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Two Realizations of the Wearable PPG Sensor Working in Reflectance Mode for Measurement in Weak Magnetic Field †

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Abstract: The paper describes and compares properties of two realizations of wearable sensors based on the photoplethysmography (PPG) principle for non-invasive acquisition of the human heart rate. The designed sensors enable measurement of the PPG signal in the magnetic field environment with the inherent radiofrequency and electromagnetic disturbance. They can monitor the stress of a tested person during examination in the scanning area of the open-air magnetic resonance tomograph. The performed auxiliary experiments verify the practical functionality of both developed sensors including real-time wireless transmission of the measured PPG signal samples to the control device for further analysis and processing.

Keywords: photo-plethysmography optical sensor; wearable sensor; PPG signal processing

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1. Introduction

For observation of dynamic changes in the vocal tract geometry during human voice phonation the 3D model of the human vocal tract is calculated using the magnetic resonance imager (MRI) data [1]. The phonation signal (typically consisting of production of five basic vowels "a", "e", "i", "o", and "u") is recorded in parallel with the MR scanning process. The examined person is exposed by vibration and noise originated from the gradient system of the running MRI device [2]. In this way, the affected stress evokes vocal cords tension and changes in the recorded human voice signal. The mental stress can effectively be identified by the heart rate (HR), the blood pressure, or other parameters using the photo-plethysmography (PPG) signal [3]. The amplitude of the picked-up PPG signal is usually not constant and it can often be partially disturbed or degraded [4]. Therefore, the sensed raw PPG signal must be smoothed before the HR determination. The filtering and the HR determination procedures work in real-time, so the implemented algorithms must be simple, but robust and stable.

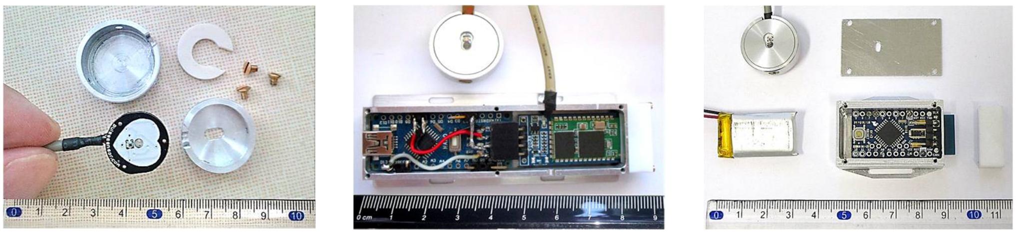
This paper describes design, realization, and testing of two developed wearable PPG sensors working in reflectance mode with real-time Bluetooth (BT) data transfer to an external recording device enabling post-processing and storage of PPG signals. Two described realizations differ in the type of a control unit based on the Arduino platform [5] and using the BT communication module (working in BT 2.0/BT4.0 BLE standards). The auxiliary measurement consists of real-time sensing, transmission, and storage operations (including signal filtering and HR value determination) in the normal laboratory conditions. Comparative measurements with the blood oximeter device for calibration of determined HR values were next performed. Finally, practical measurement experiments inside the running MRI device verify proper function of PPG sensors in magnetic field with radiofrequency (RF) disturbance and their usability in further measurements together with parallel recording of the phonation signal.

2. Subject and Methods

Generally, a wearable PPG sensor for real-time PPG signal measurement consists of four basic blocks: (1) optical part with light source and photo detector elements including a basic analog interface, (2) micro-controller part including an analog-to-digital (A/D) convertor and a serial communication interface, (3) wireless communication part for receipt/transmission commands/data from/to external devices, (4) power supply part. The optical sensor can work in transmission or reflectance modes. The sensor power supply is usually realized by rechargeable batteries or power banks. In addition, for our purpose, the PPG sensor must be made of a non-ferromagnetic material including the power supply to operate in a low magnetic field and all parts must be shielded due to strong RF disturbance in the scanning area of the MRI device—see sensors assemblage and aluminum covering in Figure 1.

