Multi-spectral photoplethysmography technique for parallel monitoring of pulse shapes at different tissue depths

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ABSTRACT

A photoplethysmography (PPG) signal can provide very useful information about a subject's hemodynamic status in a hospital or home environment. A newly developed portable multi-spectral photoplethysmography device has been used for studies of 11 healthy subjects. Multi-spectral photoplethysmography (MS-PPG) biosensor intended for analysis of peripheral blood volume pulsations at different vascular depths has been designed and experimentally tested. Multi-spectral monitoring was performed by means of a three–wavelengths (405 nm, 660 nm and 780 nm) laser diode and a single photodiode with multi-channel signal output processing. The proposed methodology and potential clinical applications are discussed.

Keywords: photoplethysmography, biosensor, vascular depth

1. INTRODUCTION

Photoplethysmography (PPG) is a simple and low-cost optical technique that can be used to detect blood volume changes in the micro vascular bed of the tissue. It is often used for non-invasive measurements at skin surface. PPG has two types: transmitted and reflected. For the transmitted type, an infrared light source (wavelength 600 – 1300 nm) is generally used. This wavelength range has a large penetration depth in the tissues and the arterial pulsations can be recorded with light transmitted through fingertip, earlobe or other relatively thin organs.

Reflection photoplethysmography (PPG) detects the tissue back-scattered radiation with time resolution. The PPG signal consists of AC and DC components. The AC component reflects the vascular pulsations, and the DC component represents the light scattered from relatively steady blood volume and tissue layers, which are the components without a pulsatile signal.

The tissue penetration volume/depth depends on the emitter wavelength: in the spectral range 400-800 nm PPG pulsations from deeper skin layers contribute to the signal at longer wavelengths. Consequently, parallel analysis of PPG signals at different wavelengths might help to distinguish assessment of skin damages and pathologies at various tissue depths.

This study continues our previous research with the aim to understand more deeply pulse shape changes at different tissue depths.

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2. MATERIALS AND METHODS

2.1 Biosensor system

The newly developed optical fiber biosensor comprises one 3-wavelengths laser diode and a single photodiode with multi-channel signal output processing; special software was created for visualization and measuring of the MS-PPG signals. BRIR (Blue, Red and InfraRed) laser diode is emitting wavelengths separately one after other – 405 nm, 660 nm and 780 nm. The contact sensor head was connected to the device by a 1 meter long cable. The measuring area for sensor head is 5 mm². Dimensions of the prototype equipment are 140 mm x 90 mm x 35 mm and weight 250 g; it is battery-powered and can operate up to 10 hours without recharging.

![Figure 1. The prototype biosensor device.](image)

A portable device with built in Li-ion accumulator was specially created for the measurements. ARM7TDI-S LPC2148, NXP (founded by Philips) 32 bit processor with clock frequency 60 MHz performed receiving and measuring of the signal. Power supply voltage was stabilized with built in current regulator (for each laser). COM – USB junction was used for transportation of the captured data from device to computer. Red and IR wavelengths radiation output could be changed in the interval 90 – 280 μW, while the blue radiation output is constant. New method was used for measuring PPG signals – digital PPG⁷ without analogue amplifier and filters.

![Figure 2. Block diagram of the biosensor device](image)

The signals acquired from measuring photodiode discharge time are inverse to the absorption of the light. The emission wavelengths were 405 nm, 660 nm and 780 nm. Time shift between 405 nm and 780 nm is 2 ms; offset for wavelength 660 nm is 1 ms and offset for 780 nm is 2 ms. The biosensor operated in contact reflection mode, with simultaneous sequential recording of PPG signals at each wavelength. Analysis of the MS-PPG signal shapes and baseline variations at
three wavelengths provided information on hemodynamic parameters at different vascular depths and could be useful in dermatology for assessment of skin damages and pathologies.

2.2 Volunteers

The multi-spectral photoplethysmography recordings were obtained from 11 male volunteers. The volunteers were healthy men. The age of volunteers was between 22 and 40 years. Measurements were performed in a laboratory (a well-ventilated room under reasonable constant temperature which is typically 20°C). Each volunteer was asked to relax and sit in the chair. Before the measurement each volunteer was asked to calm down for a 10 minutes after which measurements were performed. The MS-PPG recording time was between 90 and 120 s. The recordings were taken 5 times with pause of 2 minutes.

2.3 Methods

At the first step experimental data were analyzed with the PPG-analysis software which is a specially created for analysis.

Using this program is possible to get some important hemodynamic parameters e.g. Max ejection velocity, Stiffness index (SI) and Reflection index (RI). For obtaining correct parameters it is needed to write the correct volunteer height in centimeters in the program window before calculations of the hemodynamic parameters. The program calculates the mean single period photoplethysmography signals (SPPPG) also. The choice interval of experimental data with Origin 8.0 contribution was calculating the normalized mean value of SPPPG for each of the used wavelengths. To check repeatability of the measurements was calculated mean of mean value for each wavelength. Examples of repeatability demonstrate Figure 6. and Figure 7.

3. RESULTS

To illustrate the results after analysis with both programs, Figure 4. – 5. demonstrates that normalized mean PPG signal shape at wavelength 405 nm was unlike to signals at red and NIR wavelengths, and also systolic pulse amplitude had a shift if we compare wavelengths 405 nm, 660 nm and 780 nm. 70 % of all volunteers had PPG signal time shifts 660nm and 780nm delayed relatively to 405 nm but others had inverse situation.
Figure 4. Examples of PPG signal time shifts 405nm delayed relatively to 660nm and 780nm pulses ahead.

Figure 5. Examples of PPG signal time shifts 660nm and 780nm delayed relatively to 405 nm.

Figure 6. Mean PPG signal shapes for each wavelength with standard deviation (SD).
4. CONCLUSIONS

The newly developed biosensor confirmed its ability to detect PPG signals at three laser wavelengths simultaneously and to detect temporal differences in the signal shapes at these wavelengths that correspond to different penetration depth in skin.

Our results suggest that further tests are necessary to understand the different PPG signal shape at wavelength 405 nm and the systolic rising time shift. The time interval from foot to incisura (the notch between systole and diastole) was the same independently on the PPG pulse duration. Our hypothesis about PPG signal time shifts 405 nm delayed relatively to 660 nm and 780 nm pulses ahead is connects with hypotension or low blood pressure of the volunteers. One of the next steps will be further tests to confirm or reject this hypothesis.

Analysis of the MS-PPG signal shapes and baseline variations at three wavelengths provides information on haemodynamic parameters at different vascular depths and we may conclude that newly developed method could be useful in dermatology for skin assessment, further research is needed.

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