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ORIGINAL PAPER

Reusable Electrical Activity of the Heart Monitoring Patch for Mobile/Ubiquitous Healthcare

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Abstract In order to monitor electrical activity of the heart during daily life, we present an electrode of a medical instrument system which is able to measure the body surface potential difference by minimizing the electrode distance. The designed electrode is composed of concentric circles. It was made from the basis of the Laplacian equation, and implemented on PCB coated with gold. So that it does not cause the uncomfortable feeling of contact and possible skin troubles which are typical shortcoming of the conventional ECG measurement. The suggested method utilized three concentric circles on FR-4 substrate, so new amplifier design regarding measuring of small biological signal, is considered which has the characteristics of asymmetric input impedance since the area of concentric circular ring electrodes is not identical. Thereby, electrical activity of the heart was obtained successfully. However, its signal quality is a little bit degraded and the motion artifact still remains as a major problem as is in conventional electrocardiography measurement. Certainly stable measurement setup was needed to reduce the motion artifact originated from variation in static electricity between skin and electrode interfaces.

Keywords Concentric ring · Electrode · Electrical activity of the heart · Physiological signal monitoring · Mobile/ubiquitous healthcare

Introduction

Ubiquitous healthcare, which is recognized as a new industrial trend in healthcare arena, means that personal health status is monitored and managed unconsciously during daily life without any institutional interventions. In this respect, unconscious measuring of heart electrical activity is regarded as a core technological part for deployment of ubiquitous healthcare in home and mobile application. Even though, cardiovascular disease is the leading cause of death worldwide, a conventional intervention provides just a snapshot in time of the patients' health status, so that general physician has to rely on observations and self-measurement by the patient himself to provide a good diagnosis and select the right therapy.

Until now, to this end, conventionally, in order to observe the rhythm of the heart, body surface electrocardiography (ECG) recording in triangular electrode configuration developed by Einthoven in 1902 was generally used. But this conventional method is not adequate for daily life monitoring. The primary desiring effect of skin preparation and the use of electrolytic paste with conventional electrode is to minimize and stabilize the skin to electrode impedance with respect to the input impedance of preamplifier. Thus,

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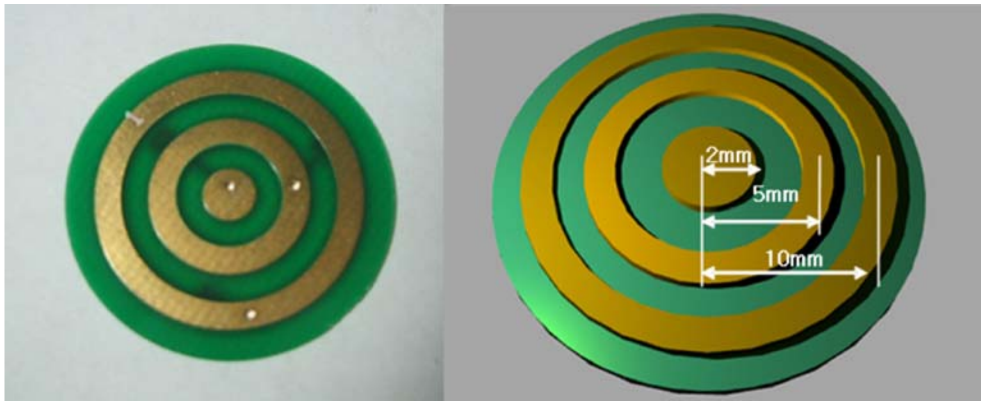

Fig. 1 The proposed concentric circular ring electrode. The *left* figure shows circular electrode implemented on FP-4 substrate and the *right* shows dimension of the proposed electrode distinction between slack and rapid

in this paper, we practically investigated the characteristics of the proposed electrode regarding the skin-metal (gold) electrode impedance. Also we describe the development of a preamplifier intended for use the proposed pasteless-electrode and the relatively high skin-electrode impedances encountered without electrolytic paste. This makes it suitable for use with portable electrical activity of the heart and heart rate monitoring instrumentation.