In correspondence with previous research [6,7] the currently developed wearable sensor is based on the optical Pulse Sensor Amped (Adafruit 1093) [8] working in a reflectance mode and having an analogue interface integrated on board with a light transmitter and receiver. Two prototypes of the wearable PPG sensor differ in the used micro-controller board, the BT communication module, and the power supply realization. The first sensor (further called "PPG-PS1") was developed by the Arduino Nano v. 3.0 board [9] based on the 8-bit processor ATmega328P by Atmel company with the clock frequency f_{CLK} of 16 MHz, eight integrated 10-bit A/D converters, and the USB interface. This board is connected with the BT module HC-06 [10] enabling the bi-directional data transfer in BT 2.0 standard at 2.4 GHz with the maximum baud rate of 115,200 bps. All three components are powered via the USB port by a cable from an external 5 V power bank THAZER with 2200 mAh capacity.

The second PPG sensor (further called "PPG-BLE") is based on Arduino Pro Mini v. 2.0 board [11] also with the processor ATmega328 but without the USB interface and running at f_{CLK} = 8 MHz. For serial communication, the BT module MLT-BT05 BT4.1 by Techonics Ltd. [12] working in the BT BLE standard was applied. The 3.7 V rechargeable polymer-lithium-ion (Li-Po) cell with 250 mAh capacity was used for sensor powering. The battery is mounted directly on the top of the shielding aluminum box.



(**a**) (**b**) (**c**)

Figure 1. Assemblage and aluminum covering of: (**a**) the optical Pulse sensor, (**b**) the body of the PPG-PS1 sensor, (**c**) the body of the PPG-BLE sensor including the Li-Po battery.

Both realizations of the proposed PPG sensor work in the slave mode, i.e., after initialization they wait for commands from the master device via the BT connection. Two possibilities for measurement and data transmission are implemented in a service program on the Arduino board: (1) PPG signal sensing in data blocks with the length of N_{MEAS} = {100, 500, 1k, 10k, and 25k} 16-bit binary data samples; (2) continual PPG signal measurement started and ended by "*Start*" and *Stop*" commands. The service program also adjusts the time delay to read the analog signal from the optical sensor and perform A/D conversion. Due to the real-time requirement, the following sampling frequencies are supported: f_S = {100, 125, 200, 250, and 500 Hz}.

The control application "PPGsensBT.exe" running on Windows platform (successfully tested under XP, 7, and 10 versions) was created for the master device. This application controls the PPG signal real-time sensing, processing (filtering and determination of

HR values), recording and storing in a Wave format. The stored PPG signal records can be further processed and analyzed off-line in the Matlab program environment.

PPG Signal Processing

In a PPG cycle, two maxima (systolic and diastolic) provide valuable vital information about the pumping action of the heart. The PPG cycle frequency corresponding to the heart rate for healthy persons is in the range 1 to 1.7 Hz (HR from 60 to 100 min^{-1}) [13], so f_S of about 150 Hz is sufficient to capture the HR variance.

The picked-up PPG signal has a typical amplitude modulation with a partially linear trend (LT) and it usually contains superimposed noise component. Therefore, the sensed raw PPG signal must be filtered before next processing including the HR values determination. A smoothing method suitable for real-time processing of this relatively slow signal is a rectangular weighted moving average (MA) filter applied to the input sequence of signal samples $x(i)$

$$y(i) = \frac{1}{2N_X + 1} \sum_{j=-N_X}^{N_X} x(i+j), \quad (1)$$

where N_X is half the length of the MA window and $y(i)$ represent samples of the output sequence. Many approaches to HR determination from the PPG are used in practice [4,13]. With respect to the requested real-time processing of the sensed PPG signal, the used algorithm must be fast, simple, rapid, and universal. Our proposed method works in four steps: (1) setting of the PPG signal threshold L_{THRESH}, (2) binary clipping of the input pulse wave, (3) determination of heart pulse periods T_{HP}, (4) calculation of HR values. The level threshold can be either fixed for all processed PPG signals or adaptive–typically one-third from the systolic pulse peak. The clipping operation produces a sequence $c_{PPG}(i)$ of values 1/0 corresponding to the input signal samples above/below L_{THRESH} as

$$c_{PPG}(i) = \begin{cases} 1 & y(i) \geq L_{TRESH} \\ 0 & y(i) < L_{TRESH} \end{cases}. \quad (2)$$

