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



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Motivation of the Work

Magnetic resonance imaging (MRI) is accompanied by vibration due to rapidly changing Lorentz forces in the gradient coil system producing significant mechanical pulses and acoustic noise.

In our experiments with 3D modeling of human vocal tract, we also monitor the mental and physiological state of tested persons during examination in the scanning area of the running MRI.

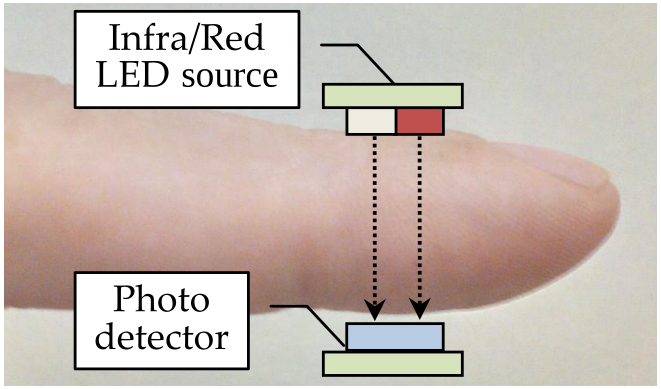
Wearable sensors based on the photoplethysmography (PPG) principle are often used for non-invasive acquisition of vital information about the cardiovascular system.

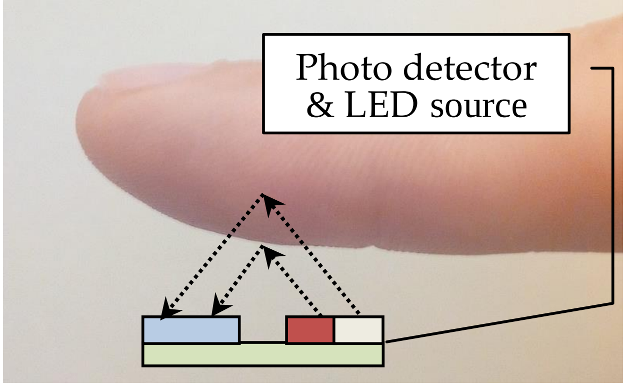
Therefore, we constructed a wearable PPG sensor for continual measurement in the magnetic field environment with inherent radiofrequency and electromagnetic disturbance.

Basic Structure and Function of PPG Sensors

➢ **A PPG sensor consists of two basic parts:**
a transmitter (*light source*) and a receiver (*photo detector*).

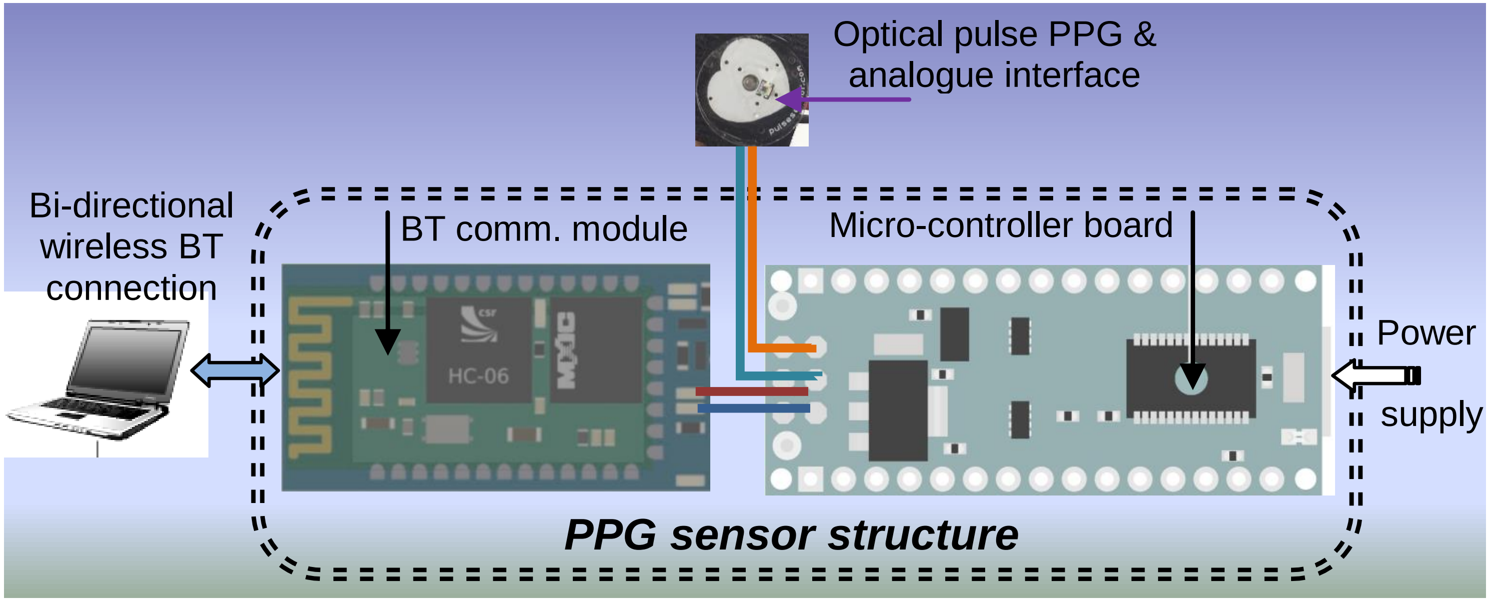
1. **PPG sensors for measuring in a transmission mode have:**
   - ❑ **the LED source and the photo detector placed on opposite sides of the measured human tissue (*on a finger or an ear lobe*).**



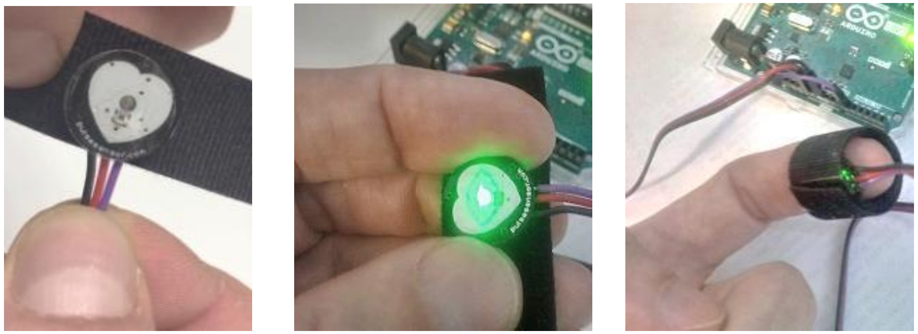


2. **PPG sensors for measuring in a reflection mode have:**
   - ❑ **the LED source and the photo detector measuring intensity of reflected light placed side by side on the same body surface.**

Design and Concept of the PPG Sensor



Principal structure diagram of a wearable PPG sensor



a) b) c)

Photos of a **reflection PPG sensor**:

(a) its front side with one LED and a photo detector element,

(b) in its functional state (lighting),

(c) fixed on an index finger by an elastic ribbon for measurement.

