Comparative Measurement of the PPG Signal on Different Human Body Positions by Sensors Working in Reflection and Transmission Modes

Jiří PŘIBIL, Anna PŘIBILOVÁ, Ivan FROLLO

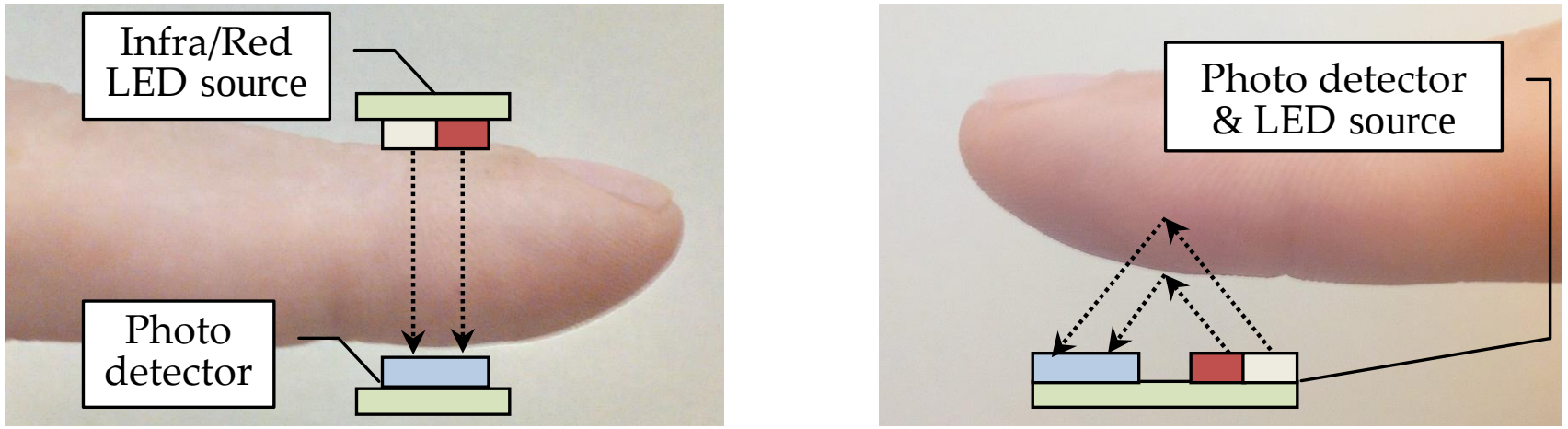
Institute of Measurement Science, Slovak Academy of Sciences,
Dúbravská cesta 9, SK-841 04 Bratislava, Slovakia.

Table of contents:

Basic Principle of PPG Sensors Function

The optical sensors for measurement of the PPG signal can work in transmission or reflection modes:

- **Generally, a PPG sensor consists of two parts: a transmitter (light source) and a receiver (photo detector),**
- **The arrangement of the light source(s) and a photo detector depends on the operation mode.**



Basic principle of PPG sensors working in:
transmission *(on the left)*, reflection *(on the right)* modes.

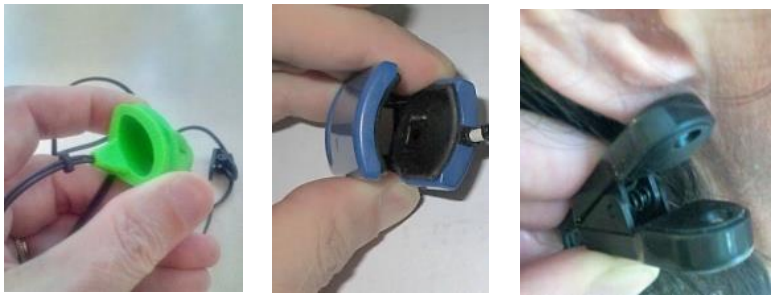
Different Realizations of PPG Sensors

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*).

