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Channel Selection Algorithm for Improvement of R-Peak Detecting Accuracy in Capacitive Electrocardiogram

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Abstract*—Capacitive electrocardiogram (cECG) is more practical in daily life than conventional contact ECG because cECG signal can be measured without skin contact. However, obtaining medically meaningful information, such as R-peak, from the cECG signal is not easy because the cECG signal is easily contaminated by noise. This paper proposes a channel selection algorithm to improve R-peak detecting accuracy in the cECG signal; the algorithm uses both intervals of three successive R-peaks and waveform around R-peaks as an index for channel selection. By using the both information together, the proposed method can effectively gather and utilize valid parts from partially contaminated multi cECG channels. To verify the proposed algorithm, indoor and outdoor experiments were conducted. For indoor experiments, the proposed algorithm showed the average sensitivity of 95.85 % and positive predictive value of 96.22 %. For outdoor experiments, the proposed algorithm showed the average sensitivity of 92.73 % and positive predictive value of 93.89 %. These result will change the existing health care system and medical instruments, enabling people to check heart diseases during daily life.

***Index Terms*—Capacitive ECG, ECG measurement system, motion noise, QRS complex.**

I. INTRODUCTION

The graph of voltage versus time produced by heart activity is referred to as an electrocardiogram (ECG) [1]. ECG signal consists of a series of QRS complexes that contain medically important information such as the heart rate (HR) and the heart rate variability (HRV). Therefore, the ECG signal can be employed to diagnose heart diseases such as tachycardia, arrhythmia and ischemic heart disease [2]. Furthermore, the ECG signal can be utilized to check physical and mental condition like fatigue and stress [3,4]. Therefore, ECG measurement during daily life can help human to enhance the quality of their lives. However, the ECG measurement is not pragmatic because the ECG measurement requires electrodes to be attached to subjects' skin, causing subjects to feel uncomfortable.

To solve the inconvenience of conventional contact ECGmeasurement, capacitive electrocardiogram (cECG) was developed based on advances in sensor technology. Since cECG sensors were developed, there have been efforts for integrating the cECG sensors to daily life products, because it gives the advantage of ECG measurement mentioned above without the inconvenience of contact ECG measurement [5, 6, 15]. To be specific, research oncECG measurement in a vehicle is gaining attention because the cECG measurement during driving enables a driver to check health during daily life and to drive safely by detecting abrupt possible cardiac abnormalities [5, 6]. However, it is still not easy to obtain medically meaningful information, such as QRS complex or R-peak, from the cECG signals measured by cECG sensors, because the signals are easily corrupted by motion noise due to movements of subjects and drivers' steering.

To overcome the disadvantage of the cECG signal, a common method is to use many sensors and to choose a high quality channel [5,7]. A noise index (NI), which is defined as the T-P interval average power over the QRS average power, was used as an index for channel selection [7]. Quality index (QI), which guarantees the similarity of QRS complex, was used as an index for channel selection [5]. However, NI and QI that only assess the waveform around R-peak have a limit to channel selection for the cECG signal. This is because the cECG signal is easily contaminated by motion noise that has similar characteristics to those of QRS complex. Therefore, this paper proposes a channel selection algorithm using both interval of three successive R-peaks and waveform around R-peaks.

II. MATERIALS AND METHODS

A. Measurement system

In prior research, several cECG measurement systems were designed to measure cECG signal during driving or daily life [5, 6]. The cECG measurement systems consisted of a chair or a driver's seat having two or more cECG sensors on the backrest, and conductive fabric placed on the bottom for a driven-right-leg circuit (DRL) [8]. Recently, an adaptive noise cancelation (ANC) concept was applied to the cECG measurement systems to overcome the disadvantage of cECG measurement that is sensitive to noise, and the effectiveness of the ANC concept was verified [9].

