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Development of Nonintrusive Electrocardiogram Monitoring System during Bathing by Only Pasting an Electrode Unit Outside the Bathtub Wall

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Daily electrocardiogram (ECG) monitoring is helpful for the early detection of cardiopulmonary disorders. In particular, bathing poses a risk for abnormal cardiac beats, respiratory failure, and drowning owing to the thermal effect and water pressure on the body. Thus, there is a need for nonintrusive measurement techniques without the attachment of electrodes and any instrument operation, that is, a bathtub ECG monitoring system. In this paper, we describe the development of a new bathtub ECG monitoring system that has electrodes pasted outside the bathtub wall, and thus the capacitive coupling was made from the electrodes to the tap water through the bathtub wall. In a previous system, the decrease in the thickness of the bathtub wall and the location of a long-tape-type reference electrode to prevent oscillation by the incorporation of environmental noise were required to obtain a stable ECG signal. To resolve these drawbacks, two electrodes covered by an active shield with an amplifier were pasted to the outside surface of the bathtub wall without the decrease in thickness, near the bather's right scapula and left hip. To prevent the signal baseline fluctuation and oscillation caused by the environmental noise, the most suitable input impedance of the amplifier was also determined. In 13 healthy subjects (21.9 ± 1.94 years), the QRS components in ECG were successfully detected during bathing with a reasonable signal-to-noise ratio of more than 14.9 dB. Moreover, the intervals of the heartbeat and respiration obtained by the bathtub system and by the direct method agreed with each other.

1. Introduction

Daily healthcare monitoring at home has been increasingly recognized as important to prevent lifestyle-related diseases such as chronic cardiopulmonary diseases, adiposis, diabetes, and dementia. Commercially available devices especially for pulse rate, blood pressure, and body weight are widely used for health monitoring. Moreover, recent devices also have data

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transmission functions using Bluetooth, appearing easy and convenient for data accumulation on a smartphone.

However, the continuous use of such devices is cumbersome because of the need to attach biological sensors to the body as well as to operate the devices. These cumbersome procedures lower users' motivation to continue monitoring for a long time and thus make it more difficult for the early detection and diagnosis of chronic diseases.

From these viewpoints, a new concept of nonconscious healthcare monitoring to measure physiological variables without interrupting normal daily life activities in a fully automated manner and without the need for the subject to attach any biological sensors to their body or operate complicated measurement devices(1–4) has been proposed. In this method, all of the necessary sensors are built into existing home facilities such as living spaces, the toilet, bathtub, and the bed and with only a smartphone. On the basis of this concept, many developments have been made for electrocardiogram (ECG), cardiac pulse, respiration, body temperature, body and excretion weight, and others.(5–13) With these methods, wearable devices, and smartphone(14,15) nonintrusive physiological measurement techniques have been recently defined as "calm healthcare technology", and many types of development have been carried out.(16)

With the abovementioned points in mind, we propose a new nonintrusive method for monitoring the ECG in daily life. While bathing, there is a risk of accidents such as a sudden malfunction of cardiopulmonary systems following thermal and water pressure loads to the body. Therefore, the importance of ECG monitoring during bathing is well recognized for the early detection of abnormal cardiac beats in subjects with chronic cardiopulmonary diseases and the prevention of drowning caused by a sudden heart attack.(17,18)

Taking these circumstances into account, we developed a system for ECG and/or respiration measurement during bathing using bathtub-installed electrodes.(19) Even if abnormal rhythms of cardiac beatings as well as respiration could not be observed by medical examinations in a hospital, the bathtub method has the potential to catch an abnormal symptom during bathing.(20–22) However, in these methods, electrodes are placed inside the bathtub wall, and thus a subject can see the electrodes directly. Such visible electrodes can usually provide a feeling of strangeness and/or discomfort for the subject and thus visible electrodes were considered undesirable. Furthermore, the ability to record the ECG signal gradually declines with the corrosion of the electrode due to repeated direct contact with tap water in the bathtub.