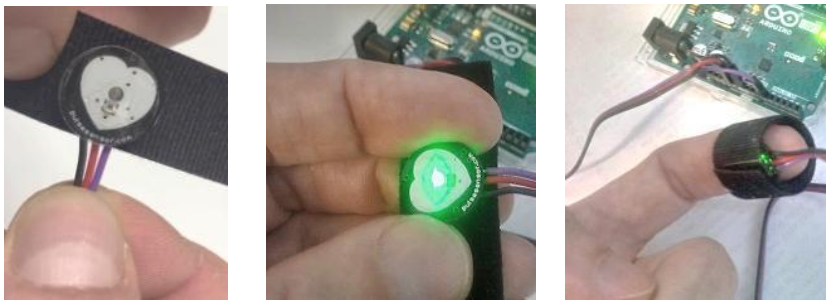
PPG sensors for measuring in a reflection mode have:

- the LED source and the photo detector measuring the intensity of the reflected light placed side by side on the same body surface.



a) b) c)

Examples of a transmission PPG sensor realization as: (a) rubber finger ring, (b) plastic finger clip, (c) plastic ear clip.



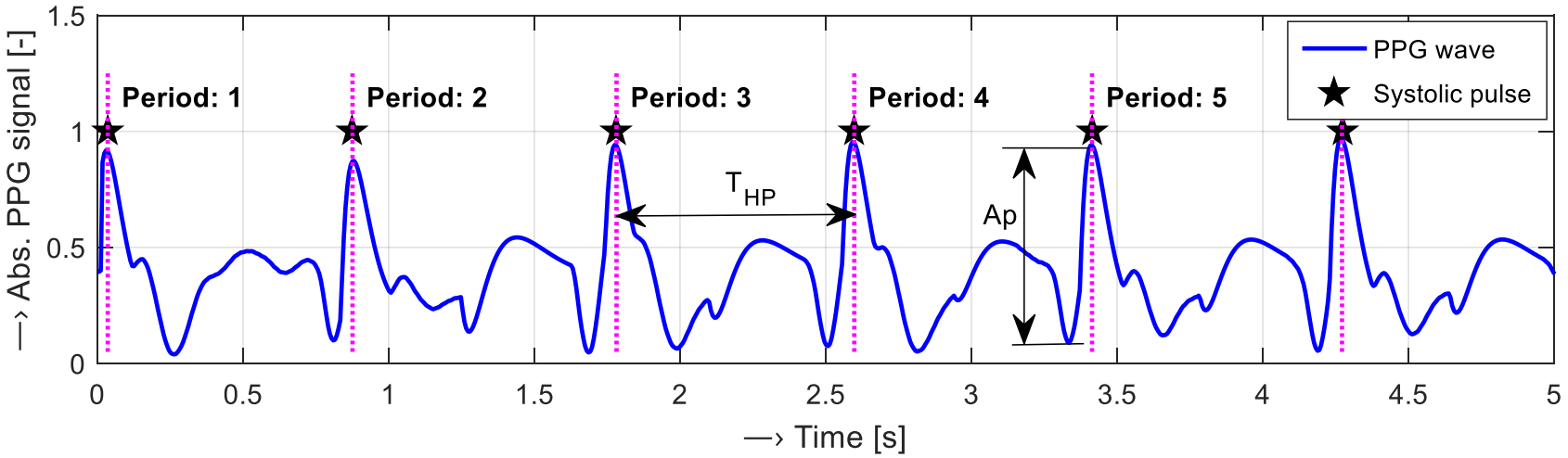
a) b) c)

Examples of a reflection PPG sensor realization: (a) its front side with one LED and a photo detector, (b) in its functional state, (c) fixed on an index finger by an elastic ribbon.

Basic PPG Signal Processing and Analysis

Basic analysis of PPG signal properties consists of:

- determination of energetic, temporal, and statistical parameters for description of PPG signal properties as:
  - PPG signal energy by root-mean-square values (S_{RMS}),
  - signal energy using absolute value of the mean of the Teager–Kaiser energy operator O_{TK} (En_{TK}),
  - signal ripple as the relative amplitude perturbation from the detected peak amplitudes (A_p) expressed in percentage.

