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# Development of a Wireless Capacitive Sensor for Ambulatory ECG Monitoring over Clothes

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***Abstract*—We present a wireless capacitive sensor for ambulatory ECG monitoring. The device is capable of detecting electrocardiographic potential through underwear. It is based on capacitive coupling involving the electrode, the underwear, and the skin. Validation of the system revealed the following: (1) The frequency response of the device with the underwear revealed that the gain of the detected signal was reduced, but distortion of the signal within the pass-band (from 6 to 45 Hz) was minimal even with the underwear. (2) The signal displayed a periodic waveform synchronized with the simultaneously recorded ECG, even when the underwear was inserted between the electrode and the skin. (3) Although the signal was seemed deteriorated slightly while walking, R-waves were recognized easily. Although there is still room for improvement in terms of its practical use, the proposed approach appears promising for application to ambulatory ECG monitoring.**

## I. Introduction

Monitoring of physiological variables, such as the electrocardiogram (ECG), during everyday life could be useful for management of individuals with chronic health disorders [1]. Furthermore, real-life long-term health monitoring could be helpful for assessing the effects of treatment at home, and would also be potentially beneficial for observing deviations in health status from the norm at an early stage, or for automatically alerting paramedics in emergency cases. In conventional ECG measurements, an electrolytic paste or a conductive adhesive is almost always required for maintaining reliable ohmic contact with the skin. Therefore, long-term ECG measurement using conventional methods causes irritation and discomfort, and is a potential cause of skin allergy and inflammation. These are considerably disadvantageous for the use of ECG monitoring on a daily basis, because practical interfaces must be as noninvasive and nonintrusive as possible to gain broad acceptance from ordinary users.

To overcome these disadvantages, we focused on the principle of capacitive sensing, which allows detection of alternating electrical potential through an inserted thin insulator, and applied it to the measurement of ECG through commonly available clothes in bed in previous our studies [2]-[4]. In this study, we have applied the similar technique to an ECG sensor with a purpose of ambulatory monitoring. We assembled a new wireless device and evaluated it.

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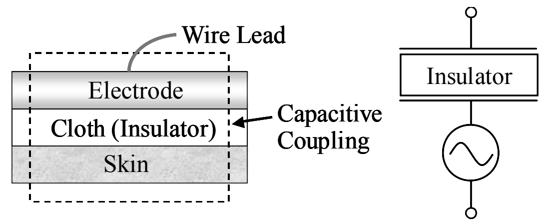


Fig.1. A schematic model of the capacitive electrode coupled to the skin with the inserted cloth and its equivalent circuit.

## II. Capacitive Electrode

The developed system is based on the principle of the capacitive (or insulator) electrode [5]. 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 as shown in Fig.1. Conventional researchers had employed hard insulator having high dielectric constant so as to achieve the high capacitance value and the stable coupling [5]. In our approach, 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. 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.

Capacitive sensing is also based on an impedance matching circuit to mediate the high impedance of the coupling with low impedance required by the subsequent circuitry. In the present study, an instrumentation amplifier with high input impedance (1000 TΩ) was employed in order to match the greater impedance of the coupling due to the smaller dielectric constant of the inserted cloth in comparison with conventional insulators.

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## III. MATERIALS AND METHODS

### A. Flexible Fabric Electrode

The ECG signal was picked up using three electrodes made of a rectangular sheet (24 mm × 41.7 mm) of conductive fabric with conductive acrylic adhesive (3M, 2191FR) , as shown in Fig.2. The electrodes were stuck to an insulating support made of flexible chloroethylene, and a convex connector (5$\phi$) was inserted between the support and each electrode. A reference electrode was placed at the center to reduce common mode noise as much as possible. The skin-cloth-electrode coupling was held by a stretch rubber band. The two lead electrodes were connected to a measuring device, to be described in the next section, by shielded wires.

### B. ECG Sensing Circuit

A pilot device was developed for sensing extracting ECG signal wirelessly. The device consists of two instrumentation amplifiers, two high-pass filters, a notch filter, a low-pass filter, and a FM transmitter. Fig.3 shows a block diagram of the device. The former part of the device was assembled using off-the-shelf components. The latter part was diverted from a custom-ordered telemeter module [6]. The first instrumentation amplifier was employed not only as a differential amplifier but also as the impedance transforming circuit. The nominal input impedance of the amplifier was 1000TΩ. The notch filter was used to reduce 50 Hz interference. The amplification factor was variable from 1000 to 2000, and was set to 1000 in all experiments in this study. A low-intensity 315-MHz radio wave was adopted for wireless communication to enable use of the device in medical facilities. The guard ring technique was employed in the lead wires between the instrumentation amplifier and the electrodes so as to reduce the power line noise. The device was powered by dry batteries.