The heart pulse periods T_{HP} in samples are determined from this clipped sequence as the length of two adjacent segments of ones T_{1P} and zeros T_{0P} ($T_{HP} = T_{1P}+T_{0P}$). Finally, for the used sampling frequency f_S, the HR is calculated as

$$\mathrm{HR} = 60 \,.\, f_s/T_{HP} \quad [\mathrm{min}^{-1}]. \quad (3)$$

For stability comparison of HR values, the variance (HR_{VAR}) is next calculated as a square of the standard deviation (std). The HR values determined from the PPG signal (HR_{PPG}) can be next compared with those measured by the oximeter device (HR_{OXI}) using the differential HR_{DIFF} parameter relative to the mean HR_{PPG} that we define as

$$HR_{DIFF} = (HR_{OXI} - HR_{PPG})/(\mathrm{mean}\ HR_{PPG}) \cdot 100\ [\%]. \quad (4)$$

The obtained HR_{DIFF} values are then analyzed using the calculated linear trend (LT), the basic statistical parameters, and histograms.

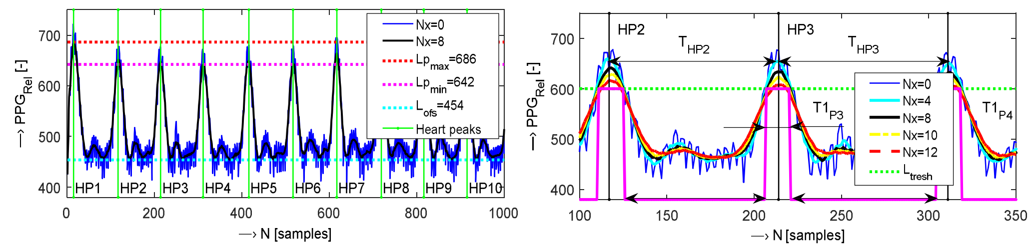
3. Measurement Experiments

The developed wearable PPG sensors were tested and compared in five phases:

1. Basic testing and verification of functionality of sensor's structural blocks were performed including measurement of the sensor's mean DC current with 5/3.3/3.7 V power supply for three functional states: without BT connection (NC), after established connection to the control device (CE), and during transmission of PPG signal samples to the laptop (MC)—compare values in Table 1.
2. Auxiliary analysis of the MA filtering effect on the PPG signal properties and HR determination for half a window length N_X = {0, 4, 8, 10, 12}—see visualization for the PPG wave from the sensor *PPG-PS1* in Figure 2 (N_X = 0 means no filtering).

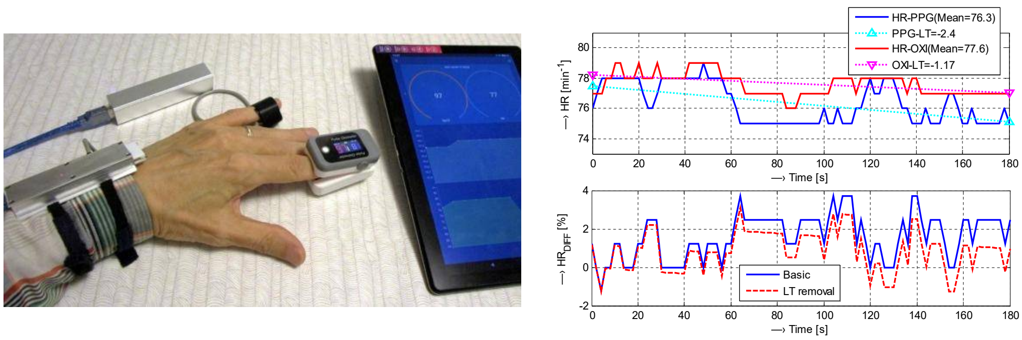
3. Comparative measurement in the normal laboratory conditions—PPG signal sensing and parallel measurement with the pulse oximeter Berry BM1000C [14] by Shanghai Berry Electronic Tech Co. Ltd. for calibration of the determined HR values. This type of oximeter with an optical sensor working in a transmission mode enables also recording of blood oxygen saturation and HR values to the control device (tablet) via BT connection. PPG sensors are mounted on little fingers of both hands by an elastic ribbon, the oximeter device on the forefingers as documented in Figure 3. The recording of PPG signals as well as oximeter values lasted for 80 s. The HR values obtained in this way were subsequently processed off-line and analyzed statistically—see the results for all tested persons in Figure 4.
4. Preliminary mapping of conditions for wireless connection through the shielding cage of the open-air MRI device E-scan Opera by Esaote S.p.A. [15] located at the Institute of Measurement Science in Bratislava.
5. First-step measurement of the PPG signals in a low magnetic field environment of the MRI device for two working states: the tested person lying in the MRI scanning area with no scanner activity and the 3D scan sequence running—see the measurement arrangement photo in Figure 5.

