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An Application of Capacitive Electrode for Detecting Electrocardiogram of Neonates and Infants

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***Abstract*- A new system has been developed for obtaining electrographic potential through thin underwear inserted between the measuring electrodes and the skin of a neonate or an infant when lying supine. The system is based on capacitive coupling involving the electrode, the underwear, and the skin. Validation of the system revealed the following: (1) the signal detected using the system displayed a periodic waveform synchronized with the simultaneously recorded ECG, even when thin underwear was inserted between the electrode and the skin, (2) the gain of the system when the cloth was inserted decreased as the frequency increased. The present system appears promising for application to bedding as a non-invasive and awareness-free method for ECG monitoring of neonates or infants. However, there is still room for improvement in terms of its practical use, because the high-frequency component of the signal was depressed in comparison with the reference ECG**

I. Introduction

Major causes of death in neonates and infants in Japan are cardiac disease, respiratory disease and sudden infant death syndrome (SIDS). Electrocardiogram (ECG) is a physiological variable that is monitored from the newborns and infants when necessary for the sake of diagnosis, medical treatment, or medical research of these diseases. ECG is monitored also in neonatal intensive care unit (NICU). In conventional ECG monitoring, an electrolytic paste or a conductive adhesive is almost always required, even for the neonates or infants, for maintaining reliable ohmic contact with the skin. However adhesion of the paste or adhesive is so tight for them that the skin is seriously damaged and, in some cases, is peeled off when detaching the electrode from the body surface. In another view, long time ECG monitoring of the neonates and infants in daily life could be beneficial for research in cardiac development or in SIDS, however, cohesive skin-to-electrode coupling poses an impediment for recruiting subjects, and accordingly for promoting the research.

Recently, the authors have studied on capacitive electrode and succeeded in detecting electrocardiographic potential through cloth from limbs [1] and from the dorsal surface of an adult subject in a supine position [2], by applying the principle of the capacitive electrode to the ECG measurement. In this paper, we have applied the principle to the detection of ECG of the neonates and infants. Since the subjects have less weight and less body surface area (i.e. less pressure at the skin-to-electrode coupling), there are still some challenges to be addressed for improving the interface of the skin-to-electrode coupling and for obtaining more stable output signal.

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II. Capacitive Electrode

The developed system is based on the principle of the capacitive (or insulator) electrode. The capacitive electrode can detect alternating bioelectric voltage by the capacitance of the capacitive coupling composed of measuring electrodes, 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 [3]. In this article, commonly available cloth, especially cotton, was substituted for the rigid insulator in order to relieve the irritation, allergy and discomfort experienced with conventional skin-to-electrode coupling, as shown in Fig. 1. Also a sheet of conductive fabric was substituted for the conventional metal electrode so as to realize a deformable coupling corresponding to the contour of the coupled region.

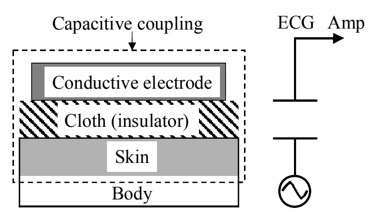


Fig.1. A model of capacitive electrode coupled onto the skin with cloth.

