Wearable System for EKG Monitoring - Evaluation of Night-Time Performance

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Abstract. We evaluated the night-time heart rate recognition performance of our wireless EKG measurement system with four persons during fourteen nights. The system uses fabric electrodes, which rely on moisture of the skin as the electrolyte for optimal operation. Even with the small amount of sweating during night, we achieved an average of 99.8 % R-peak recognition rate when data transmission failures of the wireless network were not considered. Based on our test the performance of the textile electrodes is on par with commercial disposable gel EKG electrodes that were used as a comparison.

Keywords: Wearable EKG, wireless network, textile electrode, night-time heart rate.

1 Introduction

Interest towards the night-time heart rate (HR) and heart rate variability (HRV) monitoring has been growing when understanding of the heart rate control mechanisms of the autonomous nervous system has increased. Besides medical applications, also wellness and security applications, such as elderly monitoring, may utilize the results of the night-time HR and HRV research.

Variety of methods exists and is currently being developed for night-time HR measurement. When developing and validating new methods for monitoring night-time physiological signals, it is important to have a reliable source of reference data. Traditionally contact EKG recorded with regular gel electrodes have been considered as the most reliable source of the reference data.

As a part of our earlier research, we developed a wearable and wireless system for measurement and on-line analysis of EKG during group rehabilitation training. The initial version of the system was presented in [1]. Our system that relies on the use of fabric electrodes made from silver coated polyamide yarn has proven to work very well in its aerobic exercise monitoring application where sweating provides the necessary electrolyte between the electrodes and skin. We wanted to test how reliable the system is in night-time measurement, where usually the amount of sweat is limited, but on the

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other hand, the amount of movement artifacts is also small. We are planning to use our system as a reference method when developing and validating other night-time HR measurement techniques and therefore its reliability needs to be known well.

2 Background and Related Work

Night-time EKG and HR information have been measured for diagnosing cardiac malfunctions and for other medical purposes for a long time. These measurements are normally done with Holter cardiac monitors that usually record from two, up to twelve EKG measurement leads. Currently, these devices are becoming smaller and more comfortable to wear because memory cards have replaced C-cassettes as storage medium. In spite of this trend, Holter devices are cardiac data loggers and the data must always be offloaded from the memory card for viewing or post-processing. This is acceptable in a case of an occasional medical test, but for more regular use, this would be too cumbersome. In our measurement system, all data is relayed in real-time to a computer from which it can be automatically sent further to a hospital server if desired or analyzed on-site and reported directly to the user.

Cerutti *et al* investigated wearable monitoring of biomedical signals in an EU project called “My-Heart”. In a sub-project of My-Heart, a wearable monitoring and analysing system, “Take-Care”, was developed and used to collect physiological information during sleep [2]. The same group has also further studied possibilities to use HRV and respiratory signals recorded with wearable devices in sleep stage classification [3]. In spite of the work reported in [2] and [3] that utilizes the signals recorded with a wearable systems and textile electrodes, we have not been able to find a study where night-time HR recording performance of textile electrodes has been compared with gel electrodes.

All the aforementioned systems, including ours, require measurement devices to be worn by the user, which may disturb the sleep of a sensitive person. Another possibility for monitoring night-time EKG and HR is to attach the electrodes to the bed. This method has been investigated by Devot *et al* in [4], where they achieved an 81.8 % average recognition rate for heart beats. Peltokangas *et al* [5] received an average of 95.1 % recognition coverage during 22 measurement nights. Their system uses seven bipolar channels that measure EKG with textile electrodes. The electrodes are sewn on a bed sheet and the measurement is done from the area of upper torso.

An important benefit of the wearable HR measurement systems, when compared to those installed in the bed, is that the origin of the data can be known with high confidence also when more than one person is sleeping in the bed. Another benefit of wearable measurement is that the data can be collected also when the test person gets up from the bed e.g. for going to the bathroom during the night. This enables a longer time HRV analysis to be done from the uninterrupted signals.

Night-time HR information can also be recorded by using a regular heart rate belt. Modern belts also measure beat-to-beat HR, which can be used for HRV analysis. However, the data does not contain the original EKG signal and therefore the reliability of the HRV information or possible EKG irregularities cannot be verified afterwards.

3 Materials and Methods

3.1 Monitoring System

Our monitoring system consists of a wearable unit that includes the electrodes and the measurement hardware, a wireless network, and signal processing software running on a PC. The monitoring system also includes HR display modules that could, in addition to showing the HR, be used for relaying other information related with the quality of sleep to the person after awakening. Our system was originally designed for EKG monitoring and analysis during cardiac group rehabilitation training. The system has been designed to conform to the European medical safety standards and it has received a CE approval as a class IIa medical device.