Realization of Wearable PPG Sensors

Both realizations use an optical PPG sensor working in a reflectance mode:

- ⇨ **PulseSensor Amped PRODUCT *(Adafruit 1093)* with an integrated basic analog interface, fixed by an elastic ribbon enabling measurement on different body places (fingers, wrists, etc.).**

The first prototype of the PPG sensor *("PPG-PS1")* contains:

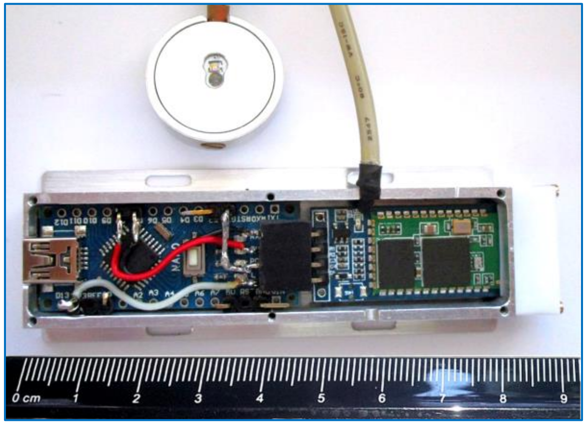
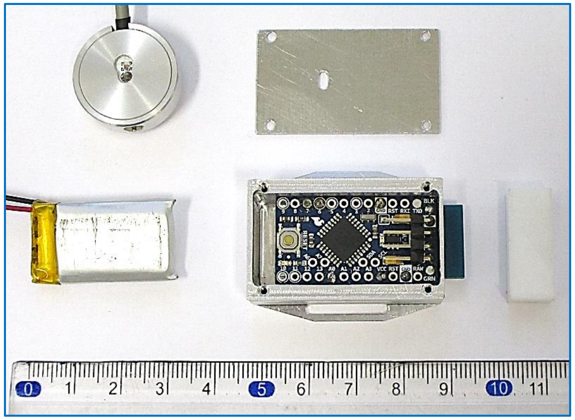
- **Arduino Nano v. 3.0 board, based on the 8-bit processor ATmega328P working at f_{CLK}=16 MHz with integrated USB interface powered via USB by a 5V *power bank,***
- **BT module HC-06 enabling the bi-directional data transfer in BT 2.0 standard at 2.4 GHz with the max. baud rate of 115200 bps.**

The second realization of the PPG sensor *("PPG-BLE")* includes:

- **Arduino ProMini v. 2.0 board, based on the same processor ATmega328 but without the USB interface, working at f_{CLK}=8 MHz, powered by a 3.7 V *lithium polymer battery cell,***
- **BT module MLT-BT05 BT4.1 working in the BT BLE standard.**

Practical Realization of the PPG Sensors

1. The PPG sensor must be made of a non-ferromagnetic material including the power supply to operate in a low magnetic field.
2. To prevent disturbance in electromagnetic compatibility inside the scanning area of the running MRI device:
   - ✓ the micro-controller board with BT module and the optical sensor must be covered by shielding boxes.

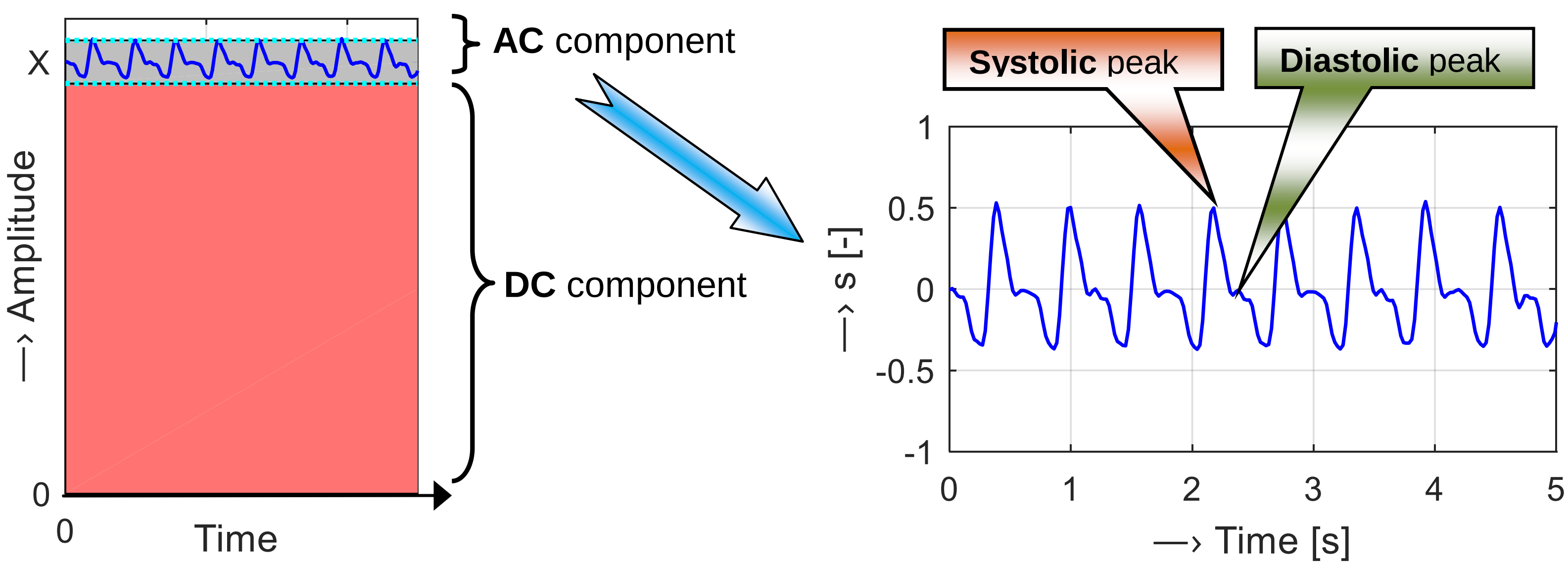
Assembling and aluminum covering of optical Pulse sensor (left) , PPG-PS1 sensor body (middle), PPG-BLE sensor body with Li polymer battery (right).

