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Article *in* Lasers in Medical Science · May 2008

DOI: 10.1007/s10103-007-0471-9 · Source: PubMed

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ORIGINAL ARTICLE

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Received: 20 November 2006 / Accepted: 24 April 2007

Abstract New technique for parallel recording of reflection photoplethysmography signals in broad spectral band (violet to NIR) has been developed based on fiber-coupled laser irradiation and time-resolved spectrometric detection. Differences in photoplethysmography waveforms that were recorded simultaneously at different wavelengths confirmed the depth variety of the skin blood pulsation dynamics, thus the proposed methodology has a potential for application in skin microcirculation studies.

Keywords Photoplethysmography · Skin blood circulation · Cardiovascular fingerprint

Introduction

Reflection photoplethysmography (PPG) is a noninvasive method for studies of the skin blood volume pulsations by detection and analysis of the back-scattered optical radiation.

The experimental accomplishment of PPG usually incorporates light-emitting diodes (LEDs) as narrow-band light sources and photodiodes as detectors commonly implemented in compact skin irradiation probes, which make the method convenient for clinical use. Due to the noninvasive and simple measurement procedure and the informative content of the PPG signal, the principles of photoplethysmography have found clinical applications providing information on heart rate, respiratory rate, and tissue blood perfusion. Besides these parameters, specific indicators of cardiac disorders, as well as peripheral vascular diseases (e.g., peripheral arterial occlusions), can be extracted by monitoring of blood transport dynamics and subsequent analysis of the single PPG pulse shape [1]. A variation of PPG is the pulse oxymetry method where blood oxygenation degree is estimated by comparison of PPG signal amplitudes at two or three wavelength bands measured simultaneously from the same body site [2]. The specifics of reflection PPG is that a fixed penetration volume/depth is monitored which depends on the emitter wavelength: PPG pulsations from deeper skin layers contribute to the signal at longer wavelengths [3, 4]. Consequently, depth-selective PPG measurements are possible, e.g., studies of blood flow at different vascular beds described in literature [5, 6]. Differences in PPG signal shapes have been reported [4] in case of subsequent application of various emitters/wavelength bands to the same skin spot. However, to authors' knowledge, there are no data available on PPG signal shapes that would be detected on the same skin location at the same moment and using several emitter wavelengths.

Parallel multiwavelength detection of reflection PPG signals related to the same heartbeats with subsequent shape analysis may yield a detailed submillimeter-scale characterization of skin microcirculation in selected skin layers.

The goal of this work is the development of a new technique, namely, the multilaser photoplethysmography that enables recording of PPG signals from the same skin location simultaneously at any selected wavelength in the range of 400 to 1100 nm.

Materials and methods

The basic concept of multilaser PPG equipment includes three basic components: (1) illumination by several laser

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light sources with emission lines within the range of 400 to 1100 nm, (2) fiber-optic contact probe for measurements on skin, and (3) detection in the range of 400 up to 1100 nm via multichannel spectrometer. The multilaser PPG setup scheme is depicted in Fig. 1.

Two parallel sets of three laser lines were used corresponding to the spectral ranges of two spectrometer inputs: (1) 405, 532, and 645 nm lines in the visible range and (2) 645, 807, and 1064 nm in the red-to-near-infrared range. The three lasers of a wavelength set were coupled to a "3-to-1" fiber assembly, which was lens-coupled to a 600-μm silica core irradiation fiber. Both the irradiation fiber and the fiber light guide for detection were mounted in a solid probe within a 3-mm distance between the centers of the light guides. The probe was positioned directly on skin during the measurements, namely, on the inner part of the middle fingertip of the examined person. The skin diffusely reflected light was collected by "round-to-line" detection fiber bundle (seven 200-μm silica core fibers) and was guided to 2048-channel CCD array spectrometer AvaSpec 2048-2 (Avantes BV, The Netherlands). The two spectrometer inputs covered spectral ranges of 187–747 and 589–1100 nm with 2.1-nm spectral resolution. All fiber optic components were designed and manufactured by Z-Light (Latvia).

