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Characterization of Dry Biopotential Electrodes

Li Xie, *Student Member, IEEE*, Geng Yang, Linlin Xu, Fernando Seoane, *Senior IEEE Member*, Qiang Chen, and Lirong Zheng, *Member, IEEE*

***Abstract*—Driven by the increased interest in wearable long-term healthcare monitoring systems, varieties of dry electrodes are proposed based on different materials with different patterns and structures. Most of the studies reported in the literature focus on proposing new electrodes and comparing its performance with commercial electrodes. Few papers are about detailed comparison among different dry electrodes. In this paper, printed metal-plate electrodes, textile based electrodes, and spiked electrodes are for the first time evaluated and compared under the same experimental setup. The contact impedance and noise characterization are measured. The *in-vivo* electrocardiogram (ECG) measurement is applied to evaluate the overall performance of different electrodes. Textile electrodes and printed electrodes gain comparable high-quality ECG signals. The ECG signal obtained by spiked electrodes is noisier. However, a clear ECG envelope can be observed and the signal quality can be easily improved by backend signal processing. The features of each type of electrodes are analyzed and the suitable application scenario is addressed.**

I. Introduction

Biopotential monitoring of citizens in home environments as well as for patients in hospital is important for ubiquitous healthcare applications [1]. Bioelectrical potentials propagate from excitable cells where they originated inside of the body to the skin surface where they are recorded [2]. The electrode is such a transducer that transforms ionic biopotentials and currents into electronic signal [3]. Therefore, electrodes are key components on any biopotential monitoring system, and their characteristics determine to a large extend the quality of biopotential signals measured by medical devices.

The Ag/AgCl gelled electrode is the most commonly used biopotential electrode in clinical practice since it is simple, low-cost, and offers good bio-signals [2]. However, this electrode requires electrolytic gel which brings drawbacks. First, the dehydration of electrolytic gel will induce noise and influence the signal quality after long-term use. Second, concern exists about the material used in the gel which may cause irritation. In addition, for skin biopotential measurements, skin preparation is required to remove the dead cells of outer layer of the skin known as stratum corneum. Skin preparation is time consuming and inconvenient for both the patients and the clinical staff. Long-term biopotential recordings require other kind of electrodes. Several researchers have introduced novel dry electrodes, which operate without electrolytic gel. Some good examples are electrodes based on textile [4][15], standard printed circuit boards (PCB) [5], flexible polyimide [6][16] using fabrication technology such as conductive yarn [7][17], printed metal plate [8][18], and metal spikes [3][14] to establish the ionic-electronic interphase with the skin. The previous paper also adapted inkjet-printing technology into bio-signal sensing application and fabricated wearable electrodes [9]. Each type of electrodes has its own distinct features and is respectively suitable for different application scenarios.

In this paper, we will compare the characterization of these novel dry electrodes. Three typical electrodes samples are fabricated. The contact impedance of electrode-skin interface and the corresponding noise characterization are measured. The performance of bio-signal transformation is evaluated by *in-vivo* ECG test.

II. Manufacture and Features of Dry Electrodes

According to the materials, manufacture technologies, working principles and suitable applications, the dry electrodes that we tested and compared can be classified into three categories including metal-plate based electrodes, textile based electrodes, and spiked electrodes. We made electrode samples in each category as shown in Fig.1. Commercial electrodes (CommE. Tyco Arbo H124sg pre-gelled electrodes) are used for comparison purpose.

A. *Metal Plate Based Electrodes*

This type of electrodes realizes the electrical connection by directly attaching the planar metal plate with skin, and show good performance for ECG measurements [2][8]. Isolated by

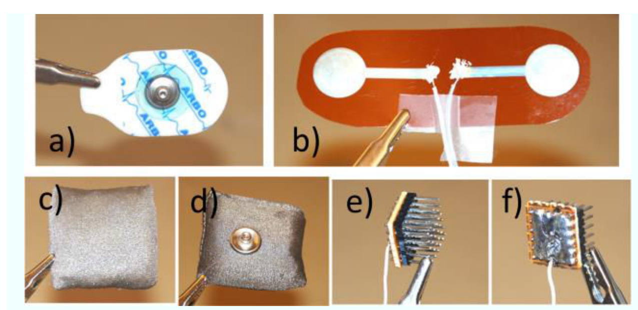

Figure 1. Samples of different types of electrodes: a) commercial electrode (CommE), b) a pair of inkjet printed electrodes on polyimide substrates (PrintE), c) the frontside of textile electrode (TextE) in d) the backside, e) the frontside of spiked electrode (SpikE), and in f) the backside of SpikE.