In a previous study, we attempted to apply a capacitive coupling electrode technique(23–29) to ECG measurement through the bathtub wall.(30,31) Capacitive coupling electrodes were placed outside the bathtub wall so that the electrodes could be hidden. However, the surface polish of the bathtub wall to decrease the thickness of wall and the long-tape-type reference electrode to prevent oscillation by the incorporation of environmental noise were required to stably obtain the ECG/QRS components. Therefore, the attachment of the system to the already existing bathtub was complicated and thus these methods were generally not practical.

To resolve these drawbacks, we investigated more suitable conditions for the input impedance, the area of the electrode, and the structure of the active shield to maintain the uniformity of the magnetic field around the electrode for detecting the bathtub ECG signal. Moreover, on the basis of these investigations, a novel bathtub ECG monitoring system was developed by only pasting an electrode unit outside the bathtub wall. The performance of this bathtub system is described through comparison experiments between the values of ECG/RR and respiratory intervals determined by the bathtub method and by a conventional direct method in 13 healthy subjects.

2. Methods

2.1 Description of ECG monitoring system

Figure 1(a) shows an outline of the nonintrusive bathtub ECG monitoring system using capacitive coupling electrodes through the bathtub wall, revealing the electrode arrangement (left side) and structural drawing of the electrode unit (right side). A commercially available bathtub [PB-1202W AL(R), LIXIL, Tokyo, Japan; inside dimensions: 1040 × 600 × 530 mm^3; thickness: 3.7 mm] made of fiber-reinforced plastics (FRPs) was used without processing the wall such as decreasing the thickness.

The capacitive coupling was made between the electrodes placed outside the bathtub wall and the tap water through the FRP as the insulating material. Electrically conductive tape (Tinned Copper Embossed Conductive Tape No. 1345, 3M, Minnesota, USA) was pasted to the wall to produce the ECG sensing electrode (50 × 50 mm^2) and directly connected with the terminal of the buffer amplifier through the pin header connector. This electrode was closely covered by the active shield (51 × 51 mm^2) made by the same conductive tape of the sensing electrode. In addition, the amplifier was covered by an electromagnetic shield to maintain the uniformity of the magnetic field around the electrode. Two electrode units were fixed to the rear surface of the bathtub wall near the subject's right scapula and left hip at a distance of 360 mm.

Figure 1(b) shows a block diagram of the electrode unit and the signal-processing unit, which consists of a differential amplifier, high-pass filters (HPFs), a low-pass filter (LPF), a notch filter (NF), and an amplifier. First, in the electrode unit, the signals are led to the buffer amplifier (ADA4530, Analog Devices, Massachusetts, USA). The ECG signals are measured in the input impedance adjusted from 1.0 GΩ to 10 PΩ. From these results, the appropriate value is 1.0 GΩ to obtain a stable ECG signal.

Second, the signals from each buffer amplifier are sent to the HPFs (0.16 Hz cut-off frequency, −6 dB/oct) and then to a differential amplifier (INA128, Texas Instruments Inc., Dallas, USA) with gain = 10. The output from this amplifier, which is the potential difference between the two electrodes corresponding to a bipolar Lead II ECG, was detected as a raw ECG signal.

Third, the low-frequency fluctuation caused by slow body motion was reduced by the 4.5 Hz HPF (−18 dB/oct). In addition, this signal was processed through the 40 Hz LPF (−18 dB/oct) and 60 Hz NF to obtain the ECG/QRS component (10–20 Hz)[32] by decreasing the high-frequency artifacts caused by quick body movements and environmental magnetic noise. Finally, the signal was amplified with a gain of 162 units using a low-noise and low-offset-voltage amplifier (OPA2277, Burr Brown Corp., Tucson, USA).