PPG Signal and Its Properties

The PPG signal consists of:

- ✓ **a direct current (DC) component;**
- ✓ **a superimposed alternating current (AC) component that follows the beating of the heart, so it is useful for the heart rate detection** *(its amplitude is about 2% of the DC component).*

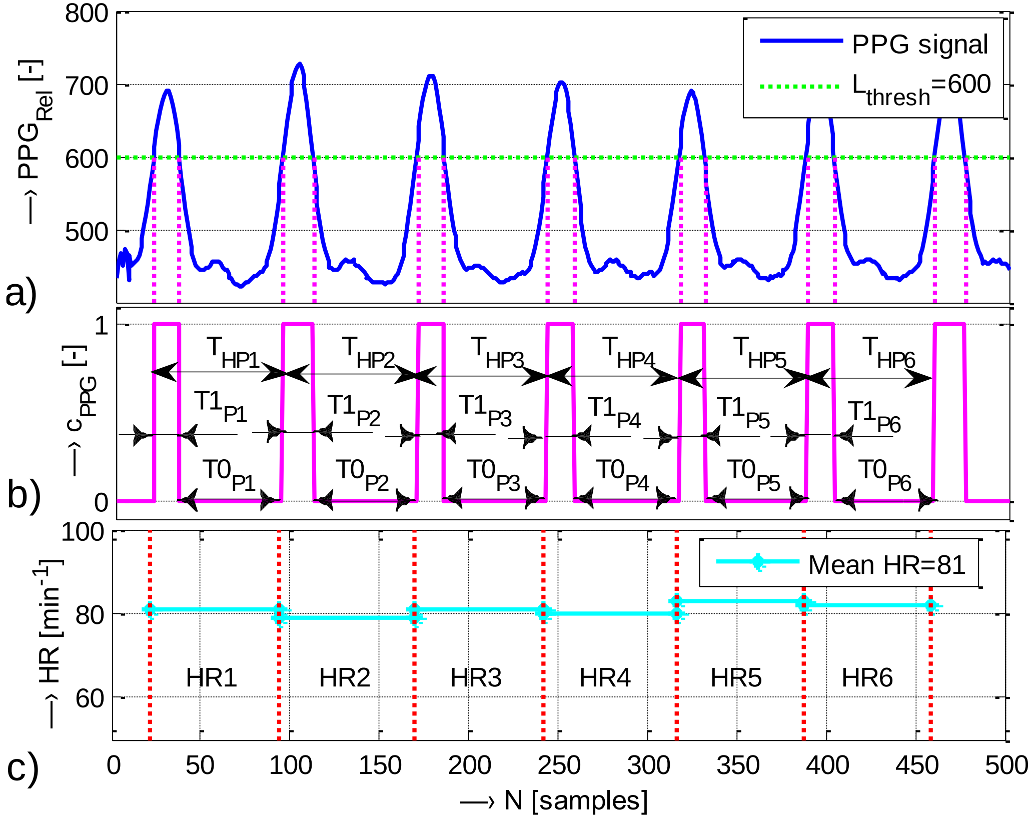
In each PPG cycle, two maxima are observed, representing systolic and diastolic peaks giving information about the cardiovascular system.



Determination of HR Values from PPG Signal

Algorithm for real-time processing consists of:

1. setting of the signal level threshold L_{THRESH},
2. clipping of the input pulse wave to obtain a sequence c_{PPG} of values 1/0 corresponding to the signal samples lying above/below the L_{THRESH},
3. determination of pulse periods T_{HP} from adjacent segments of ones T_{1P} and zeros T_{0P} : $T_{HP} = T_{1P} + T_{0P}$,
4. calculation of heart rate HR in [min^{-1}] from T_{HP} and f_s as HR = 60 . f_s / T_{HP} .



a) 500-sample ROI of the PPG wave,
b) clipped sequence with marked heart pulse periods T_{HP} from T_{1P} and T_{0P},
c) partial HR values and final mean HR.

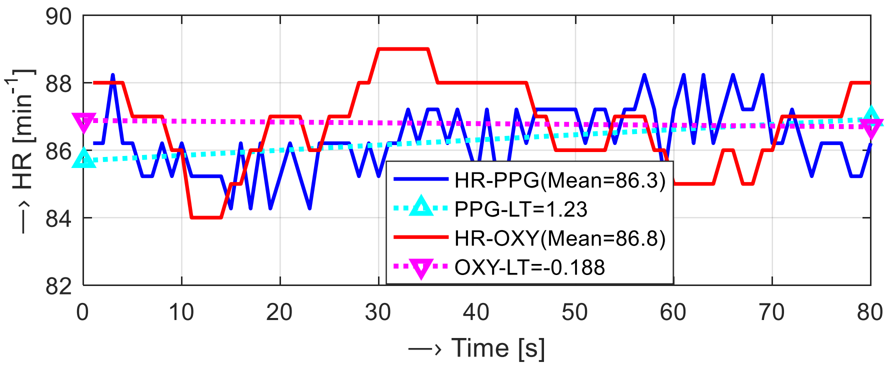
Determination of Differential HR Parameters

Post-processing as off-line calculations from the PPG signal:

