Optical noninvasive monitoring of skin blood pulsations

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Time-resolved detection and analysis of skin backscattered optical signals (remission photoplethysmography or PPG) provide rich information on skin blood volume pulsations and can serve for reliable cardiovascular assessment. Single- and multiple-channel PPG concepts are discussed. Simultaneous data flow from several locations on the human body allows us to study heartbeat pulse-wave propagation in real time and to evaluate vascular resistance. Portable single-, dual-, and four-channel PPG monitoring devices with special software have been designed for real-time data acquisition and processing. The prototype devices have been clinically studied, and their potential for monitoring heart arrhythmias, drug-efficiency tests, steady-state cardiovascular assessment, body fitness control, and express diagnostics of the arterial occlusions has been confirmed.

OCIS codes: 170.4580, 120.3890.

1. Introduction

Human skin plays an important role in various physiological processes including thermoregulation, neural reception, and mechanical and biochemical protection. The heart-generated blood-pressure waves propagate along the skin arteries, locally increasing and decreasing the tissue blood volume with the periodicity of heartbeats. The dynamic blood volume changes basically depend on the features of the heart function, size and elasticity of the blood vessels, and specific neural processes. Therefore direct monitoring of skin blood pulsations may provide useful diagnostic information, especially if realized noninvasively.

Optical technologies are well suited for noninvasive monitoring of skin blood pulsations. Radiation of the red–to–near-infrared spectral region penetrates several millimeters under the skin surface, thus reaching the dermal blood vessels. The methodology called remission photoplethysmography (PPG) proposes following the blood volume pulsations by detection and temporal analysis of the tissue backscattered optical radiation.[1] This radiation is partially modulated by the periodic arterial blood volume changes, since they cause the corresponding dynamic changes of the absorption within the covered skin tissue volume. Skin blood volume pulsations are well-reflected that way; therefore the PPG technique has good potential for express diagnostics and early screening of cardiovascular pathologies, for self-monitoring at home and in public facilities, and for telediagnostics by way of Internet or local area network (LAN). Skin blood pumping and transport dynamics can be monitored at different body locations (e.g., fingertip, earlobe, forehead) with relatively simple and convenient PPG contact probes. Simultaneous data flow from several body locations—the multichannel PPG technique—increases the reliability of clinical measurements, also allowing us to study heartbeat pulse-wave propagation in real time and to evaluate the vascular blood flow resistance, an important physiological parameter for vascular diagnostics.

In general, each recorded PPG pulse contains useful information for cardiovascular assessment. More-detailed information can be obtained by analysis of the PPG signal sequences recorded over some time interval, e.g., one to a few minutes. The amplitude, baseline, and period of the dc component of the PPG signals change with time in reaction to respiration, neural activities, and body movements. However, contemporary signal-processing technology allows us to overcome these difficulties and to provide reliable diagnostic information, e.g., by extracting the normalized averaged single-period (SP-PPG) signals. The shape of the SP-PPG signal is unique for each monitored person[2,3] because of the individual features of his or her cardiovascular system, so a proper

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SP-PPG signal shape analysis certainly may help to assess the human cardiovascular condition.

Some developments of the PPG methodology and equipment for monitoring of skin blood pulsations, worked out at the University of Latvia over the past few years, are described below. Basic designs of the newly created PPG sensor devices and biosignal processing approaches will be discussed, with illustrations of the most interesting results obtained in the laboratory and clinical trials by means of the single- and multiple-channel photoplethysmography techniques.

2. Designs of the PPG Sensing Devices: Single, Dual-, and Four-Channel Versions

A. Single-Channel PPG Sensors

Our first version of the single-channel finger sensor with biosignal averaging[2,3] was intended for clinical use in conjunction with any standard PC. Three basic modules are needed for its operation—the sensor head (fingertip probe with amplifier), standard analog-to-digital (AD) card, and a standard hard disk (preferably separate) with the signal-processing software and space for storage of the recorded data. All electronic circuits were fed by the PC power supply.

The finger contact probe–sensor head comprises a continuously emitting GaAs diode ($\lambda_{MAX} \sim 940$ nm) integrated with a 1 cm^2 active area silicon (Si) photodiode and a preamplifier chip. The preamplified output signal is passed via a flexible cable to the broadband amplifier and further to the AD-conversion card input. Only the ac component of the photodiode output signal has been amplified and further processed; the amplifier provided 400-fold magnification. Following the results of our study,[4] frequency filtering of the remitted PPG signals may deform the shape of the signals; therefore signals of all frequencies were amplified and passed to the input of the 12-byte AD card.