Materials and methods

Implementation of concentric ring electrode

The way of measuring electrical heart activity using Ag/AgCl electrode is regarded as a general diagnostics method for evaluating of heart function in clinics. But this method is not adequate for daily life because of unwieldy wires between separated electrodes and extensive processing to extract the details to detect and classify arrhythmias [1]. Another approach to determine the electrical activity at a specific location in the heart is the Laplacian electrocardiograms (LECGs) [2]. LECG uses tripolar concentric, planar epicardial ring electrodes to localize the moment of activation (MOA) of the heart at a nearby point on the chest surface [3]. But its tripolar electrode configuration is inherently susceptible to 60-Hz electromagnetic interference from the power line in daily life. In this paper, we proposed tripolar concentric ring electrode which have asymmetrical impedance characteristics considering factor affecting the quality of the recorded electrical activity of the heart, the skin–electrode–amplifier interfaces.

The application of the body surface Laplacian potential mapping was used to analyze EEG signals [2, 3]. The main goal of Laplacian potential mapping is to obtain the topological estimation of dipole origins from observed surface potential differences between various electrodes placed on subject's surface, such as chest.

At a local orthogonal coordinates system (x, y, z), the Laplacian ECG could be represented as follows:

$$V_L = -\left(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2}\right) \tag{1}$$

where V_L and V represent a local source voltage and the voltage at a point (x, y) on the chest, respectively. By introducing the finite difference of Laplacian operator, and assuming discrete five electrodes configuration, Eq. 1 could be represented as:

$$\frac{d^2 V}{\mathrm{d}x} = \left[\left(\frac{V_4 - V_0}{D} - \frac{V_0 - V_2}{D}\right)\right] \tag{2}$$

$$\frac{d^2 V}{\mathrm{d}y} = \left[\left(\frac{V_1 - V_0}{D} - \frac{V_0 - V_3}{D}\right)\right] \tag{3}$$

where D represent a radius of circle. Thus, substituting Eqs. 2 and 3 into Eq. 1, the Laplacian potential at a inner circle electrode, V_L can be given as:

$$V_L = \frac{4}{D}\left[V_0 - \frac{1}{4}\sum_{i=1}^{4} V_i\right]. \tag{4}$$

In the bipolar scheme, the Laplacian potential can be given as:

$$V_L = \frac{4}{D^2}\left[V_1 - \frac{1}{2\pi D}\oint V_2(x,y)\mathrm{d}l\right] \tag{5}$$

Table 1 Impedance of concentric ring electrode

Part/Frequency	10 Hz	100 Hz	1 KHz
Inner circular electrode	3,580 kΩ (2.209 nF)	1,588.88 kΩ (1.932 nF)	133.87 kΩ (0.661 nF)
Middle circular electrode	1,890 kΩ (5.113 nF)	1,172.53 kΩ (4.915 nF)	119.66 kΩ (3.76 nF)
Outer circular electrode	980 kΩ (14.42 nF)	560.931 kΩ (11.99 nF)	55.60 kΩ (7.56 nF)

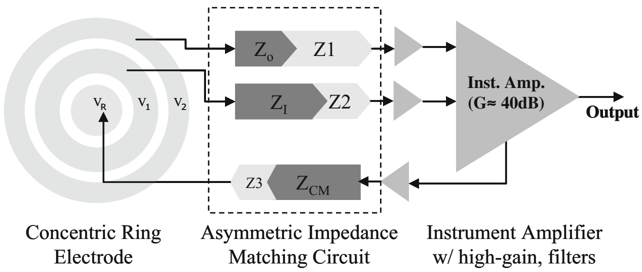

Fig. 2 In order to match asymmetric impedance characteristics of the proposed electrode, that is, Z_O+Z1=Z_I+Z2, Z1 and Z2 are selected based on the measurement of each circular electrode as shown in Table 1. Each portion of impedances was drawn proportional to its impedance value

where the integral is taken around a circle of radius *D*. Equation 5 indicates the theoretical basis of the bipolar scheme for recording the Laplacian potential. Thus, the output of the bipolar concentric electrode is approximately the difference between the potential at the center and the averaged potential over the outer ring electrode.

If no electrolyte gel is used, the accumulation of perspiration under the metallic plate will eventually moisten the skin covered by the dry electrode. Although the initial impedance is higher than in the case of gelled systems, this need not be a major problem however, as amplifier now exist with input impedances and common-mode rejection ratios sufficiently high to cope with such electrodes.

