Contact probe pressure effects in skin multi-spectral photoplethysmography

Janis Spigulis, Lasma Gailite, Renars Erts and Alexey Lihachev
Bio-optics and Fiber Optics Laboratory, Institute of Atomic Physics and Spectroscopy
University of Latvia, Raina Blvd. 19, Riga, LV-1586, Latvia

ABSTRACT
A novel technique ensuring parallel recording of reflection photoplethysmography signals in broad spectral range has been tested for assessment of pressure-induced vascular changes at various depths from the skin surface. PPG signals have been simultaneously detected at three combinations of the cw laser wavelengths 405 nm, 532 nm, 645 nm, 807 nm and 1064 nm. The PPG baseline responses to the probe-skin contact pressure changes and shapes of the PPG pulses originated from the same heartbeat but recorded at different wavelengths have been detected and analyzed.

Keywords: photoplethysmography, skin blood supply, vascular depth selectivity, pressure-induced occlusions.

1. INTRODUCTION
Reflection photoplethysmography (PPG) is a non-invasive method for studies of the skin blood volume pulsations by detection and temporal analysis of the back-scattered optical radiation. Skin blood pumping and transport dynamics can be monitored this way at different body locations with relatively simple and convenient PPG contact probes.

Reflection PPG technique traditionally uses narrow-band cw emitters – light-emitting diodes (LEDs) or lasers, so reflecting blood pulsations within a fixed penetration volume/depth that is dependent on the emitter wavelength. More advanced technology – parallel multi-wavelength detection of reflection PPG signals related to the same heartbeats with subsequent shape analysis – has been proposed recently. Radiation of different wavelengths penetrates differently under the skin surface, so the multi-wavelength PPG data can serve for comparative analysis of the dynamics of skin blood microcirculation at various vascular depths. Qualitatively different responses of the PPG signal baselines to breath-holding have been observed at different wavelengths, as well as various PPG pulse shapes related to the same heartbeat but recorded at differing wavelengths. The first clinical results demonstrated feasibility of this methodology as eventual tool for non-invasive skin assessment, based on comparison of the multi-wavelength PPG data sets recorded from the healthy and the diseased skin regions.

The PPG bio-signal parameters depend on the contact probe pressure to the skin. Increased pressure provides better optical contact with the skin surface, but, from the other hand, induces occlusions of the skin superficial capillaries and small arteries. The pressure induced de-occlusion thresholds have been estimated previously by analysis of the PPG signals subsequently measured with yellow, red and infrared LEDs. The newly developed technique of parallel multi-wavelength recording may provide more information on the occlusion processes with simultaneous depth-resolution. The first evidence on contact probe pressure-induced changes to the multi-wavelength PPG signals were reported previously; this paper presents more recent results on this topic, obtained by means of the new technique.

2. METHOD AND EQUIPMENT
The set-up scheme of the equipment is presented on Fig. 1. A dual-fiber contact probe irradiated the inner part of middle fingertip of the examined person and collected the back-scattered radiation with its further transport to the multi-channel spectrometer. The measurements were taken at 3 mm distance between centers of the fiber light guides. The input fiber (600-micron silica core) was lens-coupled to the output of a “3 to 1” fiber assembly, providing that three laser beams simultaneously irradiated the same spot of the skin. The “round-to-line” detection
fiber bundle (seven 200-micron silica core fibers) transmitted the skin back-scattered radiation to 2048-channel array spectrometer AvaSpec 2048-2 (Avantes BV, The Netherlands) which covered the spectral range 200…1100 nm with resolution of about 2 nm, or AvaSpec-2048-USB2 with similar resolution in the range 400…1100 nm. All fiber optic components were designed and manufactured by Z-Light, Ltd. (Latvia).

![Diagram of fiber optic setup](image)

**Fig. 1.** The set-up scheme for multi-wavelength reflection photoplethysmography.

The flat-surface contact probe was placed horizontally on the top of inner part of the right middle fingertip; the probe surface covered all the fingertip contact area. Calibrated hanging weights (20 g, 70 g, 130 g, 200 g, 230 g, 250 g or 430 g) have been used to change the probe-skin pressure. Assuming the contact area to be ~ 1 cm², the corresponding pressure range is approximately 2…40 kPa.