The LED and photodiode of the fingertip probe were downoriented during the measurements, and additional calibrated load was applied to provide equal pressure force (0.65 N) to the fingertip skin for all monitored patients. The contact probe was placed within a vertical cylindrical capsule that served simultaneously as a finger holder, shield of external light, and sliding guide for the optical probe. The middle finger of the left hand was used mainly for the PPG signal recording with this device, and the patients were kept in a horizontal position lying on their backs during the measurements.

The PPG signals are not strictly repeating and periodical; there are always slight fluctuations of their amplitude, baseline, and period.[5] One can assume that these fluctuations take place relative to some virtually stable mean single-period PPG (SP-PPG) signal. The mean signal can be identified by averaging a number of sequent PPG pulses over a time interval longer than 50 s (which is the longest fluctuation period[5]). A special algorithm[6] calculates the mean normalized single-period fingertip signal for the monitored person, as well as the corresponding signal shape parameters—maxima, minima, amplitude ratios, integral area, and so on. Heartbeat rate can be calculated and arrhythmias detected, as well. All these data appear on the PC monitor within 5 s, so the time necessary for the entire measurement procedure normally does not exceed 2 min.

Fig. 1. Portable version of single-channel PPG sensor: application for the fingertip monitoring.

The signal-processing software is stored on a separate hard disk, which serves for operation of the sensor device and for storage of the measured and calculated data. The initial algorithm[3] for integration and averaging of the detected PPG signals was subsequently updated, and a service program was added. At the beginning of each trial, a window for entering the monitored patient data (name, age, pathology, and so on) is opened. The measurement window with instructions appears subsequently, and after proper placement of the fingertip probe, the measurements are started. The data are recorded for 60–80 s, and then the whole PPG signal is stored in the hard-drive memory and processed.

Later another, portable, version of the single-channel PPG sensor device based on a laptop computer was developed.[7] Figure 1 shows the real-time data-acquisition process. The optoelectronic contact probe has been modified in this design version: It comprises a GaAs emitting diode (diameter of the emitting area, 2 mm; power, 10 mW; peak wavelength, 940 nm) together with a smaller Si photodiode that has a square detection area of approximately 5 mm $\times$ 5 mm. Both diodes are closely mounted on a soft plastic pillow and affixed to the measurement site by means of a sticky band. The band as shown in Fig. 1 is adjusted to the fingertip measurements; however, the band can easily be extended by spare sticky bands if necessary, thus providing the possibility to take PPG measurements eventually from any location of the body, e.g., forehead, neck, forearm, knee.

The signal AD conversion was realized in a somewhat original manner, by use of the built-in computer

sound card.[8] The frequency of the sinusoidal output signal of the sound card determines the time resolution of measurements; the upper limit for the sound card in our studies was 44,100 Hz, so theoretically the time interval 23 μs between the neighboring measured points could be achieved. To save resources, we selected a working frequency that is 200 times lower, −220.5 Hz; the corresponding time gap between the measured points was less than 5 ms, which is quite satisfactory for recording well-resolved heartbeat signals.

Special software was developed for the PPG biosignal acquisition, processing, and data storage, offering the following options:

- Filling the window for patient data: name, age, gender, complaints, doctor's comments, and so on.
- Presetting of the measurement time schedule.
- PPG signal registration and display in real time.
- Signal cleanup (special filtering algorithm) and calculation of the mean SP-PPG signal shape.
- Calculation of specific cardiovascular parameters for the registered signals: heartbeat rate, *anacrota* rise time, time delay and relative amplitude of the secondary peak (*dycrotic* notch), and so on.
- Display of the corresponding PPG parameter set with subsequent cardiovascular assessment results.
- Storage of the measurement and assessment data.

B. Dual-Channel PPG Sensor

The dual-channel device[9] comprises two optical contact probes that are applied simultaneously during the measurements, the biosignal acquisition/conversion circuit and a laptop computer with specially developed software. All equipment is placed in a handheld case of size 44 cm × 32 cm × 9 cm and weight 4.1 kg; it is battery powered and can operate up to 3 h without recharging.

Each optoelectronic contact probe emits cw radiation into the skin tissues and detects the backscattered radiation; the separated ac component of the signals precisely reflects the skin blood pulsations at the probe-covered volumes. Both contact probes comprise a pair of GaAs emitting diode and Si photodiode as described in Subsection 2.A, mounted on a sticky band or on a finger clip. The band probe with flexible extension is useful for taking the PPG signals from practically any location of the body. The functional scheme for the dual-channel device is presented in Fig. 2.

