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The effect of local cold and warm exposure on index finger photoplethysmographic signal waveform

Kristjan Pilt, Kalju Meigas, Kristina Temitski and Margus Viigimaa

Abstract— **The study was carried out in order to analyse the changes in photoplethysmographic (PPG) signal waveform, which are caused by cold and warm stimulation. The study was carried out on 7 subjects. The right hand was immersed in cold and warm water up to the wrist during the experiment. The PPG signal was registered from right hand index finger. As a reference, the temperatures of index finger and pulse transit time (PTT) values were measured. A correlation of r=-0.70 was found between normalised slope of the PPG signal and the subject's age. The normalised slope increased noticeably due to the cold and decreased due to the warm water stimulation. It was opposite to the expected results with PTTs and the behaviour has to be investigated in future studies.**

I. Introduction

There is increasing interest for simple and non-invasive screening methods and devices, which can be used for the diagnosis of cardiovascular diseases. Ageing causes the stiffening of arteries. The possibility to diagnose vascular stiffening in early stadium may be of considerable value in the prevention of cardiovascular disease. Among the other non-invasive methods, pulse wave analysis has been used for arterial stiffness estimation [1].

The photoplethysmographic (PPG) method can be used for pulse wave registration [2]. The PPG method is a simple and relatively cheap optical non-invasive technique, which can be used for the registration of blood volume and velocity changes in the microvascular bed of tissue. The light, which is often in the region of red or infrared, is emitted from the light source (e.g. light emitting diode - LED) to the examined tissue for the signal registration. A photodetector is placed adjacent to the light source (reflectance mode) or opposite side of examined tissue (transmittance mode) and the back scattered or transmitted photons are detected respectively. The PPG signal consists of a large DC component and an AC component about ten times smaller.

The DC component of the PPG signal is related to the non-pulsating blood volume in tissue. The slow changes in the DC component can be caused among the others by vasomotor activity [3]. The AC component of the PPG signal is synchronous with the cardiac cycle. It is generally accepted that the AC component of the PPG signal corresponds to the pulse wave [4].

There is still uncertainty about what the origins of different components in pulsating waveform are and what the AC component of the PPG signal actually represents at different body sites. A number of studies have been carried out on finger PPG pulse waveform analysis [3]. It has been noticed that the waveform changes with age, hypertension and arteriosclerosis. Differences have been discovered between healthy subjects and diabetes patients [5]. It can be assumed that changes of certain parameters in PPG signal waveform are related to the stiffness of blood vessels.

The AC component amplitude increases due to the local heating and decrease due to the cooling of hand [3]. The local hand cooling is associated with vasoconstriction and heating with the vasodilatation of arteries and arterioles. It can be expected that the stiffness of the blood vessels will increase due to the muscle contraction of the arterioles and arteries. With vasodilatation, the opposite effect is expected. Recently, a study was carried out about PPG signal waveform analysis during cold pressor test in order to monitor cardiovascular reactivity and describe the changes in the waveform due to the stiffness change [6]. However, this experiment was carried out on the contralateral hand from the cold water immersed hand and the changes depended on the nervous system reactivity.

In order to gain a better understanding of the origin of the PPG signal waveform and to extract more clinically useful information related to the local stiffness changes of blood vessels, we have carried out this pilot study. The stiffness of the arteries is changed through the induced vasoconstriction and vasodilatation by immersing the hand in cold and warm water. The PPG signal is studied in the time domain and the DC, AC components and slope of the PPG signal waveform front are analysed.

II. Methods

The pulse wave signal was registered from the right hand index finger by using the PPG method. The commercially available PPG finger clip sensor (Epic SpO2 Finger Sensor E400) was used for signal registration from the index finger. The sensor includes red and infrared LEDs with wavelengths of 660nm and 934nm. The infrared LED of the PPG sensor was used, because the registered signal has a higher signal-to-noise ratio (SNR) compared to the red LED by using the same current level. In addition, the temperature sensor was mounted inside the PPG sensor in order to monitor the temperature of finger. The temperature sensor TC1047A

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K. Pilt is with the Tallinn University of Technology, Technomedicum, Department of Biomedical Engineering, Tallinn 19086, Estonia (phone: +372 6202200; fax: +372 6202201; e-mail: kristjan.pilt@cb.ttu.ee).