Based on those existing cECG measurement systems [5, 6, 8, 9], our measurement system was designed. The schematic diagram of our measurement system is show in Fig. 1. Total 24 cECG sensors (PS25454 from Plessey Semiconductors)

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were attached to the backrest of a sheet cover; the sheet cover was used for ease of movement and installation. The 24 cECG sensors caused 48-multi channels based on the ANC concept [9]. In addition, conductive fabric was placed on the bottom of the sheet cover for a DRL circuit [8]. A chair and a driver's seat were covered with the sheet cover for indoor and outdoor experiments respectively. cECG signals measured by 24 cECG sensors were sampled digitally at 200 Hz by an A/D converter (NI-9205 from National Instruments). This measurement system was similar to prior designs [5, 6, 9], but the main difference was that many cECG sensors were used. The cECG sensors caused many cECG channels, and the proposed channel selection algorithm gathered and utilized valid parts from the cECG channels; this proposed method is concretely explained in NEXT Section.

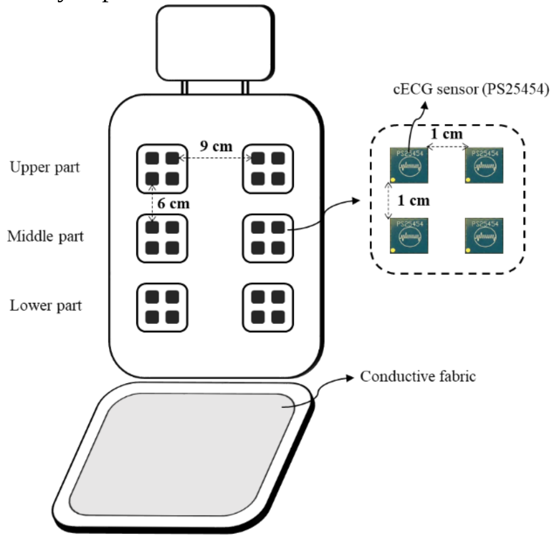

Fig. 1: Schematic diagram of cECG measurement system

B. Data acquisition

Indoor experiments were conducted to obtain significantly contaminated cECG signals by movements of subjects. A chair was covered with the cover sheet having the 24 cECG sensors for indoor experiments. Total 10 subjects with no heart-related medical history were tested in the indoor experiments. The subjects were asked to sit on the chair and to move arbitrarily to obtain cECG signals contaminated by motion noise for 30 min. The subjects were wearing their casual clothes. The reason for the motion noise by arbitrary movements was to verify the proposed channel selection algorithm in a severe environment. For the reference R-peaks, contact ECG signal was also measured by using conventional contact Ag-AgCl electrodes.

Outdoor experiments were conducted to obtain cECG signals during driving. A driver's seat in a vehicle was covered with the cover sheet having the 24 cECG sensors for outdoor experiments. Total 10 subjects with no heart-related medical history were tested. The subjects were asked to sit on the driver's seat and to drive naturally for about an hour. There was no intended motion because it can occur a serious accident. All the subjects drove the prescribed course including campus, city and highway. The objective of outdoor data acquisition was to verify the proposed algorithm in a driving environment. In the same way as the indoor experiments, contact ECG signal was measured for the reference R-peaks.

C. Channel selection

The proposed channel selection algorithm is used to obtain and to use valid information from partially contaminated multi cECG channels. The proposed algorithm chooses the channel that is expected to have the highest R-peak detecting accuracy among multi channels, every 10 s; it improves R-peak detecting accuracy.