The original software manages PPG biosignal acquisition, processing, and data storage from both input channels. In addition to the options described above for the single-channel design, it provides real-time display of both PPG signals and subsequent calculation of the time shift between the corresponding heartbeat pulses detected at two measurement sites. The data sampling rate 100 s^{-1} was usually chosen; it could be increased up to 950 s^{-1} for special cases when higher time resolution was needed, so the interchannel time shifts were determined with an accuracy of ±0.01 s or better.

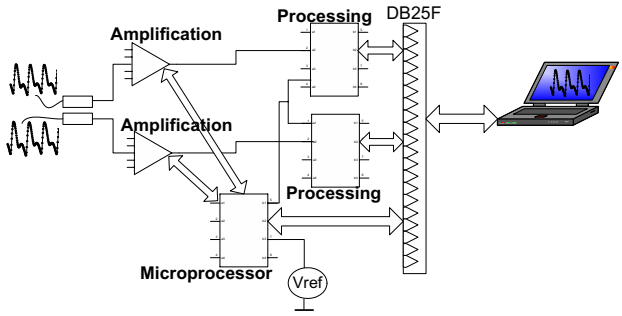

Fig. 2. Dual-channel PPG sensor device: functional scheme.

The dual-channel design proved its effectiveness for comparative clinical measurements and, especially, for the physical fitness tests.[9,10] Moreover, it has been adapted for biosignal transmission via the Internet.[9]

C. Four-Channel PPG Sensor

Following similar principles as described for the dual-channel sensor, a more-advanced four-channel PPG prototype device[11] has been designed and clinically tested. Its basic concept—to provide simultaneous PPG data flow from four body locations, e.g., the same fingertips of both arms and the same toes of both legs. Such a measurement scheme makes it possible to follow the time shifts between PPG pulses detected at any of the four body locations where the contact probes are attached, e.g., "right finger–left toe" or "right toe–left toe." The PPG signal shapes at each channel and their changes can be determined online as well. The four-channel PPG sensing results are represented in real time (Fig. 3); all data are stored digitally for further analysis. Direct online display of the time shift between the PPG pulses of any two channels is also available.

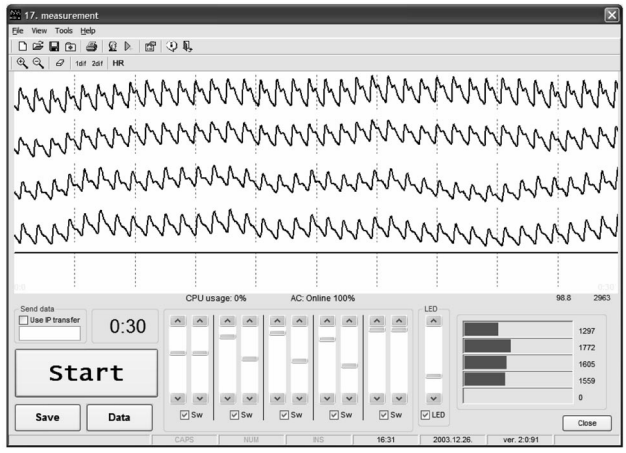

Fig. 3. Four-channel PPG monitoring screen shot during the clinical measurements.

