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Physiological Impact of Vibration and Noise in an Open-Air Magnetic Resonance Imager: Analysis of a PPG Signal of an Examined Person †

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† Presented at the 6th International Electronic Conference on Sensors and Applications, 15–30 November 2019; Available online: https://ecsa-6.sciforum.net/

Published: 14 November 2019

Abstract: The paper represents a preliminary analysis of physiological and psychological impact of vibration and acoustic noise on a person examined by a low-field magnetic resonance imaging (MRI) tomograph. First, a methodology for measurement of different signals of a tested person is found. The main investigation consists of parallel heart rate and blood pressure measurement using a photoplethysmographic (PPG) optical sensor and standard portable blood pressure monitors. The recorded PPG signal is filtered and processed to obtain a clean waveform used to determine an instantaneous heart rate. Different types of portable blood pressure monitors are tested and compared to choose the best one for further experiments.

Keywords: magnetic resonance imaging; vibration; acoustic noise; photoplethysmographic sensor

1. Introduction

Magnetic resonance imaging (MRI) is an effective method of clinical practice for non-invasive investigation of human body parts with minimal side effects. An open-air MRI scanner is often used in special cases, e.g. for claustrophobic patients [1], for post-surgical monitoring of larynx carcinoma, limb implants, restoration of degraded muscles, etc. In this type of an MRI device, a low field with a maximum magnetic induction of 0.2 T is usually generated by a pair of permanent magnets [2]. A gradient system of planar coils parallel to the magnets is used to select 3D coordinates of a tested object that is placed in the magnetic field together with a radio frequency (RF) receiving/transmitting coil. Gradient switching results in fast changes of coil current and undesirable mechanical vibration and acoustic noise. This noise has always negative physiological and psychical effects on an exposed person, depending on its intensity and exposure time.

The negative influence of the generated vibration and noise on a human body and psychic can be monitored by measuring the blood pressure (BP) and the heart rate (HR) during MR scanning. First part of the presented work is aimed at finding a methodology for measurement of different signals of a tested person lying in the scanning area of the MRI device. In the main investigation, the BP and HR parameters are measured in parallel for a person scanned during execution of the whole MR scan sequence. For this purpose, we apply the photoplethysmography (PPG) using an optical sensor for non-invasive acquisition of vital information about the cardiovascular system from the skin surface [3]. This optical sensor complies with the requirements for working in the magnetic field environment with present radio frequency and electromagnetic disturbance [4]. Variations in the photo-detector signal are related to changes in the blood volume inside the tissue. Signal filtering and further processing are necessary to obtain a clean PPG waveform that is then used to determine the instantaneous heart rate [5]. In the frame of our experiments, different types of portable BP and HR measuring devices (blood pressure monitors – BPMs) were tested and compared with the aim to choose a suitable one for further measurement in the low magnetic field environment.

2. Analysis and Processing of the PPG Signal

Processing of the recorded PPG signal can be divided into three steps. In the frame of the first step the following operations with the PPG signal are performed:

- down-sampling the original PPG signal sampling frequency f_s by a factor of Dns: $f_{dns} = f_s/Dns$,
- normalization of the down-sampled PPG signal to the range of <–1~1>,
- calculation of the first derivative,
- determination of the positive/negative polarity of the down-sampled/differentiated PPG signal – see an example for a selected region of interest (ROI) of 20 s in Figure 1,
- localization of maximum peak positions in the PPG signals separately for both polarities.

The second step consists of:

- calculation of time distances (TD) between the localized peaks (in samples) of both analyzed polarities of the PPG signal determined from the whole recorded time duration,
- building of histograms and box plots of basic statistical analysis (mean, minimum, maximum, and standard deviation) of the obtained TD values – separately for each signal polarity,
- finding the maximum occurrence of the peak distances and calculation of the number of heart beats for both polarities Ntp_{poz} and Ntp_{neg} [min^{-1}].

Finally, curves of both signal polarities are smoothed by a filter, mean Ntp is calculated and of the linear trend (LT) is determined from the whole analyzed PPG signal – see the graphs in Figure 2.

