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Photoplethysmography signal analysis to assess sauna exposure, arterial elasticity, and recovery

Abstract: The basic biomedical information on illnesses is increasing, however, diseases like arteriosclerosis (AS) is becoming a common cardiovascular disorder among elderly people, especially in females. It is predicted that the negative impacts of AS on young people can be greater than on the elderly people in the long run. Degenerative changes in the vascular tree have many causes in addition to the life style. Arterial elasticity (AE) would provide a direct indicator for cardiovascular healthiness and predict AS risk. Photoplethysmography (PPG), and especially its response pulse wave decomposition, envelope analysis, and its second order derivative (SDPPG) opens us to determine the instantaneous heart rate (IHR) which is used to seeing on fitness equipment, sports watches, and consumer heart rate devices. It is measured in beats per minute. We do not remove ectopic or anomalous beats. A physical exposure of human to sauna bath has been shown to improve endothelial function in patients with risk factors and also heart failures. Namely, sauna exposure promotes relaxation and wellbeing, which can be recommended to prevent the development of diseases also in healthy adults.

Keywords: arterial elasticity, photoplethysmography, pulse wave analysis, sauna exposure

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1 Introduction

The hemodynamic responses to the sauna exposure have specific effects which are not caused by one single stimulus. The responses, which are caused by the sauna exposure, can depend on thermoregulatory responses, age, gender, the circulatory and respiratory system, as well as traditions related with the exposure time and temperature of the Finnish sauna [2].

PPG measurement receives interest because of the simplicity, but the difficulty of adjusting parameters restrict applications. However, its second order derivative (SDPPG) opens us to determine the instantaneous heart rate (IHR) which is $60/(t_{An-1}-t_{An})$ where t_{An} is the n^{th} A peak of SDPPG. The sauna exposure can be recommended mainly in order to easier recover after physical exercise, and the various pain problems. The sauna exposures in long term effect on the motion system increases arterial elasticity. It reduces the viscosity of the blood so that blood flows easier and increases diameters of blood vessels and the joints' mobility. The IHR and variation of arterial elasticity with blood pressure are caused by the sauna exposures on healthy subjects. (Fig. 1 upper, before sauna, lower, after sauna).

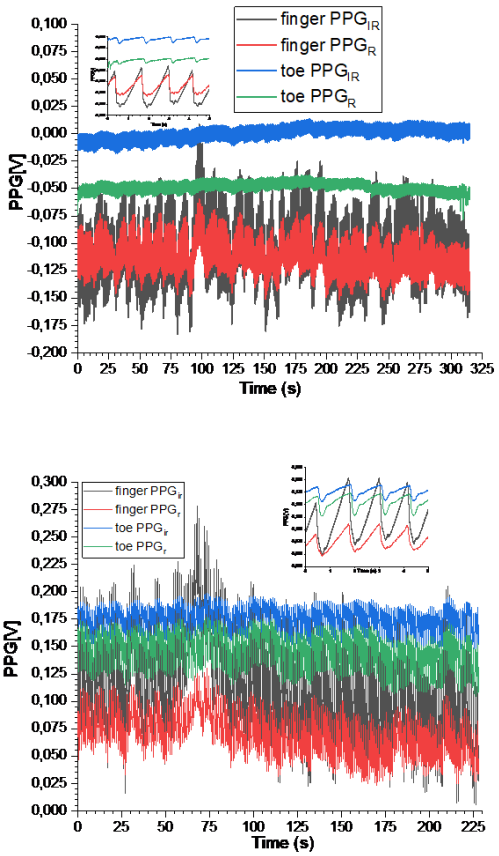

Fig. 1. Resting state PPG signal before sauna exposure for 32 years healthy male subject: finger PPG_{ir} & PPG_{red} and toe PPG_{ir} & PPG_{red} (before sauna upper, and after sauna lower). Inserts the first 5 s.

Regular sauna bathing has been shown to be protective

from cardiovascular disease according to litterature [3, 4, 5]. Our vascular system responds to interval training, especially by the sauna exposures the body to heat alternating between sauna heat and normal temperatures, the arteries are stimulated to expand and after sauna to contract. Theoretically sauna can have a great influence on the basic hemodynamic parameters such as rising the heart pulse rate, lowering blood pressure, photoplethysmography and also arterial elasticity [1]. However, the arteries expand and contract also in the resting state (Fig. 1). The sauna exposure is associated with short-term improvement in cardiac function indicated by photoplethysmographic measurements from the left forefinger and the left second toe. However, we have healthy subjects in this study. Informed consents were obtained from the test subjects, who abstained from alcohol, caffeine, and strenuous exercise in the 24 h up to the day of the tests.