### C. Measurement of Fundamental Characteristics

An experimental setup shown in Fig.4 was used to measure the frequency responses of the pilot device. Measuring electrodes having an identical area of 10 $cm^2$ were placed on an insulating support and covered with a cotton sheet 450µm thick. Then, three synthetic skins made of a rectangle piece of conductive fabric having the same area as the measuring electrode were attached to the cloth at locations just above each of the measuring electrodes, so that the whole area of each measuring electrode was involved in capacitive coupling with each synthetic skin. Using a weight, the electrodes, the cloth and the synthetic skins were subjected to a pressure of 784 Pa, mimicking a pressure less than the mean pressure exerted by the rubber band. Sinusoidal waves from 0.1 to 400 Hz were input from an oscillator to the synthetic skins, and then the outputs from the device were measured. A frequency response without any cloth inserted was also measured from cloth was also measured using the same setup. The output signal from the device was digitized at 1 kHz by an A/D converter and stored in a personal computer using a data acquisition system (Biopac Systems, MP-150 system). The room temperature was 21℃ and the relative humidity was 45%.

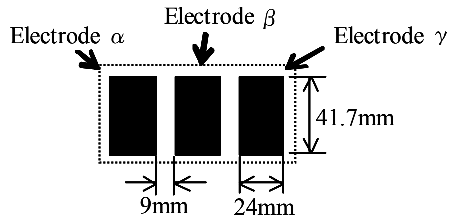


Fig.2. Configuration of the of the measuring electrode unit made of conductive fabric and mounted on an insulating support

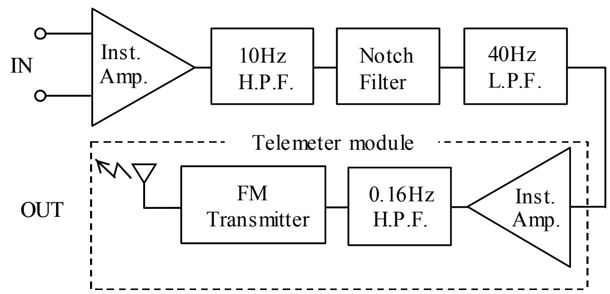


Fig.3. A block diagram of the developed ECG sensing circuit

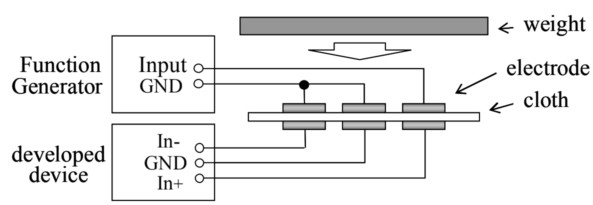


Fig.4. Experimental setup for measuring frequency responses of the developed device

### D. Simultaneous Measurement with a Conventional ECG Monitor

One male volunteer aged 22 participated to the measurement. The unit of flexible electrodes was held on the left lateral thoracis over underwear 450 µm thick using a thoracic belt. As a reference signal, a directly measured ECG (Lead I) signal was wirelessly recorded using a conventional bioamplifier (Teac Instruments, BA1104CC) and a commercial telemeter unit (Teac Instruments, TU-4). The output signal from the developed device and the reference signal were simultaneously digitized at 1 kHz using the data acquisition system. The recording from developed device was subjected to a 20-point moving average to eliminate power line noise. The room temperature was 21℃ and the relative humidity was 45%.

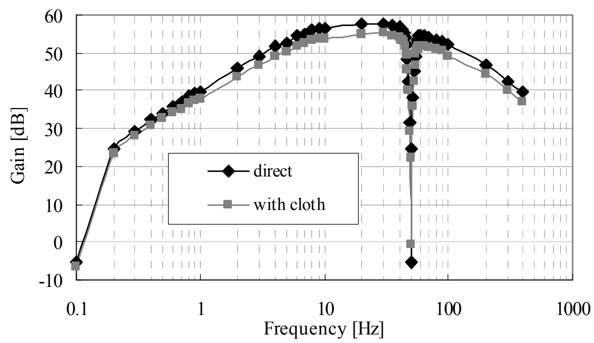


Fig.5. Frequency-gain responses obtained directly (direct), and with the 450$\mu$m underwear (with cloth)