K. Meigas, K. Temitski, and M. Viigimaa are with the Tallinn University of Technology, Technomedicum, Department of Biomedical Engineering, Tallinn 19086, Estonia (e-mail: kalju@cb.ttu.ee, kristina@cb.ttu.ee, margus@cb.ttu.ee,).

(Microchip Technology Inc., USA) was used. The PPG sensor was connected to a lab-built module, which transformed the registered signal suitable for the digitalisation.

In addition to the PPG signal registration, the pulse transit times (PTT) were measured in order to estimate the stiffness changes in the vascular branch from heart to right hand wrist (PTT_1) and from wrist to index finger (PTT_2) [7]. PTT corresponds to the time it takes a pulse wave to travel between two arterial sites. The relationship between PTT and the vessel stiffness can be described through Moens-Korteweg equation:

$$\frac{d}{PTT} = \sqrt{\frac{E \cdot h}{D \cdot \rho}}\ , \qquad (1)$$

where d is the distance between two arterial sites, and ρ is density of blood, D is inner lumen diameter, h is the wall thickness, and E is Young's modulus of blood vessel.

For the PTT_1 measurement, the electrocardiographic (ECG) and pulse wave signal from the wrist were registered. The time interval, which is measured between the peak of R-wave of the ECG signal and the rising front of the pulse wave signal, can be taken as PTT [8]. The piezoelectric transducer was used for pulse wave signal registration from the wrist. A transducer was placed on the radial artery by wrapping a bandage around the wrist. The transducer generates a measurable voltage when a deforming mechanical force is applied. A pressure waveform is obtained as a result of the piezoelectric signal integration and it can be taken as a pulse wave. It was ensured that the applied pressure from the transducer to the radial artery does not influence the PTT measurement [9]. The piezoelectric transducer was connected to an amplifier, which transformed the signal suitable for the digitalisation. For the ECG signal registration, the EG 1000 OEM module (Medlab, Germany) was used, where the optically isolated analogue signal output was utilised.

The output signals from PPG module, ECG module, piezoelectric amplifier and temperature sensor were digitalised synchronously with National Instruments NI 9215 data acquisition card (DAQ) with a sampling frequency of 1kHz. The signals were monitored in online and recorded through programme, which was written in the LabVIEW environment.

The measurements were carried out in a quiet and comfortably lighted room. The room temperature was constantly monitored by using a thermometer with a measurement error of ±1°C. The sensors were attached to the subject before the experiment. During the experiment, the subject was awake and in supine position. The experiments were carried out on healthy subjects with different physical conditions, who were participating in the study as volunteers.

In the beginning of experiment, the subject was in supine resting condition for 5 min. (Fig. 1a). As follows, the blood pressure (BP) was measured with an Omron device (M6 Comfort) and the signal registration was started. After two minutes of signal registration for baseline values (baseline period), the PPG sensor was removed and the right hand was placed inside the cold water up to the wrist (stimulation period). The temperature of the water before experiment was 7.1°C±0.4°C and it was monitored during the experiment with a thermometer. The hand was taken out of the water after two minutes, dried with a towel and the PPG sensor was reattached. Over the following 11 minutes, the signals were recorded to analyse the recovery of the parameters (recovery period). As follows, the blood pressure was measured again. After a break of 5 minutes, the signal registration was started and the experiment with warm water was carried out. The procedure with warm water was the same as with the cold water. The temperature of the warm water was before the experiment was 44.8°C±0.8°C. At the end of the experiment, the blood pressure was measured for the third time. The temperatures of cold and warm water were selected according to the previous studies [6, 10].