Several continuous wave (CW) lasers were chosen as the most convenient light sources for parallel detection of PPG signals in a wide wavelength range. Halogen lamps and LEDs have been discarded; the spectral density of the tested emitters was too low to result in PPG signals detectable by the array of a multichannel spectrometer. Considering that the relative amplitude of PPG pulsations is in the range of 5% of the total skin reflectance signal, in case of a low spectral density, the signal-to-noise ratio is too low to distinct PPG pulsations from noise pulsations. The spectral density necessary for PPG pulsation detection has a threshold value, which in general is a complex function of detector spectral sensitivity and skin absorption spectrum. On the other hand, high spectral density of a broadband light source sums up in a high integral emission power which causes skin heating or even burning. A compromise solution was the use of three fiber-coupled CW lasers with emission power in milliwatt range at the optical fiber output on skin.

Two commercial lasers supplied by BWTek (BWB-405-40-PIG-200-0.22-SMA emitting 405-nm line and BWT-532-15-SMA emitting two lines, 532 and 1,064 nm) were used, as well as two laboratory-assembled diode lasers (645 and 807 nm). All lasers were equipped with lensed SMA connectors for efficient coupling to the fiber cables; stabilized power supplies and thermostabilization assured better than 5% output power stability of all lasers. Irradiation power at the probe output varied from 1 mW at 1064 nm to 16 mW at 405 nm, which corresponds to power densities on the skin in the range 0.35–5.66 W/cm^2.

Measurements were taken from fingertips of ten volunteers in relaxed sitting position. Three 90-s-long measurement sessions were performed with each of the two wavelength sets for all volunteers. Some of the volunteers were asked to hold breath for 40 s with subsequent deep inspiration during the measurement session. These measurements were carried out to track the responses to induced change of physiological conditions of PPG signals and signal baselines simultaneously at several wavelengths.

A special Visual Basic software was developed complementary to the original spectrometer software to enable spectra measurements with the spectrometer maximal temporal resolution. Hence, the measurement principle of spectrometer, the result of a measurement session, was a sequence of skin diffuse reflectance spectra separated by time interval of 50 ms–spectrometer maximal temporal resolution (sampling rate of 20 Hz). The measured three-dimensional data set was arranged in a matrix with intensity values as matrix elements and time and wavelength as running parameters of the matrix; by means of the newly developed software, the time-resolved pulsatile reflectance PPG signal was extracted from the data matrix as intensity and time columns corresponding to arbitrary wavelength values and displayed as function of time. In accordance

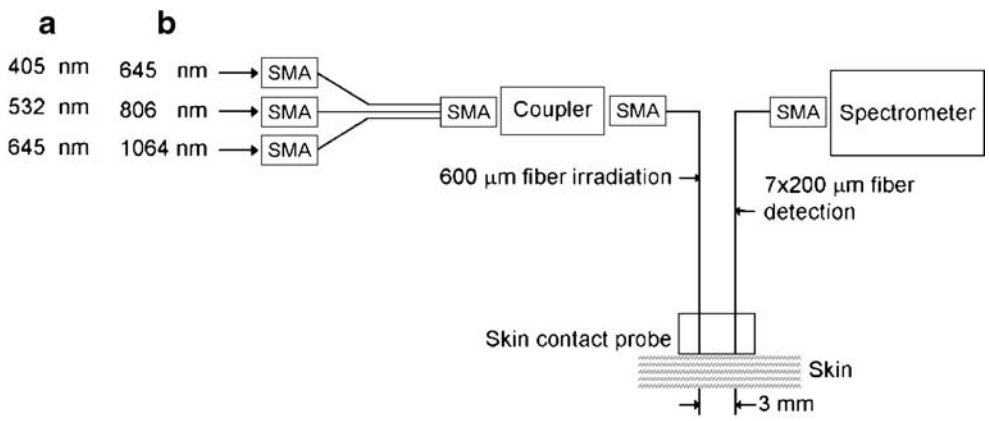

Fig. 1 Experimental setup for the multilaser photoplethysmography method

with the laser emission lines used in the setup, PPG signals were plotted at the laser emission wavelengths. This principle of data processing is shown schematically in Fig. 2.

Data values obtained from the measurement procedure of the proposed methodology were values of reflected intensity expressed in arbitrary units. Inversion was applied to show the usual PPG waveforms with the characteristic acrotic growth followed by the catacrotic decrease of a single PPG peak that corresponds absorbed intensity or absorbance units.

Further signal processing included signal smoothing (adjacent averaging), to eliminate high-frequency noise, and amplitude normalization.

