as the human physiological condition. In some cases, we did not observe DC component increase immediately after occlusion (Fig. 7c).

Typical skin blood vessel occlusion and refill response example is illustrated on Figure 7a. "A" represents normal DC signal level (AC component is only ~ 2% and in this scale is not visible). Compression of the probe dropped the baseline down to level "B". Part "C" illustrates the reappearance of blood circulation in vessels. Graph (Fig. 7a) shows 100 ms time delay between the blue and infrared signal minimum, which indicates that in the deeper blood vessels blood flow returns to normal state faster than in smaller capillaries. The kinetics of capillary refill processes delay was different from person to person and varied within interval 80 – 160 ms. Level of the blue PPG signal was significantly lower than that of infrared because of smaller penetration depth, and noticeably varied with changes of vascular condition, room temper-

ature and other properties. The infrared PPG signal was more stable. The “C” part of the graph in most cases showed very shallow rise (Fig. 7b,c). Resuming the performed measurements, the average duration between decompression moment and maximum of the DC signal was in the range 2...5 sec.

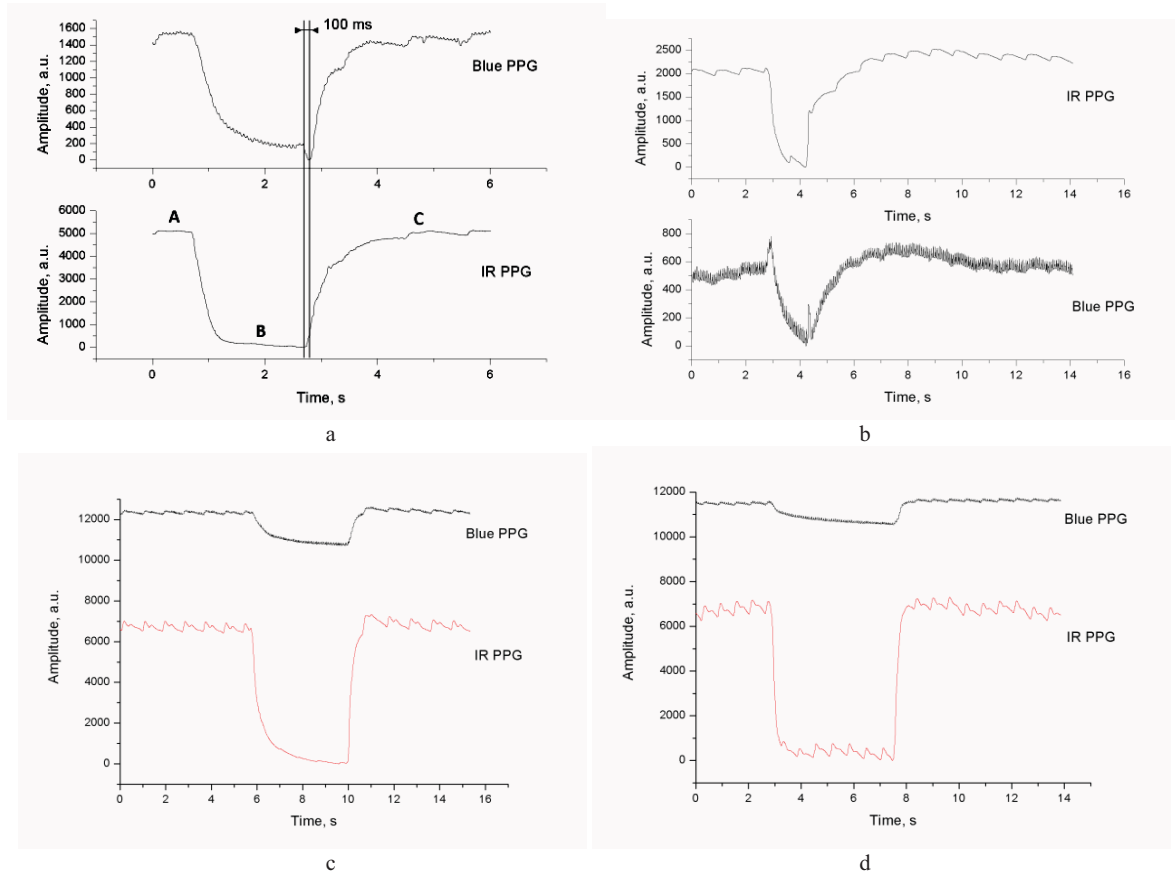


Fig. 7. Examples of the capillary refill kinetics: measured data for four volunteers.

4. CONCLUSIONS

Provisionally, the exponential capillary refill model seems more adequate for quantitative characterization of capillary refill processes. Eight time-resolved capillary refill measurements under the scheme described above were performed, taking around six minutes per patient to complete. Our results generally agreed with those of other authors [3], indicating that the experimental device has a potential of quantitative characterizing the skin capillary refill processes.

It was observed that temporal responses after compression and release of the finger were similar for both spectral ranges (blue and infrared), with 80...160 ms delay of the blue signal. Only healthy volunteers have been checked, so clinical studies with vascular patients under certified medical supervision should be performed as the next step.

It was noticed that fluctuations of room temperature were influencing the signal amplitude, especially with blue LED, and it was hardly possible to detect pulsations at low ambient temperature. Although some testing of external pressure value and pressure applying time where done, more studies are required to provide clear background information on these values.

Detailed future research should be carried out to improve the fitting process to microcontrollers, so it could be done without computer and special computer software. It is essential to accumulate more measurement statistics in order to make qualitative judgments. Improvements are needed in hardware design, as well.

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