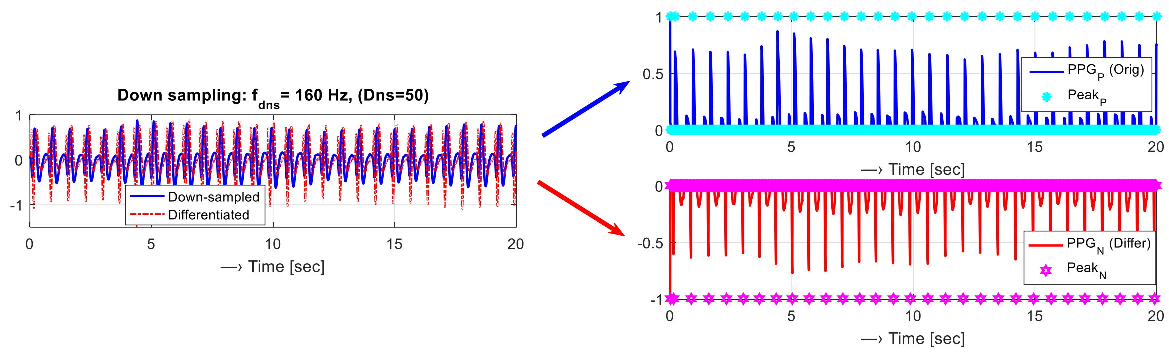
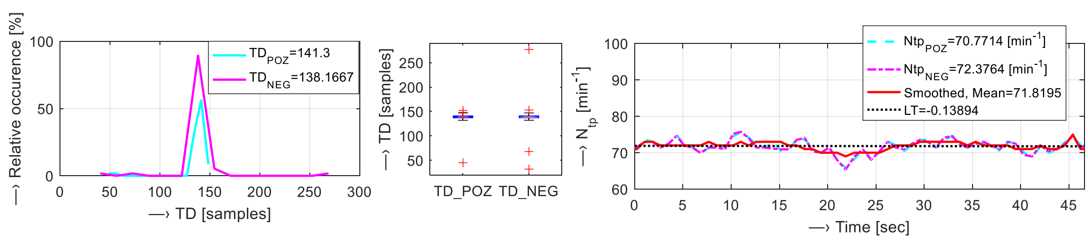


Figure 1. An example of PPG signal processing in a 20-s ROI: down-sampled signal (originally recorded at f_s = 8 kHz together with its first derivative (**left graph**), positive/negative peak positions of the down-sampled/differentiated PPG signal (**two graphs on the right**).



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

Figure 2. Second phase of PPG signal processing: (**a**) histograms of time distances between localized peaks for both signal polarities; (**b**) box plot of basic statistical analysis of TD values; (**c**) curves from both polarities of the signal, their smoothing, and the linear trend for the whole recorded PPG signal.

3. Proposed Method for Analysis of MRI Vibration and Noise Effects by PPG Signal Measurement

Duration and intensity of noise and vibration exposition and position of the tested person in the proposed measurement was set as a compromise between properly detected changes of BP and HR and minimized negative impact on a tested person during the experiment. In previous measurement [6] we have basically mapped distribution of vibration and noise intensities in the open-air and whole-body tomographs working with a low magnetic field [7] for different scanning sequences and different setting of their basic parameters. The whole experiment is divided into several phases with the first initial phase of preparation of a person for measurement inside the tomograph (adaptation to the space of the scanning area) followed by active influence of vibration and noise in only two blocks with the time duration (T_{DUR}) of about 300 s, and the "silent" relaxation phase with no MR scan sequence running (with the ambient noise from the temperature stabilizer). These main phases will be interlaced by shorter ones (with maximum T_{DUR} = 60 s) necessary for manual measurement of BP and HR by a portable BPM device. It means that the tested person will be exposed to vibration and noise for maximum of 12 minutes. During the whole experiment, the PPG signal of a tested person is recorded in real-time using an additional PC (as the PC of the MRI control console cannot be used for this purpose, only the MRI control SW can be run there [2]). The PPG signal is subsequently divided into separate files (corresponding to the current phase of the experiment) and off-line processed as described in previous chapter. During the whole experiment, the person lying in the scanning area wears a pressure cuff of a BPM device on an arm and an optical sensor on a finger which can also contribute to discomfort. Therefore, the expected experiment duration is finally about 20 minutes as documented in Table 1 with detailed description of all experimental phases. After evaluation and statistical processing, we finally obtain the PPG smoothed curves (including the slopes of the linear trend) for each of the experimental phases together with visualization of changes in BP and HR parameters – see an example in Figure 3.