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L. Xie, G. Yang, L. Xu and Q. Chen are with iPack Vinn Excellence Center, School of Information and Communication Technology, Royal Institute of Technology (KTH), Forum 120, 164-40 Kista-Stockholm, Sweden (e-mail: lixi@kth.se).

F. Seoane is with the School of Technology and Health, Royal Institute of Technology, SE-14152, Huddinge and the School of Engineering, University of Borås, SE-50190, Borås, Sweden (e-mail:fsm@kth.se).

L-R Zheng is with the State Key Laboratory of ASICs and Systems, Fudan University, 200433, Shanghai, China, and also with iPack VINN Excellence Center, School of Information and Communication Technology, the Royal Institute of Technology (KTH), SE 164-40 Kista-Stockholm, Sweden (e-mail: lirong@kth.se).

cloth or other dielectric layer, this type of electrodes can also be used for non-contact capacitive bio-signal measurements [5]. In a previous work, we proposed inkjet printed electrodes (PrintE) on paper [9] and polyimide (PI) [6]. Compared with other manufacturing methods, inkjet printing technology features multi-substrate compatible, Roll-to-Roll and mask-free ('green' and low-cost), digital and additive (easy and cheap to customize electrode patterns according to different requirements). With the use of low cost flexible substrates such as paper and plastic, PrintE is featured with cost-effective, thin, lightweight, wearable, and disposable. In this paper, polyimide-based PrintE is used as a typical representative of printed metal-plate based electrodes. NPS-JL (nano-particle silver inkjetable low-temperature ink from Harima Chemicals) is directly printed on PI foil (Kapton 500HN, DuPont) by inkjet printer (DMP2800 from Dimatix). The printed structures are sintered in oven at 145 ºC for 1 hour.

B. *Textile Electrodes*

In order to increase the user comfort, researchers consider directly using conductive textile as the electrode material, so that the electrodes can be unobtrusively embedded in clothes such as t-shirts. Conductive yarns are woven or knitted into the fabric producing the textile electrode, also known as textrode (TextE). Textrodes feature several advantages for long-term monitoring such as lightweight, ductile, washable, resisting abrasion and moisture [7][17]. Therefore, TextE is suitable for long-term continuous wearable bio-signal monitoring. Weaving, knitting, and embroidering fabrication technology can be used to manufacture the TextE [7]. In this paper, textrodes are made with the Shieldex® Fabric P130+B manufactured by STATEX Gmbh (Bremen). It is nylon knitted silver coated fabric made of 78% polyamide and 22% elastan. The textrodes are padded with foam and a snap button is used for connecting the leads, as shown in Fig.1.c-d.

C. *Spiked Electrodes (SpikE)*

The above electrodes will encounter problems when conducting the bio-signal measurement on hairy skin, for example, ECG measurement from hairy chests, EEG measurement on the head with hairs, or bio-potential monitoring for animals. In order to gain good and stable electrical connection at the skin-electrode interface, skin pre-treatment is required. This will induce inconvenience or trouble for the patients. The spiked electrodes are quite useful in such applications since the metal spikes can easily penetrate the hair and make direct contact with the skin [14]. In this paper, a pair of SpikE is proposed and fabricated as shown in Fig.1.e and Fig.1.f. The hand-made SpikE is made out of bread boards and metal pins used for electronic experiments.

III. CHARACTERIZATION OF ELECTRODES

A. *Contact Impedance Measurement*

The contact impedance measurement setup is shown in Fig.2. Four electrodes (E1 – E4) of the same type are placed on subject's lower leg (hair-free). A function generator is used to generate a sine wave with frequency spanning from DC to 10 kHz. A multimeter is used to record the voltage. Assuming the current flowing through the multimeter is negligible, the effective current can be calculated by