Approaches and electrode designs

Asymmetric electrode design Concentric ring electrodes with different diameters were designed. Figure 1 shows graphical design of the proposed electrode. Copper wires of 1 mm in diameter were soldered on circular copper pad of printed circuit board. Soldering of copper wires makes electrode surfaces which is facing a skin, convex and provide stable contact with skin during a movement of body. Due to unbalance of electrode area which is contacting with skin, the skin–electrode impedance of each ring electrode is not identical. But in our purpose of electrode design, it's desirable feature since we want to attach the proposed electrode under sticky bandage for daily life monitoring of the heart. Skin–electrode impedance of proposed ring electrode was measured [4] and measured impedances are summarized in Table 1.

Design of asymmetric input impedance amplifier In designing amplifier for asymmetric impedance electrodes, unbalance of electrodes should be considered. Also lower power consumption and small form factors are required in portable and wearable sensor designs. A micropower dry-electrode electrocardiography (ECG) preamplifier designed by Burke and Gleeson [5] is used with modification of input impedance matching. The compromise to measurement system performance is the interaction between the electrode and the amplifier's input characteristics.

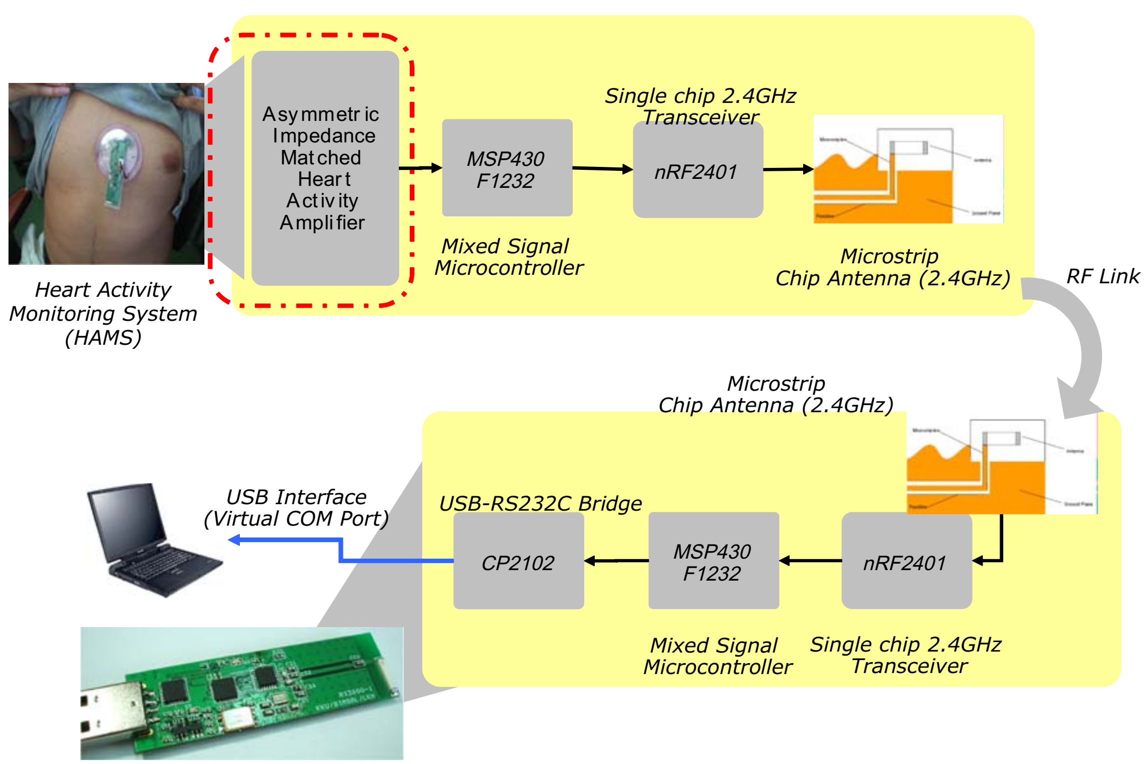

Fig. 3 The proposed heart activity monitoring system configuration

Fig. 4 Photos of the proposed heart electrical activity monitoring patch. Various types of electrodes could be attached

