A photoplethysmography device for multipurpose blood circulatory system assessment

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ABSTRACT

A novel method for photoplethysmography (PPG) signal detection has been proposed and implemented in a three-channel prototype device. The current design is simple, low cost and does not require sophisticated analogue circuits. The prototype was evaluated by physiological measurements and recorded PPG signals from conduit arteries of human subject.

1. INTRODUCTION

Photoplethysmography (PPG) [1] is an optical, non-invasive measuring technique that provides immediate diagnostic information on the cardiovascular state. PPG signals reflect the change in blood volume caused by blood vessel expansion and contraction, which can be detected by a photodiode if external light is illuminated into the tissue. Time intervals between the PPG peaks can be converted into the heart rate or pulse, but the waveform characteristics of each individual PPG pulse contain hemodynamic information. There are two types of PPG sensors: reflection and remission. The first one consists of an infrared LED and photodiode that are both located on the same side of the PPG sensor, but in the remission sensor design, they are separated. By using the reflection type sensor it is possible to detect blood pulsations from ~ 1 – 3 mm deep under the skin’s surface. The PPG signal consists of two components - a slow, varying DC offset representing the skin: blood volume in the probe-covered area, and a fast, alternating AC component that reflects the blood volume pulsations. The amplitude of the AC-component is only 0.5 – 4% of the DC offset in a PPG signal.

Dynamics of blood transport in the human vascular system can be monitored at various body locations with relatively simple and convenient, optical PPG contact probes. The PPG technique has good potential for express diagnostics and early screening of cardiovascular pathologies, as well as for scientific research (physiological measurements) and self-monitoring of vascular conditions [2].

There are commercially available PPG devices, but those are based on the standard remission photoplethysmography, which limits their use - signal can be measured only from finger, ear, and small sides of body where infrared radiation can pass through. However, reflection PPG sensors are necessary in the determination of the properties of the arteries and blood circulation dynamics.

Photoplethysmography successfully can be used in physiological measurements and supplement ultrasound, ECG, and other methods. Physiological measurements require an accurate and easy to use PPG signal measuring device that ensures low signal noise and high spatial and temporal resolution (at least 1 kHz). Such devices are not produced commercially, so a custom-made prototype was developed.

The main problem is that the conventional PPG devices are technologically complicated. Usually these devices contain an expensive analogue to digital converter, low noise operational amplifiers, and other complex hardware. These increase manufacturing costs and time for the end product. A simple, low cost photoplethysmography signal capturing device can be designed with using only two transistors, a photodiode, and a microcontroller.

The goal of this work was to develop and to test a new precise measuring device, which can be used for scientific research purposes. This article describes a photoplethysmography measurement system based on the measurements of the discharge time of the photodiode [3]. The discharge time is proportional to the amount of light detected by the photodi-
ode. The result is the PPG signal shape can be quickly restored digitally without the standard ADC-conversion. The equipment novelties are the abandonment from the standard sensors, the equipment design simplicity, and the digital signal directly in the PPG sensor.

2. METHOD AND EQUIPMENT

A new approach to capture PPG signal used a 32-bit timer built in the central processor. LED emitted 30-microsecond radiation pulses that periodically discharged the photodiode and the discharge time was captured by a microcontroller after each pulse. The PPG signal was restored by measuring the discharge time of the photodiode with a following CPU-processing [4]. Analog amplifiers and filters as well as their noise can be avoided this way. The captured data were sent to computer with further data processing, imaging and storage.

The parameters that can be measured with this device are the pulse shape of the photoplethysmography signal and the signal delay time, if two or three sensor probes are used. The sensors are placed on the extremities at different locations and then the acquired signals’ time shifts are compared. Pulse transit time can be calculated by software in real time or post processing. This gives useful information about the patient’s cardiovascular condition and arterial occlusions [5]. Calculations are necessary to pinpoint the PPG signal "footprint" or minimum. In turn, this means that the signal cannot be filtered because the filter changes the signal shape and makes a phase shift.

Our developed set up consists of: a PPG sensor, a photoplethysmography capture system - control unit and a Li-ion accumulator. The scheme's design is based on the photodiode discharge time measurement using a 32-bit timer built into the microcontroller. A special reflection PPG sensor probe was created and adapted to the artery measurement specifics, and provided the possibility to take contact PPG measurements virtually from any site of the body.

In general, this device was built to capture high resolution, low noise photoplethysmography signal from arteries. The equipment was designed for stationary use when patient is in recumbence with no movement and was tested in collaboration with colleagues from the Department of Human and Animal Physiology in the Faculty of Biology at the University of Latvia.

2.1. Design of the device

This prototype is a custom made 3-channel digital PPG device with a sampling rate: 1 kHz per channel, 875 nm LED, and photodiodes with a daylight filter and peak spectral response wavelength of 880nm. Originally this device was designed for scientific purposes, which require an analog signal output to one common data acquisition system. Therefore, the digital PPG signals were converted using a built in 12-bit eight-channel digital-to-analog converter (TLV5610). The block diagram of the equipment is shown in Figure 1.