MATLAB environment was used for the data analysis. All the signals were filtered with a low-pass FIR filter. The cut-off frequency was 30Hz and the order of the filter was 500. The filter was designed using the window method, with the Hamming window function. The DC component was obtained from the PPG signal by using a FIR low-pass filter with a cut-off frequency of 0.1Hz (order of the filter 4000, Hamming window function). The AC component was obtained from the PPG signal by using a FIR high-pass filter with a cut-off frequency of 0.5Hz (order of the filter 4000, Hamming window function).

The PPG signal was processed further for the slope determination from the AC component waveform. The slope of the signal rising front depends on amplitude of the AC component. As a result, the waveform was normalised in length for every period. The normalisation process of the waveform length was described in the previous publication [5]. Normalised slope calculation was carried out for each period, where the maximum peak value of the first derivative signal was taken and divided with the corresponding AC component amplitude.

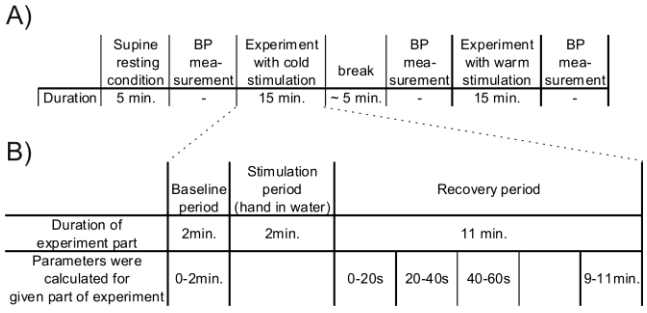

Figure 1. Overview of experiment timeline. A) General overview of whole experiment. B) Timeline overview of cold and warm stimulation experiment parts.

The piezoelectric signal was integrated and R-peaks of the ECG signal were detected by using the Hamilton-Tompkins algorithm. The PTT_1 was measured between 50% of the integrated piezoelectric signal raising front and ECG signal R-peak. The PTT_2 was measured between 50% of the integrated piezoelectric signal and PPG signal AC component raising fronts. PTT_3 is the sum of time intervals PPT_1 and PTT_2.

The average values of normalised slope, PTT_1, PTT_2, PTT_3, DC and AC component values as well as finger temperature were calculated for the following parts of the cold and warm water experiment: 0-2min. from the baseline period, 0-20sec., 20-40sec., 40-60sec., and 9-11min. from the recovery period (Fig. 1b). The beginning of recovery period was analysed with 20sec. long periods as the parameters were changing fastest in this phase of experiment. The change in each parameter as a response to the cold or warm stimulation was calculated. It is the parameter difference (Δ) between the baseline value and the value for each part of the recovery period. The differences in each parameter were averaged for the group of subjects. Paired t-test (Paired Two Sample for Means) was performed in MS Excel for every parameter with α=0.05.

III. Results

The measurements were fully carried out on 7 healthy subjects (5 males and 2 females), who were participating in the study as volunteers. The subjects were aged between 25 and 59 years (mean age of 40±14 years). The average air temperature in the room was 23°C±1.4°C. The average group blood pressure and heart rate values are separately given in Table I for the three parts of the experiment.

In Fig. 2 the group averaged finger temperature changes for both stimulations are shown. The PPG signal waveform changes due to the stiffening of arteries, which are caused by ageing. The relationship between slope values and the subject's age is shown in Fig. 3. The averaged slope values are taken from the baseline signal of the cold stimulation experiment. The Pearson correlation coefficient was r=-0.70, which shows a negative linear relationship between slope and the subject's age.

In Fig. 4 group averaged changes are shown in parameters due to the hand cold or warm stimulation in respect to the baseline values. The significance levels of t-test for every parameter are given in Table II.