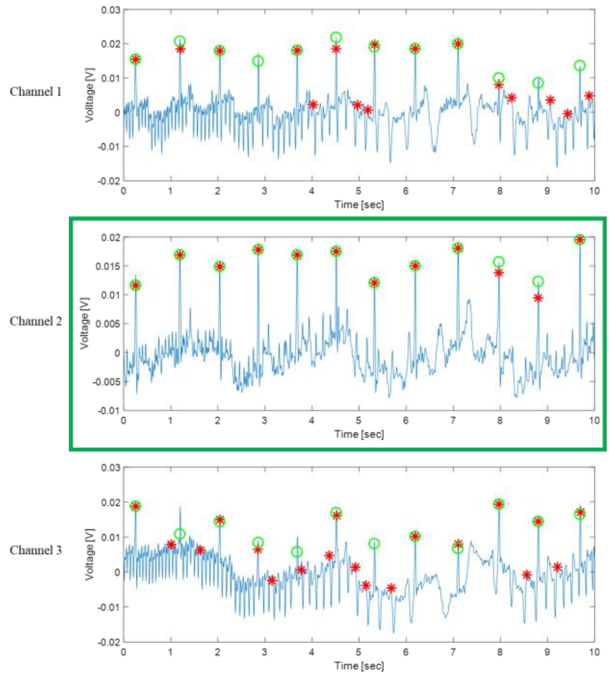

Fig. 2: Concept of proposed channel selection algorithm. The red stars denote detected R-peaks in each cECG channels. The green circles denote detected R-peaks from contact ECG signal as a reference. The green rectangle denotes selected channel by channel selection algorithm.

The concept of the proposed algorithm is described in Fig. 2. There are three cECG channels with 10-s length in Fig. 2. Only one channel that is expected to have the highest R-peak detecting accuracy is selected by the channel selection algorithm every 10 s, and the selected channel was highlighted by green rectangle to visualize.

The proposed algorithm is mainly made up of the following parts: R-peak detection, evaluation of detected R-peaks, channel selection, and peak insertion.

Firstly, each signal in each cECG channel is divided into 10-s cECG signals. Then, R-peaks in the 10-s cECG signals are detected by an open source R-peak detector (Pan and Tompkins) [10-12].

Secondly, the detected R-peaks are evaluated by using a proposed index. The proposed index that uses the interval of three successive R-peaks and waveform around R-peaks is defined for channel selection. The index is denoted by *IQI*(interval and quality index). The index is composed of two terms: *Q1*and *Q2*. The first term, *Q1*, guarantees normality of R-peak variability by using the interval of three successive R-peaks [13]. The second term, *Q2*, guarantees the similarity between the waveform around detected R-peaks and the standard waveform around reference R-peaks [5]. The indices for channel selection are calculated as follows,

$$IQI = Q1 + Q2 \quad (1)$$

$$Q1 = NS - NUS \quad (2)$$

$$Q2 = Average(QI) \quad (3)$$

Where *Q1* is calculated based on the range of R-peak variability [13]prescribed as follows,

$$2 \cdot \left| \frac{t_i - 2t_{i+1} + t_{i+2}}{(t_i - t_{i+1})(t_i - t_{i+2})(t_{i+1} - t_{i+2})} \right| < 0.5 \quad (4)$$

where t_i, t_{i+1}, and t_{i+2} are the time of three succesive R-peaks respectively. For the detected R-peaks by Pan and Tomkins algorithm [10] within 10-s cECG signals, *Q1* is calculated as the difference between *NS* and *NUS* as shown in the equality (2), where *NS* denotes the number of the detected R-peaks satisfying the inequality (4), and *NUS* denotes the number of the detected R-peaks unsatisfying the inequality (4).*Q2* is calculated based on quality index (*QI*) [5], which checks how the waveform around detected R-peaks is similar to the standard waveform around reference R-peaks. *Q2* is calculated as the average of *QI* of all the detected R-peaks within 10-s cECG signals.

Thirdly, based on *IQI*, the channel that is expected to have the highest R-peak detecting accuracy is selected. One that has the highest *IQI* value among the 48-channels is selected every 10 s. This step can be easily understood by Fig. 2.