The buffer amplifiers in the electrode units and all filter and amplifier circuits in the signal-processing unit were totally powered by a regulator (+3.3 V, AMS1117-3.3, Youtai Semiconductor

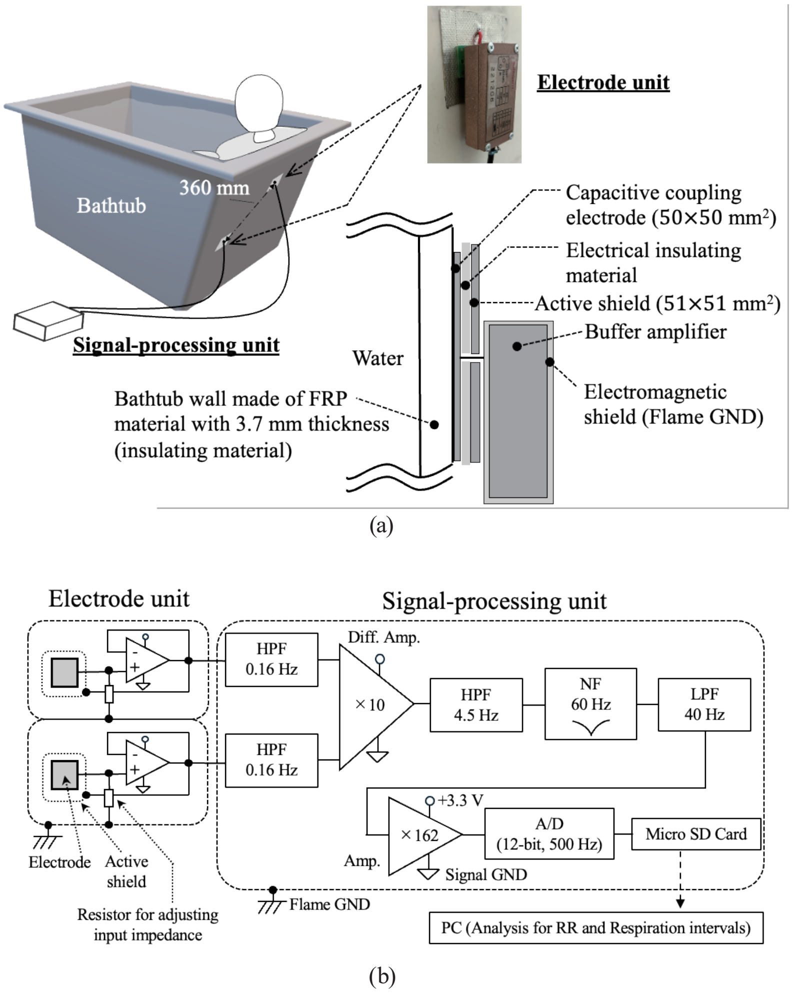

Fig. 1. (Color online) Outline of nonintrusive bathtub ECG monitoring system using capacitive coupling electrodes through the bathtub wall, showing (a) electrode arrangement (left side) and structural drawing of the electrode unit (right side) and (b) block diagram of the electrode unit (left side) and the signal-processing unit (right side) to obtain ECG signal in the bathtub system.

Co., Ltd., Shenzhen, China) with the power source of a mobile battery (+5.0 V, A1621011, Anker Japan Co., Ltd., Tokyo, Japan), and these power and GND lines were not isolated. To cancel electrical noise from the surrounding environment, the electrical grounding (GND) was not connected to the earth. The tap water inside the bathtub was also not connected to the earth. Therefore, the signal and flame GNDs are floating GNDs, and a third reference electrode with or without a driven right leg(24) was not used in this study.

The signal was continuously recorded to the SD card through an AD converter (12-bit, 500 Hz of sampling frequency, and voltage range from 0 to 3.3 V) built in a microcomputer unit (ESP32-DecKitC V4, Espressif Systems, Shanghai, China) and then transferred to a personal computer.

The beat-by-beat ECG/RR intervals can be derived using an automated analysis program developed by us on commercially available numerical analysis software (MATLAB, MathWorks, California, USA). The respiratory intervals can also be derived from the respiratory sinus arrhythmia included in the ECG/RR intervals.[33] From the time series data of RR intervals, a spline interpolation of 500 Hz and a digital filter of 0.15–0.5 Hz are processed to obtain a respiratory fluctuation curve, and the intervals between the positive peaks are detected.

By the improvements mentioned above, accurate ECG signals can be obtained in this study and thus a specialized filtering algorithm to emphasize the ECG/QRS component wave[30] was not used in this study.

