Simultaneous recording of skin blood pulsations at different vascular depths by multiwavelength photoplethysmography

Janis Spigulis, Lasma Gailite, Alexey Lihachev, and Renars Erts

A new technique for parallel recording of reflection photoplethysmography (PPG) signals in a broad spectral band (violet to near-infrared) has been developed, and its potential for assessment of blood microcirculation at various depths from the skin surface is discussed. PPG signals have been simultaneously detected at cw laser wavelength sets comprising 405, 532, 645, 807, and 1064 nm. Various signal baseline responses to breath holding and different shapes of the PPG pulses originated from the same heartbeat but recorded at different wavelengths have been observed, indicating a depth variety of the skin blood pulsation dynamics.

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1. Introduction

Reflection photoplethysmography (PPG) is a noninvasive method for studies of the skin blood volume pulsations by detection and analysis of backscattered 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.[1]

Reflection PPG technique mainly uses narrowband cw emitters, light-emitting diodes (LEDs) or lasers, thus reflecting blood pulsations within a fixed penetration volume–depth that is dependent on the emitter wavelength[2,3] (Fig. 1). Pulse oximetry[4] is probably the most widespread PPG modality where two or more wavelength bands are analyzed simultaneously to compare the corresponding PPG pulse amplitudes for subsequent estimation of the blood oxygenation degree. However, this technique does not analyze the PPG signal shapes that comprise clinically important information on vascular features, including skin microcirculation. Different shapes of PPG signals have been observed previously in conditions when the same skin area was subsequently exposed to radiation of different wavelength bands; the shape variations were generally explained as a result of wavelength-dependent radiation penetration depth under the skin surface.[5] Other optical multiwavelength systems have been also described in the literature, e.g., laser Doppler and PPG measurements at several wavelengths for analysis of blood flow at different vascular levels.[6]

More advanced technology—parallel multiwavelength detection of reflection PPG signals related to the same heartbeats with subsequent shape analysis—may lead to a better understanding of the blood pulsations in selected underskin layers. To the best of our knowledge, no data on shape parameters of the PPG signals related to the same heartbeats at multiple wavelengths have been available so far.

This work is aimed at developing and testing a new experimental technique for simultaneous detection of PPG biosignals at any selected wavelength of the 400–1100 nm spectral range with 2 nm spectral resolution and 50 ms temporal resolution. An essential feature of the multiwavelength approach is the use of a multichannel array of spectrometer instead of a traditional single-channel detector, e.g., photodiode. This adds spectral resolution to the well-established single-wavelength PPG method. The proposed approach may be regarded as a modality of the recently developed multichannel PPG methodology[1]; parallel multisite recordings at a fixed emitter wavelength are performed in the latter case, while single-site parallel multiwave-

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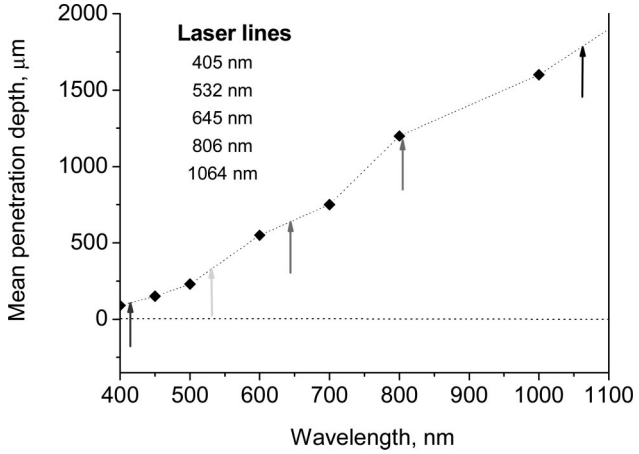

Fig. 1. Wavelength dependence of the radiation mean penetration depth under the skin surface [calculated data (Ref. 3)].

length PPG recordings are discussed here. The equipment details and biosignal processing principles are presented in this paper, as well as our first results of simultaneous multispectral reflection PPG measurements at five selected laser wavelengths.

