Indirect Skin Contact Electrocardiogram Monitoring System Using Flexible Capacitive Electrodes

Issey Takahashi[1,3], Kiyoko Yokoyama[1*] and Marco Knaflitz[2]

[1] *Graduate School of Design and Architecture, Nagoya City University, 2-1-10 Kitachikusa, Chikusa-ku, Nagoya 464-0083, Japan*
[2] *Department of Electronics and Telecommunications, Politecnico di Torino, Italy*
[3] *University of Tsukuba, Japan*
* *E-mail address: yokoyama@sda.nagoya-cu.ac.jp*

(Received April 4, 2016; Accepted March 22, 2017)

It is gaining great importance to develop and integrate physiological sensors into daily healthcare. Especially, electrocardiogram (ECG) is useful for the disease diagnosis and daily health monitoring, also for the driver's cognitive state monitoring. Capacitive ECG monitoring system, which enables to collect ECG with indirect skin contact, is implemented in this study. Signal attenuation and noise contamination is considered by installing flexible electrode, neutralization circuit, AC coupling circuit, Driven right leg (DRL), and DSP board in the configuration. The system is evaluated with 5 subjects with a car in situations of engine off and on. R-wave Detection Sensitivity (Se) and Positive Predictivity (P+) of 99.8% and 100% were obtained during the engine on.
Key words: ECG, Capacitive Electrode, Daily Health Care

1. Introduction

It is gaining great importance to develop and integrate physiological sensors into daily healthcare. Especially, electrocardiogram (ECG) is useful for the disease diagnosis and daily health monitoring, also for the driver's cognitive state monitoring, which contributes to safety driving. ECG acquisition in driving scenes needs to be non-invasive and less complex in order not to cause interferences while driving. There are three major non-contact measuring methods for ECG: radar Doppler monitoring [1], ballistocardiograms (BCG) [2], and capacitive ECG monitoring (cECG). Radar Doppler monitoring is based on the detection of back-scattered microwave signals modulated by the heartbeat. Therefore, it is very sensitive to motion artifact and requires complex data processing to identify heartbeat signals [3]. BCG is also very sensitive to motion artifacts. M. Walter *et al.* compared cECG and BCG monitoring in an actual car, and reported that BCG signal distorted too big to allow signal interpretation while ECG signal shown acceptable quality during driving [4]. H. J. Baek *et al.* also compared accuracy of cECG and BCG by calculating correlation and error between reference signals, and reported cECG obtained higher correlation and less error than BCG [5]. Although there are several issues need to be overcome such as signal attenuations or noise contamination, cECG has the most prospective potentials for vehicle use among the others. The purpose of this study is to cope with these issues and design reliable cECG monitoring system in driving scenes. The goal is to obtain adequate quality of R-R intervals, which can be utilized for heart rate variability (HRV) analysis.

doi:10.5047/forma.2017.s004

2. Method

The key issue of the system is to cope with disadvantage of the cECG measurement, which is the continuous changing of capacitance between electrodes and driver's body due to body movements, vehicle vibrations, respiration, varying thickness of clothing and materials, as well as static changes. These changes always cause a large amount of noise; therefore the techniques are needed to extract the small signals from the much larger noise signals. There are two methodologies to improve the cECG measurement.

The first methodology is to avoid signal attenuation. When bio-potentials are picked up through clothes, coupling capacitances are of hundreds of pF when the insulation layer directly placed over the skin decreases down to a few pF when the clothing intervened [6, 7]. The smaller coupling capacitance leads to the larger attenuation of signals. The common electrical equivalent circuit of a capacitive electrode forms voltage divider with bias resister Rb and input capacity Cin (Fig. 1(a)). The transfer function follows to:

$$H(s) = \frac{V_{out}(s)}{V_s(s)} = \frac{sC_cR_b}{1 + sR_b(C_c + C_{in})}.$$

The source voltage, coupling capacity, and the output voltage are denoted as Vs, Cc, $Vout$, respectively. Regarding Cc value of a few pF, Rb requires GΩ whereas Cin needs to be as small as possible to realize ultra-high input impedances in order to avoid signal attenuation. However, Cin of operational amplifiers are in the order of a few pF to tens of pF. Moreover, Cin comprises stray capacitances of a PCB (Printed Circuit Board), which values are too high to realize ultra-high input impedance. A technique called 'Neutralization' is one of the effective ways to compensate this Cin. It consists in providing by a positive feedback,