Table 1. Detailed description of the phases of the proposed measuring experiment.

Phase	Description	Status	Measurement	T_{DUR} [2] [s]
F0s	Initial and adaptation	Silent [1]	PPG signal recording	60
F1t	1st BP and HR measurement	Silent [1]	by BPM & PPG recording	60
F2m	1st vibration/noise exposition	MRI scanning	PPG signal recording	300
F3t	2nd BP and HR measurement	MRI scanning	by BPM & PPG recording	60
F4m	2nd vibration/noise exposition	MRI scanning	PPG signal recording	300
F5t	3rd BP and HR measurement	MRI scanning	by BPM & PPG recording	60
F6s	Relax after expositions	Silent [1]	PPG signal recording	300
F7t	4st BP and HR measurement	Silent [1]	by BPM & PPG recording	60

[1] Only temperature stabilizer noise is generated, [2] Total time duration is 1200 s (20 min).

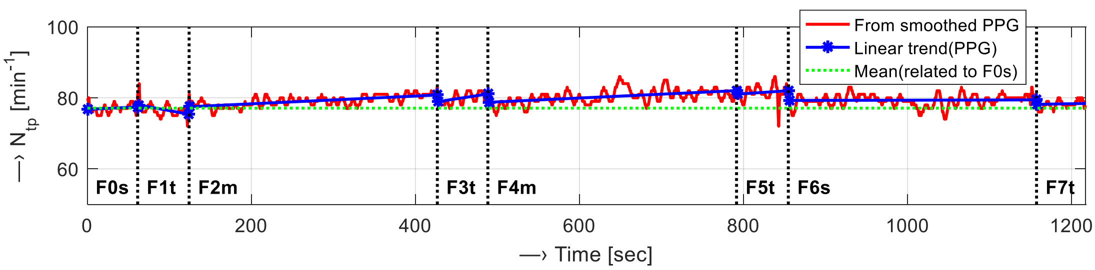


Figure 3. An example of the resulting PPG signals for all 8 phases of the measuring experiment in the scanning area of the MRI device: filtered/smoothed, linear trend and mean related to F0s phase.

4. Experiments and Results

Practical measurement experiments were realized on the open-air MRI E-scan Opera by Esaote S.p.A. [2] at the Institute of Measurement Science (IMS) in Bratislava working in a stationary magnetic field 0.178 T. Two types of measurement and comparison were practically performed:

1. The first auxiliary experiments comprised measurement and comparison of three different types of portable BP and HR measuring devices. We compared the precision and stability of the HR values measured directly by investigated devices and determined from PPG signals with the main aim to choose the best device for the main measurement inside the MRI tomograph.
2. The main measuring experiment with the tested person lying in the MRI scanning area (with an MR scan sequence running or "silent" – with no scanner activity) and his/her PPG signal recorded simultaneously for further analysis and processing. In these experimental phases the BP and HR parameters of the tested person were measured also manually by a portable BPM.

The measurement is based on real-time recording of the PPG signal using a reflective optical sensor HRM-2511E by Kyoto Electronic Co. to pick up the blood variation in the finger tissue and outputting a digital pulse synchronous with the heartbeat. This type of an optical sensor consisting of an infrared LED light source and a photo detector is worn on a little or a middle finger. The sensor body is built with flexible Silicone rubber material that helps to keep the sensor tightly hold to the finger. The signal from the photo detector is next pre-amplified and two-phase filtered processed by the analog interface Easy Pulse Version 1.1 by Embedded Lab. Disturbance of 50 Hz and its harmonics from the power-line voltage is avoided by using a battery-based power supply of 5 V via USB connection realized by the power bank "AlzaPower Source 20000". The PPG signal obtained in this way is then inputted to the mixer device Behringer XENYX Q802 and digitized via the USB interface of the laptop PC. The PPG signal originally recorded at 2 or 8 kHz was down-sampled to 160 Hz and subsequently processed. The stationary signal parts with the time duration of 60 s were selected and normalized to the level of -16 dB using the sound editor program Sound Forge 9.0a. In practical measurement, only the optical sensor HRM-2511E is placed in the MRI scanning area; the electronic Easy Pulse sensor module and the audio mixer are located outside the shielding cage.

