# Personal wearable monitor of the heart rate variability

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Abstract: The aim of the paper is to present of a prototype of wearable heart rate variability (HRV) monitor. The home care surveillance and sleep assessment system is partly embedded into a smart home infrastructure and partly worn by a supervised person. The prototype wearable device is designed to acquire and process the electrocardiogram and to send reports accordingly to a programmed schedule. The recording, processing and transmission modes are programmable, what allows the recorder to respond immediately in case of predefined thresholds excess, while the regular reporting is organized in delayed packets exchanged during a short transmission session. This approach significantly reduces the contribution to the total power consumption from the communication module. The prototype was based on the PXA-270 development kit, but due to very low power consumption (0,5 mW) the migration to a more compact system is considered.

keywords: sleep monitoring, assisted living, wireless body area network, heart rate variability,

## 1. Introduction

Wireless monitoring of basic vital parameters is currently one of the hottest research areas and prospective application fields as assisted living and home care. Current experiences show, that personalization of the devices helps in refinement of distributed diagnosis calculation. First home care implementations prove that numerous diagnostic devices restricted to clinical use so far are applicable as elements of home automation increasing the users safety. They role in the prevention or follow-up is doubtless and among other aspects brings considerable reduction of medical costs. Thanks to deep modulation of functionality achieved with the use of software and remote configuration they fit to the paradigm of personalized medicine.

The aim of the project was to built a prototype of home care surveillance and sleep assessment system including a wearable heart rate variability (HRV) monitor. The whole system is a hybrid partly embedded into a smart home infrastructure and partly worn by the supervised person. Both components are personalized by the software settings and dynamically linked executable code. The prototype wearable device is designed to acquire and process the electrocardiogram and to send reports accordingly to a programmed schedule.

The ECG-derived HRV is commonly recognized as easily available representation of autonomous nervous system (ANS) and clinically studied in pursuits for many neurological disorders [1-2]. Currents studies justify that the HRV analysis in sleep is particularly meaningful. Because of lack of the voluntary actions of the subject in sleep, all heart rate accelerations and decelerations may be interpreted as ANS-related. The advantage of heart rate analysis is a wide range of data acquisition methods. The tachogram is usually derived from the single lead ECG signal, but upon the necessity the pulseoximeter, the arterial pressure meter or the cardiac microphone may also be a reliable source of RR interval series. The ECG-derived tachogram is a low data rate signal (12 bits per second) what suggests the ECG processing to be performed directly by the embedded software of a wearable recorder. Thanks to the low datastreams, the transfer may be organized in sessions allowing for considerable power savings or through a seamless link when immediate system response is needed. In the interpretation of the HRV common time- and frequency domain parameters were used. This facilitates data referencing to the clinical results in both: development and operating stages. The algorithms for tachogram processing are more complicated [3-4], particularly due to the sampling normalization required for spectral analysis. In the sleep assessment system the HRV parameters are interpreted with consideration of simultaneously recorded subject motion and acoustic signal described by snoring-specific parameters.

The design of an ECG recorder worn at sleep must particularly consider the factor of usage comfort, therefore the weight, size and autonomous operation time are crucial parameters. Therefore several energy savings-oriented measures were taken into consideration at the design stage. Besides the use of low-power circuitry, main contribution to the longevity of the wearable recorder are: optimization of the ECG processing and organization of the wireless transfer of tachogram series. Unfortunately, due to the required mobility of the subject implying the omnidirectional radio wave propagation, the wireless connection is the main contribution to the power consumption.

## 2. Materials and methods

### 2.1 Deriving the tachogram from the ECG record

The heart rate reported or displayed for diagnostic purposes is usually the average value of seven consecutive RR intervals. Excluding two shorter and one longer intervals from the averaging increases the HR report stability in the presence of missing or extra detections. The instantaneous HR and its beat-to-beat variations (HR variability, or HRV) have been studied for many years, particularly in the framework of investigation of the ANS balance. In periods of stable HR, there are small beat-to-beat variations that result from the balance between the sympathetic system and the parasympathetic system. For this reason any pharmacologic agent that acts over ANS functions also influences the heart rate. Lower rhythms (sinus bradycardia, below 50 bpm), resulting from the prevalence of a parasympathetic system, occur in states of deep relaxation or in athletes with enlarged stroke volume. Higher rhythms (sinus tachycardia, above 110 bpm) are caused by the dominance of a sympathetic system and appear during physical effort or mental stress. The time-domain parameters of the heart rate variability are thus crucial indicators for the human surveillance in everyday life including possible assessment of sleep disorders. Since the ANS influences mainly the sinoatrial node (SA) in the heart conductive system, the HRV parameters aiming at assessment of the ANS require to be calculated from the NN (normal-to-normal) time intervals. In case of occurrence of escape or complementary stimulations, these beats need to be excluded and replaced by a hypothetical heart beat of sinoatrial origin.