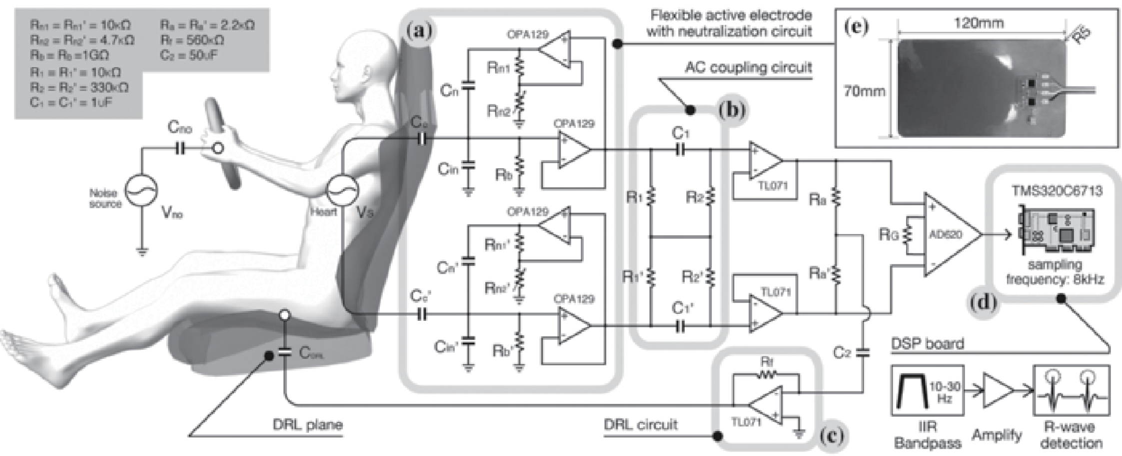

Fig. 1. Configuration of the cECG circuit. (a) Flexible capacitive electrodes with neutralization circuit. (b) AC coupling circuit. (c) DRL circuit. (d) DSP board. (e) Size of the electrode.

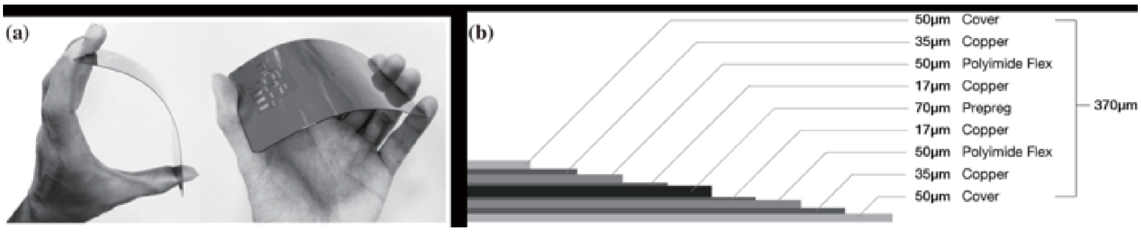

Fig. 2. Capacitive electrode. (a) Appearance of the capacitive electrode. (b) Cross section of the capacitive electrode.

a current that equals the current flowing on Cin, thus neutralizing the effect of this capacitance [8]. Another key to avoid signal attenuation is to make large Cc. Each electrode forms a coupling capacitance Cc with the driver's body, which is known to be: $Cc = \epsilon$A/d, where A is the effective surface area of the electrode, d is the thickness, and ϵ is the dielectric constant of the clothes. For a high coupling capacitance, large contact areas of electrode surface within small distances from the body are essential.

The second methodology is to reduce noises contaminated in signals. One of the effective ways is the use of a driven right leg (DRL) in which the common mode (CM) signal from the two sensors is capacitively coupled onto the driver's body inversely. This technique also provides cancellation for noise introduced by driver's movement artifacts. Another noise rejection is achieved by differential amplification and filtering after the signals are digitized. The differential amplification of the combined electrode signals provides amplification and reduces the CM noise.