The smoothing operation, used for the measurement data processing, was a mathematical filter, namely, adjacent averaging operation, which takes the average value of n neighbour data points; in our case, $n=2$, thus the number of measured data was decreased two times. The smoothing operation was needed, though, to remove the higher-frequency noise (>10 Hz) content of the measured PPG signals, whereby the general shape properties of the PPG waveforms remained.

Amplitude normalization was applied to all signals to enable the comparison of signals' relative amplitudes; signal displacement along the vertical axis was performed for clear illustration. The signals were compared: (1) regarding the relative amplitude changes of signal baselines or DC levels and (2) regarding the relative amplitude changes of single-period PPG signals, i.e., relative AC/DC values.

Results and discussion

PPG signals were detected from the same skin location simultaneously at three wavelengths for all of the ten volunteers using both of the laser sets alternatively. For three volunteers, additional measurements were carried out that included breath holding for 40 s during a single measurement session. The objective of this type of measurements was to reflect multi-PPG signal baseline response to introduced changes in physiological parameters. Characteristic example of the results of breath-holding measurements for one volunteer is displayed in Fig. 3. All PPG signal baselines are amplitude-normalized, relative to baseline maximum, and positioned one above the other for clear representation. Signal baselines both in the visible range and in the near-infrared range demonstrate simultaneous response at all wavelengths, yet marked by differences in each wavelength range. The PPG baseline at 645 nm has a clearly different trend in the breath-holding region compared with baselines at 405 and 532 nm; however, it is similar to 807-nm baseline of the near-infrared range. In the visible wavelength set, PPG baselines exhibit nearly identical behavior at 405 and 532 nm. The PPG signal baseline at 1064 nm, shown in Fig. 3, reflects typically different slope compared with 645- and 807-nm baselines for all breath-holding measurements. The observed baseline differences at 645 and 807 nm may be attributed to oxyhemoglobin absorption spectrum, according to which the arterial blood absorption is 2 orders of magnitude higher at 530 nm and 3 orders of magnitude higher at 405 nm than at 645 nm [7]. The arterial blood absorption remains low at 807 nm, as well as at 1,064 nm, though the different baseline slope at 1,064 nm may be explained with deeper penetration and PPG signal origin from a deeper vascular bed [3]. It has to be mentioned that the general trend of PPG baselines varied among the volunteers except the common feature that the baseline at 645 nm exposed a more or less pronounced difference from other two baselines in the visible range and that the baseline at 1,064 nm had a different character compared with the other two in the near-infrared range. The differences of PPG signal baseline behavior at various wavelengths serve as indicators of PPG signal specifics at various signal depths; that is, various vascular beds therefore may find use as quantitative criteria for skin microcirculation analysis after collection of sufficient number of data.

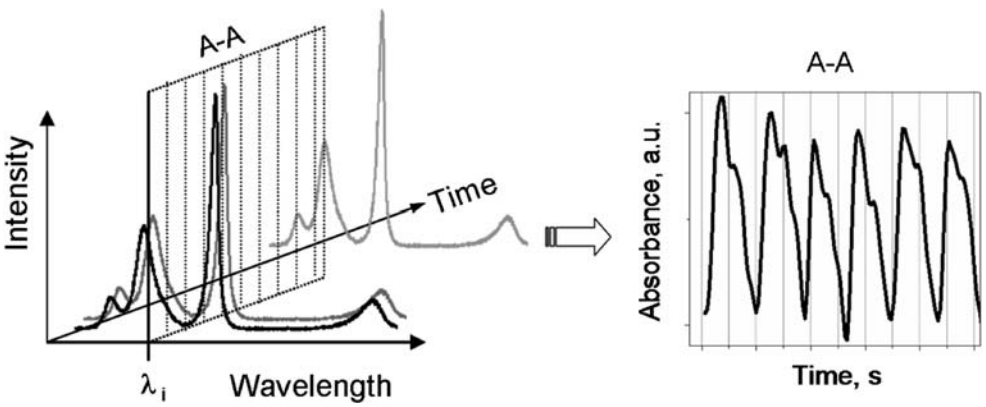

Fig. 2 Schematic illustration of the measurement processing algorithm: From a sequence of measured skin reflectance spectra (on the left), the time-dependent pulsatile PPG signal is acquired (on the right) at selected wavelengths

