A low-power wireless ECG necklace for reliable cardiac activity monitoring *on-the-move*

J. Penders, M. Altini, J. van de Molengraft, I. Romero, F. Yazicioglu and C. Van Hoof

Abstract—**This paper presents a low-power wireless ECG platform. The system relies on an ultra-low-power ASIC for ECG read-out, and a beat detection algorithm optimized for reliability in ambulatory situations. The platform is integrated in a necklace, providing ease-of-use and comfort while allowing flexibility in lead positioning and system functionality. The ECG necklace achieves up to 6 days autonomy on a 175mAh Li-ion battery. Its performances and reliability are evaluated in two pilot studies, for the detection of epileptic seizure and monitoring of Atrial Fibrillation.**

I. INTRODUCTION

WEARABLE wearable sensors enable continuous and long-term monitoring of vital signs and physiological signals *on-the-move*. In the area of cardiac activity monitoring in particular, recent advances in low-power micro-electronics have enabled the multiplication of ECG patches. These patches differ in size and functionality, and typically target a specific application.

In this paper, we present a low-power wireless ECG platform targeted to ambulatory monitoring. The platform is configurable and can be used as a starting point for developing custom prototypes addressing different applications. Preliminary results from two pilot studies are reported.

II. LOW-POWER ECG NECKLACE

The low-power ECG necklace (Figure 1) monitors 1-lead ECG (bipolar) and 3D-accelerometer. Instantaneous Heart Rate (iHR) is computed in real-time from the ECG signal, and respiration frequency is estimated from changes in the QRS amplitude. Data is transmitted wirelessly to a PC via a USB receiver. Alternatively, the data can be stored locally for further post-processing. ECG is captured using standard snap-on electrodes connected to the necklace lead wires. Reliability in ambulatory conditions is achieved by minimizing the effect of motion artifact using a light-weight design, and a beat detection algorithm optimized for noise robustness.

A. System architecture

The architecture of the low-power ECG necklace is illustrated on the block diagram of Figure 2. The core component of the system is an ultra-low-power application specific integrated circuit for bio-potential readout [1]. The ASIC only consumes 21uA, has a CMRR higher than 120dB (at 50Hz) and an input referred noise of 60nV/√Hz. The necklace integrates a low-power microprocessor from Texas Instruments (MSP430) and a low-power radio from Nordic Semiconductor (nRF24L01). A 3D accelerometer from Analog Devices (ADXL330) is used to measure acceleration in three axes. An on-board SD card provides 2GB of data storage. The power management unit consists of dedicated circuitry and a rechargeable Li-ion battery.

All electronics and battery are packaged in a pendent that can be worn around the neck, or attached to an arm using an elastic band. The size of the packaged necklace is 60mm x 40mm x 10mm, and total weight is about 20 grams. The pendent includes two lead wires that can be connected anywhere on the chest using traditional ECG snap-on electrodes (Figure 3).