In this study, cECG monitoring system is implemented with consideration of these two methodologies. Then the system is evaluated with 5 subjects in situations of engine on and off with an actual car.

3. Implementation

Figure 1 shows the configuration of the cECG monitoring system developed with the considerations of two methodologies mentioned above. Flexible electrode and neutralization circuit was designed mainly for signal attenuation avoidance, and AC coupling circuit, DRL, and digital filtering by DSP are made for noise suppression.

3.1 Flexible active electrode

Capacitive electrodes are especially difficult to employ compared to gel-based counterparts due to the high capacitive source impedance. Small effective area of electrode sensing surface and low signal frequencies (10–30 Hz) result in extremely high source impedances. Therefore, even small variations in the coupling capacitance and distance between channels can lead to large amounts of distortions due to signal attenuation and the mismatches of channels. This can be somewhat mitigated since large effective electrode surfaces are permissible. It is important to consider the size and curvature of the electrode. Because the surface of the human torso is curved, air gaps were created between the capacitive electrode face and the subject's back, resulting in poor contact and a low signal noise ratio (SNR) signal, which deteriorates signal quality. To acquire flexibility and large electrode surface is a key to improve the cECG measurement. In this study, polyimide was used to realize these features. The electrode is consisted with four layers of copper plates and two layers of 50 μm thick polyimide plates Fig. 2(b). Prepreg, 70 μm thick, is sanded with 17 μm thick copper plates, and is covered with the polyimide plates. Copper plates, 35 μm thick, are placed exterior of the polyimide plates, and one side is used for a circuit layer of the component, and the other side is for electrode face. Both outer sides of the layer are covered with 50 μm thick insulation layer of the electrode. The total thickness of the electrode is about 370 μm; therefore, it can be easily bended as shown in the Fig. 2(a) and fits to the curvature of

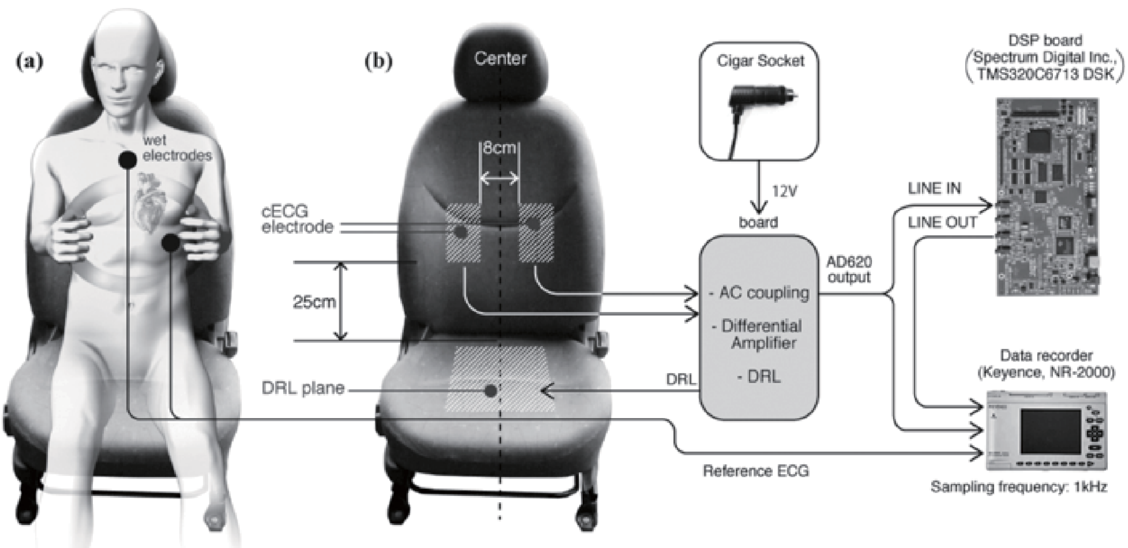

Fig. 3. Equipments and testing posture of the cECG monitoring system evaluation. (a) Sitting posture on a car seat. (b) Electrodes position and equipments of the cECG acquisition.

the body, which realizes large effective electrode surface. Fig. 1(e) is a photo of the electrode. The height and width of the electrode are 120 mm and 70 mm, respectively, and all corners are rounded radius of 5 mm.