3.1. Comparion of the Blood Pressure Monitor Accuracy

This part of the experiment is aimed at manual measurement of BP and HR together with PPG signal recording in chosen four different physiological situations (after book/journal reading, music listening, relaxation, drinking tea or coffee, physical activity, etc. with the aim to obtain maximum range of the values). This preliminary measurement was performed in normal room/laboratory conditions with a testing person sitting on a chair at a table. Three BPMs were compared:

1. automatic blood pressure monitor with stroke risk detection BP A150-30 AFIB and a comfortable cuff (of 22-42cm) produced by the Microlife AG (further called "Microlife"),
2. Omron M6 upper arm BPM with Intelligent Wrap Cuff Technology by Omron (further called "Omron M6"),
3. Omron HEM-711 DLX with Comfit Cuff by Omron (further called "Omron 711").

To prevent any influence of an inflated pressure cuff of BPM on a tested person's blood system, the PPG signal must be picked up from the opposite hand. In practical realization of this experiment, the PPG signal was always picked up from the pinkie of the right hand and the cuff was put on the left arm. Six volunteer persons (four males and two female) took part in this measurement, 12 data records per person were always collected, 72 in total. The obtained results of the relative differences in [%] between Ntp values determined from the PPG signal and measured by three tested BPMs are presented in the Figure 4.

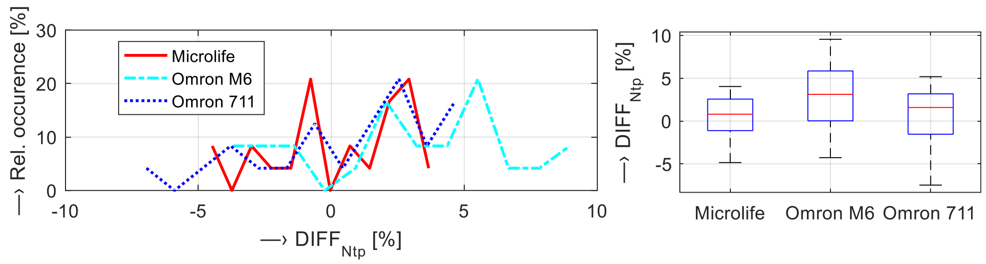


Figure 4. Statistical comparison: histograms of relative differences between *N*tp from the PPG signal for three BPMs (**left graph**); basic statistical parameters of the obtained relative differences (**right**).

3.2. Description of the Main Measuring Experiment in the Scannig Area of the MRI Device

The main measuring experiment was realized in the MRI device placed in a cover metal cage [2] to protect the external measuring devices connected to the PPG sensor for signal real-time processing and storage. Except for the portable BPM device, other instruments were located in the control room of the MRI equipment near the operating console. A tested person lied in the MRI scanning area and wore the optical sensor to pick up the PPG signal. In accordance with the proposed measurement scenario described in Table 1, all eight phases of the experiment were performed sequentially. The experimenter stayed in the control room except the time of BP and HR manual measurement using the BPM in the cage. The process of synchronization of the MR sequence execution and PPG signal recording was also realized manually.

Two persons participated in this main experiment – one male and one female weighing approximately 80/55 kg (the weight affects spectral properties of the generated vibration and noise [8]). Four experiments were performed in total (two ones with each person). Position of the tested person was chosen is such a way that the head was placed in the RF scan coil between the upper and lower gradient coils of the MRI device to maximize the noise and vibration effect on an examined person. In the active stimulation phases (F2m and F4m) the 3D SSF scan sequence with TE = 10 ms, TR = 40 ms, sagittal orientation, 3D-phases = 24, N_{ACC} = 4, T_{DUR} = 12:24 min was applied for backward compatibility with our previous experiments [6,7]. Obtained results can be presented in a graphical form – partial comparison of discrete BP and HR values and changes of HR for each of experimental phases are shown in Figure 5 for the male tested person. Final summary comparison in a numerical form as mean differential *N*tp/HR and BP values (including their standard deviations) determined in all eight experimental phases can be seen in Table 2.