TABLE I. GROUP AVERAGED BLOOD PRESSURE AND HEART RATE VALUES FOR DIFFERENT PARTS OF EXPERIMENT

	Before experiment	After experiment with cold water	After experiment with warm water
Systolic blood pressure (mmHg) ± SD	130 ± 10	131 ± 9	129 ± 11
Diastolic blood pressure (mmHg) ± SD	75 ± 7	78 ± 8	79 ± 5
Heart rate (bpm) ± SD	60 ± 9	63 ± 7	61 ± 7

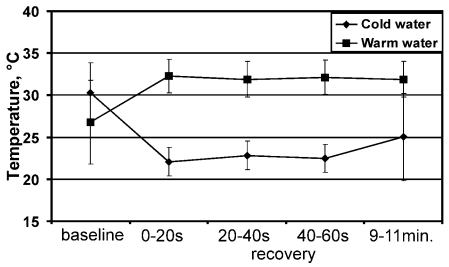

Figure 2. Temperature changes of index finger during the baseline and recovery period.

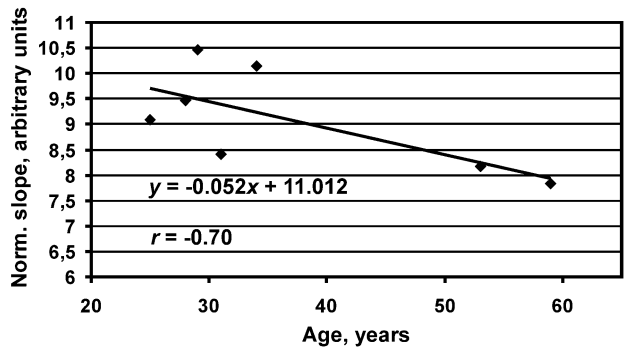

Figure 3. The relationship between the normalised slope of PPG signal and age with constructed regression line.

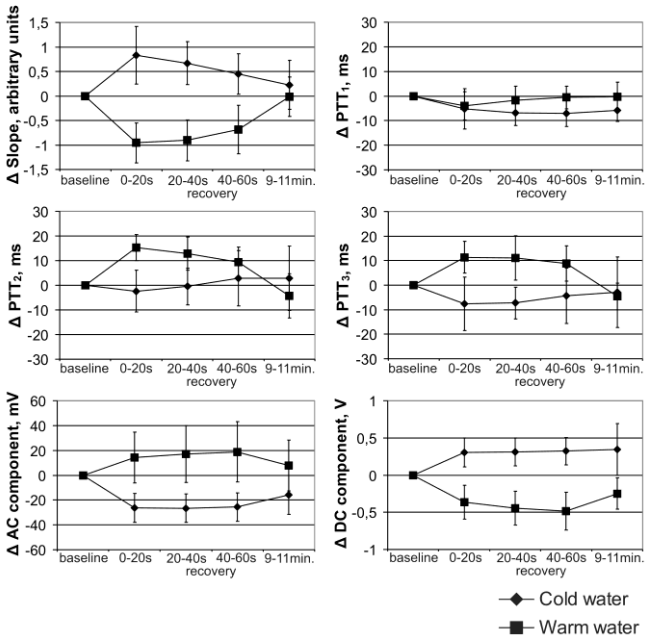

Figure 4. Group averaged changes in normalised slope, PTT_1, PTT_2 and PTT_3 intervals as well as the AC and DC components during the recovery period with respect to the baseline period.

IV. Discussion

It can be seen from Fig. 2 that the temperature of the index finger decreased after the cold stimulation. For two subjects, the temperature of the index finger recovered within 11 min. For the remainder of the subjects, the temperature either had a small increase or remained constant during the recovery period. As a result, the temperature standard deviation is higher for the cold stimulation recovery period in 9-11 min. A similarly high standard deviation of temperature is visible during the baseline period of warm stimulation as this part of experiment was followed about 5 minutes after the end of the cold stimulation recovery period. The temperature increased after warm stimulation. The temperature of the index finger did not recover within 11 min for all the subjects. Despite this, all the other parameters were recovered after 11 minutes of the warm stimulation experiment (Fig. 4). The normalised

TABLE II. SIGNIFICANCE LEVELS OF PAIRED T-TEST FOR CALCULATED PARAMETERS' CHANGES IN RESPECT TO BASELINE PERIOD.