3.2 Neutralization circuit

Input capacitances Cin from the amplifier and stray capacitances on the PCB are not avoidable. It causes signal attenuations due to the voltage divider formed by Cc and Cin (Fig. 1(a)). The idea of neutralization is to provide a positive feedback of a current that equals the current flowing on Cin. This technique was historically used for micropipette electrodes [9], and is gaining its attention to cECG measurement nowadays [8]. The neutralization circuit employs a potentiometer, $Rn1$ and $Rn2$, which controls the amount of positive feedback λ couples back to the input through the neutralization capacitor Cn as shown in Fig. 1(a). By adjusting λ, the current on Cn may exactly compensate for the current on Cin, thus neutralizing the effect of this capacitance. Complete neutralization can be realized when $\lambda = Cin/Cn + 1$. In this situation, the current flowing on Cn may exactly compensate for the current on Cin. Therefore, the signal attention can be avoided.

3.3 DRL and AC coupling circuit

Minimizing CM noise is essential for cECG measurement, because the cECG is weak for the CM noise due to high impedance between the capacitive electrode and the body, and its variations. DRL is the technique that reduces the CM noise from power line, electric devices or body movements, and it works with fully capacitive system [10]. The CM voltage (VCM) on the body is sensed by the two averaging resistors, inverted, amplified, and fed back to the third capacitive electrode (Fig. 1(c)). The third capacitive electrode is formed with 140 mm $\times$ 140 mm conductive fabric covered with thin plastic layer. The electrode is attached on the bottom of a seat. Another contributor of CM noise reduction is a differential amplifier. The differential amplifier we used, AD620 manufactured by Analog Devices, achieves a common-mode rejection ratio (CMRR) of approximately 100 dB. However, the differential amplifier gets malfunctioned due to electrode offset, so that input AC coupling is needed to suppress DC component. The simplest AC coupling technique is a passive high-pass filter in front of the amplifier. It is simple and suitable low power applications, but grounding resistor reduces the input common mode impedance, which degrades the effective CMRR due to the potential divider effect. Therefore, AC input coupling circuit was settled in order not to require any grounded resistor to realize high CMRR (Fig. 1(b)) This technique refers to [11].

3.4 Digital filter by DSP

TMS320C6713 DSP (Spectrum Digital Inc.) was used for digital filtering in order to realize real time signal processing with easy modifications and fabrications, and high reliability. The filters were designed by Filter Design Toolbox in Matlab 2009b and embedded into the DSP board through Code Composer Studio v3.3 (Texas Instruments Inc.). The IIR band-pass filter was designed by following specifications: Butterworth, sampling frequency of 8 kHz, filter order of 4, and cut-off frequency of 10 Hz and 30 Hz.

4. Evaluation

Quality of R-wave detection is investigated in order to verify the reliability of the implemented cECG monitoring system. It was tested in two situations, engine on and off, by 5 males (mean $\pm$ SD = 26.6 $\pm$ 3.9 years old) with the configuration shown in Fig. 3. Range of the body mass index (BMI) among the subjects were 16.7 to 28.6 kg/m^2. A car, SUNNY manufactured by Nissan in 2003, was used in the test. AC coupling circuit, DRL circuit, and a differential amplifier was settled on a breadboard, and the cECG electrodes and DRL plane was connected to the board. The reference signal was measured from the wet electrodes attached on a subject's chest as shown in Fig. 3(a). The electrodes were placed 25 cm vertically high from the bottom of a car seat and arranged side-by-side, 8 cm apart and mirroring each other. DRL plane was placed bottom of the seat