Lastly, because cECG signals are easily degraded by noise, all R-peaks are not always detected by Pan ad Tomkins algorithm [10]. Therefore, the selected channel by the proposed algorithm does not always include all R-peaks. This problem can be solved by inserting peaks, which are detected in other channels, into the selected channel as a post-processing step. The R-peaks, which occur in other channels and have *QI* value higher than a threshold, can be inserted into the selected channel when undetected R-peaks are in the selected channel. For example, there is a peak, which has *QI* value higher than 0.9. The peak can be considered as ture R-peak because *QI* value, which is close to 1, guarantees that the waveform around the peak is similar to the standard waveform of reference R-peak [5]. Therefore, if any peak having *QI* value higher than 0.9 exists in other channel, the peak can be inserted into the selected channel. This step can be sassily understood by Fig. 3. In Fig. 3, the top is selected channel, middle is other channel having R-peak; the R-peak has a QI value higher than a specific threshold and is not detected in the selected channel (top), but is detected in other channel (middle). The bottom is the selected channel after the peak insertion.

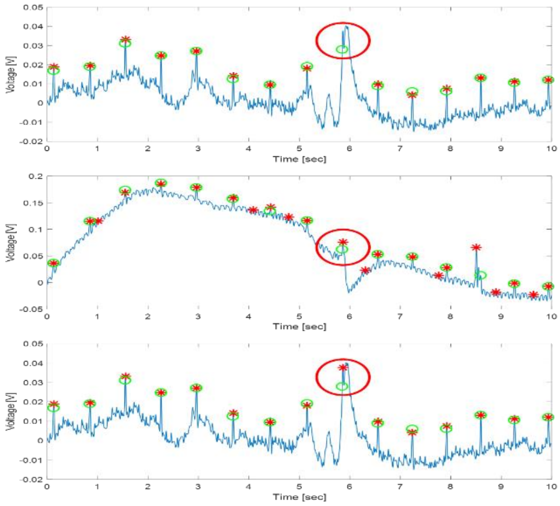

Fig. 3: Example of peak insertion. The red stars denote detected R-peaks in each cECG channels. The green circles denote detected R-peaks from contact ECG signal as a reference. The red circles show how the peak insertion operates.

III. RESULT& DISCUSSION

A. *Performance index*

The sensitivity (*Se*) and the positive predictive value (P^+) were used as indices to verify the proposed algorithm. The indices were calculated as follows,

= (5)

= (6)

where *TP*, true positive, is the number of true R-peaks correctly identified as true, *FN*, false negative, is the number of true R-peaks incorrectly identified as false, and *FP*, false positive, is the number of false R-peaks incorrectly identified as true. Therefore, Se is the ratio of correctly detected R-peaks to the total R-peaks within cECG signals, and P^+ is the ratio of correctly detected R-peaks to all detected R-peaks. If the detected R-peak is located within 50 ms from reference R-peak, then the detected R-peak is considered as true positive.

B. *Experimental results*

To verify the proposed algorithm, we applied the proposed algorithm to the indoor and outdoor experimental data. The results are shown in Table 1 and Table 2. Conventionally, detected peaks within 150 ms from reference R-peaks were considered as true positive. However, in this paper 100 ms was used as a permitting error because the cECG signals are much noisy than the conventional contact ECG signals.

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Table 1: Comparison results of R-peak detecting accuracy for indoor experiments.

data	Single best		proposed algorithm	
	Se	P^+	***Se***	P^+
1	85.24	92.69	92.23	95.26
2	95.12	99.18	98.64	99.38
3	95.16	99.67	99.02	99.53
4	94.68	93.32	99.73	98.90
5	92.13	97.73	97.56	97.95
6	88.54	89.64	95.45	96.29
7	97.09	98.20	100.00	98.59
8	83.69	84.71	82.98	89.72
9	94.52	82.44	96.13	88.17
10	84.22	98.51	96.79	98.45
Average	91.04	93.61	95.85	96.22