$$I = V_R / R \qquad (1)$$

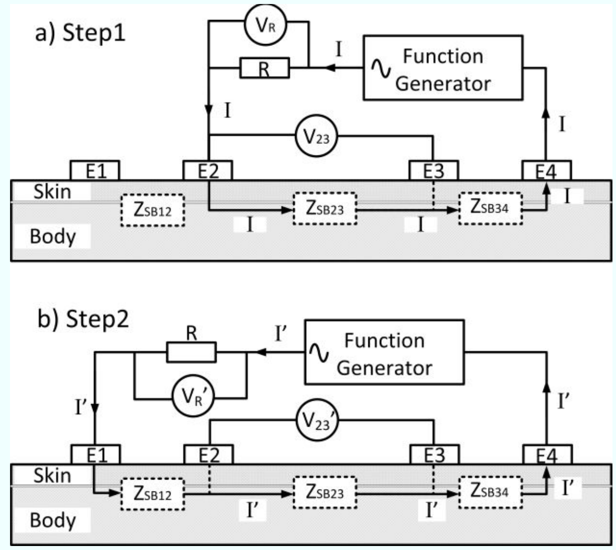

Figure 2. Experimental setup for contact impedance measurement. E1-E4 mean Electrode numbered from 1 – 4. Z_{SB} represents equivalent impedance of Skin and Body between the electrodes.

The effective voltage between E2 and E3 is recorded as V_{23} in Fig.2.a and V_{23}' in Fig.2.b. $Z_{contact}$ presents the contact impedan ce of the skin-electrode (E2) interface, and Z_{SB23} means the equivalent impedance of the skin and body between E2 and E3 [19]. For Step1 in Fig.2.a, since no current goes through the multimeter branch (E3), the total sum impedance Z_{sum} can be obtained by,

$$Z_{sum} = (Z_{contact} + Z_{SB23}) = V_{23} / I \qquad (2)$$

If the locations of E2 and E3 keep unchanged, Z_{SB23} is constant at one certain frequency point, which can be measured in Step2 and calculated by the following equation,

$$Z_{SB23} = V_{23}' / I' \qquad (3)$$

Therefore, the $Z_{contact}$ can be calculated by the equation:

$$Z_{contact} = Z_{sum} - Z_{SB23} = \left(\frac{V_{23}}{V_R} - \frac{V_{23}'}{V_R'} \right) \times R \qquad (4)$$

As shown in Fig.3a, the contact impedance of all the four

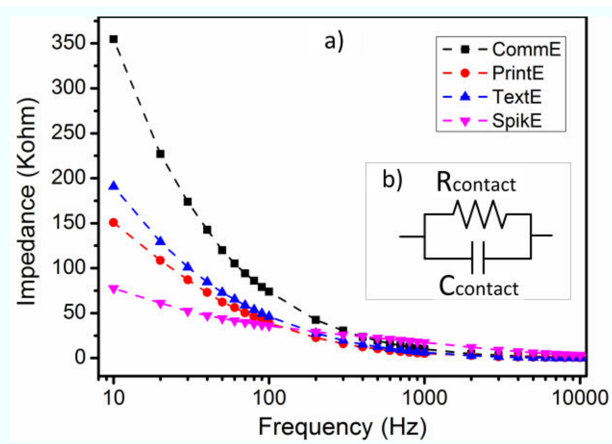

Figure 3. a) The skin-electrode contact impedance of different types of electrodes. b) the equivalent circuit model of skin-electrode interface.

types of electrodes follows the same tendency as a function of frequency, which is in line with what reported in [2][6]. The electrical behavior of the electrode is normally modeled as the parallel connected resistance and capacitance as shown in Fig.3b [2]. At low frequencies the value of the impedance is set by the resistance. With increasing frequency, the impedance contribution from the equivalent capacitance becomes more and more dominant. For SpikE, the equivalent capacitance is rather small due to the needle shape, the impedance decreases slower than the other electrodes and the impedance is the largest at high-frequency range.

B. In-Vivo *ECG Measurement*

To estimate the overall performance of different electrode types, we applied *in-vivo* ECG measurement using the test circuit board shown in Fig.4. The customized silicon chip is used to sense and amplify the bio-signals. The detailed functionality and performance of the measurement system are introduced in previous papers [12][13]. All the tests are under the same circuit settings on the same test subject. The ECG signals recorded by the four types of electrodes are shown in Fig.5 (raw signals without any digital signal processing). The ECG signals obtained by TextE, PrintE and CommE are quite similar. The ECG signal sensed by SpikE is the noisiest. However, the QRS complex can be distinguished. Further signal processing could highly improve the signal quality. An example is shown in Fig.5.e where the 50-Hz power line noise is filtered out by a notch-filter. It can be observed that the key features of ECG are clearly visible.