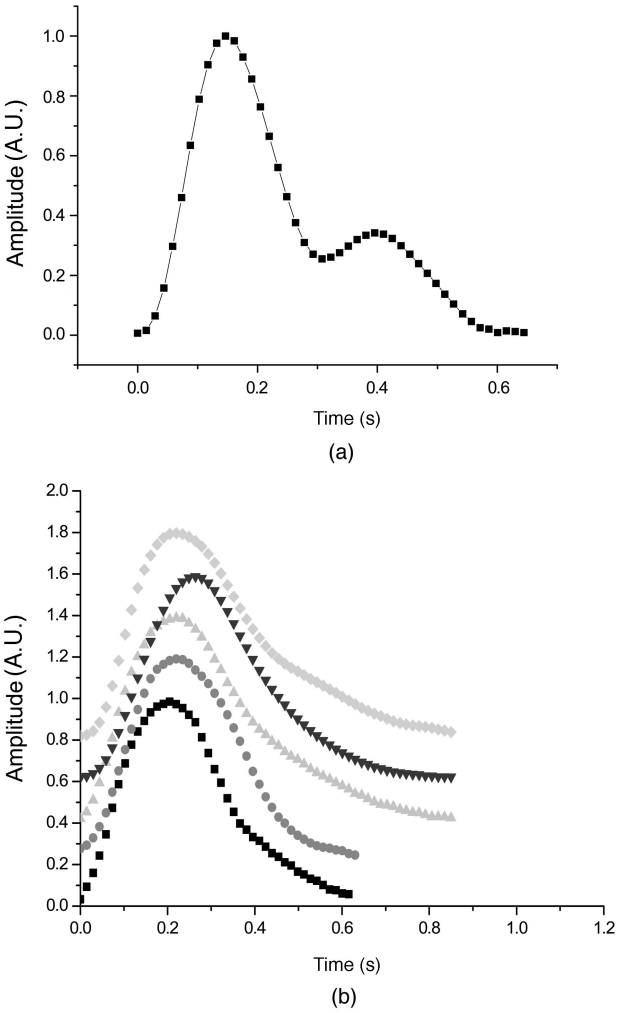

Fig. 4. Mean SP-PPG signal shape for (a) a healthy person and (b) five diabetic patients.

3. Cardiovascular Monitoring with the Developed PPG Devices

A. SP-PPG Signal Shapes and the Drug Efficiency Tests

Each PPG signal comprises a fast rising part or *anacrota*, which normally reaches its peak value within 0.1, . . ., 0.3 s, and a subsequent falling part or *catacrota*. The *anacrota* reflects the stretching of blood vessel walls under the increased blood pressure after each heartbeat; the *catacrota*, relaxation processes of the blood vessel walls in between every two heartbeats. The *catacrota* can be variously shaped, depending on the vascular condition; it normally contains a so-called *predycrotic* dip (which can be more or less pronounced) and a secondary or *dycrotic* peak (notch) caused by elastic reflections in the arterial system. A typical healthy person's mean SP-PPG signal shape is presented in Fig. 4(a).

The mean SP-PPG signal shape is highly individual to each monitored person; qualitative differences in signal shapes for healthy individuals compared with those for persons with cardiovascular disorders were observed. The shape of the SP-PPG pulse detected at the periphery (e.g., fingertip) can differ significantly from that at the magisterial arteries; it primarily depends on the vascular resistance. If the blood vessel resistance is abnormally high because of atherosclerosis, diabetes, or other vascular pathology that narrows the vessels, blood flow from big arteries to the small skin blood vessels decreases dramatically. As the result, the propagating blood-pressure pulse wave becomes broadened and delayed and may completely lose its secondary (*dycrotic*) peak when the periphery is reached. Our studies with five diabetic patients fully confirmed this assumption: All the SP-PPG signals taken from their fingertips were bell shaped, without any secondary peak at the *catacrota* part [Fig. 4(b)].

The clinical trial with atherosclerotic patients resulted in very similar SP-PPG signal bell shapes. Effects caused by pharmacological dilatation of the blood vessels by means of nitroglycerine were also investigated in this trial. As an example, the observed changes of the fingertip mean SP-PPG signal shape with time are presented in Fig. 5(a). One can follow the gradual creation and growth of the secondary peak at the *catacrota* part of the signal (time moment t_2) over the first minutes after intake of the medicine. This peak is clear evidence of increased blood flow via the damaged vessels as a result of their

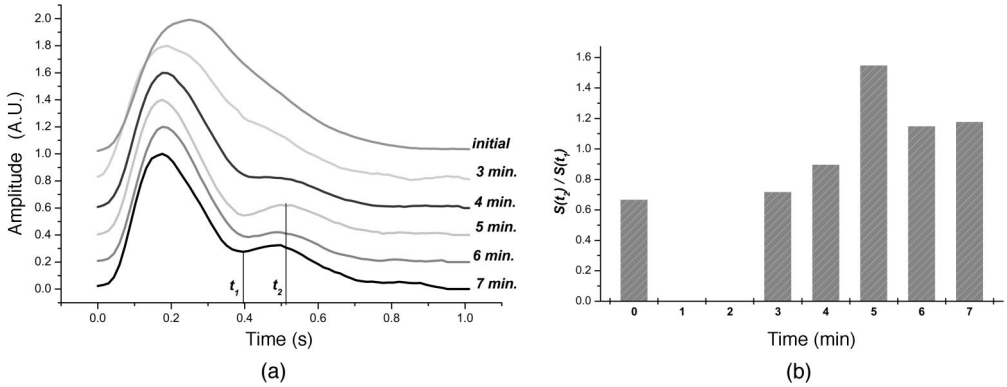

Fig. 5. Mean SP-PPG signal changes of an atherosclerotic patient (a) 3, . . ., 7 min. after taking a nitroglycerine dose and (b) [with amplitude ratio $S(t_2)/S(t_1)$] the related time development of the vessel-opening drug effect.