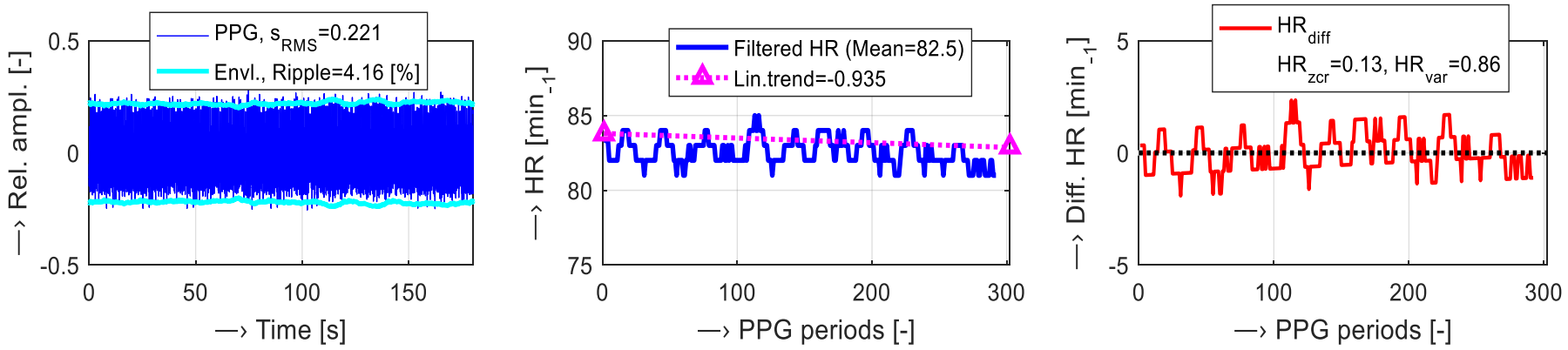


An example of the PPG signal analysis: a 5-s frame of the absolute PPG wave with localized systolic heart peaks of A_p amplitudes and determined heart pulse periods T_{HP}.

Calculation of HR Parameters from PPG Signal

The second phase of PPG signal processing:

- **HR determination from the PPG wave from T_{HP} ; smoothing the output sequence by a 3-point median filter and a linear trend (LT) calculation.**
- **mean value and LT removal to obtain HR_{DIFF} values, used for calculation of zero-crossings mean (HR_{ZCR}) and variance (HR_{VAR}).**



Relative PPG signal and its envelopes with the determined S_{RMS} and Ripple (*left*), the filtered HR sequence with calculated LT (*middle*), HR values after mean value and LT removal with a zero-crossings mean and a variance (*right*).

Instrumentation for PPG Signal Recording

For real-time recording of the PPG signal were used:

1. PPG sensors working in a transmission mode:
   - optical sensor HRM-2511E *(by Kyoto Electronic Co.)* in the form of a rubber finger ring,
   - plastic ear clip primarily used for heart rate beats monitoring during the sporting on the Kettler Consul Home Bike device,
   - both connected to the analog interface Easy Pulse *(by Embedded Lab)* for pre-amplification and filtering of the PPG signal.
2. Reflective optical PPG sensor:
   - PulseSensor Amped PRODUCT *(Adafruit 1093)* with integrated basic analog interface, fixed by an elastic ribbon enabling measurement on different body places (fingers, wrists, etc.)
3. Common for all three tested realizations of a PPG sensor:
   - battery-based power supply of 5 V *(AlzaPower source 20000)*,
   - mixer device Behringer XENYX Q802 for PPG signal digitization via the USB interface connected to the laptop PC.

Description of Performed Experiments

Two PPG signal databases were collected during experiments:

1) DB_1 *(records by sensors working in a transmission mode)*
   - PPG signal sensed from four fingers on both hands *("P1L/R,..,P4L/R")* and both ear lobes *("UL/R")*

   ➡ 5x2=10 of 180-sec records for each tested person.