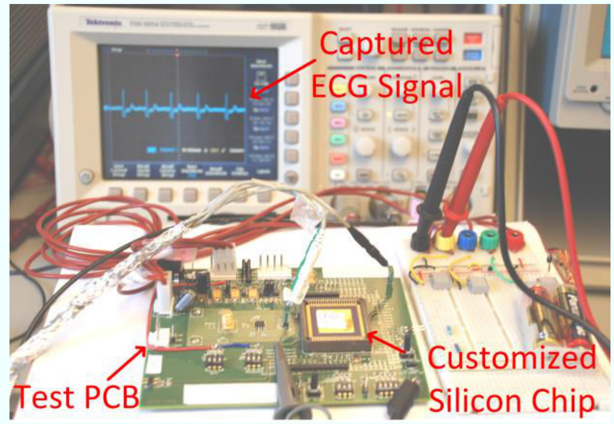

Figure 4. Experimental setup for ECG signal *in-vivo* test.

C. Noise Characterization

In order to further estimate the noise characterization of dry electrodes, the noise test is applied. Take away the signal source (functional generator) in Fig.2 and leave E1 and E4 open. Without any external signal injected, the voltage that we recorded between E2 and E3 can be regarded as the noise induced by the electrodes [1]. The noise signals captured by the oscilloscope are summarized in Fig.6. Because the bio-signal monitoring is normally applied in typical home and hospital environment, 50-Hz power-line interference is pervasive and unavoidable, which can be observed in Fig.6. The noise signal from TextE is comparable with CommE and

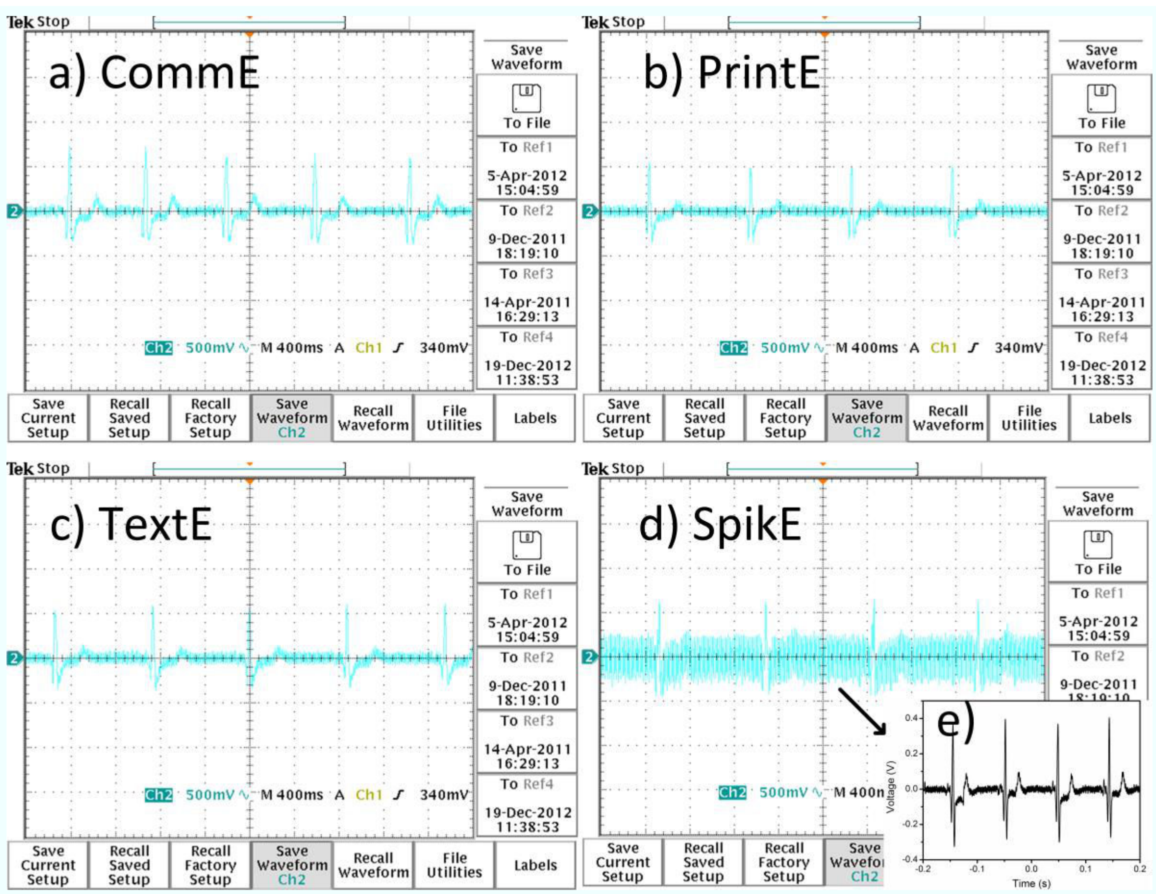

Figure 5. The oscilloscope screen shot of the ECG signal captured by a) CommE, b) PrintE, c) TextE, d) SpikE, and e) filtered ECG signal of d).