2 Method and Subjects

Accurate determination of start and peak of a PPG signal plays a central role in arterial stiffness, instantaneous heart rate, and its variability. For analysis of four PPG signals correspond to each other perfectly at a given frequency, as in the case of finger IR (infra red) and red LED. In PPG technology, the main difficulty is its quantitative analysis. PPG based on phase sensitivity technic has proved very good. In our measurements the light intensities and wavelengths (red 640 nm & infrared 920 nm) are fixed. In practice, the arterial pulse waveform is based on the propagating pulse wave from the left ventricle. It travels through the arterial circulatory system and arrives the multiple peripheral, parallel capillary arteries (in Figure 1 to finger and toe). The elasticity index was calculated as the relation of the peak time of percussion wave to the peak time sum of the other waves..

The clinical patient measurements were conducted in Oulu University Hospital (OUH, Finland) as a clinical device test (test II), where we studied 17 patients of who 10 subjects exhibited normal arterials and 7 patients with peripheral arterial disease according to the ankle brachial index (ABI). Additionally, young female and male volunteers with good heart health status were included from the University departments in the sauna test group of 28 subjects. The volunteer subjects in the clinical device test and in the sauna test participating in the study were examined in supine in the Oulu University, Workshop sauna facility (I test), and OUH (II), Blood Surgery Clinic, with PPG probes. The groups contain data from 17 (II) (5 Europeans, 3 African Africans) and 28 (I) clinical subjects. The studies were approved by the ethical review boards of the Oulu University, OUH, and the Finnish National Supervisory Authority of Health and Welfare (VALVIRA).

3 Results and discussion

In Figure 2, PPG pulse waveform is decomposed to its primary wave, percussion, tidal, dicrotic, repercussion, and retidal for one heartbeat.

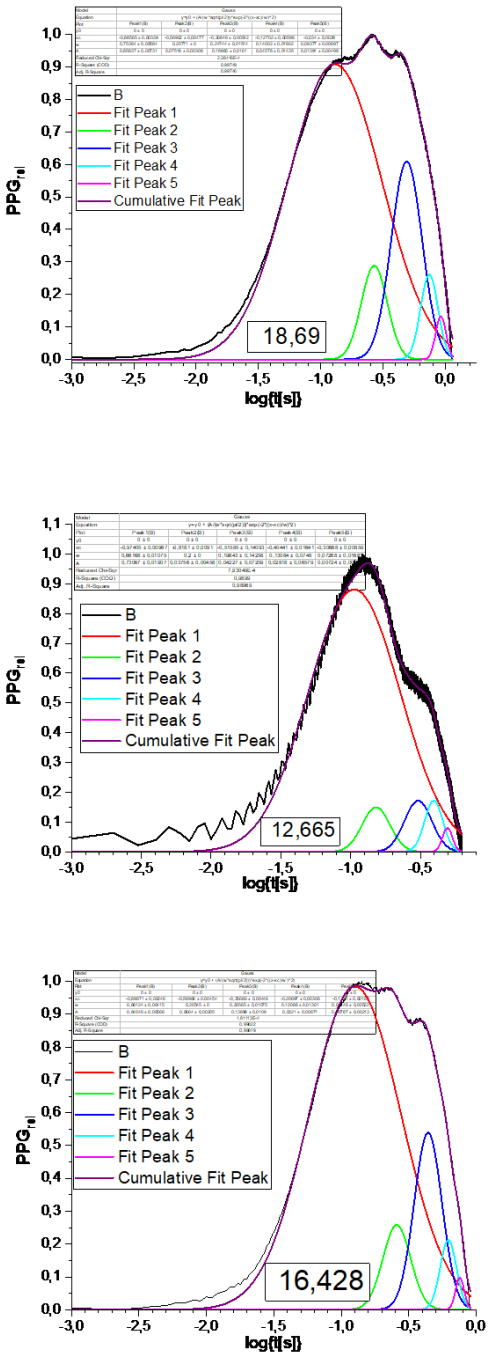

Fig. 2. PPGs from a 32 years male decomposed to its component before (upper), in sauna (middle), and after sauna (lower). Index is 18,690, 12,665 and 16,428.
The PPG pulse waves are decomposed so that they produce five primary components: percussion wave, tidal wave, dicrotic wave, repercussion wave, and retidal wave, Figure 3.