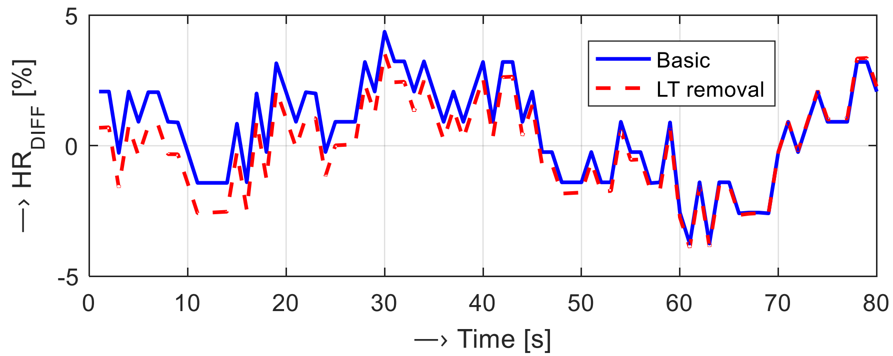
- HR values determined from the PPG signal (HR_{PPG}) can be next compared with those measured by the oximeter device (HR_{OXI}) using the differential HR_{DIFF} parameter relative to the *mean* HR_{PPG} that we define as

$$HR_{DIFF} = (HR_{OXI} - HR_{PPG}) / (\text{mean } HR_{PPG}) \,.\, 100 \ \ [\%].$$

- Obtained differential parameters are then analyzed using the calculated linear trend (*LT*), basic statistical parameters (minimum, maximum, mean, variation, etc.), and histograms.



Example of determined HR_{PPG}, HR_{OXI} and LT values.



Visualization of determined basic HR_{DIFF} values and after LT removal.

Description of Performed Experiments I.

Three auxiliary experiments were finally performed for testing of both developed realizations of wearable PPG sensors:

I. **Verification of functionality of the whole sensor 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),**
   - **during transmission of PPG signal samples to the control device (MC).**

II. **Analysis of the MA filtering effect on the PPG signal properties for half a window length $N_X = \{0, 4, 8, 10, \text{and } 12\}$.**

III. **Analysis of the influence of the used sampling frequency on PPG signal properties for $f_S = \{100, 125, 200, 250, \text{and } 500\ Hz\}$.**

Description of Performed Experiments II.

Three measurement experiments were next performed :

I. **Comparative measurement – PPG signal sensing and parallel measurement with the pulse oximeter device *(Berry BM1000C)* for calibration of the determined HR values:**
   - **tested persons were always sitting on a chair at a table without any stimuli in normal interior conditions.**
   - **PPG sensors are mounted on little fingers of both hands by an elastic ribbon, the oximeter device on the forefingers.**

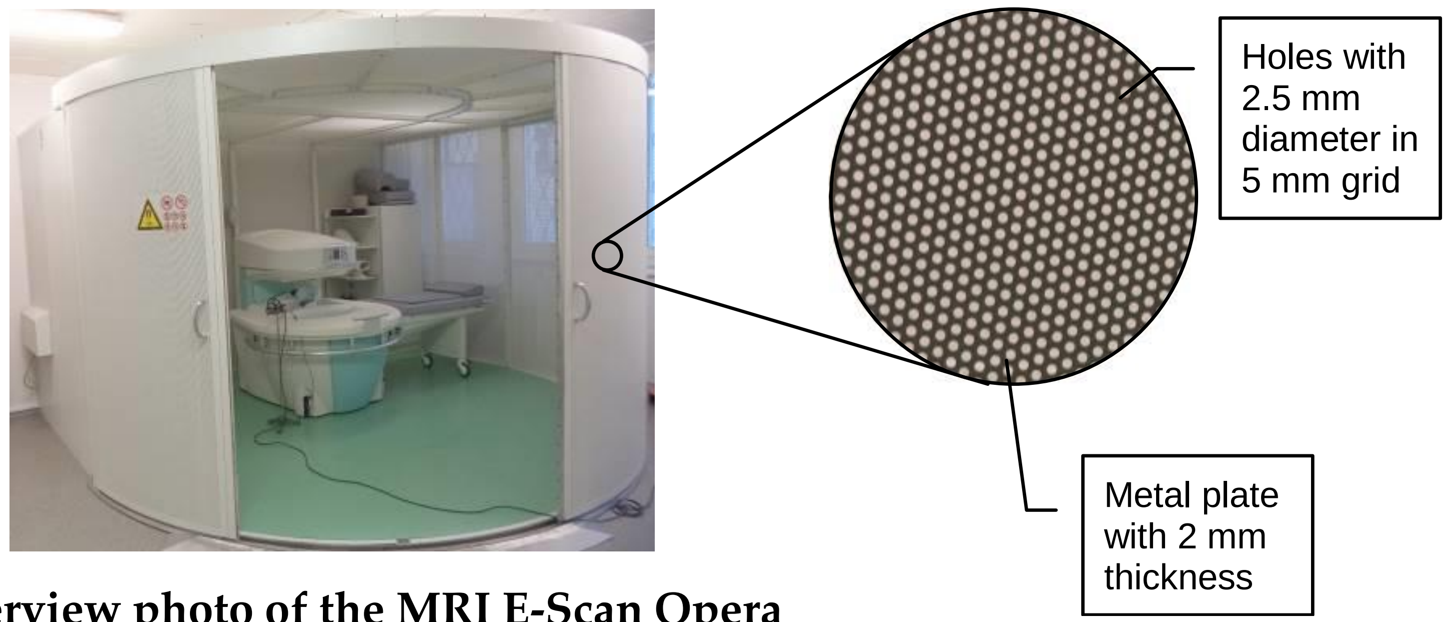
II. **Mapping of conditions for wireless connection through the shielding cage of the open-air MRI device E-scan Opera working with the basic magnetic field $B_0 = 0.178$ T.**

III. **PPG signal measurement inside the open-air MRI device realized in two working states:**
   1. **tested person is lying in the MRI scanning area but with no scanner activity,**
   2. **the MR scan sequence Hi-Res SE-HF 26 is executed.**