2) DB_2 *(records by sensors working in a reflection mode)*
   - PPG signal pickup from five fingers of left and right hand *("P1L/R,..,P5L/R")*

   ➡ 10 records with total duration of 30 min per person.

- **Six healthy volunteer persons** *(three males and three females in the age from 29 to 58)* **took part in our experiments.**
- All collected records were processed to obtain PPG signal properties (S_{RMS}, En_{TK}, and Ripple) and HR values including their zero-crossings and variance statistical parameters (HR_{ZCR}, HR_{VAR}).

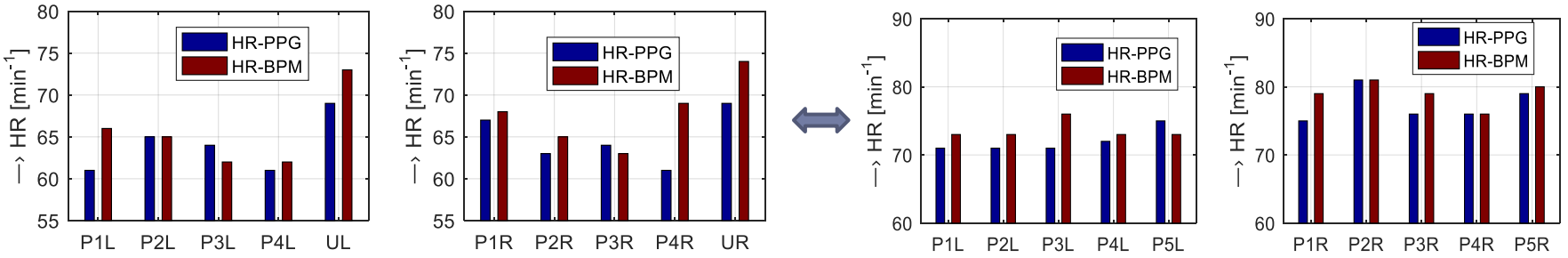
Experimental and Recording Conditions

For all measurements holds that:

→ **Tested persons were always sitting on a chair at a table without any stimuli in normal interior conditions.**

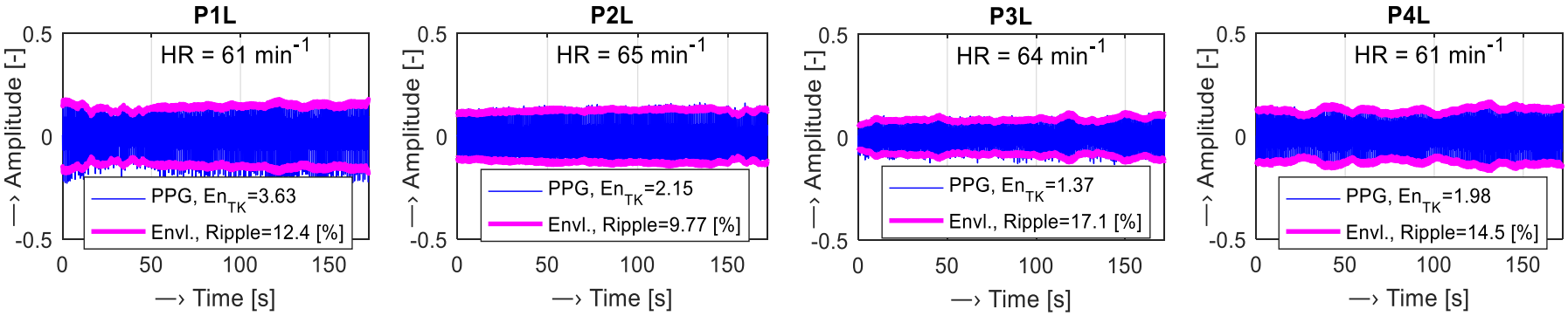
→ **The mean HR values determined from the PPG signals were compared with the ones measured in parallel by the BPM device *Microlife BP A150-30 AFIB*.**

