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Unconstrained Monitoring of ECG and Respiratory Variation in Infants with Underwear during Sleep Using a Bed-Sheet Electrode Unit

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***Abstract*—An approach is proposed for obtaining both electrocardiographic potential and respiratory variation signal from infants lying supine with underwear during sleep. Capacitively coupled bed-sheet electrode unit and a methodology of capacitive sensing were employed to realize the approach. A pilot device was fabricated to explore the feasibility of the approach and evaluation experiments were conducted for 5 infants aged from 43 to 174 days. The results revealed that two outputs of the developed device synchronized respectively with the reference ECG and sleep breath in all experiments. The present device appears promising for application to bedding as an unconstrained method for ECG and respiratory variation monitoring of neonates or infants during sleep.**

I. Introduction

It is reported in Japan that major causes of death in neonates and infants are cardiac disease, respiratory disease and sudden infant death syndrome (SIDS). Electrocardiogram (ECG) and respiratory variation are physiological signals that are measured not only from adult s but also from the newborns and infants when necessary for monitoring, diagnosis, or medical research purpose. ECG is measured for long days in neonatal intensive care unit (NICU). In conventional ECG monitoring, an electrolytic paste or a conductive adhesive is almost always required for maintaining reliable ohmic contact with the skin. Therefore, ECG measurement for a long period using conventional methods causes irritation and discomfort, and is a potential cause of skin allergy and inflammation. Besides, adhesion of the paste or adhesive is so tight for their skin that the skin is seriously damaged and, in some cases, is peeled off when detaching the electrode from the body surface after the long time monitoring. Previous authors [1], [2] have addressed this problem by employing dry electrodes or textile electrodes, which do not require any electrolytic paste or conductive adhesive for measurement, to relieve potential irritation and discomfort. Nevertheless, the potential for metal allergy or discomfort upon direct long-term contact of the skin with metal material has not yet been addressed. Moreover, both electrodes have a disadvantage in a hygiene standpoint in highly humid countries such as Japan, because they are not easily-washable.

In order to obviate these risks and the disadvantage, the authors have advanced the principle of capacitive sensing and succeeded in detecting electrocardiographic potential through commonly available cloth from the subject's limb [3], and from the dorsal surface of adults [4,5] and infants [6] in a supine position. This approach eliminates direct contact of the electrodes to the skin, and also enables the interjacent cloth being changed and washed handily.

On the other hand, the respiratory variation signal is essential for patients with respiratory disease and for subjects with a risk of SIDS. In this paper, we have proposed an approach for detecting not only ECG but also respiratory variation signal from a single capacitively coupled electrode unit placed on a commonly available bed sheet. In order to explore the feasibility of the approach, the authors have fabricated a pilot measuring device and conducted some preliminary experiments.

II. Capacitive Sensing

The developed device is based on the principle of the capacitive (or insulator) electrode [7-13]. The capacitive electrode can carry an alternating bioelectric current through the capacitance of the capacitive coupling involving a conductive electrode, an insulator, and the skin of the subject. Conventional researchers had employed hard insulator having high dielectric constant so as to achieve the high capacitance value and the stable coupling. In our approach, commonly available cloth, especially cotton, is substituted for the rigid insulator in order to relieve the irritation, allergy and discomfort experienced with conventional skin-to-electrode coupling. Also a sheet of conductive fabric is substituted for the conventional metal electrode so as to realize a deformable coupling corresponding to the contour of the coupled region.

Through our previous experiments, it has been revealed that the capacitive sensing is susceptible to body motion of the subject. This is because the motion alters geometric parameters of the capacitive coupling, and then changes the capacitance of the coupling. This disadvantage can be changed in other words that the capacitive sensing has high-sensitivity to the body motion. In fact, some obtained signals using the capacitive sensing contained in low frequency component a periodic fluctuation due to breathing

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Fig. 1. An image of a subject (#2) lying supine on the bed-sheet electrode unit. Black striped rectangles are fabric electrodes. Three wire leads from the electrodes are connected to the developed signal extraction device. Wires from the crotch portion are the lead for reference ECG measurement.