Three parallel 3-wavelength laser radiation sets were chosen for the measurements: (i) violet-green-red lines 405 nm, 532 nm and 645 nm, (ii) red and near-infrared lines 645 nm, 807 nm and 1064 nm, (iii) violet-green-infrared lines 405 nm, 532 nm and 807 nm (two of the sets are shown on Fig. 1). Two cw lasers manufactured by BWTek, Inc. (BWB-405-40-PIG-200-0.22-SMA emitting 405 nm line and BWT-532-15-SMA emitting two lines, 532 nm and 1064 nm) were used, as well as two laboratory-assembled diode lasers (645 nm and 807 nm). All lasers were equipped with lensed SMA connectors for efficient coupling to the fiber cables. Stabilized power supplies and thermo stabilization assured better than 5% output power stability of all lasers. Irradiation power at the probe output varied from 3 mW at 1064 nm to 16 mW at 405 nm, which corresponds to power densities on the skin in the range 6 … 32 mW/mm².

The multi-wavelength PPG signals were detected from fingertips of ten volunteers in relaxed sitting position; each measurement session with fixed laser wavelengths set lasted for about 2 minutes. Studies of the probe-skin pressure effects comprised several subsequent measurement sessions with each of the fixed loads and each of the three laser wavelengths sets (405/532/645 nm and 645/807/1064 nm with the AvaSpec 2048-2 and 405/532/807 with the AvaSpec-2048-USB2 spectrometer).

![Graph of PPG signal](image)

**Fig. 2.** Principle of the measurement data processing: time-resolved PPG signal extraction from the intensity-wavelength-time data set (four spectral peaks represent the four selected wavelengths for intensity-time analysis).
For the first two sets, special Visual Basic software was developed additionally to the original spectrometer software, in order to speed-up the sequential readings of the whole spectra and to increase the temporal resolution; the achieved sampling rate ~20 s⁻¹ proved to be sufficient for PPG signal shape assessment. The additional software also included data processing algorithms for saving the time-resolved measurement data in form of a 3D-data matrix (intensity-wavelength-time), with subsequent “intensity-time” sections at the fixed wavelengths. These sections after further processing were converted into amplitude-normalized “monochromatic” PPG pulse sequences (Fig. 2).

For the measurements with spectrometer model AvaSpec-2048-USB2, more advanced software was created by means of the special Avantes BV tools using the **CodeGear Delphi 2007** programming language. This software made possible to choose any selected wavelength band (up to three nanometers) for the multi-spectral PPG signal real-time recording, and to record additionally two analogue PPG signals in real-time, along with the multi-spectral PPG recordings. The hardware parameters such as integration time, number of averages and amplification of the analogue PPG signal were configurable through the software. The data sampling rate 25 s⁻¹ was usually chosen. The monitor screenshot (Fig. 3) demonstrates the multi-spectral software, set in the data acquisition mode. On the right side the input optical spectrum is identified and one external analogue PPG signal is recorded (below). Three windows in the middle are supposed for the PPG signal detection simultaneously at all three spectral bands. They were tuned off the working wavelengths at the moment of taking picture, in order to analyze the signal noise at three other wavelengths.

![Fig. 3. Screenshot of the monitor demonstrating the software capacities.](image)

**3. RESULTS OF THE MEASUREMENTS**

Two aspects of the pressure induced changes in multi-wavelength PPG signals have been studied - PPG baseline responses and single heartbeat pulse shapes at various wavelengths and pressures. All the below-presented PPG baselines are amplitude-normalized, assuming 100% at the signal maximum with extracted background; the
normalized curves are positioned one above another for convenience of comparison. The magnified PPG pulse sequences are amplitude-normalized, as well.

Increased probe-skin contact pressure in most cases has caused decrease of the PPG signal baseline amplitudes at all five exploited wavelengths. For illustration, typical pressure response is presented at Fig. 4. Such response might be expected: since the PPG baseline level is proportional to the total blood volume covered by the probe emission, pressure to the skin surface deforms the subcutaneous blood vessels, decreasing their cross section and the respective blood volume. Measurements also showed sharp decrease of amplitudes of the PPG pulsations detected at shorter wavelengths 405 nm and 532 nm (that relate to shallow penetration) when the probe load reached 430 g. This probably indicated to pressure-induced occlusions of the superficial skin blood vessels. The signals originated at deeper dermal layers (red and infrared lines) still showed pulsations at this pressure.