Wearable Unit. The electrodes as well as the detachable EKG measurement unit are worn with a special measurement shirt shown on the right side of Fig. 1 The electrode setup includes three textile electrodes, two at the chest area (attached onto a chest belt) and one around the right arm attached to the shirt sleeve. All electrodes are made from 275 dtex silver plated multifilament nylon (polyamide 6.6) yarn embroidered onto a textile base. The chest electrodes are oval shaped, whereas the arm electrode has a square wave shape embroidered on a stretchable ribbon. This special shape was selected based on work presented in [4]. The left side chest electrode is placed at the location of V4 electrode of the 12-lead EKG system, the right one being placed similarly but mirrored to the right side. We have been using both regular silicone covered copper cables and braided textile cables as electrode wires. The conductive core of the textile cables is made from the same conductive silver yarns as the electrodes. The type of the cable has not had any significant effect to the result in this application.

The shirt provides high wearing comfort when compared to the other current commercial Holter devices. Other benefits of using an EKG shirt are the easy and exact attachment of the electrodes onto right positions when using personalized shirts. Movement artifacts are also decreased and the fabric electrodes irritate the skin less than the regular EKG electrodes that contain adhesives.

Wireless Network and Measurement Hardware. Our wireless network is based on the IEEE 802.15.4 standard and is realized as a star network using TDMA channel access. Eight measurement units and displays are supported in one network. The measurement units have two EKG channels with 250 Hz/channel sampling rate and 16-bit dynamics.

Measurement channel 1 records EKG between the two chest electrodes and measurement channel 2 records EKG between the left chest and the arm electrode. The EKG amplifiers have 0.2 – 40 Hz pass-band that is realized with 1st order analog high-pass and 2nd order analog low-pass filters. The amplifier input has 250 mV DC voltage tolerance in order to withstand the potentially high difference of the half cell potentials of the textile electrodes.

The measurement units include a buffer memory of eight data packets, which equals 0.8 seconds, to cover transient data losses. Fig. 1 shows the components of the measurement system.

Fig. 1. Night time HR measurement hardware. Measurement unit marked as 1, display unit as 2, and network coordinator as 3.

Signal Processing. Even though the measurement units have their own analog high and low pass filters, the measured signals are further filtered at the PC. The baseline wandering is removed by a nonlinear filtering method presented by Keselbrener *et al* in [7]. This very simple method, which removes a 100 ms median value from the data, has shown to be especially efficient. This technique leaves the R-peaks untouched and therefore the R-R intervals unaltered. The data is also low-pass filtered with 10th order Butterworth filter with a cut-off frequency of 40 Hz to remove the 50 Hz powerline noise and other high frequency interference sometimes seen in the signal. The filter is implemented in forward-backward fashion to avoid any phase shifting.

QRS complexes are recognized simply by their falling edge. Voltage level drop during 40 ms is compared to a threshold value. When falling edge has been found the preceding local maximum which is the R peak is the searched. Recognition threshold for the voltage drop is adaptive. It is set to a half of the peak-to-peak amplitude of the signal during the previous second. The R-peak candidates found are then filtered based on their temporal separation and amplitude. The minimum separation of two consecutive peaks is 250 ms. The minimum amplitude requirement prevents finding false R-peaks from noise signal in case of loss of the electrode contact.

3.2 Test Setup

We tested the performance of our measurement system with four test subjects. All subjects were male and none of them had known medical conditions that could have affected the results. Demographical data of the subjects is shown in Table 1.

The subjects were given instructions about wearing the measurement shirt and fastening the electrodes. They were also instructed to place the network coordinator inside two meter radius from the bed. The recordings with textile electrodes were made during a total of 14 nights. During eleven nights, the subjects were also wearing another measurement unit that recorded EKG with standard gel electrodes. In gel electrode measurements the electrodes were placed below the chest belt textile electrodes and the one corresponding the arm electrode under the right clavicle. The textile electrodes were not artificially moistened during the recordings.

Table 1. Demographical data of the test subjects

Parameter	Person 1	Person 2	Person 3	Person 4
Age	31	23	29	25
Height (cm)	173	184	175	178
Body mass index	26.7	20.7	20.6	24.9
Recorded nights	6	3	3	2
Nights with reference	4	3	3	1

4 Results and Discussion

Fig. 2 shows an example EKG signals recorded with textile and gel electrodes. The signals have been picked from the middle of a night where the person has been asleep. As seen from the signals the quality of EKG recorded with the textile electrode equals the quality of the gel electrode EKG. Fig. 2 also shows the rapid HR variation observed with one test subject. The natural variations of this magnitude make it more difficult to automatically point out all the incorrect QRS detections from the R-R interval data without losing the sensitivity of the detection.

Table 2 shows the results of the test measurements. The average recognition sensitivities, calculated as TruePositives / (TruePositives + FalseNegatives), for textile and gel electrodes are very close to each other. The measurement channel 1 seems to give slightly higher sensitivity in textile recordings which suggests that the channel is less prone to movement artifacts, which are the prevalent cause of both false negative and false positive R-peak detections in textile electrode measurements. In gel recordings the higher QRS amplitude received from EKG channel 2 may be the cause of its slightly better performance. Overall the grand average calculated by weighting the amount of measurement nights of each person, shows the sensitivity of 99.8 % for both electrode types and measurement channels. This is considerably higher than what has been received with electrodes installed in the bed in [4] and [5].

When calculating the false negative and false positive detection rates we do not have had a reliable reference data available because the detection errors occur with both electrode types. Therefore the classification of the beats has been done in part manually and the resulting numbers may contain small errors.