BT Communication Conditions in the MRI device

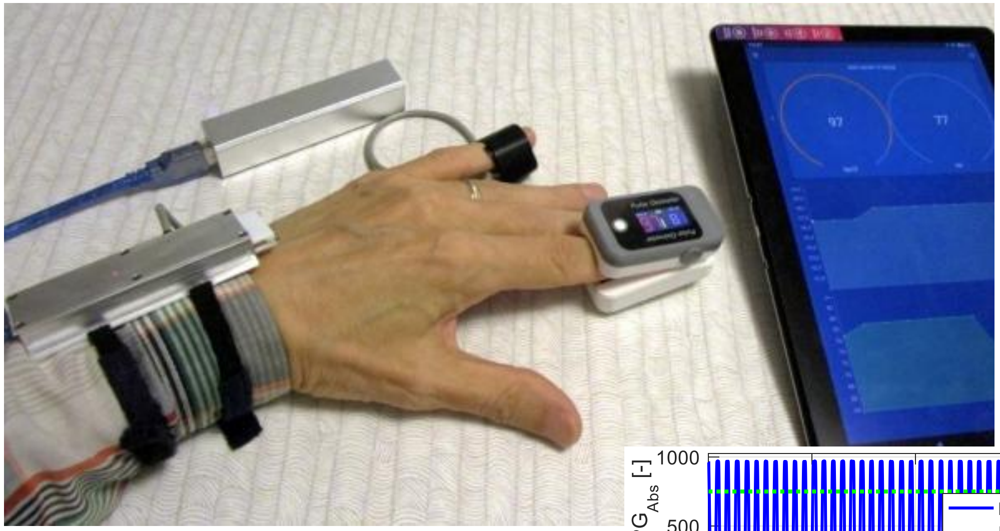
The shielding metal cage of the MRI equipment consists of 2.5-mm diameter holes which practically enable a wireless communication:

- ✓ **bi-directional Bluetooth data transfer at 4.2 GHz is possible.**



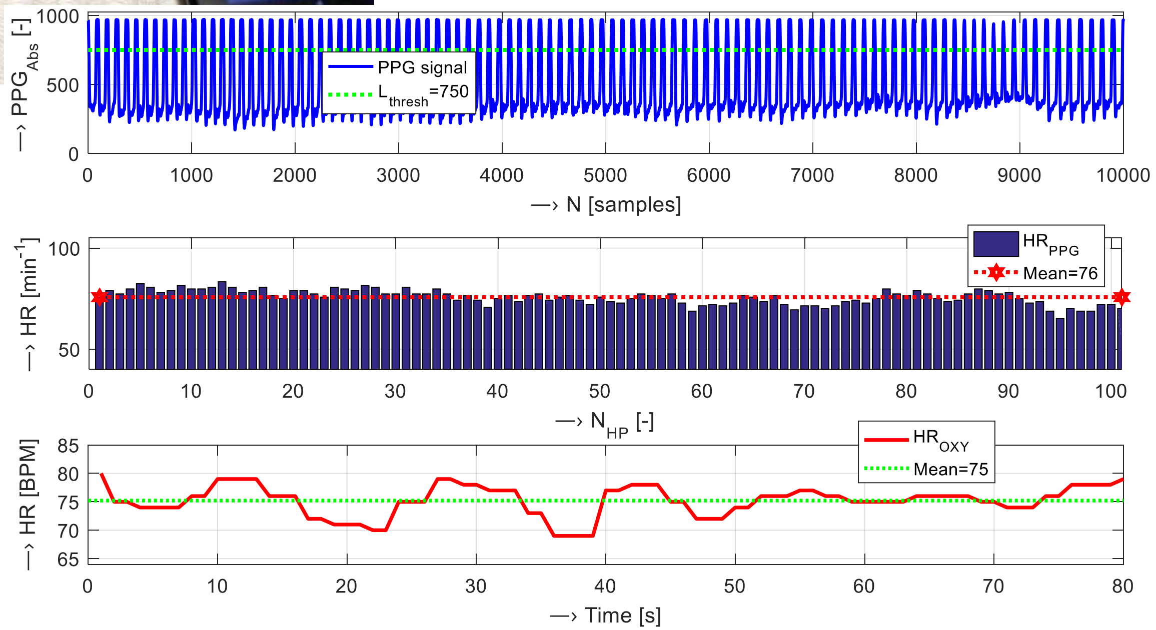
Overview photo of the MRI E-Scan Opera located at the Institute of Measurement Science, SAS, Bratislava.

Comparative Measurement with an Oximeter



Arrangement of PPG signal measurement by the developed wearable sensor and the oximeter device with BT data transfer to an external storage device (tablet).

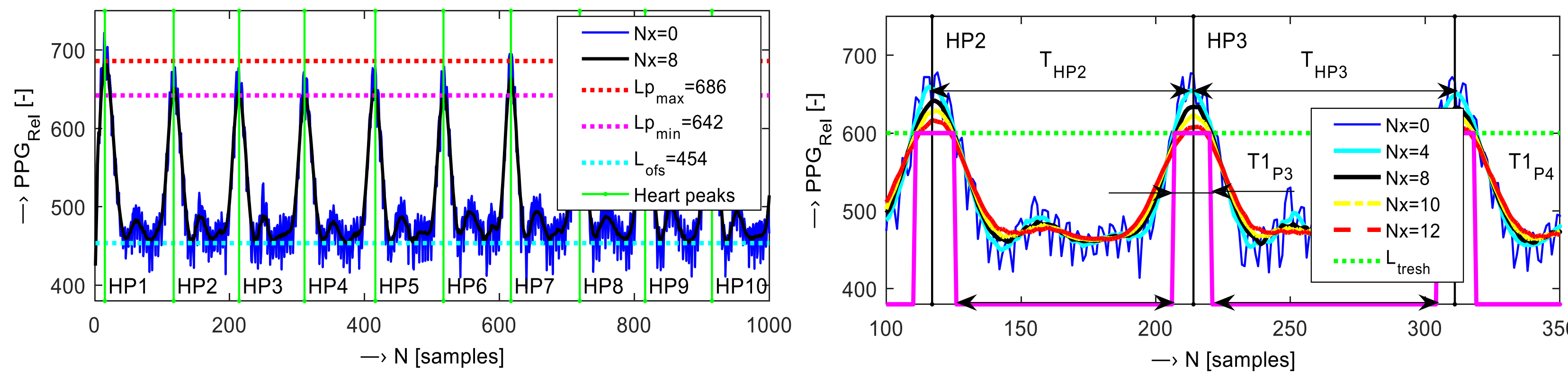
Example of a sensed PPG signal, sequences of determined HR_{PPG} values and received HR_{OXI} values from an oximeter device together with their mean values.