2. Method and Equipment

The setup scheme of our equipment for multiwavelength PPG measurements is presented in Fig. 2. A dual-fiber contact probe irradiated the inner part of the middle fingertip of the examined person and collected the backscattered radiation with its further transport to the multichannel spectrometer. The measurements were taken at a 3 mm distance between centers of the fiber light guides, according to the recommendations given by other authors.[2,7] The input fiber (600 μm 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 on the skin. The round-to-line detection fiber bundle (seven 200 μm silica core fibers) transmitted the skin backscattered radiation to 2048-channel array spectrometer AvaSpec 2048-2 (Avantes BV, The Netherlands), which covered the spectral range of 200–1100 nm with a resolution of ~2 nm. All fiber-optic components were designed and manufactured by Z-Light, Ltd. (Latvia). The contact probe was attached to the skin surface by means of double-sided adhesive tape; pressure to the skin could be varied by loading

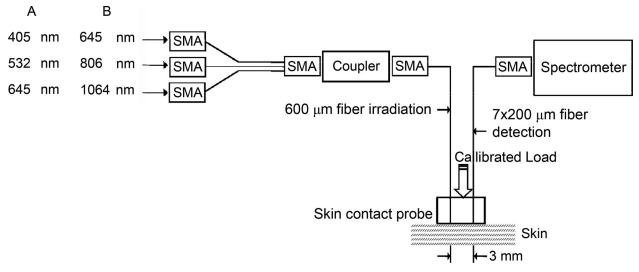

Fig. 2. Setup scheme for multiwavelength reflection PPG.

the probe with calibrated weights (20, 70, 130, 230, or 430 g).

Due to limited sensitivity of each pixel of the detector array, less than 10 counts/nW per 1 ms integration time in the working range of numerous wavelengths (estimated according to the manufacturer's data), the multichannel spectrometer is suitable for parallel PPG signal detection only if the spectral density of the irradiation source were to exceed a certain threshold value. Broadband sources that meet this condition may appear unusable for another reason: high integral emission power causes unwanted skin heating or even burning. Various halogen lamps, LEDs, and lasers have been tested experimentally from this point, and milliwatt power range cw lasers have been selected as the most appropriate sources, assuring the highest signal-to-noise ratio (SNR) without notable heating of skin.

Two parallel three-wavelength laser radiation sets were chosen for the measurements, corresponding to the spectral ranges of two spectrometer inputs: (i) visible lines 405, 532, and 645 nm, and (ii) red and near-infrared (NIR) lines 645, 807, and 1064 nm. Two commercial lasers supplied by BWTek, Inc. (BWB-405-40-PIG-200-0.22-SMA emitting a 405 nm line and BWT-532-15-SMA emitting two lines, 532 and 1064 nm) were used, as well as two laboratory assembled diode lasers (645 and 807 nm). All the lasers were equipped with lensed SMA standard connectors for efficient coupling to the fiber cables; stabilized power supplies and thermostabilization assured better than 5% output power stability of all the 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 of 6–32 mW/mm^2.

The multiwavelength PPG signals were detected from fingertips of ten volunteers in relaxed sitting position; each measurement session with fixed laser wavelengths lasted for approximately 2 min. Some volunteers were asked to hold their breath for 30 s with subsequent deep inhalation during the measurement session. These measurements were taken in order to simultaneously track the physiological responses of the PPG signals and their baselines at several wavelengths (i.e., penetration depths). Studies of the probe-skin pressure effects were composed of three subsequent ~1 min measurement sessions at each of the five fixed loads with both three-wavelength sets, so the whole trial for a single volunteer took approximately 35–40 min.

