Real-Time Heart Rate Variability Monitoring Employing a Wearable Telemeter and a Smartphone

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***Abstract*— A telemetry system for the measurement of heart rate variability (HRV) has been developed with a low-cost manufacturing process and a low-power consumption design. All the components and functions for the RRI measurement were implemented on a wearable telemeter which can operate for up to 10 hours with a rechargeable Li-Polymer battery, and the RRI data is stored into a smartphone via a Bluetooth wireless transmission. In a long-term measurement of a young subject that extended over 48 hours in total, the results showed a 1% probability of recurring errors. The obtained results suggest that the proposed fully-wearable system enables the continuous monitoring of HRV for both clinical care and healthcare operated by a non-expert.**

I. INTRODUCTION

Low cost methods of vital sign monitoring are in demanded because the healthcare costs are rapidly increasing. For the purpose of early detection of diseases and acute symptoms, long-term monitoring of the electrocardiogram (ECG) delivers beneficial evidences in both clinical care and homecare. The analysis of heart rate variability (HRV), which is calculated from the R-R intervals (RRI), gives diagnostic evidences of arrhythmia [1], chronic obstructive pulmonary disease [2], and others [3]. From the point of view of hardware implementation, the measurement system of the RRI can be realized by a simple circuit architecture that does not require power-consuming components such as analog-to-digital converters, and thus may reduce the size and power consumption of the measurement device in comparison with the full scale ECG measurement system.

The development of an HRV telemetry system described in this paper has been aimed for simple use, i.e., high mobility, and high accuracy detection of RRI. This telemeter is regarded as a consumer friendly device that can be commercially available at low cost and used by any subject without expert knowledge in ECG measurement. The telemetry system could be a supportive monitoring device because the collected data can be transferred as files of low size into the hospital's monitoring system to obtain an immediate diagnosis.

The measurement of RRI at different sex and ages can be achieved by the automatic gain control system that is capable of adjusting the gain automatically for different subjects. The embedded programs play important roles in the high accuracy detection of R waves and the quick adjustment of gain for ECG amplification. The ECG measurement performed at home is an ideal financial aid for patients and even for healthy people for the purpose of health promotion and early detection of diseases. Because the device is used by the patients at home, the important matter to be considered is the low cost, easy usage, and long life with a modest measurement performance. To confirm that the proposed system satisfies the above requirements, the experiment was directed to the analysis of the function of the automatic gain control and the accuracy of long-term measurements.

II. SYSTEM DESCRIPTION

The developed RRI telemeter measures ECG, detects the R-waves from the ECG, and transmits the RRI data to a smartphone through Bluetooth wireless communication. The smartphone stores the received RRI data and calculates the HRV indice. The details of the devices are explained in the following subsections.

A. Hardware constitution of the RRI Telemeter

Figures 1 (a) and (b) show the block diagram of the proposed RRI telemeter and the circuit diagram of the analog frontend, respectively. The ECG measured by three electrodes (+, −, GND) is amplified and conditioned in the analog frontend.To achieve the single power supply of a 3.3 V DC, the common-mode feedback (CMFB) structure is adopted for the differential signal amplification as shown in the left dashed rectangle in Fig. 1 (b). Using this structure, the output common-mode voltage of the instrumentation amplifier is set to V_{ref}, which is the reference voltage made by a resistor chain. The first-order variable-gain active low-pass filter (LPF) was designed to reduce the high-frequency noise of >38 Hz. The gain is defined by the resistor ratio R_2/R_C, where R_C is the resistor value of the variable resistor. Here R_C is controlled by the automatic gain control program that is embedded in the microcontroller, as described later. Though this LPF may reduce the amplitude of the R waves, a sufficient amplitude is obtained because it is adequately amplified due to the automatic gain control. The output common-mode voltage of the analog frontend is set to V_{ref} because the positive nodes of