Table 2: Comparison results of R-peak detecting accuracy for outdoor experiments

data	Single best		proposed algorithm	
	Se	P^+	***Se***	P^+
1	90.22	96.00	97.87	97.85
2	81.51	93.00	93.09	95.90
3	84.26	92.79	91.78	91.25
4	92.03	77.73	90.45	89.71
5	81.83	97.84	97.99	97.66
6	88.14	92.06	92.09	95.35
7	96.70	96.92	97.62	97.78
8	91.21	96.52	96.21	96.87
9	77.96	76.23	77.50	82.68
Average	87.10	91.01	92.73	93.89

In Table 1 and Table 2, 'Single best' is a single channel having the highest R-peak detecting accuracy among multi-channel, compared to the reference R-peaks; 'Single best' was introduced as a comparison index to verify whether the proposed algorithm can improve the R-peak detecting accuracy by selecting appropriate channels. In most cases, 'Single best' occurred from upper part or middle part (Fig. 1). This is because the lower part (Fig. 1) was easily influenced by movements of subjects due to the bend of waist. If selected channels by the proposed algorithm are mostly concentrated on 'Single best', the proposed algorithm does not work well. For example, if all selected channels by proposed algorithm come from 'Single best' in extreme case, the R-peak detecting accuracy is equal before and after channel selection.

In Table 1, the proposed algorithm shows the average *Se*of 95.85 % and P^+ of 96.22 %. Compared with the average results of 'Single best', the proposed algorithm shows an increase in the average *Se* by 4.81 % and in the average P^+ by 2.61 %. The maximum increase in *Se*is 12.57 % in data 10, and the maximum increase in P^+ is 5.73 % in data 9.In data 3 and 10, P^+ slightly decrease (99.67 % → 99.53 %, 98.51 % → 98.45 %), but *Se*increases relatively greatly.Similarly, in data 8 *Se* slightly decreases (83.69 % → 82.98 %), but P^+ increases relatively greatly. Except for the data 3, 8 and 10, both *Se* and P^+increase together.

In Table 2, the proposed algorithm shows the average *Se* of 92.73 % and P^+ of 93.89 %. Compared with the average results of 'Single best', the proposed algorithm shows an increase in the average *Se* by 5.63 % and in the average P^+ by 2.88 %. The maximum increase in *Se*is 16.16 % in data 5, and the maximum increase in P^+ is11.98 % in data 4. In data 3, P^+ slightly decrease (92.79 % →91.25 %), but *Se*increases relatively greatly. Similarly, in data 4 and 9*Se* slightly decreases (92.03 % → 90.45 %, 77.96 % → 77.50 %), but P^+ increases relatively greatly. Except for the data 3, 4 and 9, both *Se* and P^+increase together. These results demonstrate that the proposed algorithm can improve the R-peak detecting accuracy.Although total 10 subjects were tested for outdoor experiments; one data was discarded in Table 2. This is because reference ECG was not measured for about 5 min for the one data.

When the results of outdoor experiments (Table 2) compare with the results of indoor experiments (Table 1), The results of outdoor experiments show the greater increases than the results of indoor experimental. This is because the outdoor experimental data were more contaminated by engine quiver, driver's steering and movements than the indoor experimental data. The proposed algorithm is more effective for the more contaminated data.

IV. CONCLUSION

We proposed a channel selection algorithm to improveR-peak detecting accuracy in multi-channels cECG. The algorithm used both intervals of three successive R-peaks and waveform around R-peaks as an index for channel selection. In addition, peak insertion step helped the proposed algorithm to more improve R-peak detecting accuracy. To verify the algorithm indoor and outdoor experiments were conducted. Indoor experimental results showed the average sensitivity (*Se*) of 95.85 % and positive predictive value (P^+ of 96.22 %. Outdoor experimental results showed the average sensitivity of 92.73 % and positive predictive value of 93.89 %. These results demonstrate that the proposed algorithm can improve the R-peak detecting accuracy despite severe environments including movements of subjects and driving.cECG signal has not been used for medical applications because the cECG signal is so sensitive to noise, but these result show the possibility that the cECG signal can be used in these applications.

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