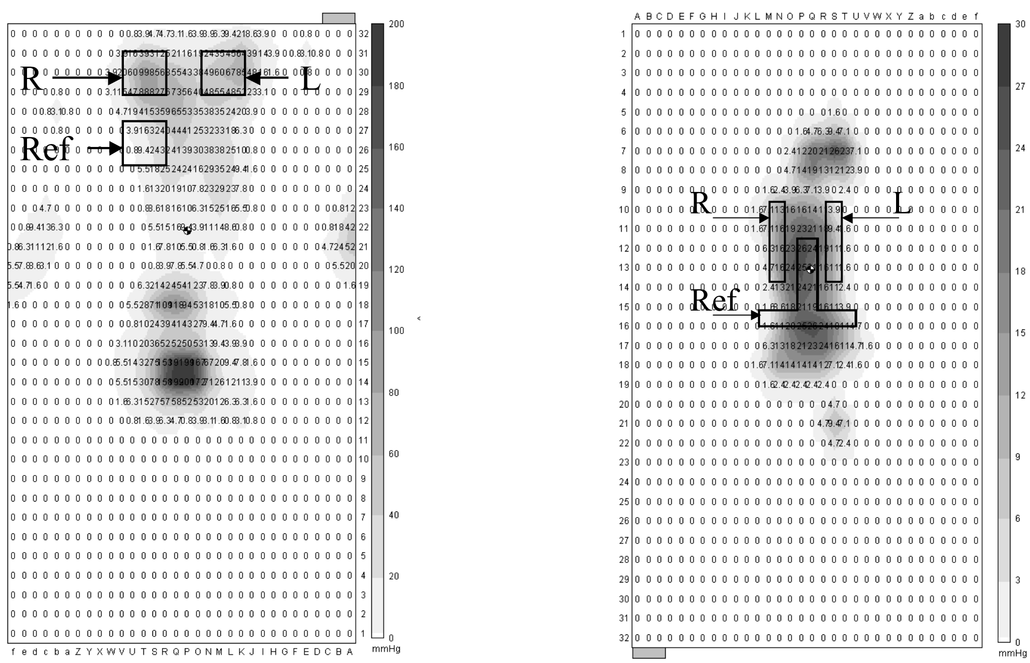
III. ECG MEASURING SYSTEM

A. Configuration of the Measuring Electrodes

In previous our study, the shape and arrangement of the measuring electrodes of the developed ECG monitoring system for adult subjects were designed only to obtain potentials similar to that of the Lead I ECG [1]. However, neonates and infants are supposed to have less pressure at skin-to-electrode coupling and smaller area of the dorsal surface than that of adult subjects. Since less pressed coupling and shorter distance between two lead electrodes incur the lowering in S/N of the output signal, we conducted preliminary experiments to design an adequate shape and arrangement of the measuring electrode for neonates and infants, by comparing pressure distributions of an adult subject and an infant subject (44 days).

Pressure distributions were measured by pressure mapping system (FSA, FSA Bed System). The adult subject was instructed to lie down in a supine on the force sensor array. The infant was also laid on the sensor array in a supine. Fig.2 shows typical results of the experiment. Fig. 2(a) is the result of upper limb of the adult subject excluding head, and Fig. 2(b) is that of whole body of the infant. The lead electrodes for the adult subject are located under the right and left scapulae, and a reference electrode is located beneath the right lumbar region. Darkest grey area at the center of Fig. 2(a) corresponds to a region under the breech. The reference electrode isn't located at the region, because total thickness of the underwear and trousers at the region is twice as much as that at the other region. Largest dark area in Fig. 2(b) is a united region under the dorsum, lumbus and breach. As can be seen in the figure, while the pressure under the lumbus part of the adult subject showed relatively small compared with that under the scapulae or breach, the pressure under the lumbus of the infant subject was almost the same with that under the other regions. According to these results, we settled the shape and the arrangement of the measuring electrodes for neonates and infants as in Fig. 2(b) We changed the shape of the lead electrodes from square to rectangle, and the reference electrode from square to inverted T-shape, so as to gain the area of the electrode as large as possible. Also position of the reference electrode was shifted to a region under the lumbus for stable and wide coupling. We didn't adopt the position under the breach for the reference electrode because bi-level insulator of baby wear and diaper will decrease capacitance of the coupling.

We used conductive fabric of Nickel on Copper Plated Polyester (2191FR, 3M) for the measuring electrodes as well as for adult subjects in order to achieve a deformable coupling corresponding to the contour of the coupled region. The electrodes were attached on a pressure-relieving mattress for a flat pressure distribution.



(a) An adult subject (Top view)

(b) An infant subject (Top view)

Fig. 2. Two-dimensional pressure distributions of (a) an adult subject and (b) a neonatal subject, in a supine position. Pressure distributions were measured with pressure mapping system (FSA, FSA Bed System). Square and rectangle figures indicate positions of measuring electrodes designed after the experiment. Square figures labeled by "R", "L" and "Ref" indicate positions of right and left lead electrodes and a reference electrode for (a) the adult subject and (b) the infant subject, respectively. Dimensions of the electrodes for the adult subject are 8.4 cm × 8.4 cm (70 cm2) × 0.014 cm thickness, and electrodes distance between "R" and "L" is 18.5 cm from each center, and that between "R" to "Ref" is 25.5cm from each center. Dimensions for the infant subject are 6.7 cm × 1.5 cm for "R" and "L", and distance between them is 7cm. On the average, pressure of the infant subject (955 Pa) was third of the pressure of the adult subject (2880 Pa).