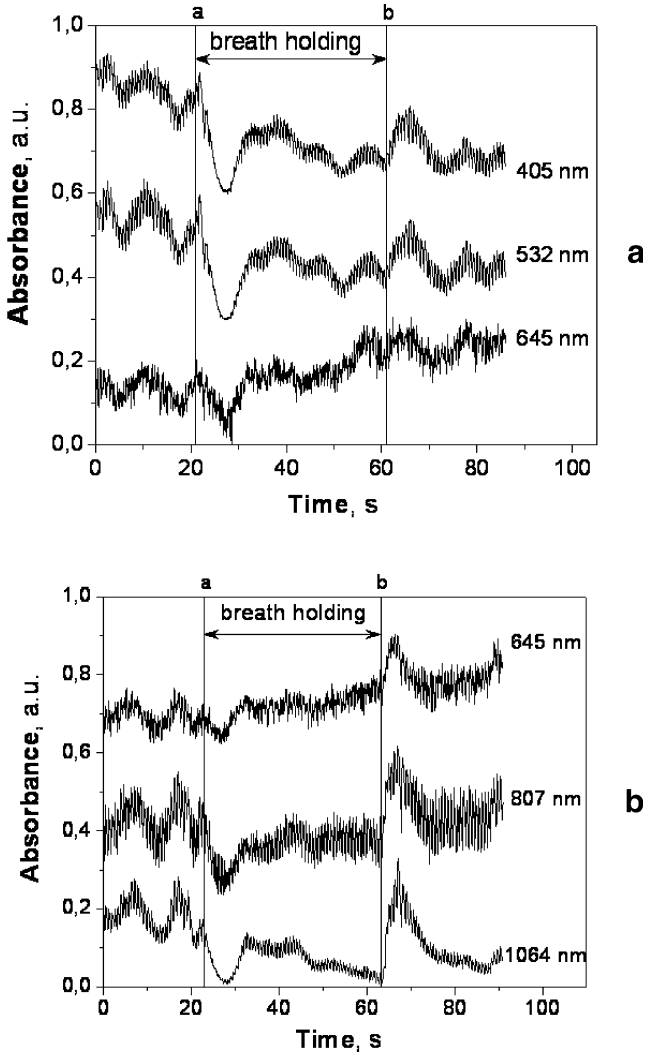

Fig. 3 The effect of breath-holding exercise on PPG signal baselines detected simultaneously at various wavelengths. Amplitude-normalized PPG baselines are plotted at three laser wavelengths corresponding to (**a**) the visible wavelength set and (**b**) the red–near-infrared wavelength set

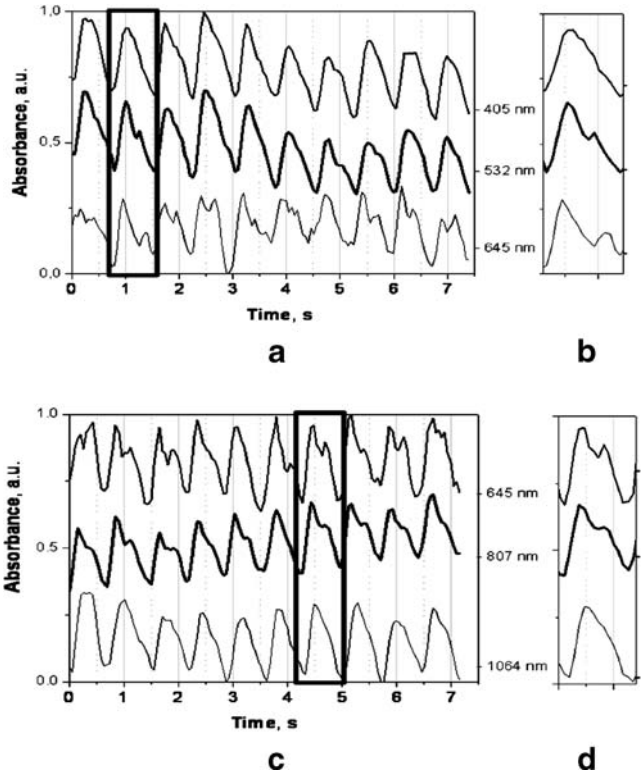

Fig. 4 Comparison of PPG signal shapes characterizing the same heartbeats at various wavelengths: Amplitude-normalized sequences of several single-period PPG pulses are depicted in the (**a**) visible and (**c**) red–near-infrared range; fragments of sequences (**a**) and (**c**) are displayed in (**b**) and (**d**), respectively, showing the characteristic single-period PPG pulses recorded simultaneously at three laser wavelengths