Fig. 4. Typical changes in multi-wavelength PPG signals with increasing probe-skin pressure: the visible (a) and red-infrared (b) spectral lines.

One can note that sharp decrease of baseline is observed at the moment of applying higher pressure; after that there is some tendency to increase, which might be connected with physiological regulation mechanisms protecting the blood vessels from occlusions. It seems to be a very individual response, as illustrated in Fig. 5. Even qualitatively opposite reactions to the probe pressures at different wavelengths have been observed, especially in the NIR region. For example, volunteers A, C and E exhibited growth of the PPG baselines at 807 nm while they were convincingly decreasing at 1064 nm.

Along with the gradually increasing pressures, measurements with subsequent increase and decrease of the probe pressure have been performed as well, using another 3-wavelength set comprising 405 nm, 532 nm and 807 nm (Fig. 6). Increased pressure dropped down the PPG baseline, as observed previously. However, one can note that de-compression of skin causes the PPG baseline increase even above the level corresponding to the same pressure before compression. It might be regarded as evidence of the physiological self-protection, a mechanism increasing the blood flow in skin arteries under a risk of occlusion.

This measurement trial also gave some primary information on the PPG single-pulse signal shapes at various wavelengths (penetration depths) in conditions when different pressures were applied – see Fig. 7, where some fragments of the PPG signals that are shown at Fig. 6 have been magnified. The signals are quite noisy, especially those at 807 nm, but there are visible differences in shapes of the same heartbeat pulses detected at different wavelengths at the same pressure. The 405 nm signals did not show any pronounced changes due to changed pressure, but some qualitative changes in the shapes of 532 nm signals with respect to applied pressure can be observed (the middle column at Fig. 7).
Fig. 5. The PPG signal baseline responses to gradually increasing probe pressures for 5 volunteers, simultaneously recorded at 405 nm, 532 nm, 645 nm (averaged signal of measurements at two wavelengths sets), 807 nm and 1064 nm.

4. DISCUSSION AND CONCLUSIONS

Multi-PPG signal baselines exhibit different probe load dependencies at different emitter wavelengths, i.e., penetration depths. As previously assumed, it was observed that occlusion pressures are lower for shorter wavelengths, i.e., shallow penetration depths that correspond to the uppermost layers of skin vasculature.
Characteristic trends were observed at the laser wavelengths 405 nm, 645 nm and 1064 nm for all volunteers, with specific individual features for each person.

Occlusions (disappearance of pulsations) were notable at 405 nm with 430 g load for all volunteers, whereas the PPG pulsations reappeared at 532 nm for some persons and at 645 nm for other persons. A decrease of the mean signal DC level at 405 nm followed every probe loading with gradually increasing weight, whereas the signal baseline increased with the applied load at 645 nm and 1064 nm. At other laser wavelengths, namely, 532 nm and 807 nm, the signal baselines demonstrated both types of responses to probe loading. In some cases, opposite trends of the PPG baseline variations were observed for a single volunteer during the same pressure change at different wavelengths.

In spite of relatively low signal-to-noise ratio of the multi-spectral PPG recordings, the obtained PPG baseline responses seemed to be reliable enough for comparison. Drawing attention to the 1064 nm signals, the observed tendencies are hard to explain. This wavelength corresponds to the deepest penetration depth and, presumably, its PPG signal would comprise details of other PPG signals originated at more superficial skin layers (i.e. at shorter wavelengths). The measurements, however, did not confirm this assumption – in several cases 1064 nm PPG signal baseline changes appeared to be more similar to the shallowest penetration wavelength 405 nm signal changes, including disappearance of pulsations regarded as the sign of arterial occlusions. PPG baseline signals of the “medium penetration” wavelengths 807 nm and 645 nm the same time were rising instead of decreasing, and still pulsating (i.e. showing no occlusion). Obviously, more detailed further studies are needed to find out the physical and physiological reasons of such behavior of the multi-wavelength PPG signals.

5. ACKNOWLEDGMENTS

Financial support from University of Latvia, Latvian Ministry of Education and Science, European Fund for Regional Development and European Social Fund is highly appreciated.

![Fig. 6. Typical PPG baseline responses to subsequently increased-decreased pressures, simultaneously recorded at 405 nm, 532 nm and 807 nm.](image)
Fig. 7. Magnified fragments of the multi-wavelength PPG signal sequences (Fig. 6) recorded at different probe pressures.
6. REFERENCES