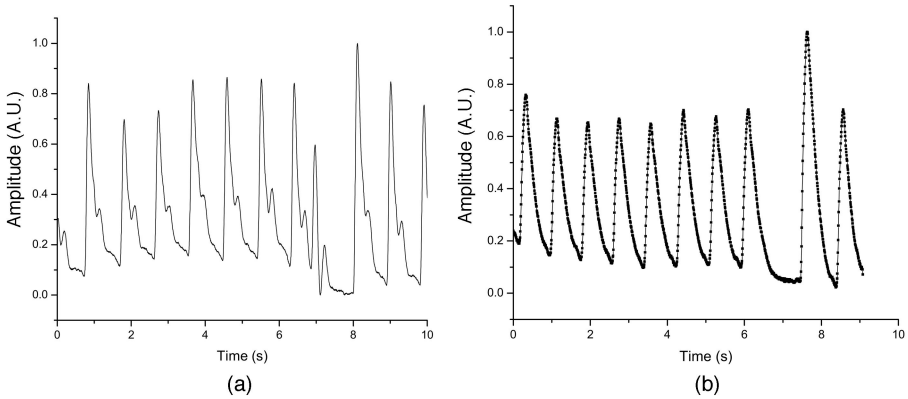

Fig. 6. Observed abnormal heart functioning: missing heartbeats for (a) a female, age 30, and (b) a male, age 65.

enlargement, and it confirms the possibility of quantitative documentation of drug efficiency by means of the SP-PPG techniques. In terms of signal amplitude ratio $f = S(t_2)/S(t_1)$ at two fixed time moments (t_1, the dip; t_2, the secondary peak), the blood flow reached its best condition (the highest f value) approximately 5 min after the intake of nitroglycerine [Fig. 5(b)]. This example confirms the promising potential of the proposed SP-PPG methodology for vascular drug-efficiency tests; more details are given in the original paper.[6]

B. Real-Time PPG Measurements

1. *Detection of Abnormal Heart Functioning*

Using the single-channel PPG finger sensor, we observed and recorded several abnormalities of heart function, including partial or total lack of one heartbeat in the cardiac sequence (see Fig. 6). Typically, the next heartbeat after the missing one is more intensive than others in the sequence, so obviously the heart is autocompensating the short-term lack of blood supply. The monitored persons did not feel any discomfort during the missing heartbeats. This phenomenon was recorded several times, so there was little doubt that both persons had trouble with heart functioning, and they were advised to visit the cardiologist for further investigation.

Consequently, the PPG sensor device appeared helpful for early warning of cardiovascular dysfunction, and there is a promising potential for primary cardiovascular assessment and early screening of risk patient groups in the future.

2. *Adaptation of the Cardiovascular System to Physical Exercise: Fitness Tests*

A series of PPG measurements were performed before and after intensive physical exercises, aiming to follow the cardiovascular relaxation process that reflects adaptability of the body to physical loads. The monitored volunteers at the first series with single-channel fingertip device were young athletes (16–22 yr) involved in field athletics; the measurements were taken in the stadium during their training. Along with the expected results, in some cases we observed abnormal responses. Two illustrations are presented below: *arrhythmic* heartbeats and sharp *spasmatic* peaks in the fingertip remission PPG signals recorded immediately after the exercises (Fig. 7, upper curves). Most likely, they can serve as markers of the body dysfunction(s) regarding adaptation to intensive physical loads; however, these effects have to be studied in more detail before we draw any serious conclusions.