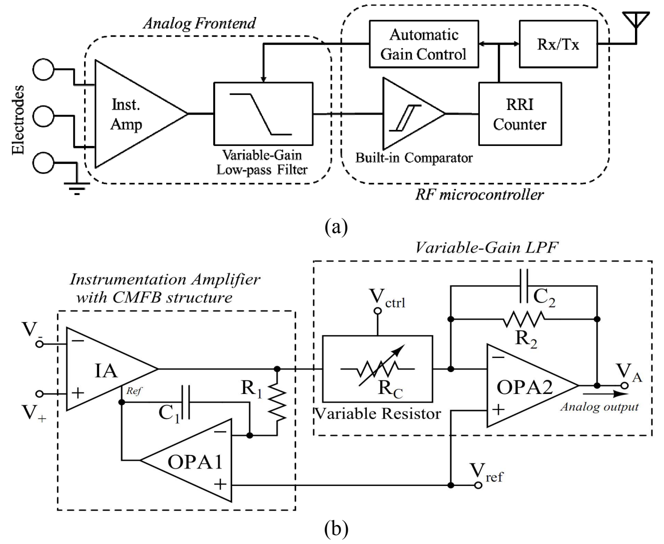

Fig. 1. (a) Block diagram of the RRI telemeter and (b) circuit diagram of the analog frontend.

OPAs are connected to V_{ref}. Here, V_{ref} of 2.49 V was obtained with a resistor chain. The current dissipation of the analog frontend was kept under approximately 80 μA by adopting the following low power ICs: INA122 for the instrumentation amplifier, MCP6042 for OPAs, and MCP4011 for the variable resistor. R_1 of 1 MΩ, R_2 of 1 MΩ, C_1 of 1μF, and C_2 of 4.7 nF were used in this prototype fabrication.

The output of the analog frontend was connected to an input node of a Bluetooth module (cB-OBS421i-14-O, ConnectBlue) as shown in Fig. 1 (a). This input node is observed by the built-in comparator, and the comparator outputs the positive pulse, lower than 1.5 V, during the input signal. In other words, the amplified ECG signal whose amplitude is larger than 0.99 V ($=V_{ref} - 1.5$) is extracted as an R wave candidate. The R wave candidates are treated by the embedded program as described in the following subsections.

B. *Embedded Programs and Automatic Gain Control*

A quasi band-pass filtering (BPF) program and the R wave detection program were installed in the microcontroller. The BPF program counts the pulse width of the R wave candidate, which is obtained by the comparator, and forwards the signal only when the pulse width is in the range of 3–50 ms to compress the noises (e.g., HF noise originated in the poor hysteresis of the comparator and wide ECG pulses such as P or T waves). The RRI counter stores the timer values of the R wave occurence and the RF transmission as described in the following subsection.

The amplitude of the ECG can be reduced due to the electrode alignment, the condition between the skin and the electrodes, and the subjects' age. Though some methods of automatic gain control (AGC) have been developed in the long history of the ECG measurement [4] [5], and most clinical ECG instruments contain the AGC function, these are not suitable for the miniaturization into a battery-powered wearable device because it mostly requires additional pieces of electronic components and/or power-consuming signal

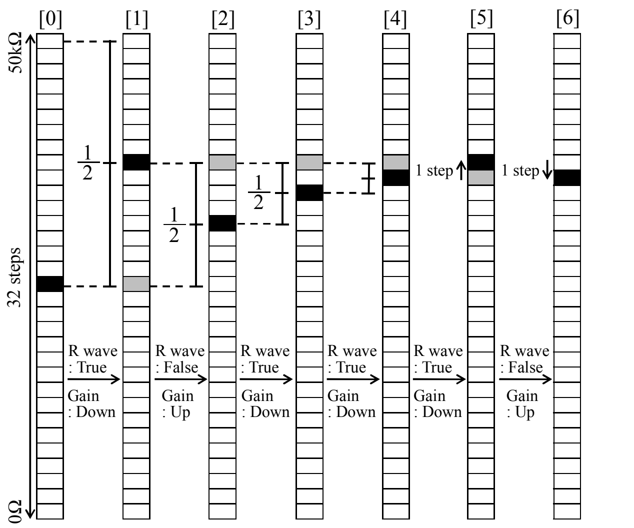

Fig. 2. Example of the proposed AGC scheme. The black cells and the gray cells show the selected R_C values and the previous R_C values, respectively.

processing procedures. In this work, the AGC function is installed with a simple circuit topology and with a simple time-domain algorithm implementable into a microcontroller to maintain a reliable R wave detection even under the above situations.

