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Reduction of Skin Stretch Induced Motion Artifacts in Electrocardiogram Monitoring Using Adaptive Filtering

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Abstract– **The effectiveness of electrocardiogram (ECG) monitors can be significantly impaired by motion artifacts which can cause misdiagnoses, lead to inappropriate treatment decisions, and trigger false alarms. Skin stretch associated with patient motion is a significant source of motion artifacts in current ECG monitoring. In this study, motion artifacts are adaptively filtered by using skin strain as the reference variable. Skin strain is measured non-invasively using a light emitting diode (LED) and an optical sensor incorporated in an ECG electrode. The results demonstrate that this device and method can significantly reduce skin strain induced ECG artifacts.**

Keywords: ECG monitor, motion artifacts, adaptive filtering, optical sensor

I. INTRODUCTION

The performance of current electrocardiogram (ECG) monitors can be significantly degraded by motion artifacts, which can cause misdiagnoses, lead to inappropriate treatment decisions, and trigger false alarms in wearable monitors [1]-[5]. The interpretation of the clinical ECG relies on physician or computerized analysis to recognize artifacts [6], [7]. In modern ECG monitoring, especially in ambulatory and stress electrocardiography, skin stretch due to patient or electrode motion is a significant source of artifacts [1], [3]-[5], [8]-[10] even with the use of sophisticated algorithmic filtering.

Skin can be considered as a current generator. It actively generates a potential difference between the inside and the outside of the skin. The outside of the skin is more negative than the inside. Skin stretching causes disturbances in the distribution of charges at the electrode-electrolyte interface, which induces a temporary change in the half-cell potential [8], [11], [12]. Stretching the skin causes a reduction in the magnitude of this skin potential. Variation of this potential is a source of artifacts in electrocardiography. Such artifacts can produce signals that resemble the actual P, QRS, and T time waveforms of the ECG, are of similar frequency, and have a comparable or higher amplitude [3].

In earlier studies, motion artifacts were reduced by removing the epidermal layer of the skin by abrasion [4], [5], or puncturing the skin in the vicinity of the electrode [4]. These approaches can cause patient discomfort, prolong procedural preparation times and even cause infection. Furthermore, they do not provide an effective solution for long term monitoring.

The use of adaptive filtering has been investigated to reduce ECG motion artifacts. Tong et al. [13], [14] monitored the electrode acceleration by attaching a 3-D accelerometer and a 2-axis anisotrophic magnetoresistive sensor respectively on the exposed surface of an electrode. The electrode acceleration signal was measured simultaneously with the ECG signal and used to estimate motion artifacts with adaptive filtering. Raya et al. [15] attached a 1-D and 2-D accelerometer on the subject's back respectively to measure body acceleration as the reference signal to reduce ECG motion artifacts. Hamilton et al. [16]-[19] mounted a strain gauge and an optical bend sensor on the exposed surface of an electrode respectively to measure electrode deformation as the noise reference. Devlin et al. [20] used 20 kHz electrode / skin impedance variations to estimate and reduce the relative amount of electrode motion artifacts in the ECG signal, so as to reduce false positive alarms triggered by motion artifacts. Luo et al. [21] obtained the voltage difference from two adjacent electrodes (5 mm apart) as a noise reference signal.

Collectively, these studies demonstrated that adaptive filtering can reduce motion artifacts in ambulatory ECG, stress tests and long term ECG monitoring. However, the estimated noise reduction varied significantly depending upon the source of skin stretch, namely applied electrode motion or deformation, or body motion. The results suggest that an important contributing factor for the lack of consistency in the estimated noise reduction is that the reference variables used, namely electrode acceleration, or electrode strain, were not adequately correlated with the induced noise. In addition, the induced motion artifacts in previous studies do not take into account the skin stretch caused by daily activities. As a result, motion artifacts generated by skin stretch that do not deform the electrode or are not caused by electrode motion will not be reduced by the methods previously discussed. None of the previous studies have directly measured skin strain signal as the auxiliary input to adaptive filtering.