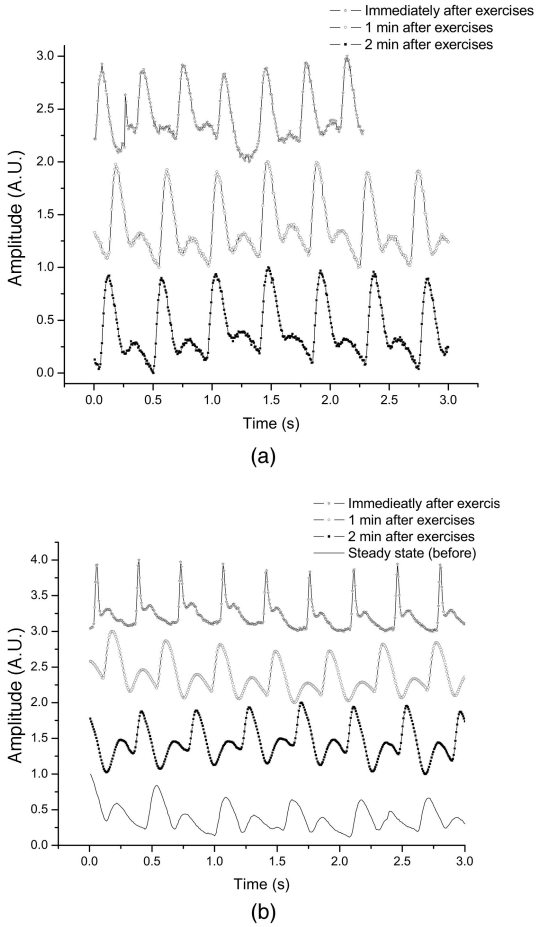

Fig. 7. Abnormal responses of the cardiovascular system to intensive physical exercises: (a) arrhythmic, (b) spasmatic.

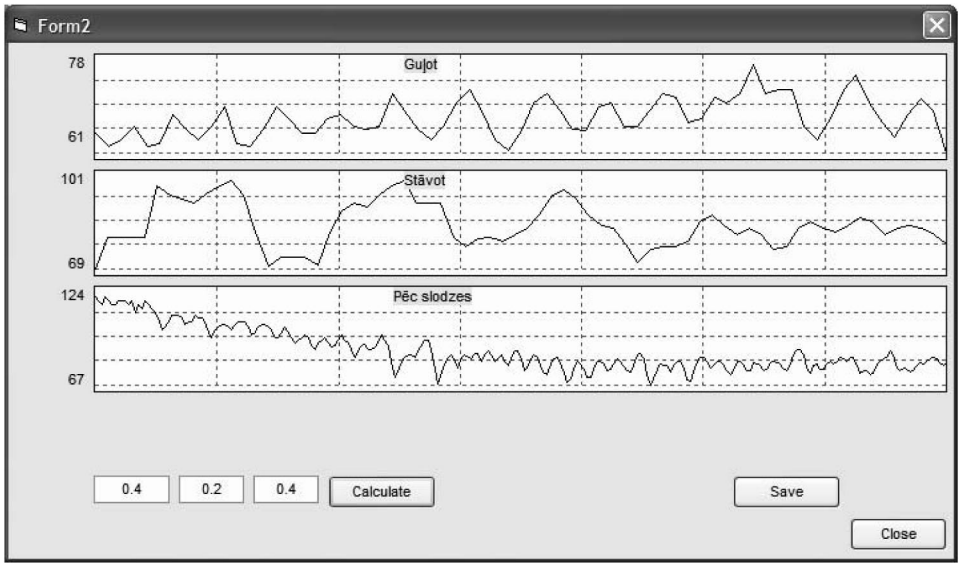

Fig. 8. Data extraction example: pulse-rate variations during rest phases of the fitness test: horizontal, vertical, and relaxed sitting.

As the next step we performed dual-channel PPG measurements before, during, and after intensive physical exercise. Specific exercise-induced features of the biosignals that might give evidence of person's adaptability to physical loads and possible cardiovascular disorders were studied. The monitored volunteers—approximately 200 in total—were of both genders at various ages and of different training backgrounds (including 30 professional athletes). The PPG signals were detected simultaneously from the left middle fingertip and from the carotid artery area on the left side of the neck. The test protocol included four stages: horizontal relaxation (1 min), steady standing position (1 min), metronome-controlled stepping up and down (so-called Harvard step test[12], 3 min), followed by relaxing in the sitting position (5 min). The dual-channel PPG signals were recorded continuously over the whole test, 10 min in total for each volunteer.

The after-exercise heart arrhythmias (if they appeared) were always convincingly detected simultaneously at both channels. A Microsoft Access database with Visual Basic 6.0 software was created for further analysis of the functional parameters at different test phases. The illustrated pulse-rate variations (Fig. 8) were calculated from the varying time intervals between the neighboring PPG peaks: the dominant pulse-rate oscillation frequencies, with Fourier analysis; the mean recreation time after the exercise, by finding the time constant of exponential pulse-rate decay. The pulse-wave transit time (PWTT) between the neck and fingertip was measured as the time delay between the corresponding PPG pulses recorded at carotid and fingertip, in a similar manner as at the fingertip–toe measurements.[13]

The data analysis showed that even the initial test phase—transfer from horizontal to vertical steady state—might give useful data for assessment of the cardiovascular condition. Pulse rate increased for all volunteers passing this transfer. We selected 50 trained athletes and 31 untrained volunteers to study the statistical distribution of such heartbeat rate in-