The other type of results represents differences in the shapes of single PPG pulses at various wavelengths. Detected PPG signal sessions were split in PPG sequences, consisting of four to ten single pulses, to compare pulse shapes related to the same heartbeat at various wavelengths. Amplitude-normalized PPG sequences in the visible range and in the near-infrared range are plotted in Fig. 4, revealing the generally characteristic pulse shapes of a single volunteer. The typical feature taken into consideration was the relative amplitude of the secondary peak of a single PPG pulse. By qualitative comparison of PPG pulse sequences, it was observed that the relative amplitude of secondary peak is higher at 645 nm than at 405- and 532-nm signals for all of the volunteers in the visible range. In the infrared range, PPG pulses of all ten volunteers were distinctive at 1,064 nm by a remarkable decrease of the secondary peak relative amplitude compared with the same heartbeat pulses at 645 and 807 nm. For the single-period pulses at 1,064 nm, the secondary peak was less pronounced or it was not distinguishable.

It has been established in conventional PPG studies earlier that the mean single-period PPG pulse serves as the "cardiovascular fingerprint" of a person by maintaining the individual shape related to person's cardiovascular condition [8]. In our study, the results of five participating volunteers were in agreement with this finding: The multilaser PPG measurements repeated on the same fingertips after 6 months confirmed that the single-period PPG pulse shape of a person preserves its characteristic shape features at various wavelengths.

Our approach of signal processing was to analyze the relative amplitudes of various single-period PPG signals, i.e., comparison of normalized single-period PPG shapes detected at various wavelengths simultaneously. It has been ascribed in prior studies that the single-period PPG signal shape holds parameters linked to vascular resistance; furthermore, relative blood volume can be characterized by differences in relative amplitudes of various single-period PPG pulses [9]. The properties of single-period PPG

pulses have been investigated in case of diseases, such as atherosclerosis or diabetes, that locally affect the properties of blood vessels [8, 9].

On basis of the studies mentioned above, we assumed that skin diseases, like hemangioma or various types of nevi, may have influence on single-period PPG shapes since these pathologies have effect on local skin vascularization. Consequently, the comparison of single-period PPG shapes at healthy and pathological skin regions might work as indication of certain skin diseases.

Conclusions

The newly developed multilaser 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 measurements. The first obtained results demonstrated the feasibility of this methodology for simultaneous detection of PPG signals from various under-skin layers, which has a potential application in skin microcirculation assessment. The further evolution of the multilaser PPG methodology involves experimental data accumulation for the establishment of quantitative descriptive criteria, as well as creation of physical model to associate measured PPG signals with particular depths in skin. A modification of the experimental setup, e.g., a skin contact probe with various irradiation-detection fiber separations, might enhance the method depth resolution.

Acknowledgements The authors L. Gailite and A. Lihackev are thankful to the European Social Fund for financial support.

References

1. Spigulis J (2005) Optical non-invasive monitoring of skin blood pulsations. Appl Opt 44:1850–1857
2. Johansson A (2000) Photoplethysmography in multiparameter monitoring of cardiorespiratory function. Department of Biomedical Engineering, Linköping University, Linköping
3. Ugnell H, Öberg PÅ (1995) Time variable photoplethysmographic signal: its dependence on light wavelength and sample volume. Proc SPIE 2331:89–97
4. Lindberg LG, Öberg PÅ (1991) Photoplethysmography. Part 2. Influence of light source wavelength. Med Biol Eng Comput 29:48–54
5. Hales JR, Roberts RG, Westerman RA, Stephens FR, Fawcett AA (1993) Evidence for skin microvascular compartmentalization by laser-Doppler and photoplethysmographic techniques. Int J Microcirc Clin Exp 12:99–104
6. Sandberg M, Lundeberg T, Lindberg LG, Gerdle B (2003) Effects of acupuncture on skin and muscle blood flow in healthy subjects. Eur J Appl Physiol 90:114–119
7. Jacques SL (1998) Skin optics. Oregon Med Laser Center News 1:1–9. http://omlc.ogi.edu/news/jan98/skinoptics.html
8. Erts R, Spigulis J, Ozols M (2005) Optical systems for non-invasive cardiovascular biosensing. Proc SPIE 5908:170–176
9. Allen J (2007) Photoplethysmography and its application in clinical physiological measurement. Physiol Meas 28:R1–R39