Figure 2 shows an example of the proposed AGC flow scheme. The gain of the LPF in the analog frontend is controlled by the RC value which is chosen from 32 steps between 0 and 50 kΩ based on the binary search algorithm. At the beginning of the AGC mode, the RC value is set to $16{*}R_{step}$ (the half value of the maximum R_C) where $R_{step} = 50\ k\Omega/32$. If the R wave is detected with this gain, the R_C value is changed to the half between the maximum R_C and the previous R_C (e.g., $R_C = 24{*}R_{step}$) to reduce the gain. Subsequently, if the R wave is not detected with the new gain, the R_C value is changed to the half between the previous R_C and the R_C value of two times before (e.g., $R_C = 20{*}R_{step}$) to raise the gain. After this process is repeated six times as shown in Fig. 2, the final gain is decided. This AGC scheme determines the appropriate gain within six steps due to the limitation of the available R_C values. Because the R wave detection procedure and the R_C modification only take approximately 1.5 s and 1 ms, respectively, the whole ACG procedure is finished within 10 s. The AGC procedure is activated when the power of the telemeter is turned ON or the button mounted on the circuit board is pushed.

C. *Wireless Communication and Power Supply*

The RRI telemeter uses the wireless transmission of the RRI data to miniaturize the circuit. To be compatible with the current supply capability of a litium polymer (Li-Po) battery and to improve the battery life, the duration of the current consumption during the wireless communication must be minimized. In this work, the telemeter works in three modes: Tx mode, Rx mode, and Standby mode. In the Tx mode, the telemeter transmits the header information and the RRI data within 3 ms with the current consumption of 36 mA and moves to the Rx mode. When the data have been successfully transmitted, the receiver sends back the Success Message and the standby latency (a time length of waiting for the next transmission) to the telemeter. The current consumption of the telemeter is 16 mA during the Rx mode of 3.8 ms. After the bidirectional wireless communication has been finished, the telemeter moves to the Standby mode whose current consumption is 0.1 mA until the next transmission.

To prevent the colligion of the multiple telemeters, the transmission timing for the each telemeter is predetermined in the receiver, and all the telemeters sequentially acquire the correct timing with the replied standby latency after the initial RRI transmission. In this work, the cycle for the intermittent RF communication of 500 ms was determined on the assumption of multiple use i.e., up to five telemeters.

Throughout the steady state, where the wireless communication between the telemeter and the receiver is coordinated in the correct timing, the telemeter operates in the Standby mode for 99% of the communication cycle, and thus the mean current consumption is 0.51 mA. This power reduction theoretically enables the continuous operation for more than two weeks (215 h) with a 110mAh Li-Po battery.

III. Fabrication and Experimental Results

A. Fabrication

The RRI telemeter was fabricated on a four-layer printed circuit board (PCB) of 45 × 60 mm, and was enclosed in a plastic case of 50 × 70 mm with a thickness of 15 mm. Using low-cost electronic components and the PCB manufacturing technology suitable for mass production, the volume cost of the proposed system, excluding the initial costs of the PCB fabrication, was reduced to less than 200 USD per system.

B. HRV measurement

The experiments were performed according to the protocols approved by the Research Ethics Committee of Shizuoka University and with the informed consent by the subjects.

To investigate the measurement accuracy of the telemeter, four subjects (21-24 year-old males) were selected to observe how accurately the R-R intervals were extracted from the ECG measured by the fabricated device. The subject's ECG was measured using disposable electrodes (Vitrode Bs-150, Nihon Kohden) in accordance with Lead II for 30 minutes. The all subjects were during office work (such as typing or writing) in a sitting position without leaving their desk. Figure 3 shows the examples of the RRIs simultaneously measured by the fabricated telemeter and the reference ECG monitor. Arbitrary 500-beat data points in the middle of the measurement period were sampled in order to highlight the fluctuations of the RRI and the measurement errors. In the statistical comparison of the obtained RRIs, the differences were less than 5 ms except the R-wave detection errors which may occur in both the telemeter and the reference as shown in the upper figure of Fig. 3, even though the ECG amplitudes varied due to the subjects' individual difference [6]. This indicated that the proposed system has the sufficient temporal precision to monitor the RRIs because the sampling rate of the ECG measurement required for the HRV analysis is higher than 100 Hz [3].