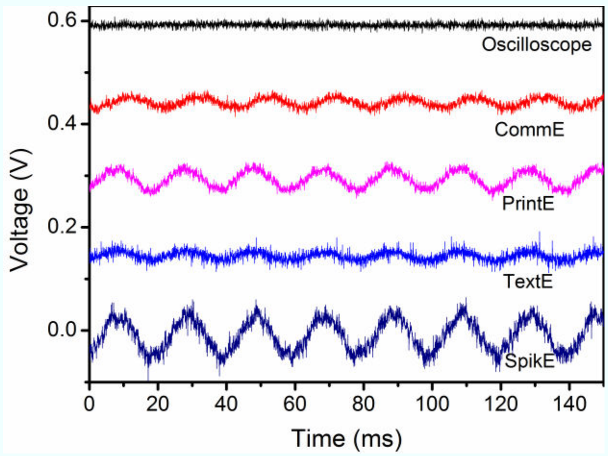

Figure 6. The noise signal captured by the oscilloscope.

smaller than PrintE. The noise induced by SpikE is much larger than the other electrodes. This phenomenon explains the noisy ECG signal gained by SpikE in the previous section. It is worth mentioning that an efficient way is needed to fasten the dry electrodes towards the skin to ensure good contact, especially for TextE. During the experiments we noticed that TextE is easy to get shift-movement and deformation. This induces motion artifacts. In addition, the pressure of TextE against the skin highly influences the results. In our experiments, an elastic strap is employed for fixation.

IV. Conclusion

The electrical behavior of the electrode determines the quality of sensed bio-signals, while the physical features influence the user-comfort and user-experience. In this paper, the commercial pre-gelled electrode (CommE), the inkjet printed metal-plate electrode on polyimide substrate (PrintE), the textile electrode (TextE) and the spiked electrode (SpikE) are evaluated. For the first time, these four types of electrodes are measured and analyzed under the same measurement setup. The results indicate that these electrodes feature different performances. TextE and PrintE obtained similar ECG signals with CommE. TextE is more preferable in terms of user-comfort and wearability. It is suitable for long-term ECG monitoring. However, TextE is sensitive to motion and pressure. Therefore, an efficient way is needed to fasten it. Manufactured by inkjet printing technology, PrintE features low-cost, thin, lightweight, ‘green’, and disposable. Although PrintE induces slightly larger noise, the ECG signal gained is usable for most applications. SpikE induces the largest noise and leads to noisy ECG signal. However, the QRS complex is visible and the signal quality can be easily improved by the backend signal processing. This indicates SpikE is one potential option for bio-signal monitoring on hairy skin. Each type of biopotential electrodes has its distinct features. The choice of which one to adopt is left to the user, the patient and the doctor according to the specific application scenario.

References

[1] T. I. Oh, S. Yoon, T. E. Kim, H. Wi, K. J. Kim, E. J. Woo, R. J. Sadleir, "Nanofiber Web Textile Dry Electrodes for Long-Term Biopotential Recording," *IEEE Transactions on Biomedical Circuits and Systems*, vol.PP, no.99, pp.1, 0.

[2] D.M.D. Ribeiro, L.S. Fu, L.A.D. Carlos, J.P.S. Cunha, "A Novel Dry Active Biosignal Electrode Based on an Hybrid Organic-Inorganic Interface Material," *IEEE Sensors Journal*, vol.11, no.10, pp.2241-2245, Oct. 2011.

[3] P. Char. Griss, H.K. Tolvanen-Laakso, P. Merilainen, G. Stemme, "Characterization of micromachined spiked biopotential electrodes," *IEEE Transactions on Biomedical Engineering*, vol.49, no.6, pp.597-604, June 2002.

[4] M.M. Puurtinen, et al, "Measurement of noise and impedance of dry and wet textile electrodes, and textile electrodes with hydrogel," *Engineering in Medicine and Biology Society, 2006. EMBS '06. 28th Annual International Conference of the IEEE*, vol., no., pp.6012-6015, Aug. 30 2006-Sept. 3 2006.