Special VISUAL BASIC software was developed in addition 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 of ~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 the form of a 3D data matrix (intensity-wavelength-time), with subsequent intensity-time sections at the

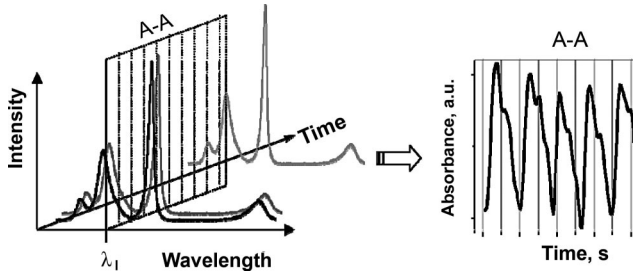

Fig. 3. Principle of the measurement data processing: time-resolved PPG signal extraction from the intensity-wavelength-time data set (four spectral peaks represent the four selected wavelengths for intensity-time analysis).

fixed wavelengths. After further processing, these sections were converted into amplitude-normalized "monochromatic" PPG pulse sequences (Fig. 3).

The SNR (defined as relation of the amplitude of detected cardiac pulses to the dark background noise) was wavelength dependent, mainly owing to differences in detector array sensitivity and skin absorption efficiency at various wavelengths. In particular, the estimated mean SNR values were ~7 at 405 nm, ~40 at 532 nm, ~3 at 645 nm, ~4 at 807 nm, and ~9 at 1064 nm. The noisiest signals were detected at 645 nm, where blood hemoglobin absorbs less efficiently if compared with the other applied wavelengths.[2,3] One should note that the SNR values of PPG signals may also be influenced by individual anatomical and physiological features such as skin thickness and vasomotions.

The estimated long-term uncertainties in the measured data owing to slight differences between the sampling periods (depending on the number of counts at the scanned detection channels during one sampling cycle) and the signal processing and/or smoothing software, were in the range of 10%–15%. The long-term drifts, however, could not noticeably affect the PPG signal shapes that were compared in the short term, e.g., at different wavelengths during the same heartbeat lasting for approximately 1 s.

Reproducibility of the obtained data has been checked by qualitative comparison of several subsequent PPG signal sequences measured at the same conditions. Most of the measured data showed acceptable reproducibility; all nonreproducible data were discarded.

3. Results and Discussion

Reflection PPG signal sequences at various laser irradiation wavelengths before, during, and after the breath holding exercise were simultaneously detected in the visible and red-IR spectral ranges. For illustration, the pair of three-wavelength set recordings from the same fingertip is presented on Fig. 4. All the PPG baselines are amplitude normalized, assuming 100% at the baseline as maximum with the extracted background; the normalized curves are positioned one above another for more convenient comparison.

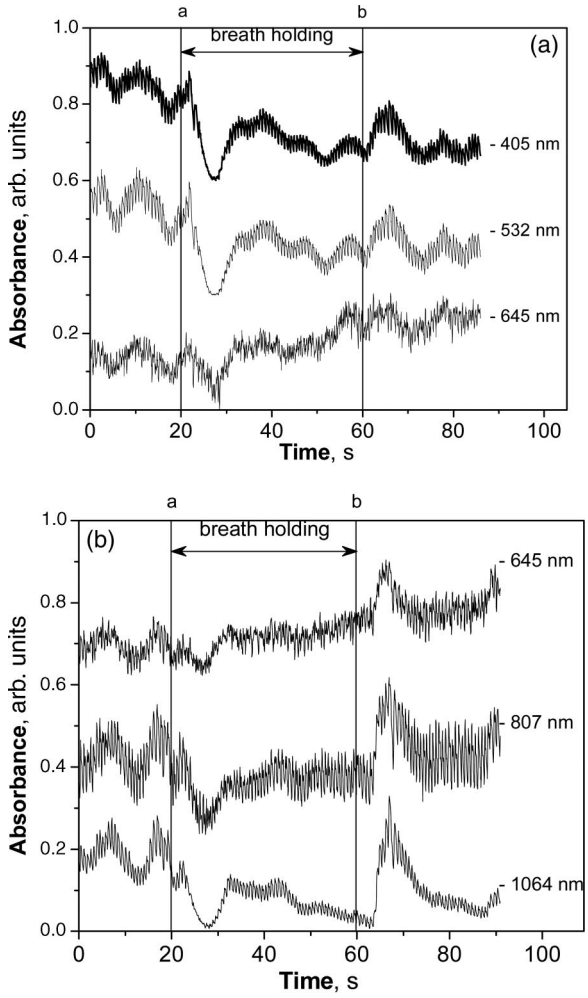

Fig. 4. PPG signal sequences detected simultaneously at three laser wavelengths in the (a) visible and (b) red-NIR spectral ranges during the breath-holding exercise.