Fig.6. ECG recordings using the developed device with cloth (top) and using commercial telemeter system without cloth (bottom)

TABLE I
CMRR at 10Hz obtained directly (direct), and with the 450$\mu$m underwear (with cloth)

| | Direct | with cloth |
|---|---|---|
| CMRR [dB] | 64.9 | 35.4 |

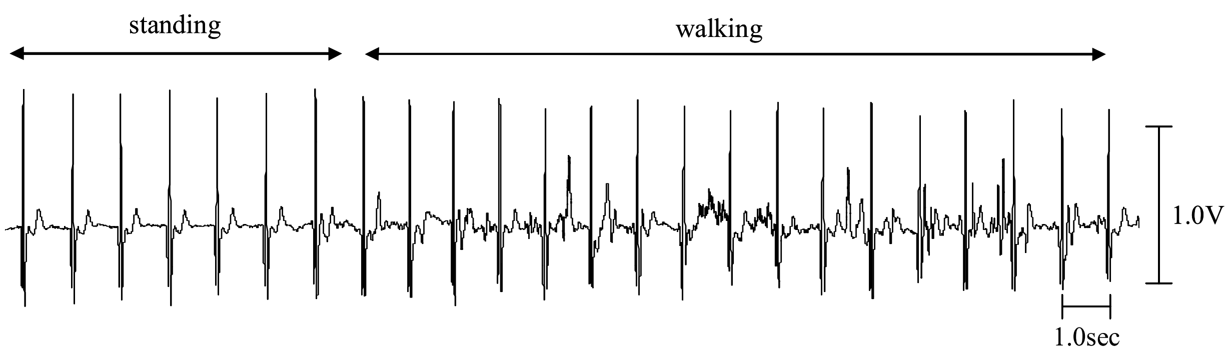


Fig.7. ECG records with the underwear while the subject was standing or walking. The electrodes were clamped by a stretch rubber band.

### *E. Measurement during a transient from Standing to Walking*

To explore an applicability of the developed device to ambulatory ECG monitoring, an ECG signal with the underwear was recorded using the device during a transition period from standing to walking. The room temperature was 24℃ and the relative humidity was 48%

## IV. RESULTS AND DISCUSSION

### *A. Fundamental Characteristics of the Device*

As can be seen in Fig.5, gains within the pass-band (6 to 45Hz) were reduced by 2 dB independent of frequency when the underwear was inserted. Therefore distortion due to cloth insertion was considered minimal. However, in contrast to the frequency-gain response, CMRR was decreased considerably to a value below a level needed for commercial diagnostic electrocardiographs in the standard (40 dB). This decrease in CMRR was considered to be due to heterogeneous voltage losses at the skin-to-electrode couplings originating from heterogeneity of the mediated material. Therefore, it is essential to introduce some technologies for the improvement of the CMRR in the future work.

### *B. Simultaneous Measurement with a Conventional ECG Monitor*

Fig.6 shows recordings typical of those obtained. The output signal of the developed device showed periodic waveforms synchronized to the reference ECG. Therefore, it was confirmed that the developed device was possible to detect heart rate even with the cloth inserted.

### *C. Measurement during a transient from Standing to Walking*

As shown in Fig.7, ECG signal was successfully obtained even when the subject was walking. However ECG signal was deteriorated slightly during walking. Thus, it is a next challenge to reduce the motion artifact. In addition, the method of electrode fixation is also the key to acquire a high-quality signal. In this study, the electrodes were held tightly by a stretch a thoracic belt. Since tight fixation is not practical for daily use, more consideration should be paid for the method of fixation in the next step.

## V. CONCLUSION

We have developed a device capable of monitoring ECG ambulatory through underwear. Validation of the device revealed the following:

1) The frequency response of the pilot device with the underwear revealed that the gain of the signal was reduced by 2dB by the insertion of the underwear, but the distortion of the detected signal within the pass-band was minimal. However CMRR was decreased considerably.
2) The detected signal displayed a periodic waveform synchronized with the simultaneously recorded ECG, even when the underwear was inserted between the electrode and the skin.
3) ECG signal was successfully obtained while walking, however the signal was deteriorated slightly,.

Although there is still room for improvement in terms of its practical use, the proposed approach appears promising for application to ambulatory ECG monitoring.

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