In comparative measurement experiments two female (F1-2) and six male (M1-6) volunteer persons (with average age of 59 years) were joined, in the frame of measurements inside the MRI device two persons (M1 and F1) were tested.



(**a**) (**b**)

Figure 2. Visualization of MA filtering effect on the PPG signal: (a) 1k-sample ROI of the raw and filtered ($N_X = 8$) PPG waves with determined signal levels, (b) detailed situation around the third heart pulse for different N_X values; sensed from the left forefinger of M1 person by *PPG-PS1* sensor.



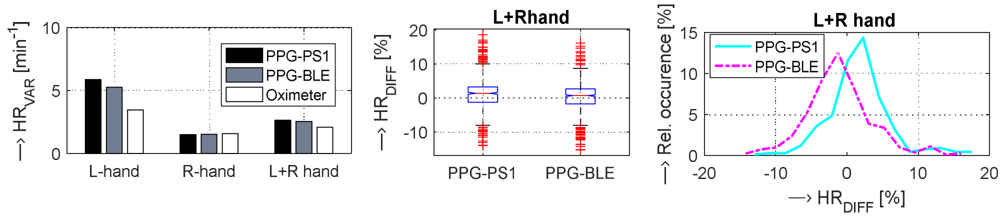
(**a**) (**b**)

Figure 3. Comparative measurement of HR values from the PPG wave and with the oximeter device: (**a**) arrangement photo, (**b**) HR and LT values (upper graph), basic HR_{DIFF} values and after LT removal (bottom graph); using the *PPG-PS1* sensor, left hand of M1 person.

Table 1. Comparison of PPG sensors' mean DC current values for three functional states.

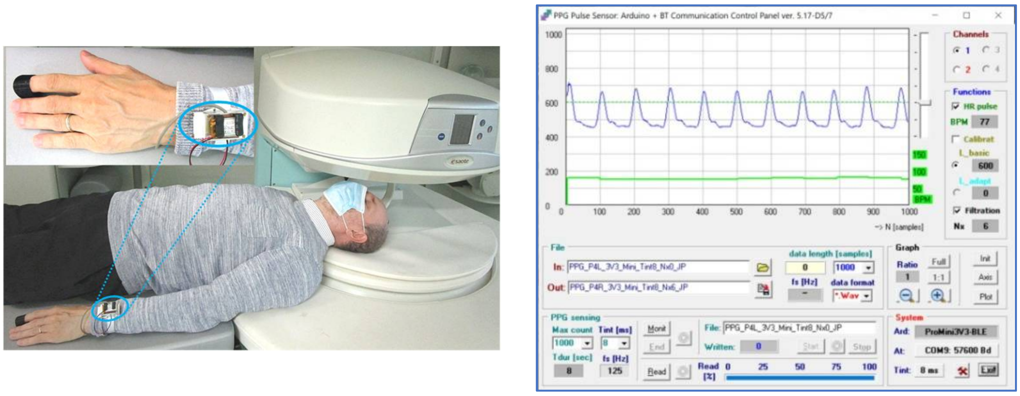
Sensor Type/Func. State	NC	CE	MC
PPG-S1 [1]	18 mA	26 mA	30 mA
PPG-BLE [2/3]	10.5/13.5 mA	11/14 mA	13/17 mA

[1] Vcc = 5 V via USB. [2] Vcc = 3.3 V by a voltage stabilizer from 5 V USB. [3] Vcc = 3.7 V from Li-Po battery.