Figure 1: Low-power ECG necklace

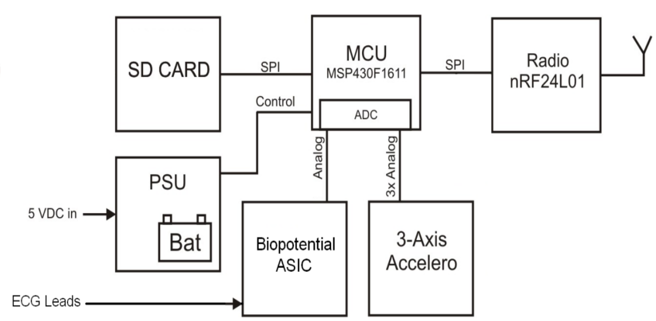

Figure 2: Low power ECG necklace, block diagram

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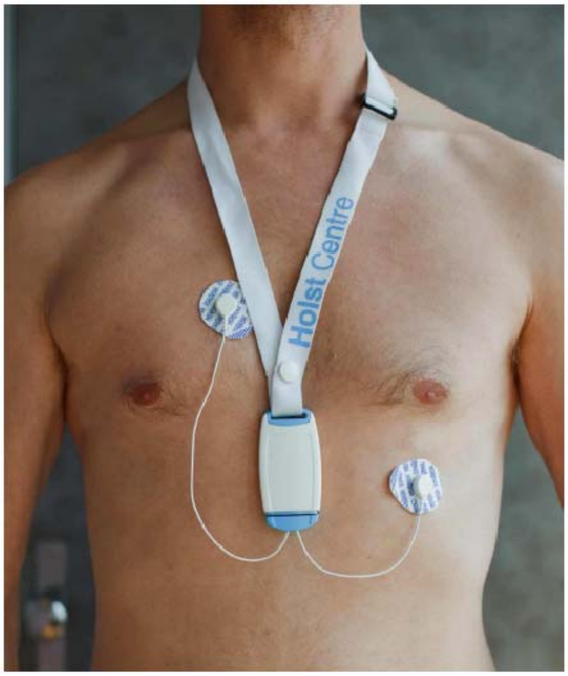

Figure 3: Low-power ECG necklace connected to the chest, with electrodes following a Lead-II configuration

B. Embedded beat detection algorithm

A beat detection algorithm is implemented in the ECG necklace. The algorithm is based on Continuous wavelet transform, and has been optimized for robustness to motion artifact. The algorithm achieves best-in-class performances, with 99.8% sensitivity and 99.77% positive predictivity on both the MIT-BIH database and a proprietary database of ambulatory ECG recordings [2].

The beat detection has been optimized for resource constrained hardware, and implemented in the MSP430. It requires 4KB of code memory and 2.5 KB of RAM memory. The execution time of the algorithm on the MSP430F1611, running at 8 MHz, is 40 ms, for a total current consumption of 150 uA.

C. Embedded ECG-derived respiration algorithm

Respiration rate can be estimated from changes in the ECG. To this end, an ECG-Derived Respiration (EDR) algorithm has been developed that uses changes in the amplitude of the QRS complex to estimate the respiration wave [4].

The ECG-derived respiration algorithm is implemented in the MSP430. To improve efficiency and reduce memory usage, the EDR and beat detection algorithm share resources (e.g. data buffers). The combination of both algorithms requires 10KB of code memory and 6.5 KB of RAM memory. The execution time of the algorithms on the MSP430F1611, running at 8 MHz, is 190 ms, for a total current consumption of 600 uA.

In addition to the embedded heart rate and respiration algorithm, the firmware includes a light-weight communication protocol (beacon-based TDMA) and lightweight filesystem (FAT16, 1.6 KB of RAM).

D. Power consumption

The ECG necklace can be operated in continuous streaming mode, in which the data is continuously transmitted to the receiver; or in data logging mode, in which data is stored directly on the on-board SD card. The embedded beat detection and EDR algorithms can be enabled to measure instantaneous heart rate and respiration rate in real time. The average power consumption in each mode is summarized in TABLE I. Power numbers are given for an ECG sampled at 256 Hz and accelerometers sampled at 10 Hz. Depending on the mode of operation, this provides from 2.5 to 6 days autonomy on a 175mAh Li-ion battery.

TABLE I: ECG NECKLACE AVERAGE CURRENT CONSUMPTION

	ECG + accelerometer	iHR + accelerometer*	iHR + EDR + accelerometer*
Streaming	1.2 mA	1.35 mA	1.8 mA
*Logging***	2.3 mA	2.25 mA	2.7 mA

* Heart rate is computed locally and in real-time using the beat detection algorithm described in [2]

**raw ECG data sampled at 256 Hz is stored on SD card in all cases

TABLE I shows that it is more power efficient to transmit the data wirelessly than to store it locally on SD card. It also shows that processing the data locally does not result in power savings at the system level: the increase in power due to local processing exceeds the gain associated to reducing the data rate. These conclusions hold for the particular architecture of the necklace (TI MSP430 and Nordic radio), and for the radio protocol implemented. The situation is expected to change radically as new, ultra-low-power, components are being integrated.