The envelopes were determined before the decomposition. In pulse waveform analysis, SDPPG waveform envelopes produce the distinction of five sequential waves called the initial positive wave, the early negative wave, the late upsloping wave, the late down sloping wave, and the diastolic positive wave, the last one is during the diastole, Figure 3. The heart rate is based on SDPPG beats between the peaks A, Figure 3.

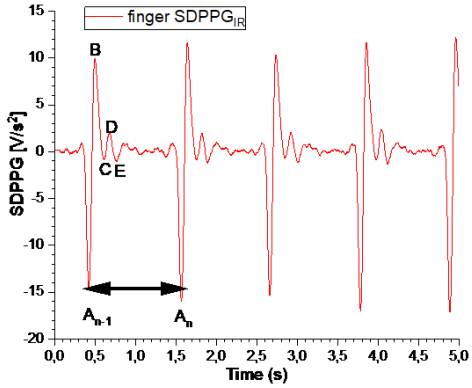

Fig. 3. SDPPG for 5 s from the left index finger by infrared led from a 32 years male healthy cohort, where A, B, C, D, and E are characteristic points of SDPPG from Figure 1 PPG. The IHR is shown with the arrow.

The wave components (A, B, C, D, and E) can be used for further calculations /2/. Further study would be needed to make clear the different causes of response patterns. Biophotonics and applications would be helpful in the future studies. However, full understanding of PPG waveforms and their physiology are still lacking. After investigation the intrinsic connection between infrared and red PPGs from finger and toe, and derived an elasticity index to describe the relationship between biophysical parameters, is based on fewer assumptions than other methods.

SDPPG of the pulse wave is also an indicator to evaluate the elastic properties of blood vessels. By calculating the maximum and minimum values of the SDPPG waves, we found that they contain possibly the elastic properties of the blood vessel wall. In order to validate and generalize the sauna exposure results, a study with larger number of healthy subjects and a more comprehensive reference method (e.g. ultrasound) would be needed, including both cardiovascular patients and healthy control subjects.

IHR in beats per min increases as in an exercise during the sauna exposure, Figures 4, 5, 6, 7, and 8. This phenomena supply blood to all the peripheral locations of body because the arteries and veins dilate. It is known the diastolic blood pressure drops with the systolic blood pressure. The increased blood circulation stimulates also sweat glands.

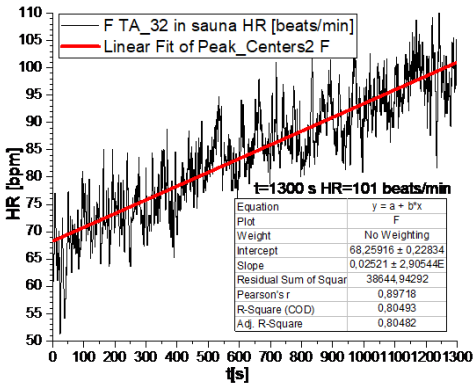

Fig. 4. During the sauna exposure for 1300 s at 80°C, the IHR increased from 67 to 101 beats/min in a 32 years male healthy cohort. The slope value is 0,0252.

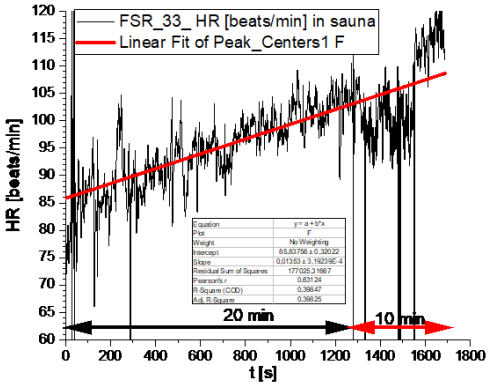

Fig. 5. During the sauna exposure for 1700 s at 80°C, the IHR increased from 85 to 120 beats/min in a 34 years male healthy cohort. In sauna the heart rate increased during the first 20 min linearly having the slope value 0,0135. After it can be change of state.