If signals of the visible region are compared [Fig. 4(a)], one can observe nearly identical PPG baseline changes at 405 and 532 nm. The PPG baseline response at 645 nm (penetrating deeper due to considerably weaker blood hemoglobin absorption[2]) is slightly different; however, the same main maxima and minima are there. Regarding the longer wavelengths [Fig. 4(b)], all of them belong to the so-called therapeutic window where the scattering in tissue prevails over absorption; the radiation penetrates under the skin surface increasingly with wavelength of the three given laser lines (Fig. 1). If those three PPG signal sequences are compared, one can note a good correlation between the baseline changes at 645 and 807 nm. A somewhat different baseline response to the breath holding, a decrease within the 30–60 s time interval, was detected at 1064 nm, the deepest penetration wavelength in this group. This may indicate different physiological mechanisms of blood–oxygen supply at subepidermal and deeper dermal blood vessels during the exercise.

Another interesting finding was the observed shape differences of the PPG signals related to the same

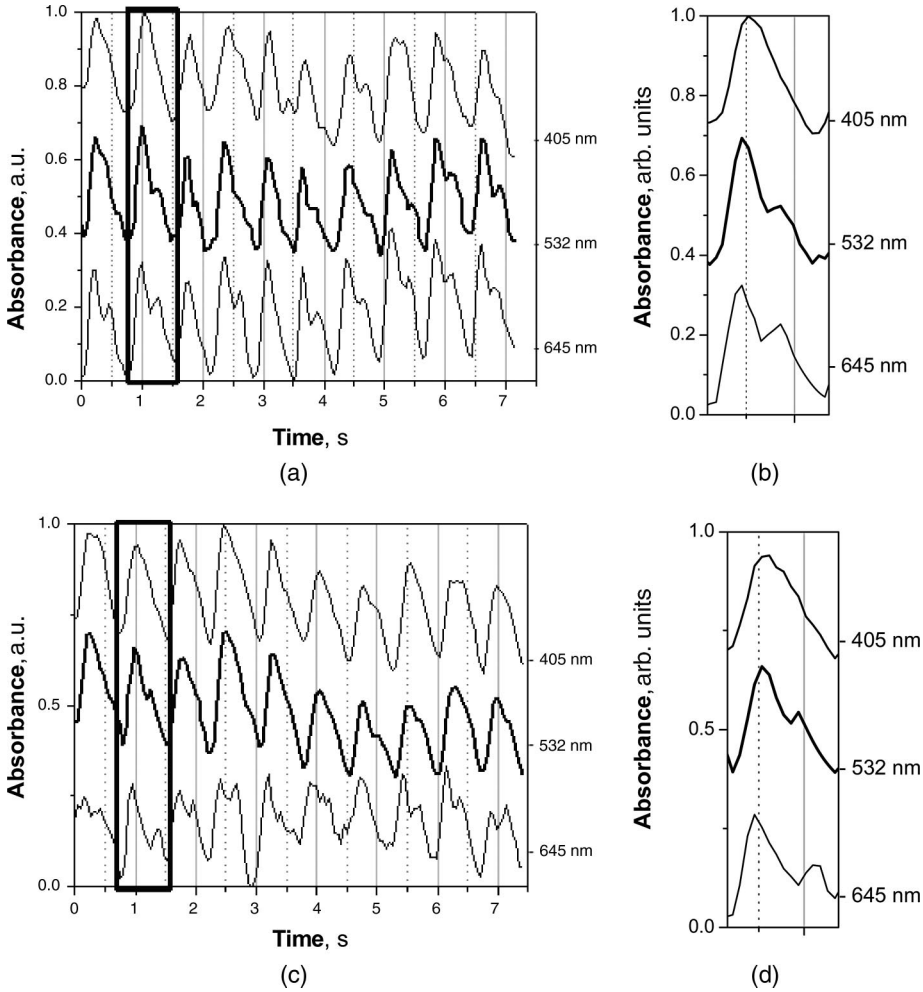

Fig. 5. Comparison of multiwavelength PPG pulse shapes in the visible spectral range: (a), (b) volunteer 1; (c), (d) volunteer 2. Right: enlarged normalized same-heartbeat pulses.