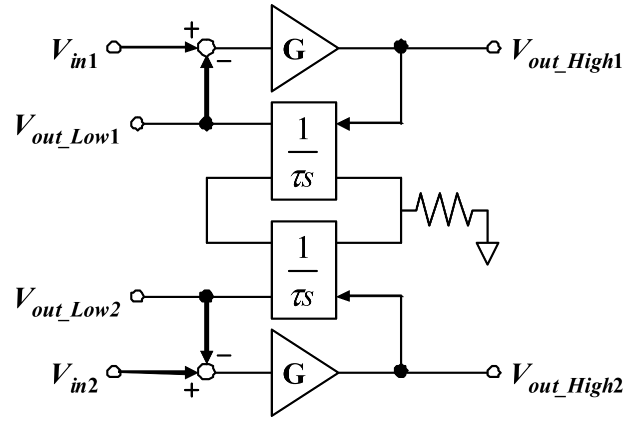


Fig. 3. Block diagram of the differential separation filter. The time constant τ of the integrator was set to achieve the separation frequency of 1 Hz.

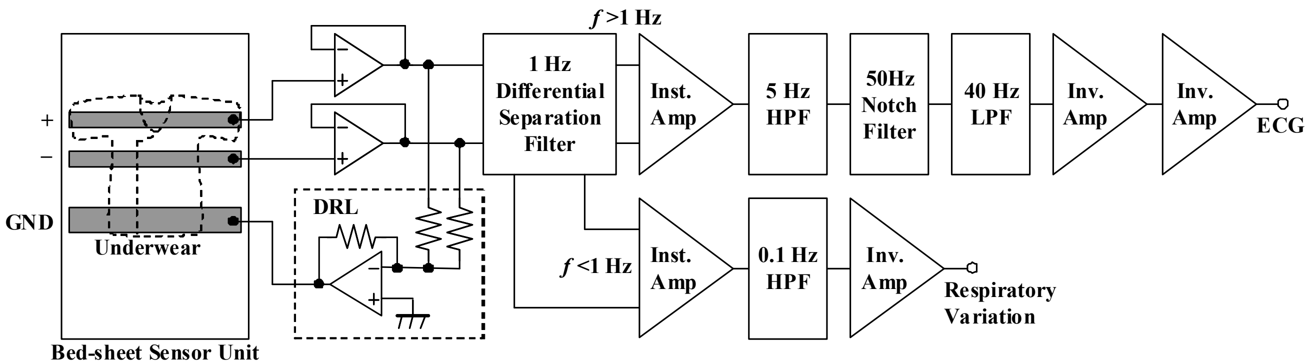


Fig. 2. Configuration of the bed-sheet electrode unit and block diagram of the developed circuits for detecting ECG and respiratory variation.

chest movement. Therefore, a separation filter is employed in the developed device to discriminate the ECG signal and respiratory variation signal.

III. Materials and Methods

A. Bed-Sheet Electrode Unit

Both the ECG signal and the respiratory variation signal are picked up by a single bed-sheet electrode unit placed on a mattress. The unit is composed of a commonly available cotton bed sheet and three pieces of rectangle conductive carbon-coated fabric with conductive adhesive (Kitagawa Industries, CSTK). The electrodes are stuck to the bed sheet with the adhesive. Two lead electrodes having 25mm width are located under the dorsum of the subject when lying in a supine position, as shown in Fig. 1. Two sets of lead electrodes are prepared for adjusting the electrode locations to the physical constitution of the subject. A reference electrode having 40mm width is placed beneath the breech wearing a disposable diaper. Skin-underwear-electrode capacitive coupling is held by the subject's weight on the underwear and by repulsive force from the mattress. The electrodes are connected to a measuring device, as described in the next section, by using shielded wires.

B. Signal Extraction

The pilot measuring device with filtering and amplification circuitry was fabricated using off-the-shelf components. The device consists of a common part and independent parts for detecting ECG signal and respiratory variation signal, as shown in Fig.2. The device is powered by regulated batteries to obviate the possibility of electric shock.