A common-mode signal present at the input to the electrodes gives rise to a differential component at the amplifier input, due to mismatch in the common-mode impedances on either side of the amplifier. It has a different input resistor for compensation. An important factor common to all amplifiers is the first stage, or preamplifier [6]. We decide a value of resistor based on Table 1. In experiment, we placed 10 MΩ on middle circular electrode, 13 MΩ on outer circular electrode to match the input impedance so that Z1+Z2=Z3+Z4. So we choose the resistor Z2 and Z4 which are used to define the input impedance on each side of the amplifier. In order to check impedance matching, a single frequency sinusoidal signal (10 Hz) is applied, and then check whether common-mode signal is removed or not. The amplifier consists of differential input-output stage followed by a differential to single ended stage. The operational amplifier used were selected from the OPA2335 (Burr-Brown Inc., USA) and INA326 (Texas Instruments Inc., USA) was used in the instruments amp (Fig. 2).

Experiments and results

The proposed wearable heart monitoring system using concentric circular electrode was implemented. Figure 3 shows system configuration diagram and Fig. 4 shows the implemented system.

Pre-amplified signal is then digitized by analog-to-digital converter (ADC) functions of MSP430 micro-controller (12-bits resolution, Texas Instruments Inc., USA) at a sampling frequency 250 Hz. The wireless communication part, which is implemented using 2.4 GHz radio transmitter, nRF2401 (Nordic Semiconductor, Norway) transmitted to personal computer. Then, transmitted signals is displayed and stored for future processing. Figure 5 shows signal recordings of the heart activity using the proposed system. This figure clearly shows an effect of input impedance unbalance. When input impedance is not matched, that is, not identical, we may have signal deterioration. But in case of measuring rhythms of the heart, this may be useful to detect heart beat.

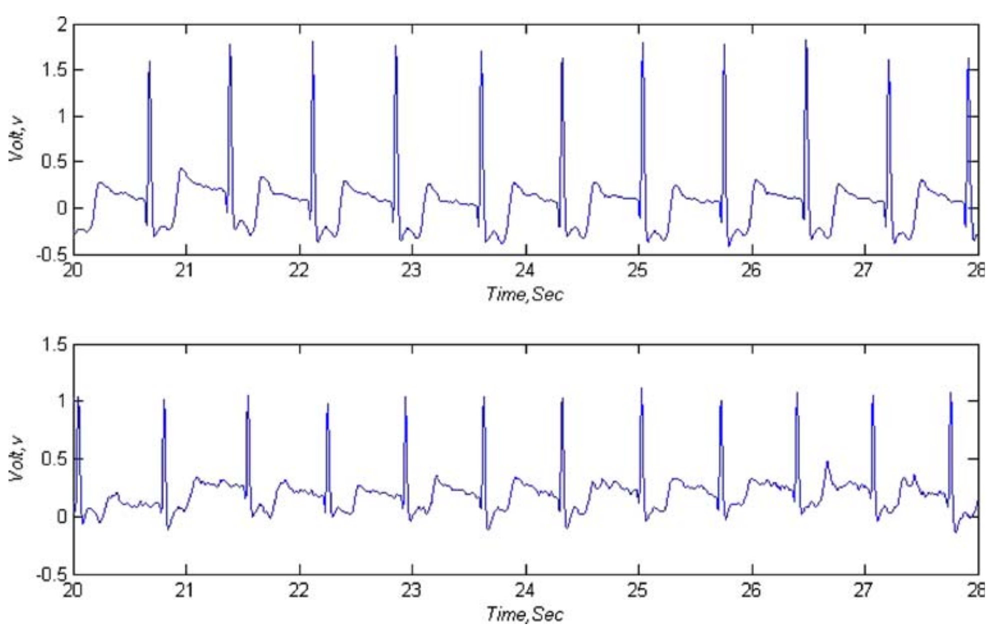

Fig. 5 Recording electrical activity of the heart using the proposed system and comparison of signals regarding the asymmetric input impedance characteristics. Input impedance matched (*top*) and unmatched (*bottom*) cases are shown