2.2 Comparison experiment and participants

In the 13 healthy volunteers (12 males and a female; 21.9 ± 1.94 years old), the ECG signals obtained from the bathtub and conventional direct methods were simultaneously measured. In addition to the bathtub system, spot electrodes were also attached to the wrist surface without direct contact with the water to obtain bipolar Lead I ECG.

The signal-to-noise ratio (SNR) in the bathtub ECG signal was also calculated from the ratio of RMS between the ECG component from 5.0 to 20 Hz and the noise component of more than 20 Hz separated by a digital filter. The automatically determined values of the bathtub ECG/RR intervals and the corresponding ECG/RR intervals obtained by a conventional direct method with spot electrodes were compared to evaluate the measurement accuracy for heartbeat intervals.

The values of respiration intervals obtained using the bathtub ECG/RR intervals and by a conventional direct method with a nasal thermistor (103JT-050, SEMITEC Corporation, Tokyo, Japan) were also compared simultaneously. The participants were asked to take a bath in the usual manner without big body motions as much as possible for 300 s and to control their respiration conditions of rest (0–60 s), deep breath (60–120 s), respiratory arrest as simulated drowning (120–180 s), and rest once again (180–300 s). Note that all the values used in this study were automatically determined without any manual data selections.

3. Results

Figure 2 shows recording examples of ECG signals in two male subjects (Sub. 3: 19 years old and Sub. 7: 22 years old). Each upper panel (a) is a full-length ECG record, and the middle panel (b) shows its expansion from 30 to 140 s. The lowest panel (c) is the corresponding record simultaneously measured by the direct method using spot electrodes (ECG/Lead I). The circular marks in (b) and (c) indicate the ECG-R waves automatically detected using the analysis program, clearly demonstrating a synchronization of both ECG signals including QRS components. Moreover, as shown in Table 1, reasonable SNR values are also obtained with 16.8 ± 1.02 dB in all the subjects.

Figure 3 shows trend charts of time-series data of ECG/RR intervals obtained by the (a) bathtub and (b) direct methods in a female subject (Sub. 4: 25 years old) and a male subject (Sub. 13: 23 years old), indicating that the changes in RR intervals coincide well with each other.

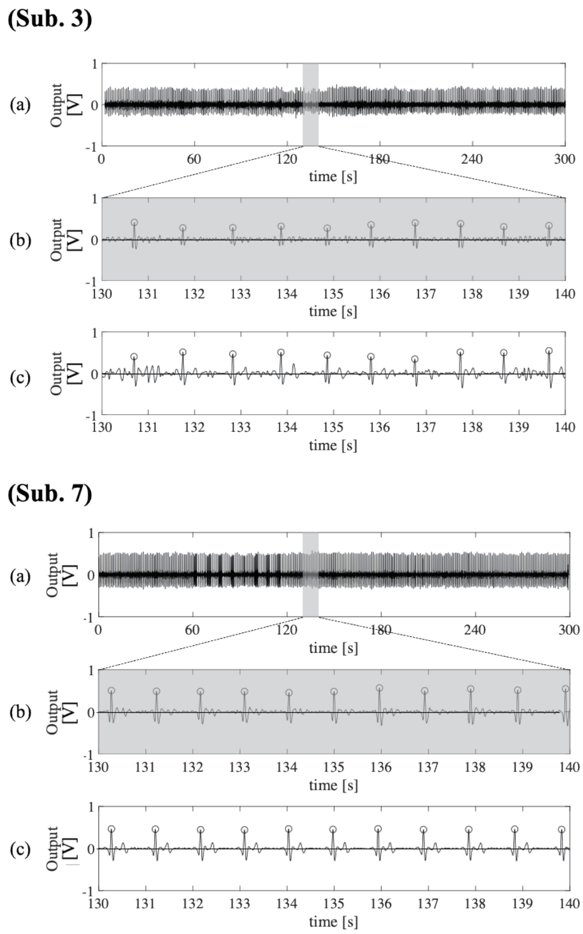

Fig. 2. Recording examples of bathtub ECG signals in two male subjects (Sub. 3: 19 years old and Sub. 7: 22 years old). The upper panel (a) is an ECG record, and the middle panel (b) shows its expansion from 30 to 140 s, and the lowest panel (c) is the corresponding record simultaneously measured by the direct method using spot electrodes (ECG/Lead I). The circular marks in (b) and (c) indicate the ECG-R waves.