Results of Auxiliary Measurements I.-II.

Comparison of PPG sensors' mean DC current values.

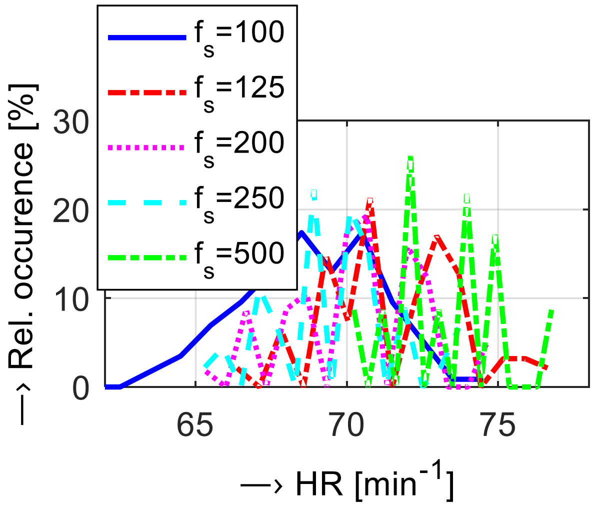
Sensor type/ functional state	*NC*	*CE*	*MC*
PPG-S1 *(5V via USB)*	18 mA	26 mA	30 mA
PPG-BLE *(3.3V from USB stabil.)*	10.5 mA	11 mA	13 mA
PPG-BLE *(3.7V by Li-Po battery)*	13.5 mA	14 mA	17 mA



Visualization of MA filtering effect on the PPG signal: the raw and filtered ($N_X = 8$) PPG waves with determined signal levels (left), detailed situation around the third heart pulse for different N_X values (right).

Results of Auxiliary Experiments III.

Analysis of influence of the used sampling frequency on PPG signal properties:



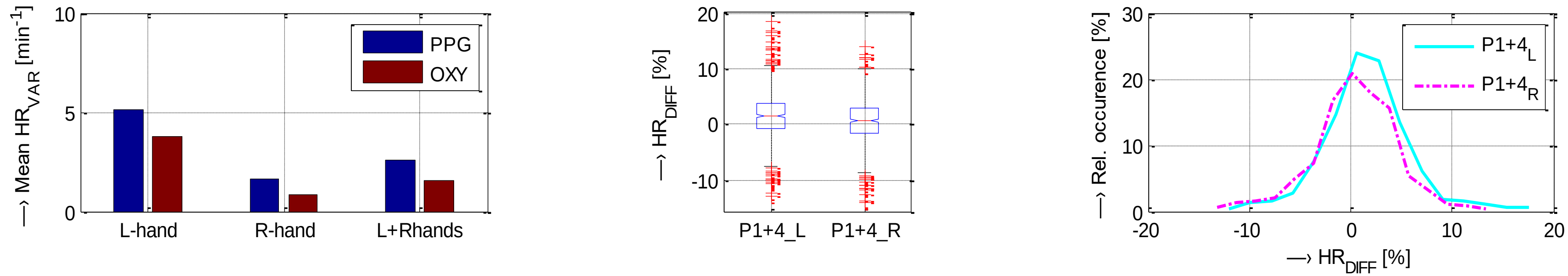
Influence of used f_s on histograms of determined HR values.

Influence of used f_s on detected number of heart periods N_{HP} and lengths of parts T_{1P}, T_{0P}.

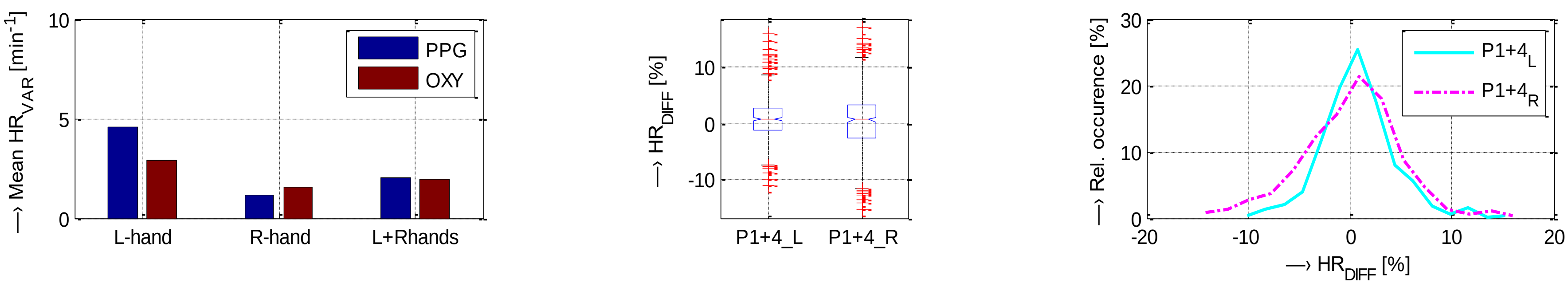
f_s [Hz]	N_{HP} [samples]	T_{1P} [samples]	T_{0P} [samples]
100	87	11	76
125	105	20	85
200	170	34	136
250	215	42	173
500	409	83	326

- ➢ **Lower number of detected N_{HP} due to higher used f_s *(more than 250 Hz)* can cause inaccuracy of the statistical analysis results.**