[5] Y. M. Chi, P. Ng, C. Maier, G. Cauwenberghs, "Wireless non-contact biopotential electrodes," *In Wireless Health* pp. 194-195. ACM, 2010.

[6] L. Xie, G. Yang, M. Mäntysalo, L. L. Xu, F. Jonsson, and L.-R. Zheng “Heterogeneous Integration of Bio-Sensing System-on-Chip and Printed Electronics” *IEEE Journal on Emerging and Selected Topics in Circuits and Systems (JETCAS),* vol.2, no.4, pp.672-682, Dec. 2012.

[7] T. Pola, J. Vanhala, "Textile Electrodes in ECG Measurement," *2007. 3rd International Conference on Intelligent Sensors, Sensor Networks and Information (ISSNIP)*, vol., no., pp.635-639, 3-6 Dec. 2007.

[8] T.-H. Kang, C.R. Merritt, E. Grant, B. Pourdeyhimi, H.T. Nagle, "Nonwoven Fabric Active E lectrodes for Biopotential Measurement During Normal Daily Activity," *IEEE Transactions on Biomedical Engineering*, vol.55, no.1, pp.188-195, Jan. 2008.

[9] Michal Teplan, et al. "Impedance analysis of acupuncture points and pathways," Journal of Physics: Conference Series, 329 012034, 2011.

[10] Li Xie; G. Yang; M. Mantysalo, F. Jonsson, L.-R. Zheng, "A system-on-chip and paper-based inkjet printed electrodes for a hybrid wearable bio-sensing system," *Engineering in Medicine and Biology Society (EMBC), 2012 Annual International Conference of the IEEE* , vol., no., pp.5026-5029, Aug. 28 2012-Sept. 1 2012.

[11] T. Komensky, M. Jurcisin, K. Ruman, O. Kovac, D. Laqua, P. Husar, "Ultra-wearable capacitive coupled and common electrode-free ECG monitoring system," *Engineering in Medicine and Biology Society (EMBC), 2012 Annual International Conference of the IEEE* , vol., no., pp.1594-1597, Aug. 28 2012-Sept. 1 2012.

[12] G. Yang, L. Xie, M. Mäntysalo, J. Chen, F. Jonsson, H. Tenhunen, and L.-R. Zheng, "Bio-Patch Design and Implementation Based on a Low-Power System-on-Chip and Paper-based Inkjet Printing Technology," *IEEE Transactions on Information Technology in Biomedicine*, vol.16, no.6, pp.1043-1050, Nov. 2012.

[13] G. Yang, J. Chen, F. Jonsson, H. Tenhunen, and L-R. Zheng, "A Multi-Parameter Bio-Electric ASIC Sensor with Integrated 2-Wire Data Transmissio n Protocal for Wearable Healthcare System," *Design, Automation & Test in Europe Conference & Exhibition (DATE)*, pp.443-448, Mar., 2012.

[14] http://www.miyuki-net.co.jp/jp/product/catalog/BciActiveElectrode.pdf.

[15] A. Lanatà et al. "A Novel EDA Glove based on Textile Integrated Electrodes for Affective Computing," Medical & Biological Engineering & Computing, vol. 50, pp. 1163-1172, Springer, 2012.

[16] G. Yang, J. Chen, L. Xie, J. Mao, H. Tenhunen, and L.-R. Zheng, "A Hybrid Low Power Bio-Patch for Body Surface Potential Measurement," accepted *by IEEE Journal of Biomedical and Health Informatics (J-BHI)*, 2013.

[17] R. Paradiso, G. Loriga, N. Taccini, "A wearable health care system based on knitted integrated sensors," *IEEE Transactions on Information Technology in Biomedicine*, vol.9, no.3, pp.337,344, Sept. 2005.

[18] J. Yoo, et al “A Wearable ECG Acquisition System With Compact Planar-Fashionable Circuit Board-Based Shirt,” *IEEE Trans. Inf. Technol. Biomed.*, vol.13, no.6, pp.897-902, Nov. 2009.

[19] Y.M. Chi, T.-P. Jung, G. Cauwenberghs, "Dry-Contact and Noncontact Biopotential Electrodes: Methodological Review," IEEE Reviews in Biomedical Engineering, vol.3, no., pp.106,119, 2010.