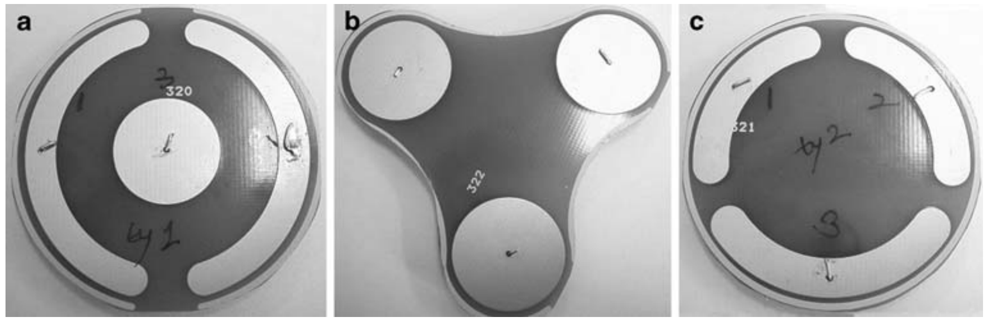

Fig. 6 Various types of miniaturized electrode to measure electrical activity of the heart. **a** Symmetric type, **b** equiangular type with circular electrode, and **c** equiangular type with elliptical electrode

Regarding rhythm of the heart, we have experimented with various types of miniaturized electrodes. Figure 6 shows various types of miniaturized electrodes. Figure 6a shows symmetric type electrode. Center electrode is used as a common-mode elimination reference and two pairs of electrodes, Fig. 6b and c, are used to sense weak electrical activity of the heart. In equiangular types, one of three electrodes is selected as a common-mode reference. All input impedances of electrodes are matched by making their areas equal. Figure 7 shows recorded signals by using various types of electrodes. When we used Fig. 6a, symmetrical type, we could clearly observed electrical activity of ventricles, R-wave. But when we used equiangular type electrodes, we could observe more electrical activities of ventricles. But this additional information doesn't provide clinical meanings since the configuration of our electrodes, such as distance between electrodes, are not identical to clinical electrode lead