Figure 4, Figure 5 and Figure 6 illustrate the power breakdown for three particular cases: the ECG and accelerometer data is streamed (Figure 4); the iHR and EDR are computed locally, then streamed with the accelerometer data (Figure 5); the HR and EDR are computed locally, then all data (iHR, EDR, ECG and accelerometer data) is stored on SD card (Figure 6). Power consumption values are given for at a supply voltage of 3.7V. The following contribution of the total power are considered: *Sensors* correspond to the power dissipated in the analog front-end and the accelerometers; *Radio* is the power dissipated in wireless transmission of the data (this includes Reception of beacons and Transmission of data); *MCU-analog* is the power dissipated in the analog part of the micro-controller, and include the ADC, *MCU-digital* is the power dissipated in the digital part of the micro-controller, and include data handling, data processing and communication protocol; *SD card* is the power dissipated in writing the data to memory; *Additional hardware* is the part dissipated in other hardware components of the system. The comparison of Figure 4 and Figure 5 shows that local processing of the ECG data significantly increases the power consumption of the MCU from 1.35mW to 3.3mW, whereas the radio power reduces from 0.31mW to 0.27mW only. Figure 6 shows that writing to SD card consumes close to 10 times as much than transmitting the data wirelessly. This is due to a higher peak current (4.5 times higher for the SD card than the radio), and to a longer time required to handle the data.

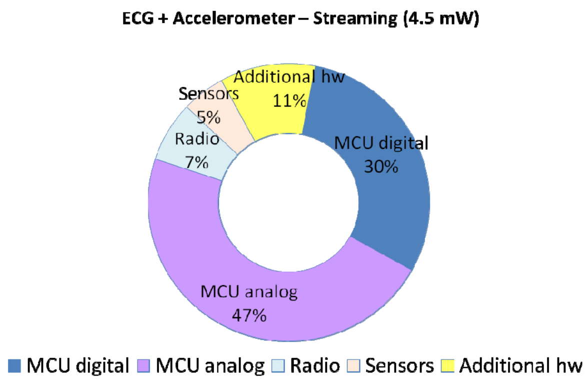

Figure 4: Power consumption break-down in the case that ECG data (256Hz) and 3D-accelerometer data (10Hz) is streamed

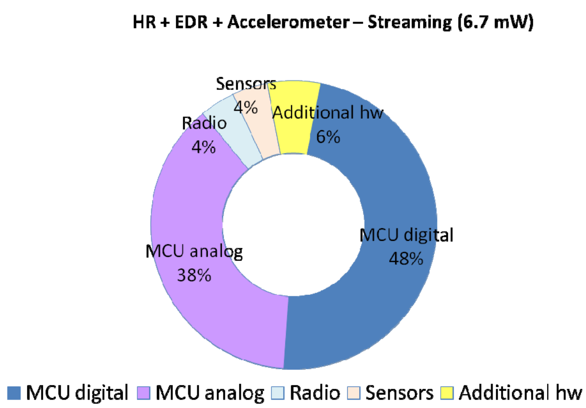

Figure 5: Power consumption break-down in the case that ECG data (256Hz) is processed locally to extract iHR and Respiration rate; and the outcome is streamed wirelessly together with the 3D-accelerometer data (10Hz)

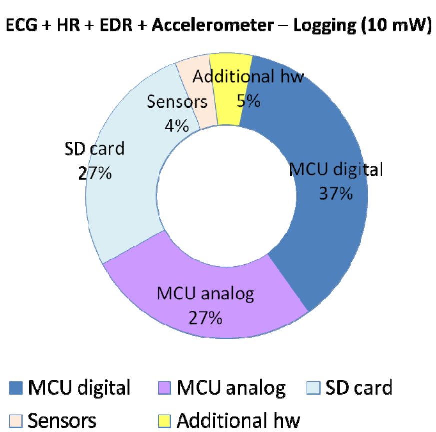

Figure 6: Power consumption break-down in the case that ECG data (256Hz) is processed locally to extract iHR and Respiration rate; and all measurements (ECG, iHR, Respiration rate and 3D-accelerometer @ 10Hz) are stored locally on SD-card

E. Tests in real-life environments

The necklace has been used to record ECG and acceleration in various environments, under real-life conditions. Figure 7 shows typical traces recorded at rest (sitting), during walking and while running at 12 km/h. This suggests the robustness of the ECG necklace for recording ECG *on-the-move*. The next section discusses two studies in which the ECG necklace is used to record ECG of specific patient population as they undergo normal daily life activities.