Table 1
Analysis results for SNR in ECG signal detection. The values were calculated using the ratio of RMS between the signal component from 5 to 20 Hz and the noise component of more than 20 Hz separated by a digital filter.

Subject	Age	Gender	SNR (dB)
1	22	Male	15.9
2	23	Male	17.2
3	19	Male	15.5
4	25	Female	16.7
5	22	Male	14.9
6	22	Male	18.4
7	22	Male	18.4
8	19	Male	17.6
9	19	Male	17.2
10	21	Male	17.3
11	23	Male	17.2
12	25	Male	16.1
13	23	Male	16.2
Average	21.9 ± 1.94		16.8 ± 1.02

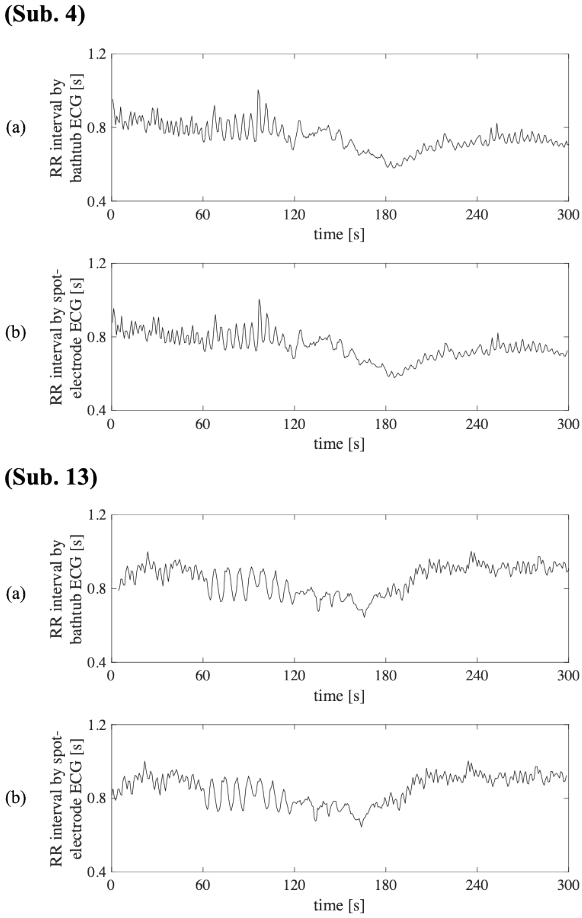

Fig. 3. Trend charts of time-series data of ECG/RR intervals obtained by (a) the bathtub and (b) direct methods in a female subject (Sub. 4: 25 years old) and a male subject (Sub. 13: 23 years old).

Figure 4 shows sample recordings of respiration curves simultaneously obtained from the (a) bathtub and (b) direct methods using the nasal thermistor during bathing in two male subjects (Sub. 2: 23 years old and Sub. 9: 19 years old). The records of three conditions during periods of rest, deep breath, and respiratory arrest are shown in these recordings. The lower two panels show an expanded record from the corresponding upper two records. From the result of Sub. 2, it is demonstrated that the patterns of increase and decrease in signal obtained from the bathtub system were synchronized with the exhalation and inhalation phases (indicated by arrows) and the decrease in the amplitude of respiration curves during respiratory arrest. However, while the patterns in bathtub and conventional methods coincided well with each other during rest and deep breath in Sub. 9, the amplitude decrease could not be observed during simulated drowning.

Figure 5 shows the accuracy evaluations for detecting the (a) RR and (b) respiration intervals using the scatter diagram and Bland–Altman plots, respectively, in 13 subjects. In result (a), altogether 7309 paired data sets were analyzed as follows: $y = 0.984x + 0.0117$ and $r = 0.984$. Moreover, in result (b), altogether 1412 paired data sets were analyzed as follows: the fixed bias was 0.1250 s and 1298 data were within the limit of agreement from −2.6974 to 2.9474 s.