This study develops a method and hardware to directly measure skin stretch simultaneously with the ECG. This involves the integration of an optical sensor in an ECG electrode. The optical sensor is used to capture the skin strain. Using the measured skin stretch data, skin stretch induced noise will be reduced in the measured ECG with the adaptive filtering technique.

II. INTEGRATION OF AN OPTICAL SENSOR INTO AN ECG ELECTRODE

Optical components integrated in the electrode are illustrated in Figure 1. The skin-mounted electrode assembly has a foam pad with the front surface contacting the skin with adhesive and a rear surface connecting the lead wires. The front surface of the foam pad has a central recessed region filled with liquid gel or solid gel to establish good electrical contact between the electrode and the skin. The Ag / AgCl electrode resides in the central recess of the foam pad with a connector end protruded from the foam pad. A clip grips the connector end of the electrode and connects a lead wire to recording and processing equipments. An optical sensor and a light emitting diode (LED) are embedded in the foam pad near the electrode site, with a recessed region underneath the sensor and the LED.

The LED illuminates the skin surface, revealing surface details (slight imperfections) that the optical sensor can use to track movement. The optical sensor consists of a CMOS image sensor and a digital signal processor, which determines the direction and amount of the relative movement between the sensor and the imaging area beneath it. Lenses are integrated with the optical sensor and LED to focus the light and image.

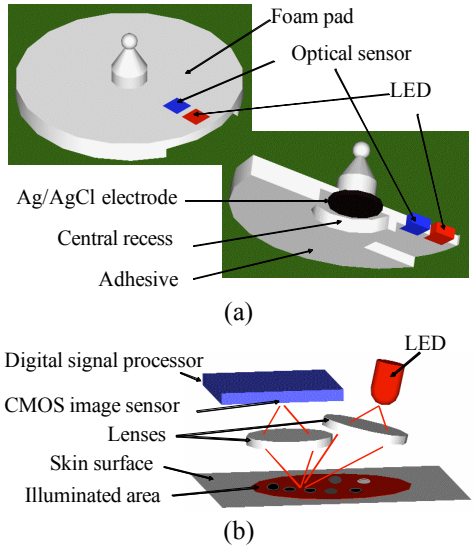

Figure 1. (a) Integration of an optical sensor into an ECG electrode; (b) Components in the optical sensor

The resolution of the sensor used in this study is 0.03175 mm. Based on optical navigation technology, the sensor measures changes in position by optically acquiring 1500 sequential surface images each second and mathematically determine the direction and magnitude of movement. When the skin under the electrode is stretched, there is relative movement between the area and the sensor due to skin strain of the adjacent area. The optical sensor integrated with a digital signal processor identifies common features in sequential images to determine the direction and amount of relative displacement of the area underneath the sensor.

Figure 2 shows the region underneath the sensor. The round region represents the illuminated skin surface underneath the optical sensor. Let L be the initial distance between the imaging area and the adhesive pad boundary / fixed edge. When the skin under the sensor is stretched and elongated by ΔL, assuming the strain is one dimensional along L, the strain is ΔL / L, with ΔL calculated from the sensor output.

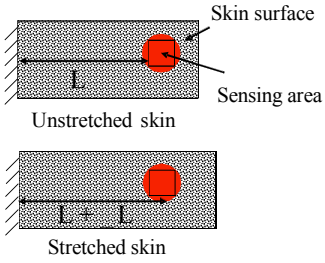

Figure 2. Unstretched and stretched skin

To demonstrate the feasibility of using the optical sensor as a skin strain sensor, in vitro calibration experiments were performed, as illustrated in Figure 3. A piece of animal skin specimen was clamped and stretched in a controlled condition. The optical sensor was attached and fixed at one end of the specimen, with the sensor connected to a computer and the output recorded. The distance between the two parallel edges of the clamp was measured using a micrometer caliper. The specimen was stretched step-by-step and the strain calculated as the ratio of the amount of elongation to the initial distance between the two clamp edges.