→ **The BPM's cuff was put on the opposite arm than the PPG signal was sensed to prevent any influence of an inflated pressure cuff of the BPM on a tested person's blood system.**

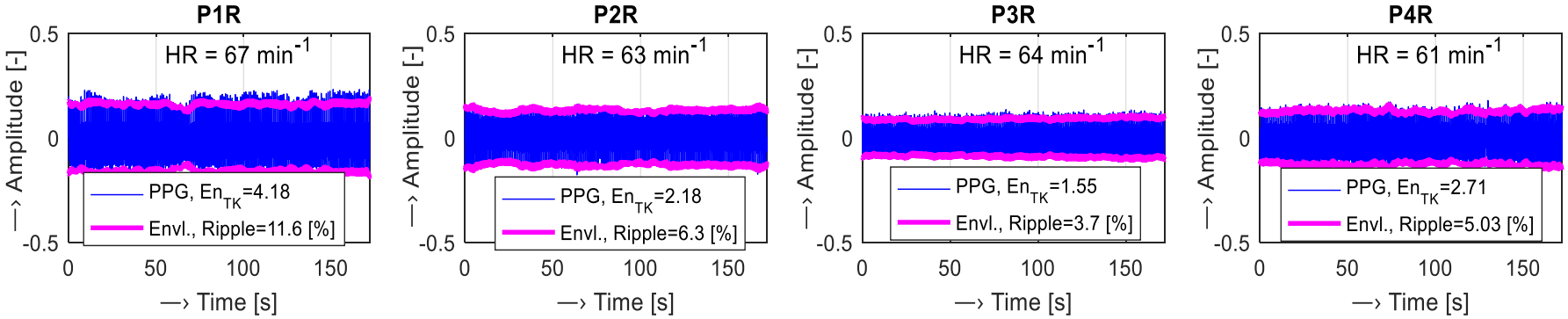


Comparison of mean HR values from PPG signals and measured by a BPM device: from four fingers of L/R hands and both ear lobes by *FRS* and *ECS* sensors (*left two graphs*), from five fingers of L/R hands using the *REFS* sensor (*right two graphs*); male person JP.