Cold water stimulation				
	Recovery period			
	0-20s	**20-40s**	**40-60s**	**9-11min.**
Slope	0.0048	0.0035	0.0140	0.1406
ΔPTT_1	0.0716	0.0066	0.0055	0.0077
ΔPTT_2	0.2395	0.4401	0.2646	0.2920
ΔPTT_3	0.0586	0.0128	0.1737	0.3057
AC component	0.0005	0.0005	0.0005	0.0191
DC component	0.0032	0.0023	0.0017	0.0193
Warm water stimulation				
	Recovery period			
	0-20s	**20-40s**	**40-60s**	**9-11min.**
Slope	0.0004	0.0006	0.0051	0.4540
ΔPTT_1	0.0607	0.2315	0.3699	0.4452
ΔPTT_2	0.0001	0.0011	0.0034	0.1304
ΔPTT_3	0.0018	0.0087	0.0091	0.0348
AC component	0.0571	0.0483	0.0437	0.1757
DC component	0.0028	0.0010	0.0012	0.0108

slope of PPG signal, PTT_2, PTT_3 and AC component were recovered after the cold water stimulation experiment.

A temperature decrease in the hand causes vasoconstriction. As a result, the lumen diameter is decreased in the small arteries and arterioles of the hand and the whole blood volume is decreased. In addition, it can be assumed that the stiffness is increased through muscle contraction of the blood vessels. Vasoconstriction causes an increase in the DC component of the PPG signal according to the results, because more light is passed through the finger as the blood volume is decreased (Fig. 4). Similarly, the AC component is decreased, because there is less pulsating blood. Vasodilatation is caused by an increase of temperature in the hand and all the previously described effects are opposite (Fig. 4).

During the experiment, there was no noticeable rise found in blood pressure and heart rate within the group before and after the stimulations (Table I). However, a heart rate increase was noticed after the immersion of the hand in the warm or cold water and at the beginning of the recovery period. No constant rise of heart rate was noticed during the stimulation period.

The PTT_1 decreases within 10ms during cold and warm stimulation. Statistically, the change is more probable in the case of cold stimulation (Table II). The changes in PTT_1 can be explained through Eq. (1). Inner lumen diameter or Young's modulus of arteries from the heart to the wrist may be affected through the nervous system due to vasoconstriction or vasodilatation in the hand. In addition it has to be mentioned that the PTT_1 includes pre-ejection period (PEP), which was not monitored separately during this study. This may have effect in the results of PTT_1 and PTT_3.

The PTT_2 and PTT_3 decrease during cold and increase during warm stimulation. Statistically, the change is more probable in the case of warm water (Table II). The decrease and increase in PTT_2 can be explained through the stiffness and lumen diameter change in small arteries and arterioles of the hand due to vasoconstriction and vasodilatation. The results are in accordance with Eq. (1).

It is visible that there is a linear relationship between the slope of the PPG signal and the subject's age (Fig. 3). The deviations of slope values from the regression line in younger subjects can be explained by the difference in stiffness of the blood vessels, which is caused by a difference of physical activity in everyday life. It can be assumed that stiffening of the blood vessels causes a decrease in the slope of the finger PPG signal.

Cold stimulation caused a noticeable increase in the PPG signal normalised slope for all subjects (Fig. 4). The slope values at the beginning of the recovery period are statistically different from the baseline values according to Table II. The slope results in Fig. 4 show the decrease in the stiffness of the blood vessels according to the results in Fig. 3. The effect is opposite with warm stimulation and the stiffness of the blood vessels should increase according to the results in Fig. 3. This behaviour is very interesting as it is opposite to the expected results and not in correspondence with PTT_2 and PTT_3. It can be assumed that the normalised slope changes and the PTT_2 and PTT_3 changes are not caused by the same factors or it is the sum of different factors that gives the opposite result. Furthermore, the Eq. (1) is not fully compatible to describe the changes in the periphery, as it is fully valid for one blood vessel. Within this paper, the behaviour of the slope change cannot be explained and it has to be investigated more in future studies.

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