The common part is composed of two buffers, a differential separation filter, and a driven right leg (DRL) circuit [14]. Each buffer functions as an impedance matching circuit to mediate the high impedance of the capacitive coupling with low impedance required by the subsequent circuitry. In the present study, operational amplifiers with high input resistance (National Semiconductor, LF356, 1TΩ according to the specification sheet) are employed. The differential separation filter separates the input signal into high frequency component (>1Hz) and low frequency component (<1Hz). The separation filter is introduced to discriminate ECG signal and respiratory variation. The separation filter is composed of

TABLE I
AGE IN DAY AND PHYSICAL CONSTITUTION OF THE SUBJECTS ON THE MEASUREMENT

Subject No.	Age in day	Weight [kg]
#1_1	64	4.9
#1_2	133	6.7
#1_3	168	7.0
#2_1	43	4.4
#2_2	91	6.6
#2_3	122	7.2
#3_1	67	7.1
#3_2	132	8.5
#4	174	8.1
#5	69	5.1

two subtracters, two amplifiers and two integrators as shown in Fig.3. The block diagram in Fig.3 is a modification of the so called DC suppression circuit [15]. The DRL circuit is employed in order to reduce common mode noise mainly due to power line interference.

The independent part for extracting ECG signal consists of an instrumentation amplifier, a high-pass filter, a notch filter, a low-pass filter and two inverting amplifiers (see Fig.2). The circuit elements of the high-pass filter and the low-pass filter are determined in order to obtain a cutoff frequency of 5 and 40 Hz, respectively. The notch filter is used in order to reduce 50-Hz interference. The other independent part for extracting respiratory variation signal consists of an instrumentation amplifier, a high-pass filter and an inverting amplifier. The high pass filter is introduced to avoid saturation due to DC offset voltage.

C. Measurement of Fundamental Characteristics of the Device

Frequency-gain responses of the developed device were measured from 0.01 to 1000Hz using a frequency response analyzer (NF, FRA5022). The responses were investigated for both signal extraction circuits for detecting ECG signal and respiratory variation signal, respectively. CMRR of the device for ECG detection were measured at 10, 20 and 30 Hz, respectively. Finally, input capacitance of the device was measured using a method described in previous our work [5].

D. Measurement of ECG and Respiratory Variation in Infants during Sleep

Five infants, aged 43 to 174 days, participated to the experiments (see TABLE I). Three of the five infants participated more than once to the experiment on different age in day. Totally ten experiments were conducted. Each subject with cotton underwear was laid in a supine on a bed sheet bearing the measuring electrodes, according to the configuration shown in Fig.1 and Fig. 2. Both high frequency and low frequency components were detected using the developed system from the dorsum of the subject through the underwear (and a diaper at the reference electrode).

As a reference signal, a directly measured ECG signal was wirelessly monitored using a commercial bioamplifier (Teac Instruments, BA1104CC) and a telemeter unit (Teac Instruments, TU-4). Three disposable electrodes were attached to the right and left flank, and to a frontal surface of the subject's abdomen. The output signals from the system and the reference ECG were digitized at 1000 Hz by an A/D converter and stored in a personal computer using a data acquisition system (Biopac Systems, MP-150 system).

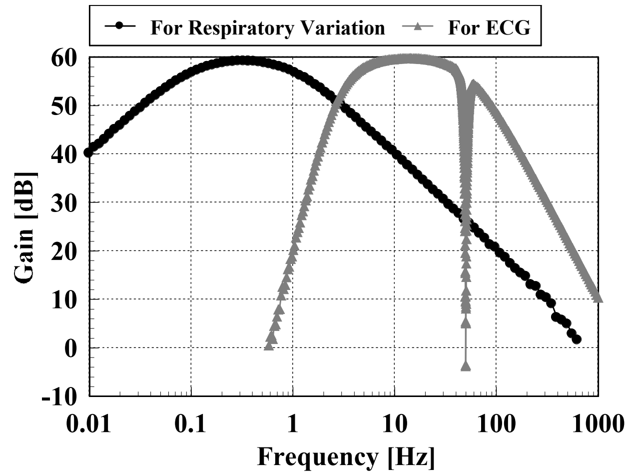


Fig. 4. Frequency-gain responses of the developed system for detecting respiratory variation and ECG. Black circular plots show the response of the circuit for respiratory variation detection. Grey triangle plots show the response of the circuit for ECG detection.