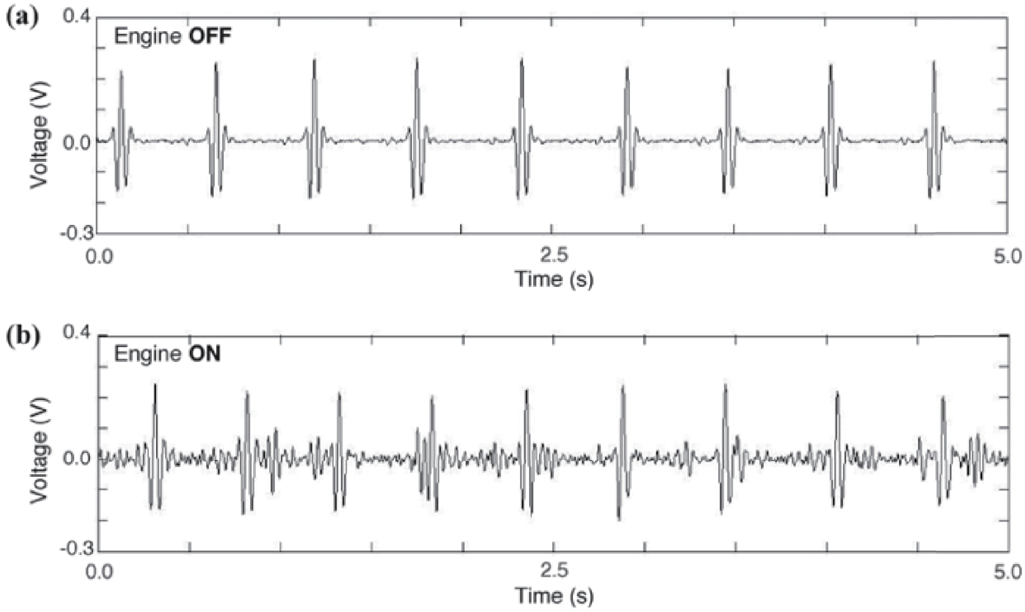

Fig. 4. Signals obtained from implemented cECG monitoring system from a subject. (a) Engine off. (b) Engine on.

Table 1. Summary of Se, P+, and RMSE during the engine off and on.

			Se (%)		*P+*(%)		*RMSE*	
Subject #	Age	BMI	Engine OFF	Engine ON	Engine OFF	Engine ON	Engine OFF	Engine ON
1	23	19.5	100	100	100	100	1.8	30.6
2	27	28.6	99.0	100	100	100	1.3	7.8
3	26	19.0	100	98.9	100	100	2.2	2.3
4	33	19.5	100	100	100	100	0.6	0.8
5	24	16.7	100	100	100	100	1.0	14.9
Average	26.6	20.66	99.8	99.8	100	100	1.4	11.3

(Fig. 3(b)). During the test, subjects kept still on the seat for 60 seconds with 1 shirt. The material and thickness of the shirt was not identified.

5. Result and Discussion

Figure 4 shows an example of the signals obtained from a subject. Though noise contaminated into the signal during the engine on compared with the situation engine off, R-waves are visible and it is clear enough to detect its' peaks. Quality figure of R-wave detection algorithm is given by Detection Sensitivity (Se) and Positive Predictivity (P+):

$$Se = TP/(TP + FN) \times 100\%,$$

$$P+ = TP/(TP + FP) \times 100\%,$$

where TP stands for true positives, which is the total number of peaks correctly detected by the detector. FN and FP denoted as false negative and false positive, respectively. The RRI detection performance analysis metric, which is used for the validation of the test result, is the root mean square errors (RMSE) between the reference signals. The algorithm is tested on 60 seconds ECG data for each subject, which obtained from cECG system. Table 1 tabulates the test results of R-wave detection for cECG measuring. Overall averages of Se and P+ during the engine off were 99.8% and 100%, and the engine on were 99.8% and 100%, respectively. Although RMSE increased during engine on compared with when it is off, the average is 11.3 ms. The sampling rate of commercial heart rate variability instruments varies from 128 to 1000 Hz [12]. The accuracy of QRS detection is 8 ms in case the sampling frequency is 128 Hz. The 11 ms RMSE is only a little larger than the 8 ms which is the sampling rate of heart rate variability instruments. It is considered that the detection accuracy is acceptable for HRV analysis. The proposed system is prospective for practical use from the point that these results are obtained from the subjects who had wide range of BMI, 16.7 to 28.6 kg/m^2, and different materials and thickness of the wearing shirt.