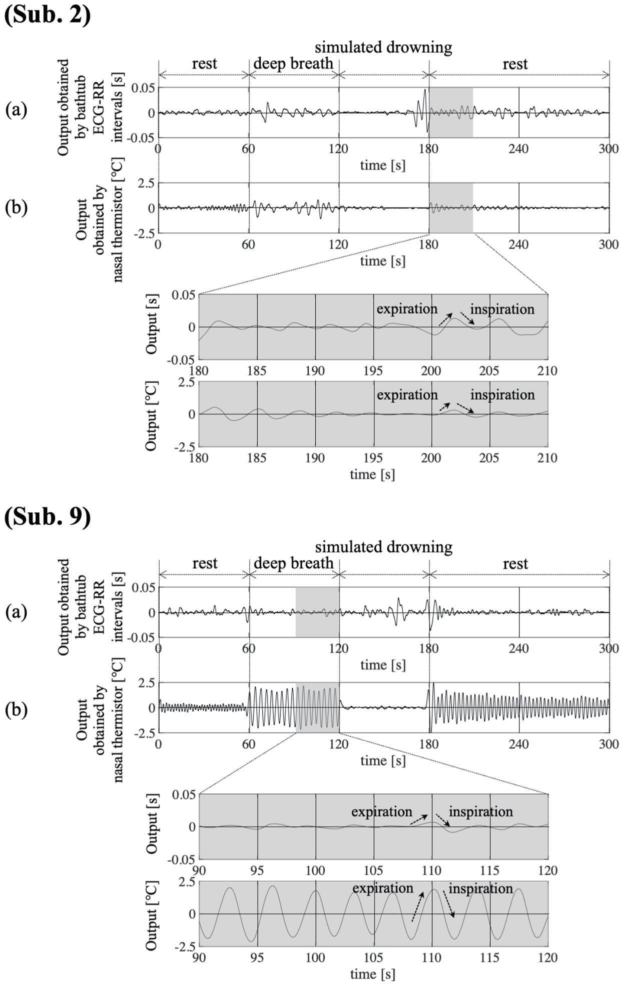

Fig. 4. Sample recordings of simultaneously measured respiration curves obtained from the (a) bathtub and (b) direct methods using the nasal thermistor during bathing in two healthy male subjects (23 and 19 years old). The records of three conditions during periods of rest, deep breath, and respiratory arrest are shown in these recordings. The lower two panels show an expanded record from the corresponding upper two records.

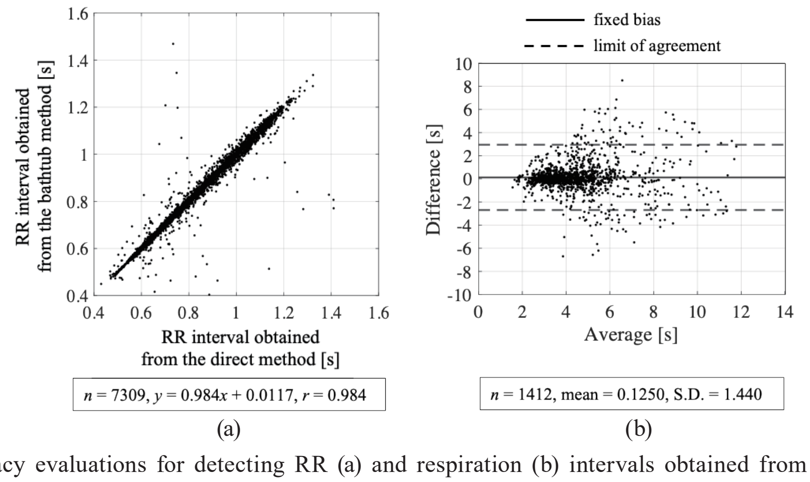

Fig. 5. Accuracy evaluations for detecting RR (a) and respiration (b) intervals obtained from the bathtub and direct methods were performed using the scatter diagram and Bland–Altman plots, respectively, in 13 healthy subjects.

4. Discussion

Through the improvement of the previous ECG monitoring system using capacitive coupling electrodes placed outside the bathtub wall,[30,31] it was demonstrated that ECG signals can be successfully measured using the tape-type electrodes affixed only to the outer wall, as compared with the conventional direct methods.