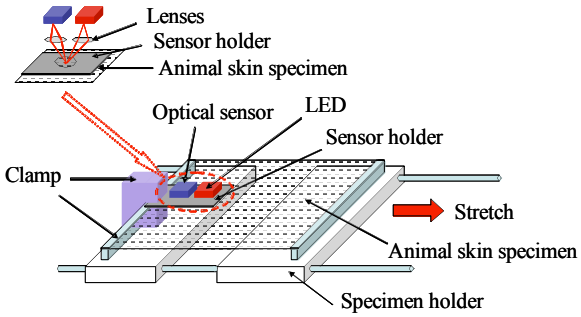

Figure 3. Measuring the strain of a pig skin sample using the optical sensor

A linear relationship between the sensor output and the skin strain was achieved from the in vitro calibration experiments, as shown in Figure 4. The x-axis indicates the strain calculated from the displacement of the tissue clamps, and the y-axis indicates the optical sensor output. The results demonstrated that the optical sensor can be used as a skin strain sensor.

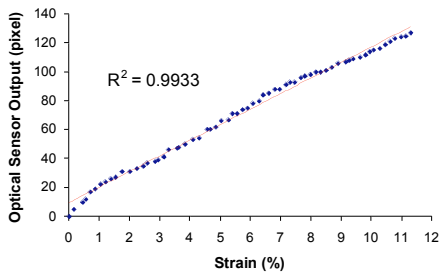

Figure 4. In vitro calibration - optical sensor output versus the strain of an animal skin specimen

III. ADAPTIVE MOTION ARTIFACTS REMOVAL

Adaptive noise canceling is a method of estimating signals corrupted by additive noise or interference. The method uses the corrupted ECG signal as a "primary" input and a "reference" input correlated with the noise in the primary input. The noise is adaptively filtered and subtracted from the primary input to obtain the signal estimate. In the adaptive noise canceling system, the system output serves as the error signal for the adaptive process. With a proper algorithm, the filter can operate under changing conditions and readjust itself continuously to minimize the error signal [23].

Figure 5 shows the electrode-sensor system and adaptive filter structure to reduce ECG motion artifacts. The system consists of two electrodes, with an optical sensor on one electrode, an ECG amplifier and a computer. A primary input *d(k)* contains the ECG signal corrupted by additive and uncorrelated noise. The skin strain signal *u(k)*, which serves as an auxiliary input, is measured from an optical sensor incorporated in an electrode. The adaptive filter estimates noise in an adaptive manner and eliminates the additive noise *y(k)* through the noisy ECG resulting in an electronic signal *e(k)* with fewer motion artifacts.

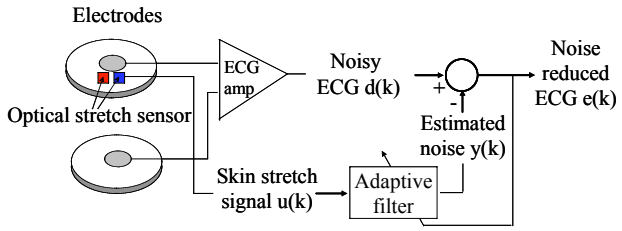

Figure 5. Electrode-sensor system and adaptive filter structure to reduce ECG motion artifacts

Let *s* be the true ECG signal and *n* be the artifacts added to the true ECG signal. *d* is the corrupted ECG signal given by $d = s + n$, and *u* is the skin strain signal from the optical sensor. *y* is the estimate of the artifacts. The system output / error *e* is defined as $e = s + n - y$. The objective of the adaptive filtering is to minimize $n - y$. This can be achieved by minimizing $E(e^2)$:

$$E(e^2) = E[(s+n-y)^2] \quad (1)$$
$$= E[s^2] + 2E[sn] - 2E[sy] + E[(n-y)^2]$$

ECG signal and noise are uncorrelated, so that

$$E(e^2) = E(s^2) + E[(n-y)^2] \quad (2)$$

The smallest possible output power is $E[e^2] = E[s^2]$. When this is achieved, $E[(n-y)^2] = 0$. Therefore, $y = n$ and $e = s$. This means minimizing output power causes the output signal to be noise free [24].