The ECG record needs specific processing to yield the RR time series. This includes the temporal localization of the heart beats and basic classification of beat types. Single-lead electrocardiogram is sufficient to provide a reliable temporal markers and usually also information of origin for each heart beat. The use of three bipolar lead system (Holter type) is considered, but not implemented in the prototype for the reason of subject's comfort. The ECG is acquired with the sampling frequency of 500 sps and 12 bits resolution. The processing is performed in real time with the use of mathematical signal transformation revealing the common features of the QRS complex. Next the adaptive threshold is applied to discriminate the QRS section. The localization of the R wave peak is further refined to 1 ms with use of five points-based parabola fitting [5]. Beat origin labeling needs further processing of the signal sections isolated in 100 ms vicinity of the R wave peak. Certain features of the signal most discriminative for atrial and ventricular beats [6] are calculated and supports the final decision on the beat origin attribute. The beats are next qualified to the time-domain HRV analyzer. The whole processing yields for each heartbeat a pair of numerical descriptors aggregated in a word:

- the relative position coded in 12 bits,
- the origin coded in remaining 4 bits,

For the reason of data integrity one beat type is reserved for a synchronization time marker.

Since the ECG interpretation algorithm is embedded and raw ECG record is not available in normal operation mode, the performance of the processing and pertinence of the sleep analysis rely on the robustness of the beat detection and classification methods to interferences and noise. The algorithm applied as recorder's embedded software was developed as a part of real-time Holter interpreter and complies with the essential performance requirements (IEC60601-2-51). The wearable device is thus considered reliable in standard recording conditions, therefore particular attention should be paid by the user to the signal quality and electrodes placement. Although the implementation of advanced methods for signal recognition is technically possible, extending the range of usage conditions causes the increase of computational complexity and shortens the autonomy time.

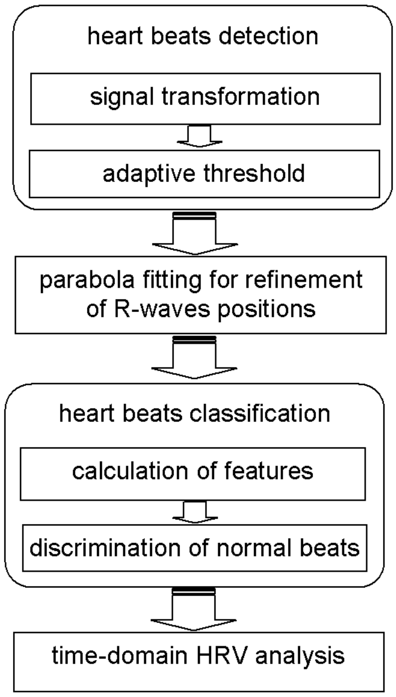


Fig. 1 Scheme of embedded ECG interpretation algorithm

2.2. Dataflow organization

The recording, processing and transmission modes are programmable, what allows the recorder to respond immediately in case of predefined thresholds excess. The embedded time-domain HRV analyzer provides values for decision on the dataflow mode (fig. 2). The available modes are:

- packet reporting for off-line transfer of the HRV data,
- conditional reporting which switches between the packet and the seamless data transfer accordingly to specified conditions on the HRV parameters value,
- seamless reporting for the time-synchronized transfer of the HRV data.