The device had an integrated LED driver which provided stable power throughout the battery’s discharge range. LEDs were driven by 55 ± 15 mA (5 mA stepping), so that no perceptible warming of the upper tissue layer was produced. Three channels of DAC were used to regulate the LED current.

An important improvement was the use of a solid state digital field transistor which was physically close to the photodiode. In this case, it was necessary to place the sensor ~ 1 – 1.5 m away from the measuring unit. Thus, the impact of the movements during the measurements would cause PPG signal to be corrupted. The key novelty was the absence of analog amplifiers, filters, and capacitors in the signal input circuit.
The only filter integrated in the design was a digital second order Butterworth low pass filter with the cut off frequency of 42Hz @ 3dB. This filter did not distort the photoplethysmography signal shape and phase because the typical bandwidth of the PPG signal is 0.05 – 40Hz. The measured noise level of the device was -30 to -40dB compared to the PPG signal level. The true physiological noise was considered as a signal recorded from sensor placed on the skin with completely occluded blood circulation.

The time was captured in the hardware and therefore, did not require software resources. The appliance stored the data using a 255 point FIR digital filter. It removed noise from the electrical network and ambient light. It is important to mention, that this filter worked in real time with a known constant time delay to the actual signal. To obtain specific data for further analysis, the filter could be disabled with the push of a button.

The device dimensions are 90 x 47 x 145 mm, weight 300 grams, one 2x16 character liquid crystal display, with three rotary encoder and push buttons which are shown in Figure 2. The sensors are connected using three DE9 9-pin D-sub RS232 connectors. The outputs are 3 gold-plated RCA jacks. The signal output is single ended 0 – 5V. The device has ten discrete digital gain levels.

Figure 1. Block diagram of the device.

Figure 2. Complete measuring device.
2.2. Sensor construction

Three custom-made, reflection type PPG probes were created and adapted to meet criteria necessary for the measurements of arterial blood pulsations from the skin over the conduit artery. The PPG method is very sensitive to tissue movement and to the sensor-to-tissue contact force. Therefore, to prevent signal artifacts, the arterial PPG sensors were fastened with custom-made holders.

![Figure 3. Photoplethysmography sensor.](image1)

The sensor is built on a small PCB that contains an electronic circuit shown in Figure 4. The entire sensors dimensions are 10x15x8 mm. LED is the only element in the sensor which consumes a lot of power 30 – 50mA (depending on the place where the sensor is located on the patient’s body).

A selected silicon PIN photodiode OSRAM - BPW34-FA - with daylight filter and the active surface area of 7mm² and the peak spectral response wavelength of 880nm was used. A SMD type of an infrared radiant diode model which is SIR91-21C/F7 was used with a peak wavelength of 875 nm, a transmission angle of 20°, and a diameter of 1,9 mm. A sensor’s housing material is cured polyurethane sealant, which is especially suitable for mounting the electronic circuit components. A special screening barrier for the photodiode was made within the sensor to lower the influence of ambient light. A barrier is located between the LED and the photodiode and is 5mm from the edge of sensors end (darker vertical line Figure 3).

In the sensors, there is an integrated signal conversion scheme (Fig. 4). The PPG method uses N-channel transistors that are digital FET. The transistor Q2 charges the capacitor C15 and a photodiode with a supply voltage of +3,3V. While Q1 converts the signal level from analog to digital, the resistor R12 is a pull-down resistor that discharges capacitor C15 and diode D4. R10 is a pull-up resistor, so that the cable length connecting the sensor to the main circuit board is almost irrelevant because of the transmitted logic levels of +3,3V.

![Figure 4. Electronic circuit of the sensor.](image2)

The added capacitor C15 with a capacity of 1nF is parallel to the photodiode D4. The photodiode capacity following the manufacturer's specifications is 72pF, which is little compared to the C15 that acts as ballast. If the duration of the discharge is prolonged, this will increase the signal amplitude, but reduce the sample rate. The discharge time is fixed to 1ms, which corresponds to the 1000 measurements per second that is considered as more than enough for the PPG measurements and analysis. Capacitor C15 and photodiode D4 are charged with the clock frequency of 1 kHz. The capacitor

![Figure 5. Digital PPG waveform captured with oscilloscope (TDS2002B).](image3)
charging time is constant - 30us (lower waveform Figure 5). The tests were performed with different charging times and the minimum required to charge the 1nF capacitor was discovered. After each charging cycle, the discharge takes place, which is measured and depending on the photodiode, the incident radiation intensity is also measured.

Using this measuring technique, one must consider that the more light that photodiode D4 captures, the quicker capacitor C15 discharges and results a signal with lower resolution. And vice versa situation if less light fall on photodiode D4, capacitor C15 discharges slowly, and if there is no light, the whole process is stopped. This effect is considered as a disadvantage, because if a signal from deeper tissue layers is desired, usually the LED brightness is increased. However, if that is done with this measuring technique, the signal amplitude decreases. The only solution is to adjust the value of capacitor C15 to achieve the required resolution. A lower capacitor value is suitable for small and shallow blood vessels, and a larger value for deeper vessels. Capacitors are matched experimentally, depending on measurement methodology and the needs of researcher.