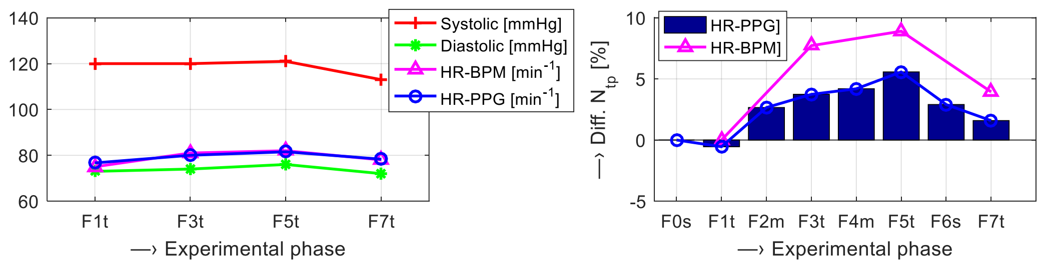


Figure 5. Partial comparison of values measured by the BPM device and determined from the PPG signal: BP and HR values in four measuring phases (**left graph**); relative differences in [%] between *N*tp/HR values determined from the PPG signal/by the BPM device in all eight experimental phases relative to the F0s/F1t as a baseline (**right graph**), for the male tested person, experiment no. 2.

Table 2. Comparison of mean relative differences in [%] (and std values in braces) of *N*tp/HR and BP (systolic/diastolic) determined in all eight experimental phases.

Phase	From PPG signal [1]	BP and HR by BPM device [2]

	***N*tp**	$\mathbf{BP_{SYST}}$	$\mathbf{BP_{DIAST}}$	**HR**
F0s	0 (0)	–	–	–
F1t	1.18 (0.46)	0 (0)	0 (0)	0 (0)
F2m	1.75 (0.54)	–	–	–
F3t	2.65 (0.67)	1.93 (0.88)	-1.44 (0.52)	6.06 (0.70)
F4m	2.77 (0.82)	–	–	–
F5t	4.14 (1.06)	2.67 (0.78)	-1.95 (0.59)	7.94 (0.74)
F6s	3.04 (0.86)	–	–	–
F7t	2.39 (0.61)	1.33 (0.89)	-0.09 (0.70)	5.77 (0.67)

[1] Relative to the values of the F0s phase as a baseline, [2] relative to the values of the F1t phase as a baseline.

5. Discussion and Conclusions

The preliminary experiments show that all three tested BPM devices give HR values comparable with those determined from the PPG signal. Finally, the BPM *Microlife* was used in the main experiment apart from the PPG sensor to obtain the best statistical results - minimal dispersion and approximately zero mean value of calculated relative differences – see Figure 4.

Results obtained in the main measurement experiment confirm that exposition to MRI vibration and noise affects the human physiology and psyche, as documented by the values *N*tp/HR increased by 4/8% in comparison with the silent (initial) state in the phase F0s/F1t – see the values in Table 2. This effect was accompanied by changes in BP parameter – about 3% increase of systolic and approx. 2% decrease of diastolic blood pressure differential values. More statistically significant results can be obtained by carrying out more measuring experiments with different persons lying in the scanning area of the MRI device.

In near future, we plan experiments with parallel recording of a speech signal when a speaker lies in the scanning area of our tomograph as this arrangement is used in MR imaging of vocal folds during phonation [9]. We will try to verify of our working hypothesis that stress induced by vibration and acoustic noise of the MRI tomograph is manifested also in the voice of an examined person. This future work will be oriented to analysis of proper speech features which could be next used for stress detection based on statistical approaches (ANOVA, GMM, etc.)

Author Contributions: Conception and design of the study, J.P., A.P. and I.F.; measurement, J.P. and A.P.; data collection and processing, J.P.; writing, J.P. and A.P.; English correction, A.P.; paper review and advice, I.F.

Funding: This work was funded by the Slovak Scientific Grant Agency project VEGA 2/0001/17, 2/0125/19, and the Slovak Research and Development Agency, project no. APVV-15-0029.

Acknowledgments: We would like to thank all our colleagues and other volunteers who participated in the BPM devices evaluation experiment.

Conflicts of Interest: The authors declare no conflict of interest.

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