Results of Comparative Measurements

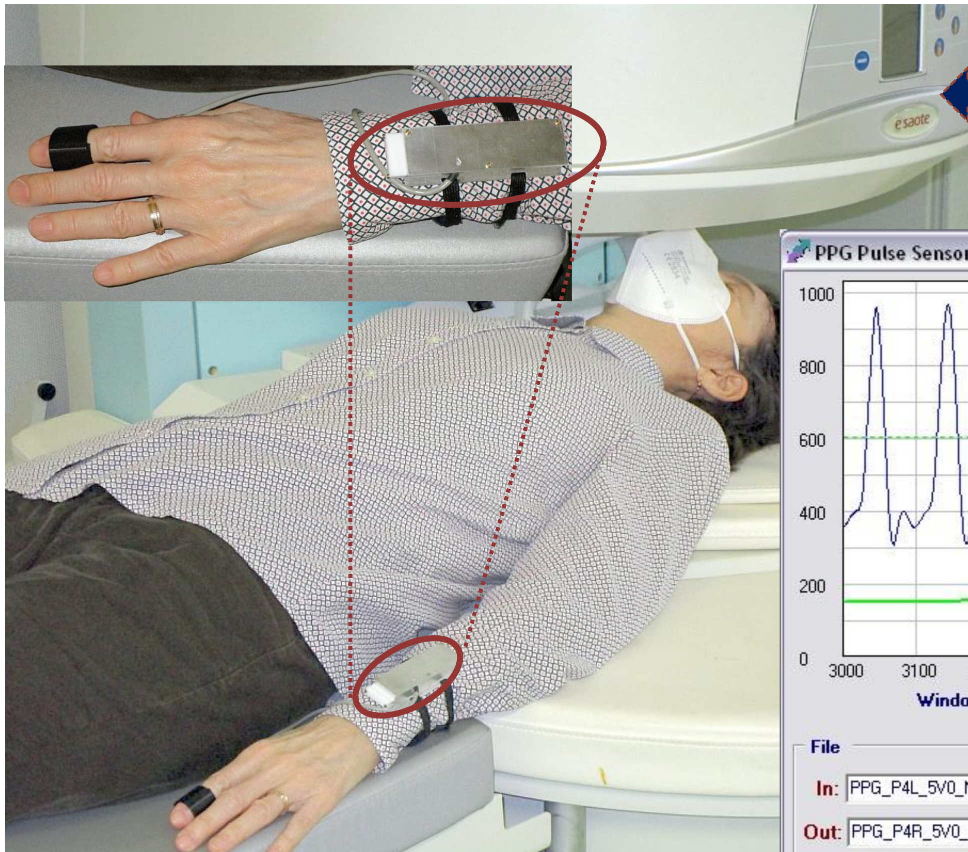


Mean variation of $HR_{PPG/OXY}$ values separately for both hands (left), basic statistical parameters of HR_{DIFF} values (middle), histograms of HR_{DIFF} values(right); used sensor *PPG-PS1*, for eight tested persons (*2 female + 6 male*).

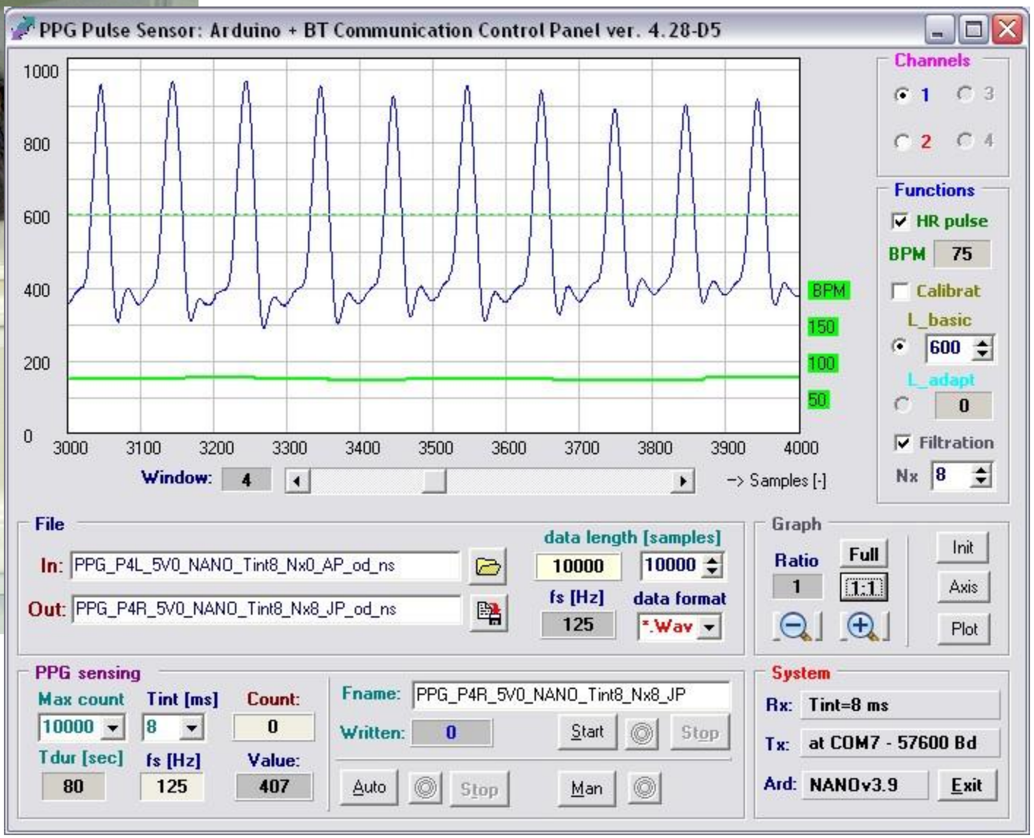


Bar-graph of mean variation of HR values separately for both hands (left), box-plot of basic statistical parameters of HR_{DIFF} values (middle), histograms of HR_{DIFF} values (right); used sensor *PPG-BLE*, *all tested persons.*