Comparison of PPG Signals from four Fingers

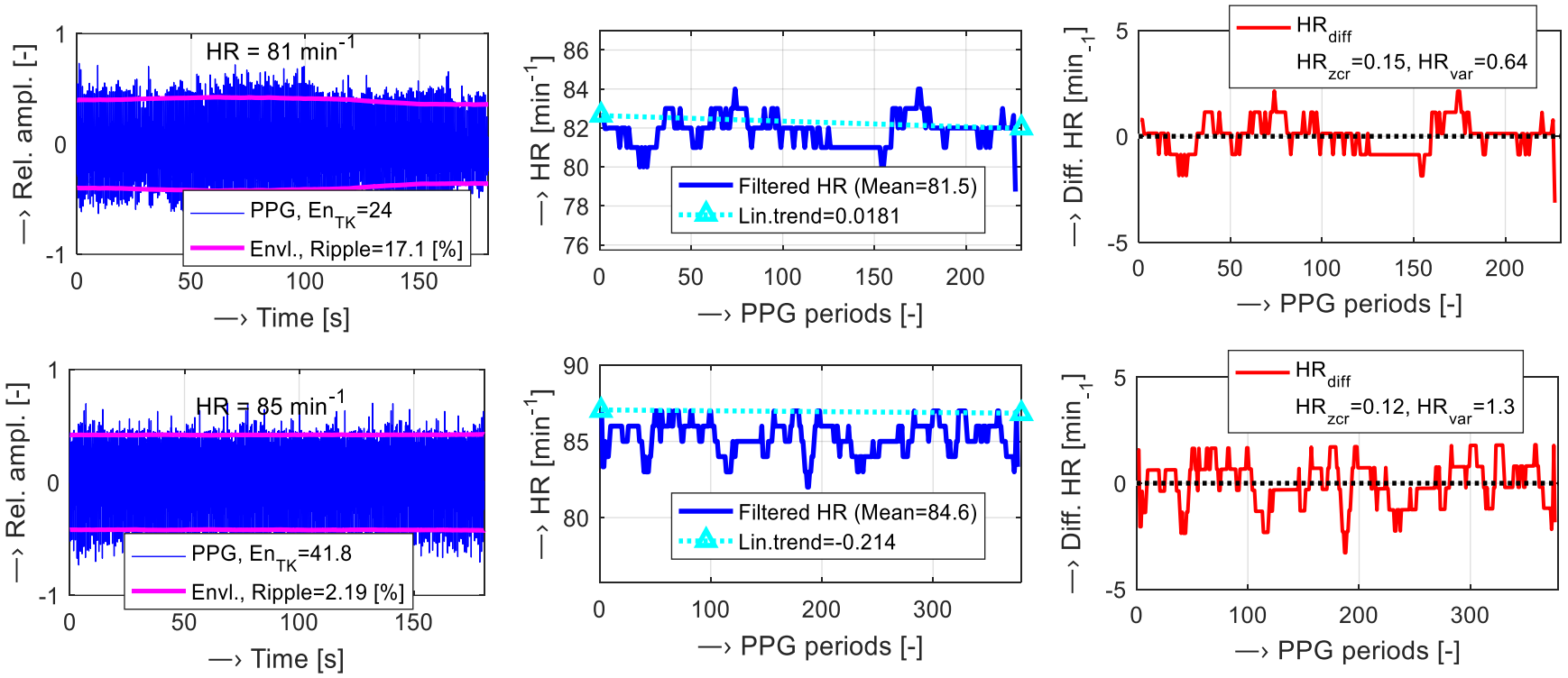


PPG waves with envelopes of the signals sensed from four fingers together with En_{TK}, Ripple, and mean HR values; the *FRS* sensor placed on the male JP left hand.



PPG waves with envelopes of the signals sensed from four fingers together with En_{TK}, Ripple, and mean HR values; the *FRS* sensor placed on the male JP right hand.

Comparison of PPG Signals from Ear Lobes

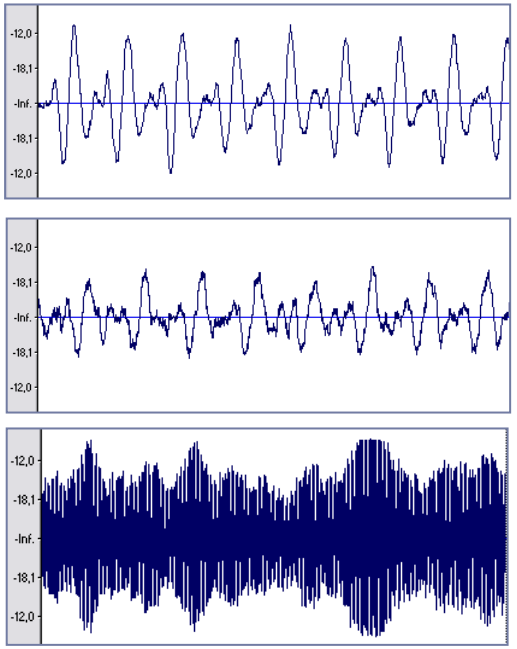


The relative PPG signal and its envelopes with the En_{TK} and Ripple values (*left graphs*), the filtered HR sequence with calculated LT (*middle graphs*), the HR values after mean value and LT removal with a zero-crossings mean and a variance (*right graphs*);

***FRS* sensor placed on the female AP left (*upper set*) and right (*bottom set*) ear lobes.**

Testing PPG Signal from a Wrist

Documentary photo of the *REFS* PPG sensor placed on the left wrist



PPG wave sensed on a wrist: for correct location of a sensor on a vein (*upper*), disturbed PPF signal (*middle*); signal with too high ripple (*bottom*).