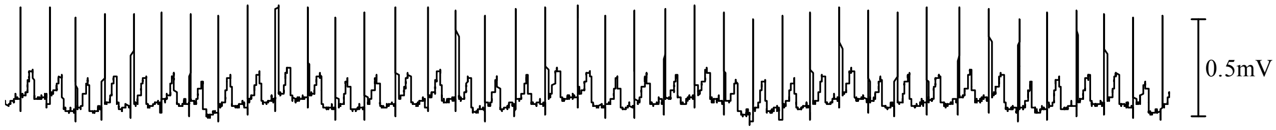
IV. RESULTS AND DISCUSSION

A. Fundamental Characteristics of the Device

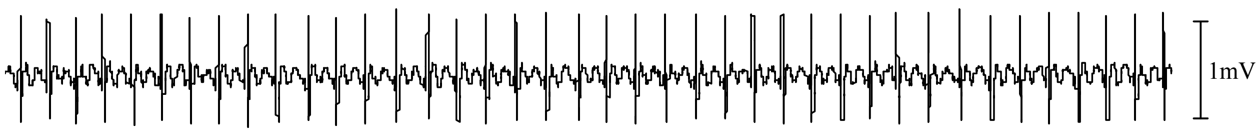
Frequency-gain characteristics of the both devices are shown in Fig. 4. As can be seen, the band pass characteristics were obtained as designed for both circuits (i.e. from 0.1 to 1 Hz for respiratory variation detection, and from 5 to 40 Hz for ECG detection). CMRR were 61.1 dB at both 10 and 20 Hz, and 59.3 dB at 30 Hz. Input capacitance of the device was 26 pF, which was less than 1/10 of the estimated value for the device in the article [5].

B. Measurement of ECG and Respiratory Variation in Infants during Sleep

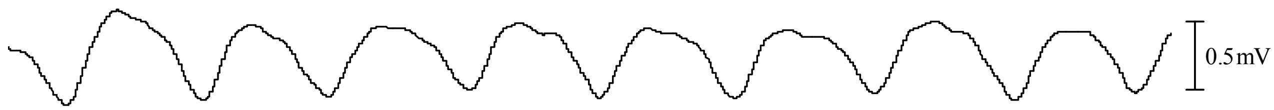
Fig. 5 shows recordings typical of those obtained while a subject (#1_2) was sleeping. As can be seen in Fig. 5(a) and Fig. 5(b), the output signal of the developed circuit for ECG detection showed periodic waveform synchronized with the reference ECG. For the output signal of the other developed circuit for respiratory variation detection, we confirmed synchronization of the waveform with sleep-breath of the subject. These synchronizations were obtained from all subjects. Although precise validation tests should be followed, the developed system seems having a potential not only for detecting heart rate and/or other periodic ECG parameters but also for detecting respiratory variation of infants during sleep even with underwear worn. As regarded in previous our studies [3-6] and other similar works [16,17], however, the



(a) Reference ECG obtained from the commercial telemeter unit



(b) Output signal from the developed circuit for ECG detection through underwear



(c) Output signal from the developed circuit for respiratory variation detection

Fig. 5. Typical recordings of the (a) reference ECG obtained from the commercial telemeter unit, (b) output signal from the developed circuit for ECG detection through underwear, and (c) output signal from the developed circuit for respiratory variation detection (subject #1_2). Waveform in (c) was filtered off line by 1 Hz digital low pass filter.

capacitive sensing method is known to be susceptive to motion artifacts. Thus, the proposed device is not stable at current stage while the subject stays awake.

V. CONCLUSION

We developed a system capable of detecting not only ECG but also respiratory variation simultaneously from an infant lying supine on a bed-sheet electrode unit even with an underwear and a diaper worn. Measurements for validation were conducted in 5 infants aged from 43 to 174 days, and revealed that two outputs of the developed device synchronized respectively with the reference ECG and sleep breath of the subject. Future issue that needs to be addressed is reduction of the motion artifacts.

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