PPG Signal Measurement in the MRI Device

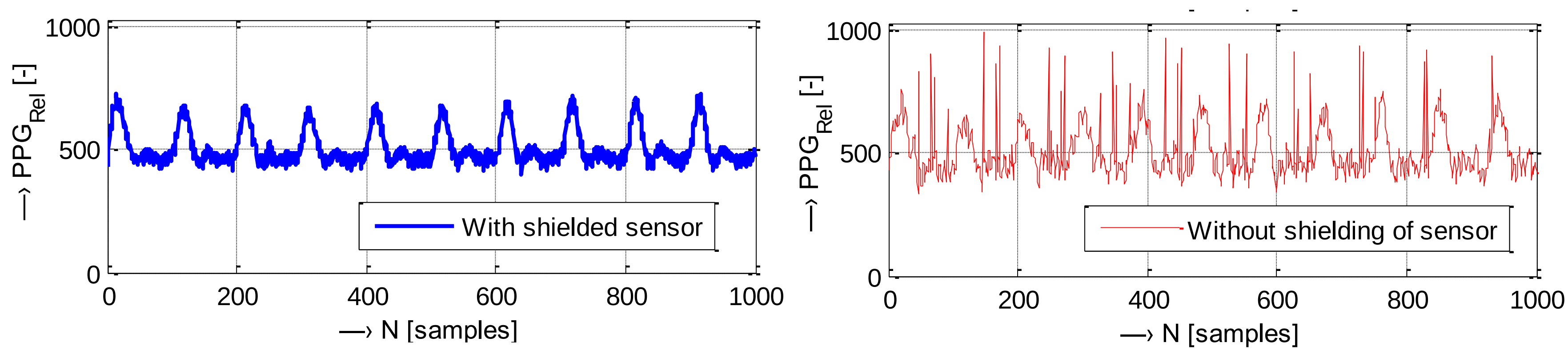


Arrangement of PPG signal measurement inside scanning area of the open-air MRI device E-Scan Opera (B_0=0.178 T).

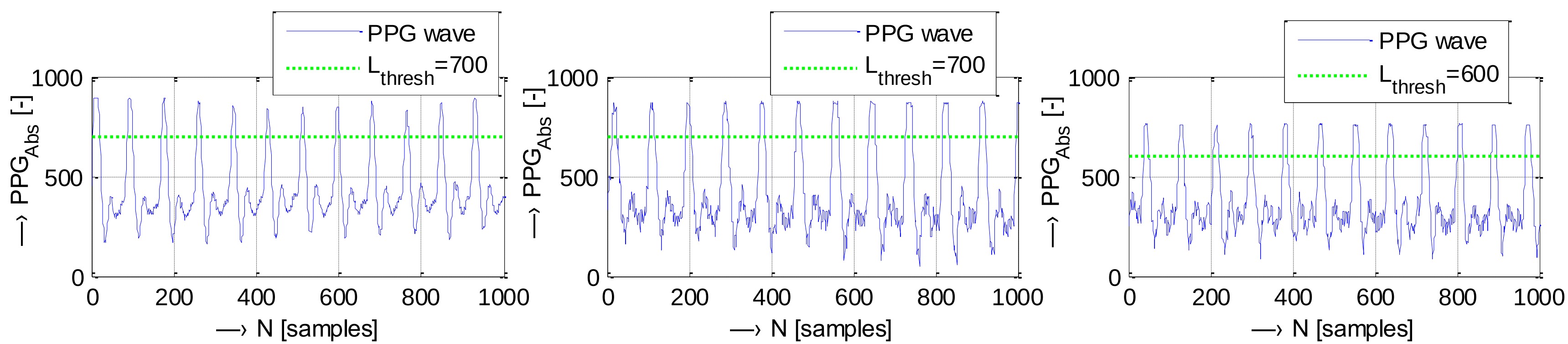


Screen copy of the control application *PPGsensBT.*

Example of PPG Waves Sensed in MRI Device



PPG signal sensed in the MRI device with a running MR scan sequence using shielded optical part and body of the sensor (left), without any shielding (right).



Examples of PPG waves sensed in the scanning area of the MRI device Opera without scan activity using PPG-PS1 sensor (left), with running MR sequence by PPG-PS1 sensor (middle), with running MR sequence by PPG-BLE sensor (right).

Discussion of Obtained Results I.

From the performed auxiliary experiments follows:

- ✓ **Both compared realizations of a wearable PPG sensor enable real-time PPG wave sensing and recording using sampling frequencies from 100 to 500 Hz.**
- ✓ **In addition we discovered that:**
  - **sensing of the PPG signal with $f_S > 250$ Hz is reasonable only for determination of the systolic pulse width with higher accuracy,**
  - **the MA filter window length has direct influence on the PPG signal: too high value of the N_X causes an undesirable effect on the amplitude and width of the systolic heart pulses.**

⇨ **setting of $N_X = 8$ and $f_S = 125$ Hz was finally chosen for use in all comparison measurements.**

Discussion of Obtained Results II.

From comparative measurement by the oximeter device in the normal laboratory conditions follows:

✓ **Both compared realizations of a wearable PPG sensor have acceptable and similar accuracy of HR values determination.**

Detailed statistical analysis shows:

- **Slightly higher variation of HR_{DIFF} values from PPG signals sensed by the *PPG-PS1* than by the *PPG-BLE* realization.**

- **Essential differences between HR_{PPG} values determined from PPG signals from left and right hands occurred.**

  ⇨ **To obtain better separable data for precise statistical analysis *(using ANOVA etc.)*, use of the forefinger of the left hand is preferable for PPG signal sensing.**

Discussion of Obtained Results III.

- ✓ **Preliminary investigation shows that the metal shielding cage of the tested MRI device enables wireless BT communication.**
- ❖ **Practically, the BT signals have lower magnitude but data connection and transfer are still functional.**
  - ⇨ **To guarantee secure serial BT connection between the PPG sensor and the control device through the shielding cage the baud rate must be decreased *(max. at 57600 bps*).**

- ✓ **5V powered sensor realization using the HC-06 BT module has typically twice more mean DC current than the PPG-BLE *(during transmission of PPG samples)*.**
- ❖ **To enable long-term PPG signal recording, the acquisition should be battery saving:**
  - ⇨ **use of the low energy type of the PPG sensor *(PPG-BLE realization)* can solve this requirement.**

Summary and Conclusion

- ✓ The first-step measuring experiments confirm practical usability of both proposed sensors for continual measurement of the PPG signal in a low magnetic field environment with additional radiofrequency and electromagnetic disturbance.

- ❖ The main measurements inside the MRI device have shown few problems to be solved to obtain sufficient PPG signal amplitude, and correct HR and other parameters.

  - ⇨ *Main limitation of this work consists in a relatively small number of tested persons joined in our measurement experiments, caused by the current pandemic situation and government restrictions.*

- ➢ It is also important to analyze the influence of the BT transmission in the scanning area on the quality of the scanned MR images.

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Thank you for your attention !