heartbeat and simultaneously detected at different wavelengths, i.e., penetrations. For illustration, magnified fragments of the PPG signal sequences recorded from two volunteers in the visible spectral range are presented in Fig. 5. If single-heartbeat pulse frames are selected at certain time intervals and the amplitudes of these signals are normalized [on the right, Figs. 5(b) and 5(d)], the PPG signal shapes for both persons appear to be wavelength dependent. In particular, the red (645 nm) backscattered pulses are more structured, with a more pronounced secondary notch than those of the green (532 nm) or violet (405 nm) light.

Similarly, the same-heartbeat-PPG pulse shapes differed also in the case of red-NIR wavelength composition (Fig. 6). The relative amplitude of the secondary notch in the PPG pulse, being well distinguished at 645 nm, becomes less pronounced or disappears at the longer wavelengths of 807 and 1064 nm that correspond to deeper underskin penetration. This may be explained by certain differences in microcirculation dynamics at various depths from the skin surface.

The single-heartbeat-PPG signal shapes changed individually with wavelength for each volunteer. However, some general effects were also observed, e.g., less structured signal shapes at shallow (405 nm) and deep (1064 nm) penetrations if compared to medium penetrations (645 and 807 nm).

Responses of multiwavelength PPG signals to a gradual increase in contact pressure have been studied as well. Increased probe-skin contact pressure has caused a decrease of the PPG signal baseline amplitudes at all five exploited wavelengths for all volunteers. For illustration, a typical response for the visible three-wavelength set is presented in Fig. 7 (the normalization and positioning of baselines have been performed the same way as in Fig. 4). Such response may be explained qualitatively: the PPG baseline level is proportional to the total blood volume covered by the probe emission, and pressure to the skin surface deforms the subcutaneous blood vessels, decreasing their cross section and the respective blood volume. Measurements also showed a sharp decrease of amplitudes of the PPG pulsations detected at shorter wavelengths of 405 and 532 nm (that relate to shallow penetration) when the probe