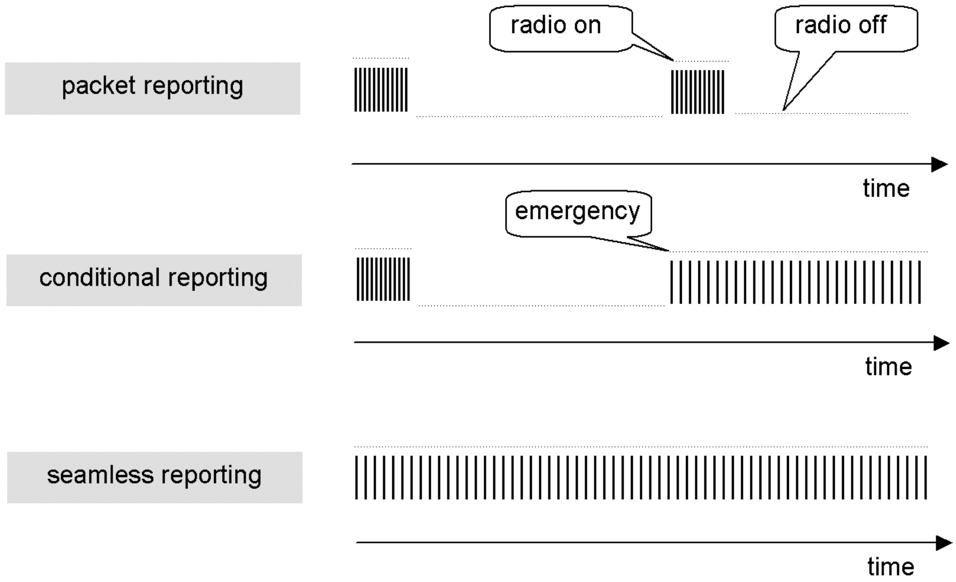


Fig. 2 Summary of the HRV data reporting modes

In first (regular) reporting mode the data are stored in a buffer of predefined length (300 - 3600s) and organized in packets exchanged during a short transmission session. This mode provides delayed information about the subject's state, but significantly reduces the contribution to the total power consumption from the communication module.
In the conditional reporting mode, depending on predefined settings and actual parameter values, the data are stored in a buffer and reported in packets in a given time interval or transmitted immediately to the Bluetooth interface of house-embedded monitoring system. Programmable parameters are:

- epoch length – determining the epochs averaging time and thus the borderline between the fast (RMSSD) and slow (SDANN) ANS components (usually set to 5 min),
- tachycardia and bradycardia limits – determining the possible continuous reporting mode (default values are 110 and 50 bpm respectively),
- local variation limit – determining the possible continuous reporting mode in case of HR instability,
- abnormal beats percentage limit – determining the acceptable contribution from non-sinus rhythms,

In case of continuous monitoring, the report content is also specified by the software settings and may range from the raw ECG to the tachogram and HRV parameters. In this mode the surveillance and sleep assessment system reads the subject's HRV data simultaneously with the results of other measurements.

2.3 Prototype design

The target device is designed as a lightweight and reduced in size (below 1 sq inch) and provides a Bluetooth wireless interface and mini-USB connector. It is powered by a built-in Li-Ion accumulator charged via USB. The prototype was based on the PXA-270 development kit (fig. 3), but due to very low power consumption (0,5 mW) the migration to a more compact system is considered. Initially we used the commercially available ECG recorder (Aspekt500, Aspel) as the subject's front-end, but this 12-leads recorder was replaced by a single-channel custom-built module with similar measurement specification (full range ±12mV, noise 1μV RMS, $k_u$ = 85V/V), but with significantly reduced power requirements (0,5mV). Further reduction of the power consumption was studied, but below the given value, the amplifier was increasingly prone to interferences.

The host surveillance system was based on the task-oriented analysis of the video and audio data and mounted in a dormitory ceiling. The embedded system provided a Bluetooth interface for a two-way digital communication with the wearable monitor of subject's HRV parameters. The surveillance system was designed for studies on sleep quality and detection of the apnea and other sleep disturbances. Recent interpretations show the correlation of the subject's motion with HRV parameters as an important health factor.

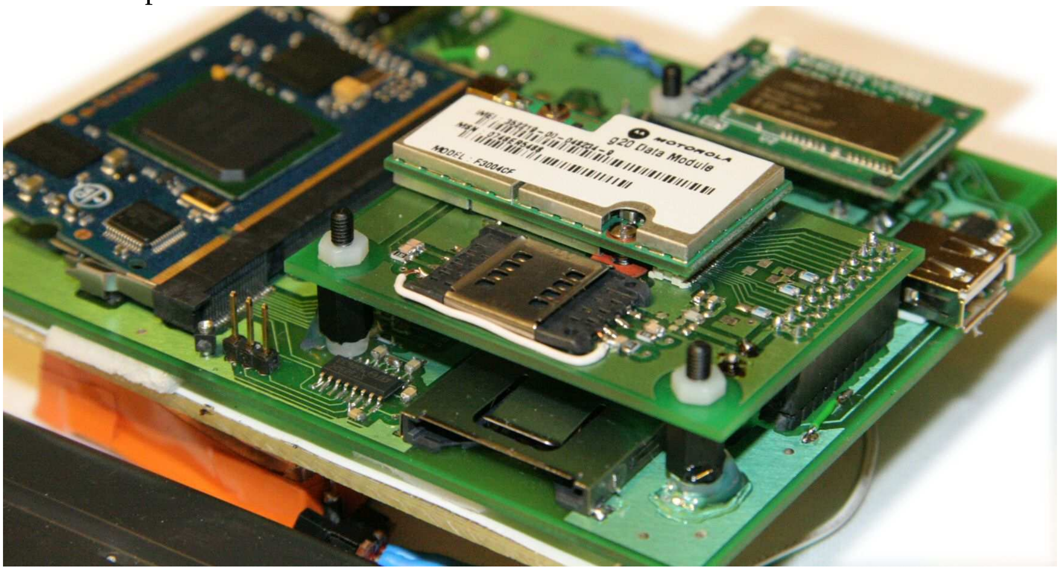


Fig. 3 Prototype wearable recorder with wireless interface

2.4 Testing procedure

The HRV recorder was tested for the conformance with a conventional HRV analysis with use of selected (best) lead of the MIT-BIH Arrhythmia Database [7], resampled to 500Hz. The reference positions of the heart beats and the beat types were verified by a commercial Holter analysis software (Holcard 24W, Aspel).