Main disadvantage:

× quality of the sensed PPG signal depends on the placement of the source LED and PHD element directly on the vein.

Comparison of Partial Results

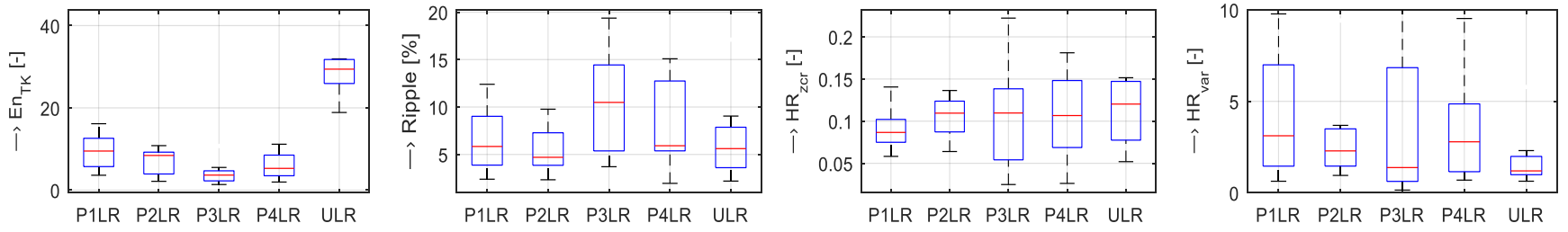
PPG signal parameters and HR features for fingers (P1-P4) and an ear lobe (U);
the right hand of the female person AP, used transmission sensors (*FRS/ECS*).

Parameter	$P1_{FRS}$	$P2_{FRS}$	$P3_{FRS}$	$P4_{FRS}$	U_{ECS}
S_{RMS} [-]	0.24	0.22	0.14	0.19	0.40
En_{TK} [-]	9.49	8.50	3.60	6.69	24.0
Ripple [%]	11.8	9.11	10.0	11.0	6.31
HR_{ZCR} [-]	0.058	0.065	0.026	0.112	0.123
HR_{VAR} [-]	0.63	3.30	1.75	3.48	1.28

PPG signal parameters and HR features for five fingers (P1-P5);
the right hand of the female person AP, used reflection sensor (*REFS*).

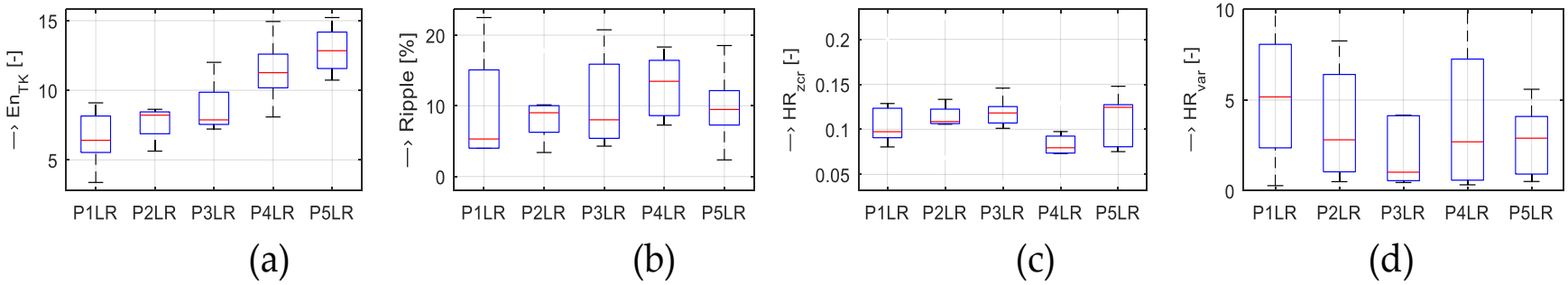
Parameter	$P1_{REFS}$	$P2_{REFS}$	$P3_{REFS}$	$P4_{REFS}$	$P5_{REFS}$
S_{RMS} [-]	0.20	0.21	0.22	0.23	0.27
En_{TK} [-]	6.11	7.16	7.64	8.09	11.7
Ripple [%]	18.5	18.3	7.84	3.40	5.81
HR_{ZCR} [-]	0.091	0.224	0.119	0.129	0.126
HR_{VAR} [-]	0.51	0.32	0.57	0.61	1.07