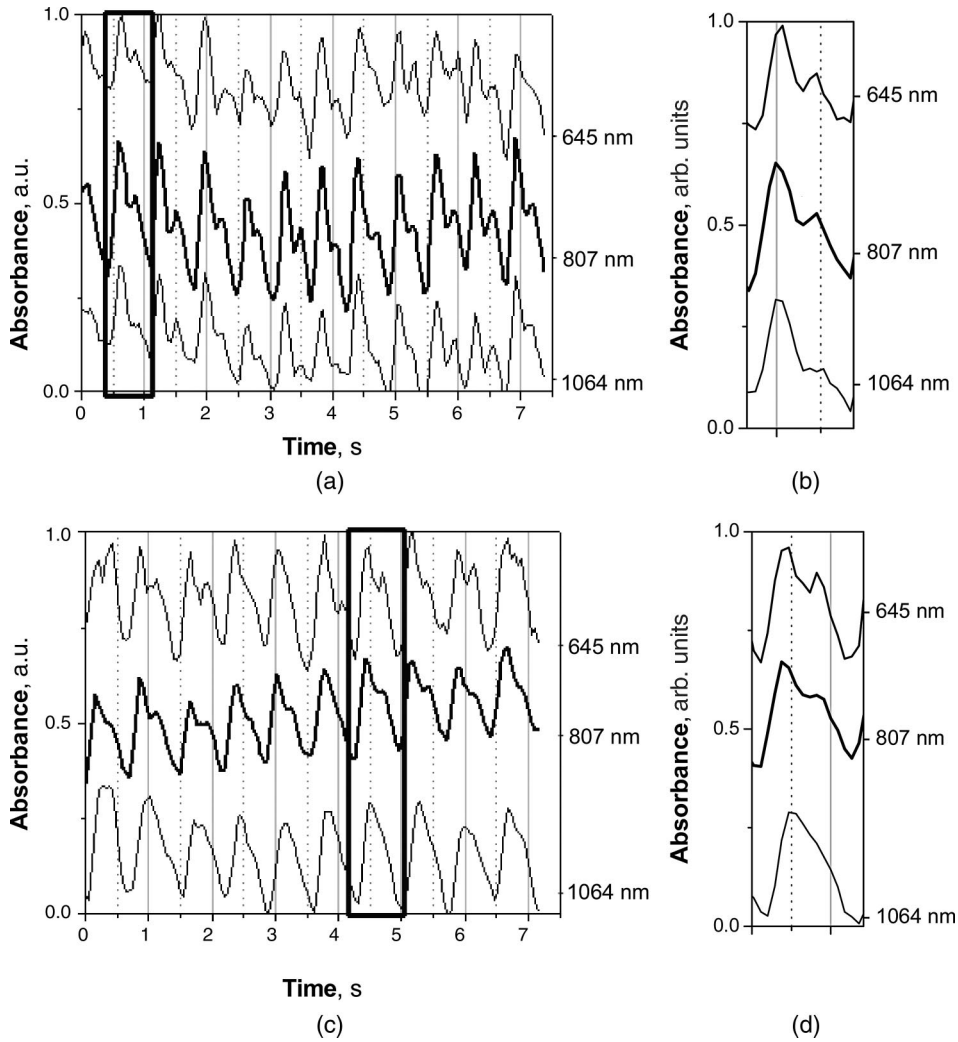

Fig. 6. Comparison of multiwavelength PPG pulse shapes in the red-NIR spectral range: (a), (b) volunteer 1; (c), (d) volunteer 2. Right: enlarged normalized same-heartbeat pulses.

load reached 430 g. This is probably indicative of pressure-induced occlusions of superficial skin blood vessels.

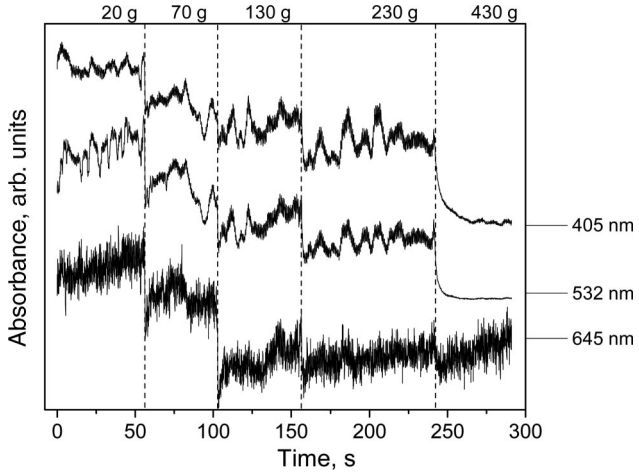

Fig. 7. Typical changes in visible multiwavelength PPG signals with increasing probe-skin pressure.

4. Conclusions

The newly developed multiwavelength PPG measurement principle has been implemented and tested. Simultaneous use of several cw lasers with multifiber coupling to skin and further to a standard multichannel array spectrometer proved to be successful for this kind of measurement. The first obtained results demonstrated the feasibility of this methodology; it might be further applied for studies and assessment of skin blood microcirculation at various vascular depths. This approach may have good future prospects in skin diagnostics, e.g., by comparing the multiwavelength PPG data sets recorded from healthy and diseased skin regions.

The measurement data presented here are qualitative rather than quantitative, and well-planned clinical trials are needed in order to establish exact correlations between multispectral PPG data and skin blood microcirculation features at various distances from the skin surface. Better temporal resolution may be achieved by use of spectrometers with an increased sampling rate. To improve the SNR, stabilized high

intensity fiber-coupled broadband emitters (e.g., superbright LEDs) would be useful for further studies. More sophisticated skin contact probes providing simultaneous measurements at several interfiber separations would be designed in the future. Adequate physiological models and more advanced processing algorithms are to be developed for fast and reliable analysis of the measured multiwavelength PPG data.

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