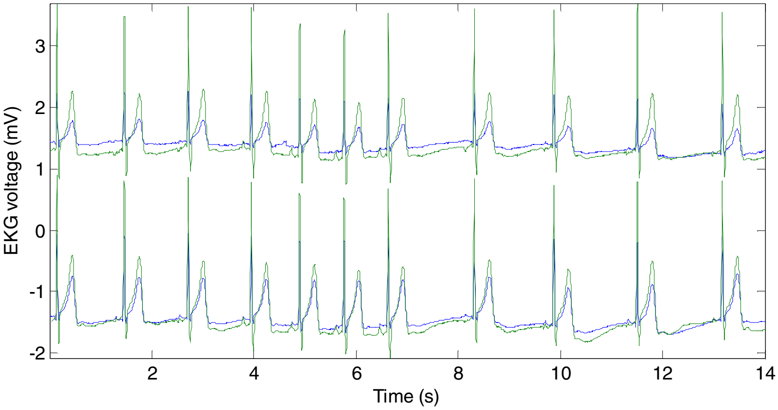

Fig. 2. An example of raw EKG signals recorded with our system. The upper curves are received from the textile electrodes and the lower from the gel electrodes. Blue curves are recorded between the chest electrodes and green between the right arm and the left chest electrode.

Table 2. Average heart rate recognition and data receiving rates for the test subjects

Parameter		**Person 1**	**Person 2**	**Person 3**	**Person 4**	**Grand average**
HR recognition sensitivity with textile electrodes (%) *	ch1	99.90	99.70	99.66	99.92	99.81
	ch2	99.89	99.71	99.63	99.86	99.79
HR recognition sensitivity with gel electrodes (%) *	ch1	99.89	99.28	99.96	99.99	99.75
	ch2	99.80	99.62	99.96	100.0	99.81
False positive recognitions, ch 1 / ch 2, textile electrodes**		0/2	3/19	48/53	8/17	12.1 / 18.7
False positive recognitions, ch 1 / ch 2, gel electrodes**		1/3	38/14	17/12	1/5	15.6 / 9.2
Data loss due to radio interruptions, textile recorder (%)		0.59	0.60	0.43	0.49	0.54
Data loss due to radio interruptions, gel recorder (%)		0.12	0.84	0.21	0.01	0.33
Total length of the record with textile electrodes (h)		34.3	20.7	25.5	16.1	
Total length of the record with gel electrodes (h)		23.9	20.7	25.2	8.0	

* The sections with data loss due to radio interruptions are not taken into account.

** The average number of false positives per night.

Fig. 3 shows an R-R interval series from one measurement night of the test subject 1. The quality and accuracy of the data is sufficient for HRV analysis when sections with no missing QRS-complexes are selected. The waveform in the end of the series, called microarousal, relates to sleep fragmentation and can be used as one measure in sleep quality analysis.

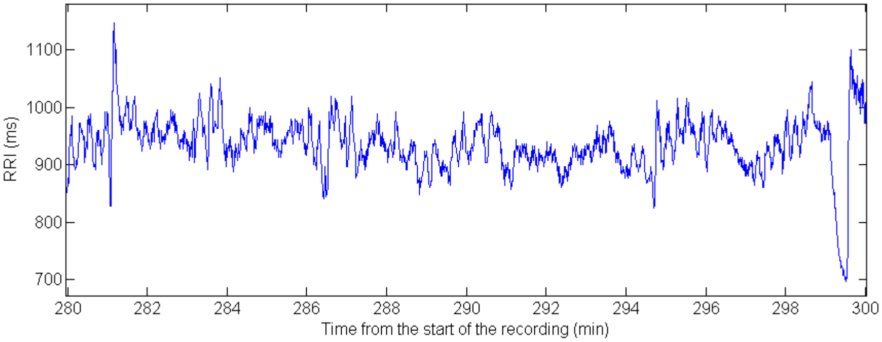

Fig. 3. A 20 minute R-R interval signal produced by our system

As seen from the data loss rates presented in the Table 2, an average of 0.54 % and 0.33 % of the EKG data from textile and gel electrode records were lost during the radio transmission. This is a relatively high value especially when considering that the measurement units include 0.8 second data buffers and that the network allows an average data transmission loss of 25 % while still being able to cover the packet dropouts with retransmissions. The system has performed without complications during the group rehabilitation sessions at various gyms where the transmission distances are much longer as in our tests. The interruptions in night-time measurements mainly occur in bursts at certain time periods during the night. We believe that they are related to decreased radio signal strength due to certain sleeping postures, e.g. sleeping in prone position and having the measurement unit under the body. Unfortunately we do not have any data source for evaluating the correlation of missing data and sleeping posture.

5 Future Work

In the future we are planning to develop the signal processing algorithms so that the QRS detection results of both measurement channels are combined. The target is to further enhance the detection coverage and especially increase the confidence of the correct QRS recognitions, which is important when using the system as a reference method in night-time HR measurements.

The performance of our system still needs to be evaluated with female subjects and people with higher body mass index. The operation of the wireless network also has to be improved.

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