B. Circuit Configuration of the Measuring Device

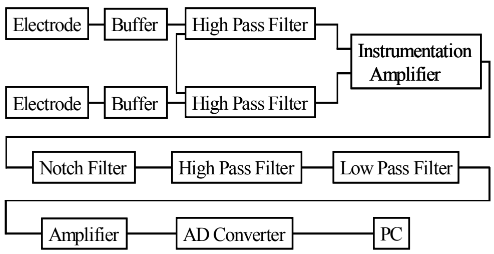


Fig. 3. A block diagram of the developed ECG measuring device.

Fig. 3 shows a block diagram the developed ECG measuring device. The device consists of two buffer circuits, a differential high pass filter, an instrumentation amplifier, a low pass filter, a high pass filter, a band elimination filter, an inverting amplifier, an A/D converter, and a personal computer. Two buffer circuits with high input impedance (1000GΩ according to the specification sheet) were employed as impedance matching circuits to mediate a high impedance at the coupling involving cloth with a low impedance required by the subsequent circuitry. The differential high pass filter circuit (cutoff frequency: 0.05Hz) was inserted before an instrumentation amplifier to reduce the low frequency component in the detected signal effectively before the amplification. Cutoff frequency of the low pass filter was set to 100Hz. The notch filter was used in order to reduce 50 Hz interference. The total gain of the device was designed as 60dB. The device is powered by two serial batteries, which produce a nominal supply voltage of 18 V, to obviate the possibility of electric shock. A three-terminal regulator (Toshiba, TA7815/TA7915) was used to step down the nominal 18 V supply to a regulated ±15 V.

IV. Validation of the System

A. Simultaneous Measurement with a Conventional Device

Four infants, aged 10 to 133 days, participated to the experiment for validation of the developed system. One subject participated twice in different day. Totally five measurements were conducted (see Table 1). Each subject with his/her underwear was laid in a supine on the mattress bearing electrodes made of conductive fabric, according to the configuration shown in Fig. 2 and described in Section III-A. Electrocardiographic potential was recorded using the developed measuring system from the dorsum of the subject through the cotton underwear. The output signal from the system was digitized at 1000 Hz by an A/D converter and stored in the personal computer using a data acquisition system (Biopac Systems, MP-150 system). As a reference signal, ECG was recorded using a conventional bioamplifier with a telemeter unit (NEC Sanei, SYNA-ACT MTI1) and disposable electrodes (Ambu, BlueSensor, NF-50-km). The disposable electrodes were attached to the lateral surface of the subject's abdomen. The reference signal was wirelessly transmitted and received, and then digitized simultaneously with the output signal of the developed system using the data acquisition system.

Table 1. Age in day and physical constitution of the subjects on the measurement

Subject No.	Age in day	Height [cm]	Weight [g]
#1	133	65	7,600
#2	115	62.8	8,005
#3	79	-	-
#4-1	10	49	3,600
#4-2	44	54.6	4,690

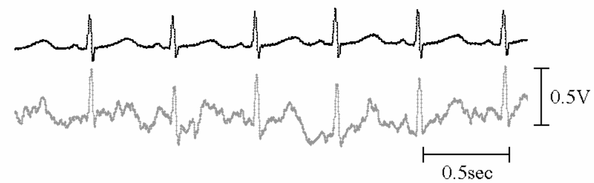


Fig. 4. Recordings obtained simultaneously using a conventional bioamplifier without a cloth from the lateral abdomen (top) and using the present system with a cotton underwear from the dorsum (bottom) of the subject #2. The bottom recording was subjected to a 20-point moving average to eliminate power line noise.

A successful recording in the subject #2 is shown in Fig.4. The bottom recording is obtained using the developed system with cotton underwear inserted between measuring electrodes and the body surface of the subject. The top recording is the reference ECG. As can be seen in Fig. 4, the output signal of the developed system showed a periodic waveform synchronized to the reference ECG. Therefore the developed system was considered potentially useful for detecting heart rate and/or other periodic parameters of the ECG in neonates and infants even with the cloth worn. However, the measurement resulted in failure for subject #4-1. In addition, output of the system was unstable while crying and/or flopping even for other subjects. Therefore, there is still room for improvement in terms of its practical use,.