Summary Comparison of PPG Signal Features



Box-plot comparison of PPG signal properties and HR statistical parameters: (a) En_{TK} energy values; (b) Ripple values; (c) HR_{ZCR} values; (d) HR_{VAR} values;

***FRS* and *ECS* sensors on four fingers of both hands and both ear lobes, all tested persons.**



Box-plot comparison of PPG signal properties and HR statistical parameters: (a) En_{TK} energy values; (b) Ripple values; (c) HR_{ZCR} values; (d) HR_{VAR} values;

***REFS* sensor on five fingers of both hands, all tested persons.**

Discussion of Obtained Results I.

1. Measurements using the *FRS* transmission PPG sensor

- there exist differences in the signal energy expressed by En_{TK} and S_{RMS} parameters, and the signal short-time stability represented by the envelope ripple:

a) PPG signal from the little finger has the greatest energy and approximately average ripple,

b) the smallest energy and the highest ripple of the PPG signal is picked up from the thickest middle finger,

c) relatively good signal energy and approximately average ripple are obtained from the index finger .

× PPG signals from thumbs cannot be sensed due to their too thick tissue.

✓ Essential differences were not detected according to the type of hand (left vs. right) or gender (male vs. female) of a tested person.

Discussion of Obtained Results II.

2. Measurements using *ECS* type of a transmission sensor

a) **Signal energy from an ear lobe is higher *(a lobe is thinner than a finger)*:**

- ⇨ **PPG wave has higher ripple and generally worse signal properties,**
- ⇨ **HR values determined from the PPG signal and the reference BPM device have the greatest differences in comparison with the results obtained from fingers .**

b) **This realization of a PPG sensor seems not very suitable for longer precise measurement:**

- ⇨ **tested persons have often a problem to rest without any movement of a head.**

× **Worse PPG signal properties are probably the result of a small number of weak capillaries in an ear lobe which causes weaker blood flow detection.**

Discussion of Obtained Results III.

3. **Measurements using a reflection type of a PPG sensor**
   a) **Signal energy and PPG wave properties depend on the size of a finger surface:**
      ⇨ **the best signal properties (*higher energy and smaller ripple*) were observed by sensing from the thumbs.**
   b) **The differences in stability and precision between HR values determined from the PPG and the BPM are relatively small:**
      ⇨ **excluding the middle finger PPG signal.**

× **PPG signals from wrists cannot be successfully sensed due to too great dependence on the right localization of a measurement position of the PPG sensor directly on the vein.**

✓ **No important differences were observed between signals taken from left/right hands or male/female tested persons.**

Conclusion

1. Comparison of *FRS*/*ECS* realizations of the PPG sensors working in a transmission mode shows:
   - ✓ PPG wave taken from the finger ring type is more stable and cleaner than that from the ear lobe type.
   - ✓ PPG signals from fingers demonstrate dependence of the energy and ripple on the tissue volume without relevant differences between the left and right hand.
2. Analysis of PPG signals picked-up by a sensor working on a reflection principle shows:
   - ✓ dependence on the size of a finger surface,
   - × but no dependence on the tissue volume.

Future plans:

- to test the *REFS* PPG sensor in more detail,
- to modify the *REFS* sensor enabling measurement in the low magnetic field environment with RF pulses disturbance.

Acknowledgement

The work has supported by:

- **the Grant Agency of the Slovak Academy of Sciences (VEGA 2/0125/19 and 2/0001/17).**
- **The COST Action CA16116.**

Thank you for your attention !