(**a**) (**b**) (**c**)

Figure 4. Comparison of statistical results of determined HR values for both sensor realizations: (**a**) bar-graph of mean variances of HR values separately for both hands, (**b**) box-plot of basic statistical parameters of HR_{DIFF} values, (**c**) histograms of HR_{DIFF} values; for left and right hands together.



(**a**) (**b**)

Figure 5. Measurement inside the MRI device E-Scan Opera: (**a**) arrangement of the PPG signal recording by the *PPG-BLE* sensor, (**b**) screen copy of the control application *PPGsensBT*.

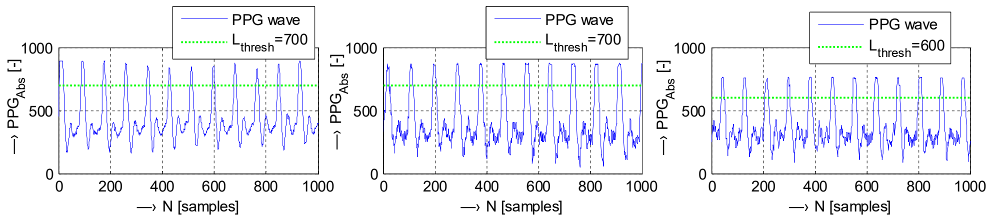
4. Discussion and Conclusions

Both developed prototypes of the reflection PPG sensor work in real time in normal laboratory conditions and use the sampling frequencies from 100 to 500 Hz. Sensing of the PPG signal with f_S higher than 250 Hz is reasonable only in the case of the systolic pulse width determination with higher accuracy and using the *PPG-PS1* realization. The length 2 N_X +1 of the MA filter window has direct influence on the recorded PPG signal: too high value of the N_X parameter causes an undesirable effect on the amplitude and width of the systolic heart pulses—see Figure 2. Therefore, to obtain a properly smoothed PPG signal without secondary negative influence, the window duration and the sample rate are set by a compromise. The setting of $N_X = 8$ and $f_S = 125$ Hz was finally chosen for use in further measurement experiments.

From comparative measurements in the laboratory conditions with the help of the oximeter device follows that both tested realizations of the wearable PPG sensor have acceptable and similar accuracy of HR values determination. Detailed statistical analysis shows slightly higher variance of HR_{DIFF} values in the PPG signals sensed by the *PPG-PS1* type while the oximeter device produces the smallest variance. There are essential differences between HR_{PPG} values determined from PPG signals of left and right hands as presented by the graphs in Figure 4.

Preliminary investigation shows that the metal shielding cage of the tested MRI device enables wireless BT communication, because the cage iron plates consist of 2.5-mm diameter holes [15]. Practically the BT signals have lower magnitude but data connection and transfer are still functional. However, it is also important to analyze the influence of the BT transmission in the scanning area on the quality of the scanned MR images.

First-step measuring experiments confirm practical usability of the proposed sensors for long-term sensing of the PPG signal in the magnetic field environment with additional RF and electromagnetic disturbance. To guarantee secure serial BT communication between the PPG sensor and the control device through the shielding cage the baud rate must be decreased, especially in the case of the *PPG-BLE* realization (max. 57,600 bps). While both realizations have practically the same fully aluminum shielding body and optical sensor part, the *PPG-BLE* type produces a PPG signal with lower amplitude due to lower supply voltage (as documented in Figure 6) giving worse signal-to-noise ratio in the final effect. On the other hand, to enable long-term PPG signal recording, the acquisition should be battery saving. Therefore, using the low energy type of the PPG sensor (*PPG-BLE* realization) successfully solves this requirement.



(**a**) (**b**) (**c**)

Figure 6. Examples of sensed PPG waves in the scanning area of the MRI device: (**a**) without scan activity using *PPG-PS1* type, (**b**) with running scan sequence by *PPG-PS1* type, (**c**) with running scan sequence by *PPG-BLE* sensor realization; used left forefinger of M1 person.

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