B. Frequency Characteristics of the System

In Fig. 4, the output signal of the developed system showed periodic waveforms synchronized to the reference ECG. However, waveform of the output signal was distorted and some components such as S-wave disappeared. In order to understand the distortion precisely, frequency characteristics were investigated. Sinusoidal waves with a peak to peak amplitude of 1 mV and a frequency of 0.01 to 400 Hz were input directly to the electrodes, and the output voltage was measured at each frequency. In addition, the frequency-gain characteristics while a cotton cloth was inserted were also examined according to the experimental setup in Fig.5. As shown in Fig.5, three measuring electrodes were placed on the mattress with the same configuration as that in Fig. 2(b),

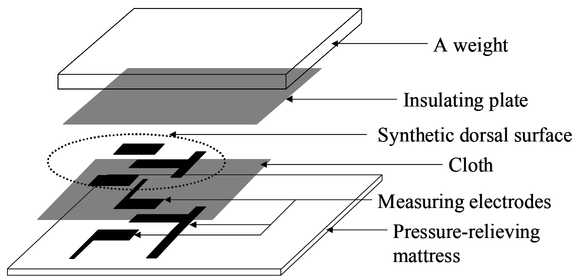


Fig. 5. Experimental setup for measuring frequency-gain characteristics of the developed system while a cotton cloth was inserted

and covered with a cotton sheet. Then, three synthetic dorsal surfaces, which were made of conductive fabric and had the same dimensions as the measuring electrodes, were attached to the cloth at locations just above each of the measuring electrodes. The electrodes and synthetic dorsal surfaces were subjected to 569 Pa pressure with a weight to mimic the pressure resulting from a supine infant subject 62.13 cm in height and weighing 5.979 g (dorsal area 0.103 m^2). Then sinusoidal waves with a peak to peak amplitude of 1 mV were input to the synthetic dorsal surface from 0.01 to 400 Hz, and the output voltage at each frequency was measured.

The results are shown in Fig. 6.As can be seen in the figure, a band pass from 0.05 to 100 Hz was obtained as designed when the electrodes were directly attached to the signal source. The gain at 50 Hz was sharply attenuated because the 50-Hz band elimination filter was used in the system. This frequency response satisfied the Japanese Industrial Standard for an electrocardiograph (JIS T1201), except around the 50-Hz frequency band. On the other, the gain of the developed system with the cloth decreased as frequency increased. Consequently, the band pass of the system with the cloth was from 0.05 to 2 Hz, which fits the simultaneously measured recording obtained with the cloth in Fig. 4. In Fig. 4, the low-frequency component of P-waves and T-waves was emphasized, and the high-frequency component of R-waves and S-waves was attenuated compared with those in recordings obtained by the conventional device. Therefore it will be necessary to improve the system so that it acquires a less distorted signal for practical use.

V. Conclusion

We have developed a system capable of detecting electrocardiographic potential from the dorsal surface of a neonate or an infant lying supine under conditions whereby a thin underwear is inserted between the electrodes and the skin. Validation of the system yielded the following;

1) The signal detected using this system displayed a periodic waveform synchronized to the simultaneously recorded ECG obtained directly from the lateral the lateral abdomen using a conventional electrocardiograph, even when cotton underwear was inserted. However, detected waveform was distorted and high frequency component was especially attenuated.

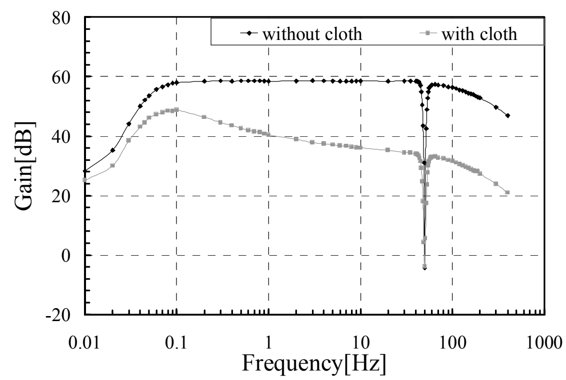


Fig. 6. .Frequency response obtained without cloth and with an inserted cotton sheet subjected to 569 Pa pressure. . Black rhombus plots show the original frequency-gain response of the developed system without an inserted cloth and grey square plots show the one obtained with the cloth.

2) The gain of the system with the cloth decreased as frequency increased.

Since this new system employs commonly available underwear over the skin-electrode interface to reduce the likelihood of irritation, allergy or discomfort compared with conventional skin-to-electrode coupling, it has promise for introduction to bedding as a non-obtrusive and awareness-free method of ECG monitoring. However, there is still room for improvement in terms of its practical use.

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