To investigate the R-wave detection error, five subjects of different ages (5, 21, and 73 year-old females, and 24 and 43 year-old males) were examined under varied circumstances. The 21 year-old female (21F) and 24 year-old male (24M) subjects rested in a sitting position, and the 5 year-old female (5F), 43 year-old male (43M), and 73 year-old female (73F) subjects rested in a supine position (mostly sleeping). The probability of reoccurring errors was estimated to prove the accuracy and reliability of the R wave detection. The total amount of collecting data of the subject 24M was 2768 for 30 min. In this case, the error region where the RRI data is regarded as the inappropriate value should be under 0.3 s and over 1.3 s. Here, the error region was determined individually for each subject by considering the mean value of the measured RRIs and the expected RRI fluctuation depending on the autonomic function related to the posture of the subject, with the agreement of three medical experts. Eight errors were found within the error region of this subject. The probabilities or reoccurring errors were calculated by dividing the number of errors by the total number of data as the following values: 0.75% for 21F, 0.28% for 24M, 1.33% for 5F, 0.50% for 43M, and 1.63% for 73F. These slim probabilities of errors are negligible because the effect of the errors can be compressed in the frequency analysis commonly used in the HRV analysis [7–10]. The major reason of errors is presumed to be the

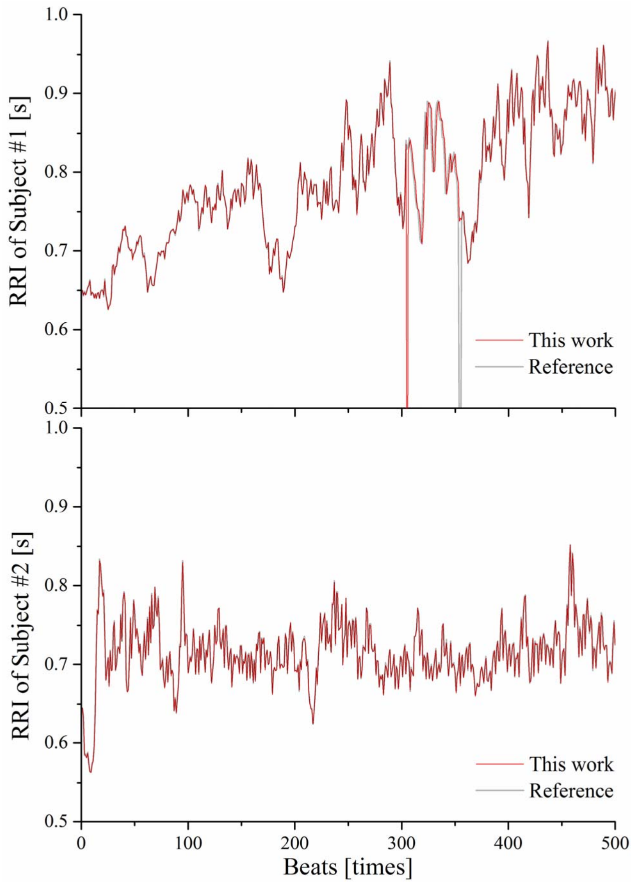

Fig. 3. Examples of the measured RRIs by the fabricated device (red) and the reference ECG monitor (gray) in the different subjects.

motion artifacts derived by analyzing the ECG simultaneously recorded by a Holter monitor.

To evaluate the capability of long-term measurements, the accuracy of the RRI detection was quantified for the measurement period of 48 h. The 24 year-old male was selected and the measurement was executed during his daily routines excluding bedtime. The total number of acquired RRI data was 268,312. The probability of recurring errors was calculated as previously mentioned. Its value turned out to be 0.752%, suggesting that the physiological signals in the long-term measurement were successfully detected with minimum errors. Even though an algorithm of the HRV analysis for medical diagnosis or for the evaluation of health status requires to be developed, the proposed system may contribute to make patients unnecessary to be restrained at hospital in order to get a long-term ECG.

IV. Conclusions

A wearable HRV telemetry system equipped with an automatic gain control scheme has been developed for easy use and high accuracy RRI detection toward both clinical care and homecare for subjects with different ages. The desired functions and the validity of the system were proven for subjects different in age and sex. The obtained results showed that the proposed system has a sufficiently low error probability and an adequate temporal resolution for HRV analysis. The fabricated device may contribute to the improvement of quality of healthcare at home with continuous monitoring, and operated by non-experts.

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