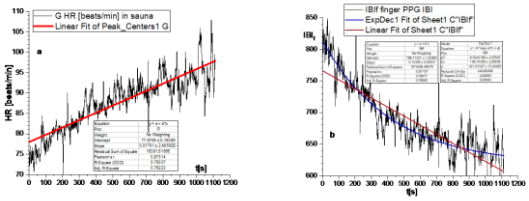

Fig. 6a and b. During the sauna exposure for 20 min, the IHR increased from 75 to 100 beats/min in a 58 years male healthy cohort with the correlation coefficient for exponential grow 0,810 and the corresponding exponential decaying IBI with correlation coefficient 0,840. During the first 20 min heart rate increased linearly with the slope value 0,0179.

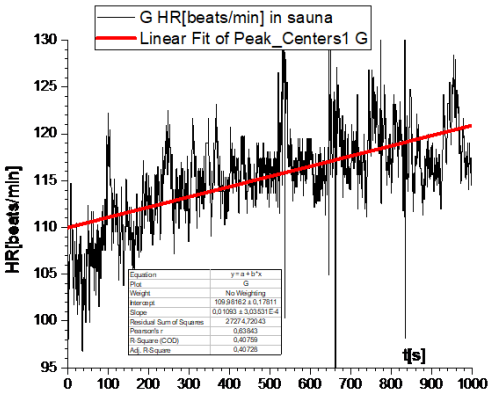

Fig. 7. During the sauna exposure for 15 min, the 10 min would be enough in this case based on the IHR increased from 105 to 120 beats/min in a 58 years female healthy cohort. During the first 15 min heart rate increased nonlinearly with the slope value 0,0109.

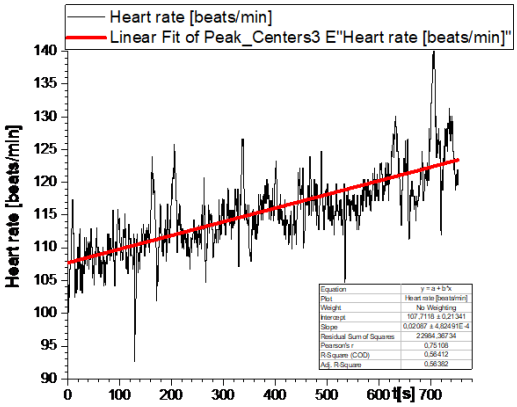

Fig. 8. During the sauna exposure for 15 min, the 10 min would be enough in this case based on the IHR increased from 107 to 125 beats/min in a 28 years female healthy cohort. During the first 15 min heart rate increased linearly with the slope value 0,0209.

There are many illnesses and diseases for what sauna exposure can be helpful and recommended, but not shown yet. The following diseases were identified: hypertension, hypotension, cardiac failure, peripheral circulatory disturbance, sensitivity to cold, arterial obstructive disease, collagen disease, Raynaud's disease, anemia, ischemic organ derangement, all kinds of rheumatoid arthritis, rheumatism, hypercholesterolemia, hyperlipidemia, hyperuricemia (including gout), glucose intolerance (diabetes mellitus, insulin resistance) [3].

IHR increased almost linearly during the first 20 min in sauna exposures. The promising results encourage us for further studies related to the PPG amplitude and rate measurements and their usage also in clinical diagnosis or screening of vascular changes. Also instantaneous heart rate variability (IHRV) would be interesting signal. HRV represents a promising marker of the autonomic nervous system (ANS) regulation exposed in the sauna. Our needs to analyze the signal on a case by case basis so long as we don't have the proper automatic measurement and analysis system. For automated clinical diagnosis based on PPG would be also important in the future healthcare.

4 Conclusions

The heart rate increased almost linearly in many cased during the sauna exposures. In each case, it is important to have the same resting period. It would be difficult that all the subjects arrive at 8 in the morning to the sauna, and we have no parallel measurement system. However, in Japan and in Finland, the frequent use of sauna or onsen exposure times during a week is important factor. The test subjects who had Finnish sauna for 7 times per a week were in the healthiest conditions for the heart and brains [4, 5]. PPG measurement gives big data records unless proper analysis procedures, like decomposition of pulse waveforms, or the linear heart rate function. The PPG pulse waveforms in sauna were difficult to decompose. The Japanese Onsen and the Finnish Sauna would be interesting in comparison measurements by PPG.

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