6. Conclusion

Sufficient results, Se of 99.8% and P+ of 100% with low RMSE of 11.3 ms were obtained from 5 subjects in the situation of engine on with an actual car. The flexible active electrode with neutralization circuit, AC coupling, DRL circuit, and digital filtering by DSP helped to reduce noise as well as signal attenuation. As further studies, it needs to be tested in driving scenes. Road vibrations, steering, pedaling, or levering movements, as well as driver's multi layers of clothes might deteriorate the signal quality. These issues need to be investigated for practical use of the system.

Acknowledgments. This work was supported by a Grant-in-Aid for Scientific Research (C) from the JSPS (Japan Society for the Promotion of Science) and the JSPS Research Fellowship for Young Scientists.

References

[1] B. Lohman, O. Boric-Lubecke, V. M. Lubecke, P. W. Ong, and M. M. Sondhi, A digital signal processor for Doppler radar sensing of vital signs, *Eng. Med. Biol. Soc. 2001. 23rd Annu. Int. Conf. IEEE*, No. 1, pp. 3359–3362, 2001.

[2] C. Brüser, K. Stadlthanner, S. de Waele, and S. Leonhardt, Adaptive beat-to-beat heart rate estimation in ballistocardiograms, *IEEE Trans. Inf. Technol. Biomed.*, **15**(5), 778–786, Sep. 2011.

[3] K. Kurita, *Non-contact Detection of Human Heartbeat Based on Measurement of Current Generated by Electrostatic Induction*, pp. 988–992, 2012.

[4] M. Walter, B. Eilebrecht, T. Wartzek, and S. Leonhardt, The smart car seat: personalized monitoring of vital signs in automotive applications, *Pers. Ubiquitous Comput.*, **15**(7), 707–715, Jan. 2011.

[5] H. J. Baek, G. S. Chung, K. K. Kim, and K. S. Park, A smart health monitoring chair for nonintrusive measurement of biological signals, *IEEE Trans. Inf. Technol. Biomed.*, **16**(1), 150–158, Jan. 2012.

[6] A. Ueno, Y. Akabane, T. Kato, H. Hoshino, S. Kataoka, and Y. Ishiyama, Capacitive sensing of electrocardiographic potential through cloth from the dorsal surface of the body in a supine position: a preliminary study, *IEEE Trans. Biomed. Eng.*, **54**(4), 759–766, Apr. 2007.

[7] Y. G. Lim, K. K. Kim, and K. S. Park, ECG recording on a bed during sleep without direct skin-contact, *IEEE Trans. Biomed. Eng.*, **54**(4), 718–725, Apr. 2007.

[8] E. Spinelli and M. Haberman, Insulating electrodes: a review on biopotential front ends for dielectric skin-electrode interfaces, *Physiol. Meas.*, **31**(10), S183–S198, Oct. 2010.

[9] E. Amatniekt, Measurement of bioelectric potentials with microelectrodes and neutralized input capacity amplifers, *IRE Trans. Med. Electron.*, **32**, 3–14, 1958.

[10] K. Keun Kim, Y. Kyu Lim, and K. Suk Park, Common mode noise cancellation for electrically non-contact ECG measurement system on a chair, in *27th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, Vol. 6, pp. 5881–5883, 2005.

[11] E. M. Spinelli, R. Pallàs-Areny, and M. A. Mayosky, AC-coupled front-end for biopotential measurements, *IEEE Trans. Biomed. Eng.*, **50**(3), 391–395, Mar. 2003.

[12] H. L. Kennedy, Heart rate variability instruments from commercial manufactures, in *Heart Rate Variability* (eds. M. Malik and A. J. Camm), Futura Publishing, pp. 127–132, 1995.