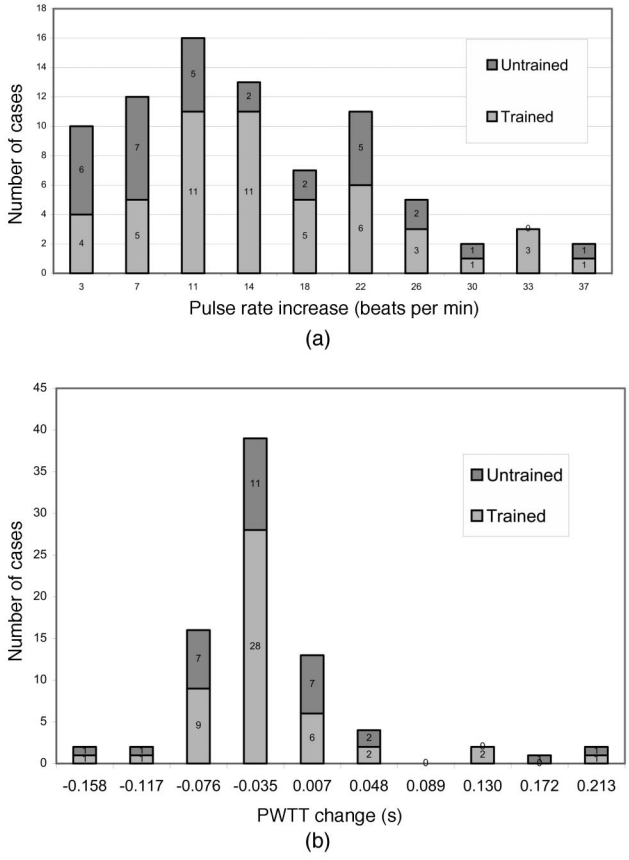

Fig. 9. Distributions of (a) the mean pulse-rate increase and (b) the change of the pulse-wave transit time after patient stands from a lying position.

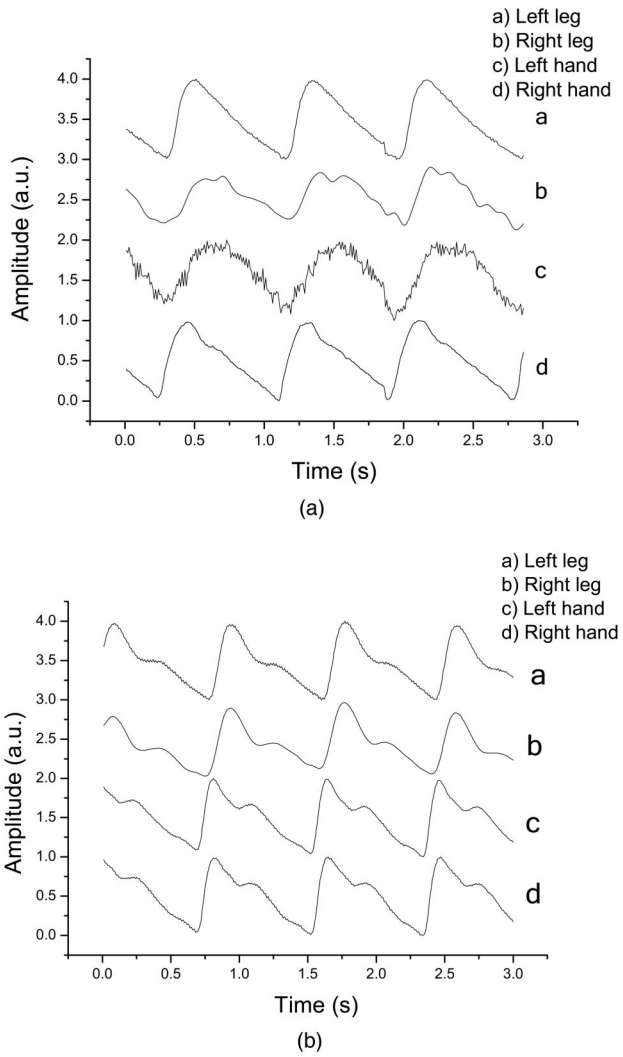

Fig. 10. Comparison of the four-channel PPG recordings taken from a patient with signs of the left arm occlusion (A) and from a healthy volunteer (B).

crease. Results with selected pulse-rate increase intervals of 3 beats/min (0–3;4–7;8–11; and so on) are presented in Fig. 9(a).

No substantial differences between trained and untrained persons were observed from this point; however, significant increase of pulse rate (e.g., for more than 30 heartbeats/s) resulting solely from change in body position seems suspicious and might indicate vascular tonus problems.