In general, the capacitor discharge is an exponential curve (Figure 6); the device had a sampling rate of 1 KHz, which is fast enough to consider each captured time interval is a linear discharge.

![Figure 6. Digital PPG capacitor discharge curve.](image)

The only condition for the device to fully operate and to gain analyzing PPG signals with a resolution of 1ms is to use a high-speed microcontroller. The device design uses NXP LPC2148 ARM7, which works at 48MHz clock frequency. Also, a micro-timer built-in capture module was used to automatically maintain the capacitor discharge time value. One measurement composes a single point on the time-axis and the PPG signal is restored by an accumulation of such points. The software code was written in C with an optimization of the sleep time that resulted in minimal power consumption ~15mA@48MHz (only for CPU).

Each volunteer was subjected to three five minute measurement series. During the experiment, a subject was held in a supine position on an ergonomic pedestal at room temperature (24°C) in quiet and comfortable conditions. Prior to data recording, the PPG sensors were placed while the subject adapted. The volunteers were cautioned not to intake any caffeine or eat a meal within 2 hours before the experiment.

3. RESULTS OF THE MEASUREMENTS

High quality photoplethysmography signals were acquired by using the proposed technique and device. The device was used in parametric studies of the leg arteries. High demands on the signal to noise ratio ensured clean PPG signals from a single artery. The requirement for equipment error was to be less than fluctuations in the physiological parameters. It was essential that the device did not introduce additional errors.

18 to 26 years old volunteers (2 males, 4 females) with a healthy lifestyle and a body mass index range of 16.2 to 25.9 kg/m² and no signs or symptoms of cardiovascular diseases gave their informed consent to participate. The Scien-
tific Research Ethics Committee of the University of Latvia, Institute of Experimental and Clinical Medicine approved the research protocol.

Photoplethysmography sensors were placed as follows: over popliteal artery in the popliteal fossa, over posterior tibial artery near the ankle and on leg’s big toe. Distances between sensors were noted to derive the pulse wave velocities from the pulse transit time – delay time of the pulse wave reached all three PPG sensors consecutively.

Results of the measurements are illustrated in Figure 7A and comparisons of the previous digital PPG device outputs are presented in Figure 7B. Acquired PPG signal is considered as a significant improvement of the method, device and equipment. The signal had low noise and directly outputted from the device without post processing on a PC. Resolution is high for further analysis and conclusions about the arteries. The best PPG signal amplitudes corresponded to decay times of about 800 – 1500 us (AC component of the photoplethysmography signal), and is considered as very good result. CPU timer capture runs at 48MHz, so that the mean PPG signal is about 1/48 from the whole scale and is ~2% of the DC component.

Sensors were placed on the skin over the conduit arteries. Pulse transit time also was measured and analyzed because of device’s high resolution of 1ms. Since physiology measurements require several devices, like PPG, ECG, pressure monitoring, ultrasound, and sphygmogram, they must be connected to one common data acquisition module – in other words, it is necessary that the entire system is driven by the same clock. The analog signals from the developed PPG device and a Finometer (beat per beat pressure monitoring) were captured simultaneously by a 12-bit ADC USB data acquisition module at 1 kHz per channel, and stored in a PC. Later, a PPG signal was processed offline with custom developed Matlab software (signal smoothing with wavelet and Savitsky-Golay filters to reduce signal artifacts and ADC stepping noise). Foot-to-foot pulse wave transit time and waveform second derivative parameters were computed for each PPG signal in a beat per beat manner.

4. CONCLUSIONS

A new method and equipment for acquiring photoplethysmography signals were developed and successfully tested. The device showed good measurements and accuracy sufficient for PPG scientific research. The sampling rate of 1 KHz seems to be enough for the photoplethysmography signal shape characterization. The digital signal already in the sensor
(using only two transistors) is a way to transmit low level PPG signal for about two meters without inducting additional noise. This approach does not require any expensive operation amplifiers, low noise power supply, analog multiplexors or ADC.

Equipment advantages are the low noise, low power, low weight, the digital PPG signal in the sensor, and professionally produced remission PPG sensor, as well as there is no need for device calibration and high tolerance resistors. The method is inexpensive, easy to build and particularly appropriate for small, low cost, portable devices – for example, integrating it into a garment (smart clothes). By using this method, it is easy to create a device that measures PPG signals at different wavelengths of radiant diodes, i.e., multispectral device with a one perceptive photodiode [6].

However, setting up the sensors for measurement from the arteries requires special skills. Also, a screening barrier and a photodiode with daylight filter are essential. The main disadvantage of this PPG signal capture device is the capacitor discharge dependence on light intensity. To resolve this, fast capture and separate sensors for capturing PPG signals from various sites of the body can be an option. When using this approach, only remission PPG sensors can be used because transmission photoplethysmography signal is too weak to reach the threshold of photodiode discharge level.

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