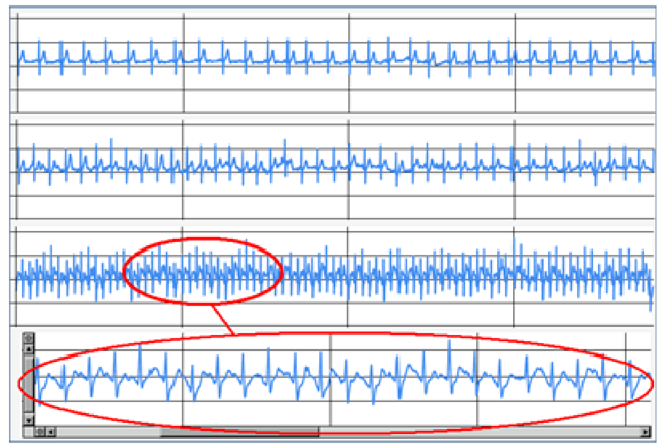

Figure 7: ECG data recorded with the ECG necklace: (a) sitting; (b) walking; (c) running at 12 km/h.

III. VALIDATION IN PILOT STUDIES

The proposed low-power ECG platform is tested in two applications, to validate the technology and evaluate its reliability in daily-life situations. Pilot studies are on-going, and preliminary results are reported here.

A. Epileptic seizure detection based on HR changes

In the first study, the necklace is used to detect epileptic seizures based on heart rate changes [3]. Tests are run overnight, and standard epilepsy monitoring equipment is used as reference. The system is worn at the arm. An ECG-based seizure detection algorithm is implemented in the system to detect epileptic events in real-time. Events are then transmitted wirelessly to a computer synchronized with the reference system. Three patients have been included in the study so far. Patients were selected after confirmation that seizures are associated to heart rate changes. Hypermotor, tonic and tonic-clonic seizures are considered.

Examples of ECG traces recorded with the necklace at rest and during a seizure are given in Figure 8, showing that most of the beats can still be detected even during the seizure. Examples of iHR traces recorded overnight on epileptic patients are given in Figure 9, showing that significant changes in iHR are detected during the seizure. The specific iHR patterns has been observed to change with the type of seizure, and from patient to patient.

Seizures detected with the necklace are compared with the ones detected using the reference video-monitoring system [3]. The results are summarized in TABLE II, suggesting that major seizures can be detected by the system.

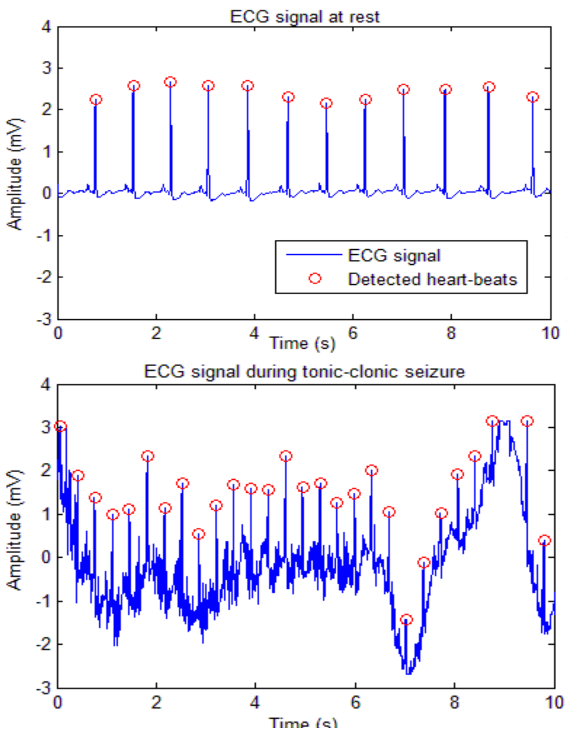

Figure 8: ECG signals and detected heart beat at rest (top) and during an epileptic seizure (bottom)