- The validation of the embedded software was performed first and used digital ECG records. The output RR sequences acquired from wired USB connection was compared to the reference provided by the commercial software.
- The overall verification of the wearable device includes the participation from the analog circuitry and wireless communication module. For these tests the corresponding ECG signal was generated in the analog form (amplitude scale 3.9μV/LSB, $f_p$ 200Hz, output impedance 500Ω). This signal was captured, interpreted and the result RR sequences provided by a wearable reorder via Bluetooth interface was compared to their references.

3. Results

Results of the comparison between two RR interval series and heart beat annotation are presented for software and overall tests in table 1 and 2 respectively.

Table 1. Difference of RR intervals between the tested and commercial interpretation software, and the sensitivity and specificity of normal heart beats labeling (testing of the embedded software)

| MIT-BIH ID | avg ΔRR [ms] | std ΔRR [ms] | sens NN [%] | spec NN [%] |
|---|---|---|---|---|
| 100 | 5.7 | 3.1 | 98.8 | 99.1 |
| 101 | 6.6 | 4.7 | 99.1 | 99.2 |
| | | ..... | | |
| 234 | 12.1 | 7.1 | 97.3 | 95.4 |
| **average** | **6.83** | **5.37** | **98.5** | **97.9** |

Table 2. Difference of RR intervals between the tested and commercial interpretation software, and the sensitivity and specificity of normal heart beats labeling (overall verification of the system)

| MIT-BIH ID | avg ΔRR [ms] | std ΔRR [ms] | sens NN [%] | spec NN [%] |
|---|---|---|---|---|
| 100 | 10.1 | 5.3 | 98.7 | 99.0 |
| 101 | 9.3 | 4.9 | 98.9 | 99.0 |
| | | ..... | | |
| 234 | 13.1 | 9.1 | 96.9 | 95.0 |
| **average** | **8.17** | **6.96** | **98.3** | **97.7** |

Complementary results reveal the benefits from the applied data transfer modes. The Bluetooth module requires 160 mW of power for operation, while only 3.1 mW in standby mode. For the HRV data packet collected in one hour (9 kB) the measured duration of the transmission session is 7 s (including the connection setup, confirmation and backward settings of parameters). The average power consumption in the longest packet reporting mode may thus be significantly reduced from its initial value of 161 mW to 1,3 mW i.e. by 99.2%. The corresponding extension of subject's device autonomous operation allows for 230h instead of 1,8h in seamless reporting.

## 4. Conclusion

A simple diagnostic system for the assessment of the human ANS in motion and during the sleep was designed and tested. The system is based on HRV parameters calculated on an ECG-derived tachogram. Thanks to the use of a single recording channel and simplicity of the embedded signal processing, the target system can be shrink to less than 1 sq inch, what allows for integrated mounting on the electrode. The recording of heart rate is continuous, however significant extension of autonomy time (up to two hundreds of hours) is achieved thanks to the programmable organization of the transfer. Differences between the custom-build and reference algorithms expressed in tables 1 and 2 originate from different detection technique, low sampling frequency and unknown RR intervals averaging applied in the commercial software.
In author's opinion, the principal benefit of the system comes from the possibility of conditional reporting based on on-board calculated HRV parameters.


## 5. Acknowledgment

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## Bibliography


[1] Malik, M., & Camm, A. J. (2004). Dynamic electrocardiography. Armonk, NY: Blackwell Futura.

[2] Mironova, TF., Mironov, VA., Antyufiev, VF. Analysis of heart rate variability at sinoatrial dysfunction in patients with coronary disease. Electrocardiology 2009 pp. 211-220
[3] Task Force of the ESC/ASPE. (1996). Heart rate variability: Standards of measurement, physiological interpretation, and clinical use. European Heart Journal, 17,354-381.
[4] Tkacz, E. (1996) Nowe możliwości diagnostyczne analizy zmienności rytmu serca (HRV) Nakładem Instututu Biocybernetyki i Inżynierii Biomedycznej PAN, Warszawa
[5] Augustyniak, P. (1997) The Use of Shape Factors for Heart Beats Classification in Holter Recordings" w materiałach konferencji Computers in Medicine Zakopane 2-6. 05. 1997, str. 47-52
[6] Augustyniak, P. (1999) Recovering The Precise Heart Rate From Sparsely Sampled Electrocardiograms w materiałach konferencji Computers in Medicine, Łódź, 23-25.09.1999, str. 59-65
[7] Moody, G. (1993) MIT/BIH arrhythmia database distribution. Cambridge, MA: MIT Division of Health Science and Technology.