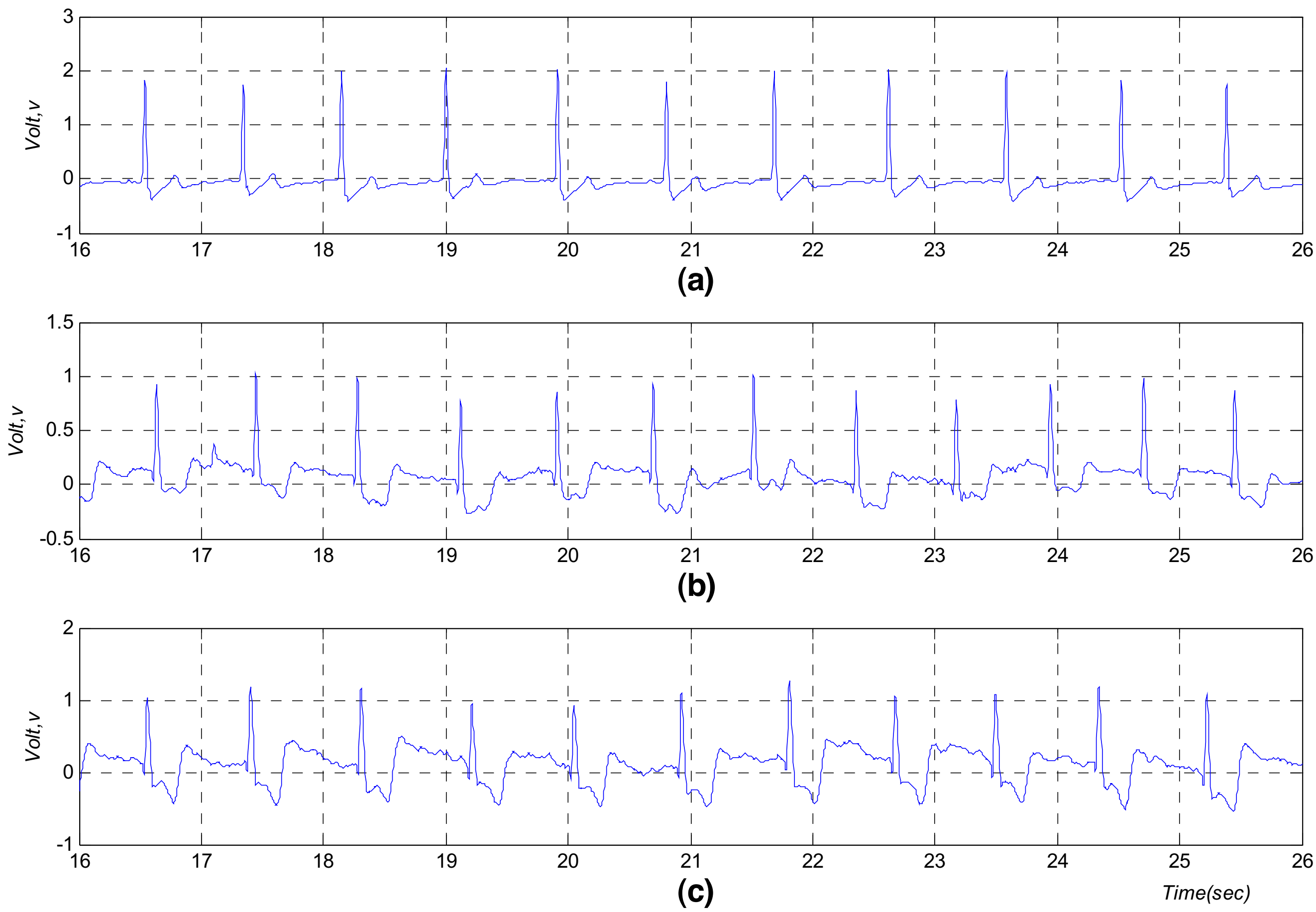

Fig. 7 Recording electrical activity of the heart using various types of electrodes. **a** Symmetric type, **b** equiangular type with circular electrode, and **c** equiangular type with elliptical electrode

system, ECG. Even though, our results were not identical to clinical cases, our approaches provide a feasible application regarding heart beat monitoring during ubiquitous environment for effective healthcare delivery. As for daily life application, we need to attach the proposed system and patch to certain area of chest reliably.

Discussion

Compared with normal electrode, conventional ECG measurement system using concentric circular electrodes is more suitable for daily life. From this preliminary study, we could found the followings. As it is now, the proposed method can be applied without difficulty to assess heart rate variability by detection of R-peaks. Requirements in wearable heart monitoring system are simple electrode such as concentric circle electrode but we should consider matching the asymmetrical input impedance because the contact area of skin/electrode surface is not identical. The results from the experiments showed a little bit lower signal quality and motion artifact. Furthermore, the signals obtained from the same electrode are different from each other depending on the contact condition and position. But in case of heart beat monitoring applications such as in ubiquitous computing environments, the proposed method provides reliable results.

Therefore, further studies on enhancing the signal quality through the reliable contact position such as around the collarbone or a rib bone. Also, studies regarding attachment of electrode patch on the human body are needed. If these problems could be solved then this makes it ideally suitable for use as a portable electrocardiographic equipment and heart rate monitoring system for ubiquitous healthcare.

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References

1. Webster, J. G., *Medical instrumentation application and design*. Wiley, New York, 1998.
2. Hjorth, B., An on-line transformation of EEG scalp potentials into orthogonal source derivation. *Electroencephalogr. Clin. Neurophysiol*. 39, 526–530, 1975.
3. He, B., and Cohen, R. J., Body surface ECG Laplacian mapping. *IEEE Trans. Biomed. Eng*. BME-39, 1179–1191, 1992.
4. Bergey, G. E., Squires, R. D., and Sipple, W. C., Electrocardiogram recording with pasteless electrode. *IEEE Trans. Biomed. Eng*. BME-18(3), 206–211, 1971.
5. Burke, M. J., and Gleeson, D. T., A micropower dry-electrode ECG preamplifier. *IEEE Trans. Biomed. Eng*. 47(2), 155–162, 2000.
6. Hill, O. W., and Khandpur, R. S., The performance of transistor ECG amplifier. *World Medical Instruments*. 7(5), 12–22, 1969.