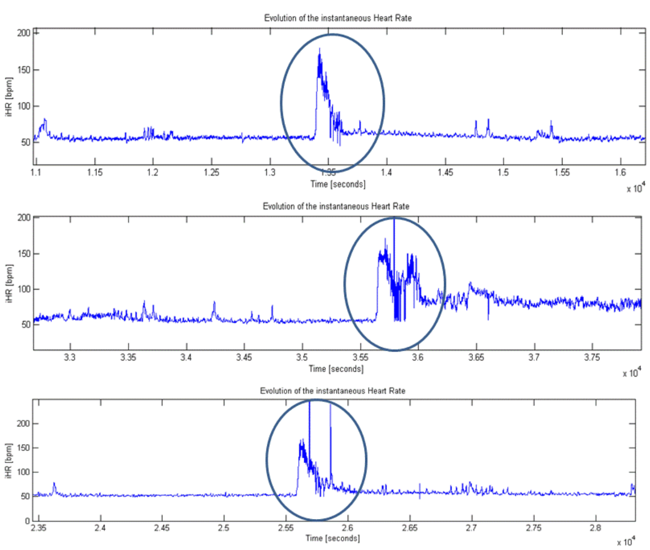

Figure 9: Examples of iHR traces recorded overnight on epileptic patients. Each epileptic seizure is accompanied with significant changes in iHR.

TABLE II: EPILEPTIC SEIZURE DETECTION USING ECG NECKLACE WITH EMBEDDED ALGORITHM

	# nights	# seizures	Detected	Missed	False detections
P1	14	4	4	0	0
P2	13	3	3	0	0
P3	9	12	3	9	12

B. Monitoring Atrial Fibrillation Burden

In a second study, the necklace is used to monitor patients diagnosed with atrial fibrillation. Patients wear the system around the neck for a period of 7 days, following the set-up illustrated in Figure 3. Data is stored locally for further analysis and inspection by a cardiologist. Preliminary results have confirmed the good signal quality in daily life activities. One patient has been included so far.

Figure 10 shows examples of the ECG signals recorded with the ECG necklace during an Atrial Fibrillation event.

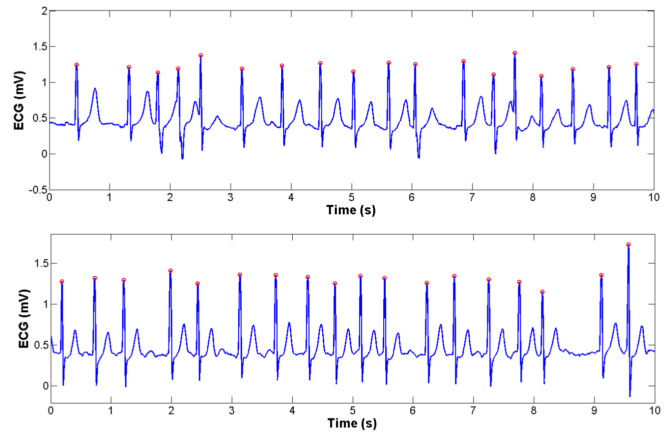

Figure 10: Examples of ECG recorded with the ECG necklace during Atrial Fibrillation events

IV. Conclusions

A low-power wireless ECG necklace is reported, for simultaneous monitoring of 1-lead ECG, beat-to-beat heart rate and acceleration. It provides a configurable platform on which concept applications can be prototyped. Power consumption ranges from 1.2 mA when raw data is streamed wirelessly, to 2.7 mA when instantaneous heart rate and respiration rate are computed locally, and all data is stored on SD card on the device. This provides from 2.5 to 6 days autonomy on a 175mAh Li-ion battery. The ECG necklace is used in pilot studies for the detection of epileptic seizure based on heart-rate changes and monitoring of Atrial Fibrillation. These pilot studies demonstrate the possibility to achieve ambulatory ECG monitoring today using the necklace, and also points to possible improvements. Future developments will focus on the development of motion artifact reduction algorithms, supported by ultra-low-power circuits and integrated in light-weight patches and wearable systems.

References

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