Following all phases of the test, we also observed notable variations in the pulse-wave transit time PWTT (proportional to the vascular resistance) during the test. When focusing on only the first two stages of the test, for most volunteers we observed an approximately 0.05–0.08 s decrease of the PWTT after they stood up [Fig. 9(b)]. Unexpectedly, for some volunteers the opposite response—increased PWTT values—were detected. That probably reflects some vascular problems, e.g., spasmatic narrowing of the blood vessels induced by the change of body position.

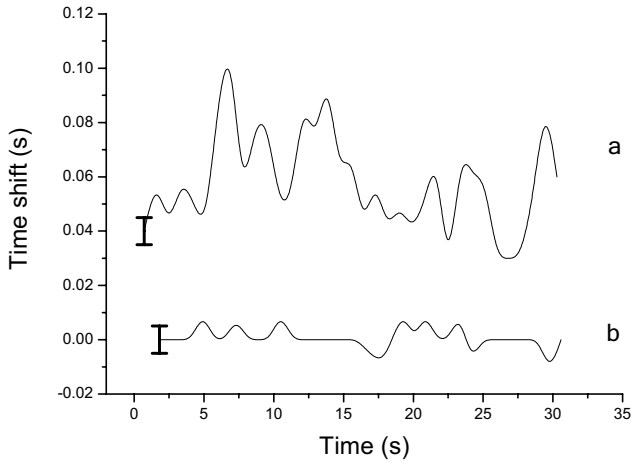

Fig. 11. Variations of the time shift between PPG pulses detected from the fingertips of both arms: (a) 65-year-old patient with left-side arterial occlusion, (b) 26-year-old healthy volunteer.

3. Studies of Arterial Occlusions in the Extremities

The four-channel PPG system had undergone its first clinical tests at the Latvian Institute of Cardiology. For example, a patient (male, age 65), had signs of arterial occlusion in his left hand (diagnosed by a medical doctor after routine local blood-pressure examinations: 135 $\pm$ 5 mm Hg for the right hand, 105 $\pm$ 5 mm Hg for the left hand); his right leg artery had been occluded and surgically treated several weeks before. A fragment of his four-channel peripheral PPG signal set (measured from the middle fingers and the middle toes) is presented in Fig. 10(a).

Figure 10(a) shows a clear difference in the shapes of both finger signals (c, d) and also, less notable, of both toe signals (a, b). Moreoever, the signal from the left-hand finger (c) is delayed relative to that from the right-hand finger (d). This delay may be explained by increased vascular resistance in the left hand as confirmed by routine occlusion diagnosis. To compare, in the case of a healthy volunteer [Fig. 10(b)] the PPG signal shapes in all four channels were similar and no time shifts between the finger–finger (c–d) or toe–toe (a–b) signals were detected.

The right–left fingertip PPG time delay in the case of the occlusion patient was quite unstable: Its variations over 0.5 min are illustrated in Fig. 11(a). This "floating" delay might be related to the abnormal vascular resistance changes caused by neural or other regulatory processes. In the case of the healthy volunteer [Fig. 11(b)], no time delay between fingertip signals within the measurement errors was detected (note the error bar).

Generally, these data let us assume that the time delay between PPG signals recorded from symmetric parts of the body eventually may serve as a diagnostic marker of arterial occlusion.

4. Summary

Our findings can be summarized as follows:

- Four design versions of optical sensor devices with original software for monitoring skin blood pulsations have been developed: a stationary fingertip SP-PPG sensor and portable (44 cm × 32 cm × 9 cm, 4.1 kg, battery-powered) single-, dual-, and four-channel PPG sensors.
- The corresponding prototype devices have been constructed and tested in laboratory, hospital, and field environments.
- Application examples related to detection of heart arrhythmias, drug-efficiency tests, steady-state cardiovascular assessment, body fitness control, and detection of arterial occlusions have been presented and discussed.
- The performed studies have confirmed the promising potential of the proposed methodologies and techniques for cardiovascular monitoring and early mass screening.

The above-described studies were carried out with the participation of a number of collaborators and contributors. The presented results would never have been obtained without the valuable assistance of my students Uldis Rubins, Maris Ozols, Girts Venckus, Eva Fridenberga, Karlis Prieditis, and Renars Erts. Sincerest thanks also to Indulis Kukulis for his clinical support and to Juris Aivars for his physiological comments. Financial support from Latvian Council of Science grants 01.0067 and 04.283, Latvian Ministry of Education and Science grant TOP 02-13, and University of Latvia grant LU-14 is highly appreciated.

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