As shown in Fig. 2, the synchronization of both ECG signals obtained from the bathtub and body-surface methods was clearly observed. However, to obtain a stable ECG signal like this in the previous monitoring system that we developed, an electrically conductive coating was applied to the wall to produce the beaten-copper electrode. Moreover, the approximately 2-mm-thick surface polishing of the bathtub wall and the location of the long-tape-type reference electrode were also required, showing the impracticality for field use.

To resolve these drawbacks, we attempted to improve the signal processing method in this study as follows: decreasing the input impedance in the buffer amplifier to reduce the detection of the surrounding environment noise, changing the material and area of the electrode, changing the location of the active shield closely attached to the electrode, and improving the circuit, including filters and amplifiers. Accordingly, the ECG signal could be obtained with a reasonable SNR as shown in Table 1, revealing the availability for detecting the R wave and calculating the heartbeat interval. In particular, a high input impedance is ordinarily adapted to obtain a stable ECG signal. However, a low value was used in this study, showing the effectiveness for detecting ECG signals in the bathtub. A more detailed investigation will be needed on this point.

On the other hand, the respiration curve processed with the spline interpolation and digital filter from the time-series data of the bathtub ECG/RR intervals was similar to that measured by the direct method using the nasal thermistor as shown in Fig. 4, while a few fluctuations of the respiration curve could be observed during simulated drowning in Sub. 9. To clarify this reason, we should further investigate the signal fluctuation caused by the body motion with low-frequency and the individual variation of the heart rate in respiration-holding[34,35] during bathing.

To improve the drowning detection accuracy, it would be necessary to detect the baseline fluctuation from 0.15 to 0.5 Hz in the bathtub ECG signal synchronized with the subject's respiration caused by the chest impedance variation[19] and thus the filter characteristics should be improved to conclude that respiratory intervals are measured with reasonable accuracy using the bathtub-installed system. The respiration interval detection can be helpful for the early diagnosis of a bather's cardiac failure, stress evaluation, and risk assessment for drowning.[19,20,22] As shown in Fig. 5, some errors attributed to mistakes in the automatic detection of R-waves and thus further improvement of its analysis program will be also needed to increase accuracy.

The several limitations of this study are as follows. First, the participants were young and healthy adults; thus, the sample data was insufficient to conclusively evaluate the accuracy of the bathtub method. Therefore, it is recommended that the method should be re-evaluated across a wide age range of participants including patients with cardiopulmonary diseases. Second, the input impedance and area in the electrode unit should be adjusted to detect accurate ECG and respiration signals in other commercial bathtubs, and thus measurement in more types and sizes of bathtubs is recommended. Third, an analysis program for physical condition should be developed for daily healthcare through the measurement for a long period of time in the fields of medicine, nursing care, sports, ordinary home healthcare, and others. In these cases, technical advancements to detect body movements such as posture changes and body washing actions will be necessary. The detection of several ECG signals with Leads I, II, and III would be also needed, especially in medical use. Other investigations will be needed, such as the automated detection of the presence of a person, biometric identity verification for bathers, and the reduction of artifacts caused by body motion.

5. Conclusions

In this paper, we described a new technique to obtain ECG signals in a bathtub through tap water utilizing capacitive coupling electrodes. By improving the input impedance of the electrode unit, constructing an active shield, and so on, stable ECG signals could be detected by only pasting the electrode unit outside the bathtub wall, without the cumbersome installation operation of surface polishing to decrease the thickness of the bathtub wall, demonstrating that the ECG/RR and respiratory intervals obtained from the bathtub coincided well with those obtained by conventional methods using body surface electrodes and a nasal thermistor. Towards practical use, further investigations will be needed, such as evaluation across a wide age range of participants including not only healthy subjects but also patients with cardiopulmonary diseases, suitable input impedance and area in the electrode unit for many types of bathtubs, and an analysis program for health condition. Through these improvements, this method would be useful for calm healthcare monitoring during bathing without the need to interact with the device.

Ethics Approval

This study was approved by the ethics committee of Shizuoka Institute of Science and Technology (No. 2023-11).

Declaration of Competing Interest

The authors have no conflicts of interest directly relevant to the content of this article.

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