Least-Mean Squares (LMS) algorithm is applied in this study. An adaptive filter W(k) is a set of filter weights at time k, and M is the order of the filter.

$$W(k) = \begin{pmatrix} w_0(k) \\ w_1(k) \\ \cdots \\ w_{M-1}(k) \end{pmatrix}, \quad U(k) = \begin{pmatrix} u(k) \\ u(k-1) \\ \cdots \\ u(k-M+1) \end{pmatrix}$$

W(k) is iteratively updated after each sample according to the following equations, where μ is a constant determined from experiments.

$$y(k) = W^T(k)U(k) \quad (3)$$
$$e(k) = d(k) = y(k) \quad (4)$$
$$W(k+1) = W(k) + \mu U(k)e(k) \quad (5)$$

An ECG lead II signal was acquired in this study under an IRB-approved protocol with a standard ECG amplifier (Harvard Apparatus ECG100C). The sampling rate is 200 Hz. Skin strain was measured by the optical sensor simultaneously and recorded. The adaptive filter was implemented in Matlab. Motion artifacts were induced by stretching the skin around the electrode on the right forearm.

An example of the noise removal result is shown in Figure 6. The three traces in the data set are the optical sensor output, the noise corrupted ECG signal, and the recovered ECG after noise removal, respectively. Skin strain induced artifacts were induced at 1.6 second, and before that the ECG data was noise-free.

The lead II ECG was acquired as the absolute potential difference between two sites: the right forearm and the left leg. Since the potential on the right forearm is smaller than that of the left leg, and skin stretch on the right forearm causes its potential to increase, the acquired ECG signal showed a significant decrease when the skin around the electrode was stretched. Therefore, all the negative peaks in the second trace in Figure 6 were artifacts due to skin stretch.

We noticed that there is a time lag between the skin stretch and the response of the corrupted ECG signal. The time lag was estimated to be 0.28 second by averaging the time frame between the peaks of the optical sensor output and the negative artifacts peaks. The time lag corresponds to 56 data samples with a 200 Hz sampling rate. According

to this, *U(k)* was modified as follows to correlate with the artifacts in the ECG signal:

$$U(k) = \begin{pmatrix} u(k-56) \\ u(k-57) \\ \dots \\ u(k-M-55) \end{pmatrix}$$

The filter order M was set as 6 in this study. In Figure 6, the second trace (ECG signal corrupted by artifacts) contained 10 negative peaks which were skin strain induced artifacts during 7 seconds. In the third trace (estimated ECG after noise removal), all the negative peaks were eliminated except for the first one, while the positive ECG features in the second trace were kept the same. The results demonstrated that the proposed method can significantly reduce ECG artifacts generated by skin strain.

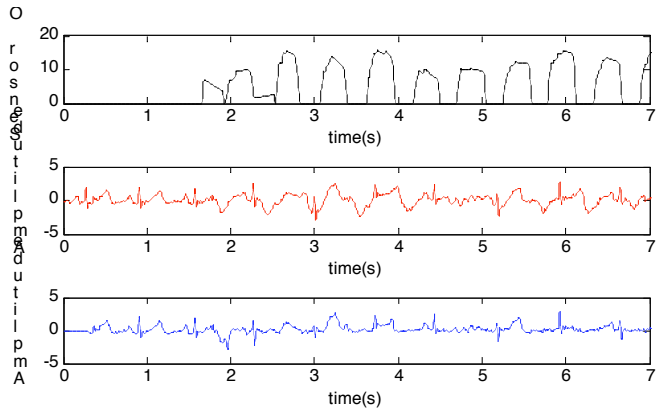

Figure 6. First trace: optical sensor output due to skin strain; second trace: ECG signal corrupted by artifacts; third trace: estimated ECG after noise removal

IV. CONCLUSIONS

A method to reduce ECG motion artifacts with adaptive filtering has been demonstrated. Skin stretch, as a reference input for the adaptive filter, is measured non-invasively using an optical technique incorporated in an ECG electrode. In vitro calibration results demonstrated that the optical sensor can be used as a skin strain sensor. Experiments have shown that this method can effectively remove skin strain induced noise from ECG signals.

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