Wearable Technology (2021) Volume 2 Issue 2, *pp.* 27–34.
doi: 10.54517/wt.v2i2.1633

REVIEW ARTICLE

Research progress of fabric electrodes in wearable electronic clothing

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ABSTRACT

Aiming at the application requirements of fabric electrodes in wearable electronic clothing, the current materials and structure types of fabric electrodes are introduced respectively, the influence of fabric electrodes materials and structure parameters on the stability of ECG signal acquisition is analyzed, the use principle of fabric electrodes and the relationship between signal acquisition stability and comfort are summarized, and the application prospects and development direction of fabric electrodes in wearable electronic clothing are prospected in the future.

Keywords: fabric electrodes; wearable electronic clothing; biosingnals; comfortability; stability

1. Introduction

In recent years, the proportion of human patients with chronic diseases (such as cardiovascular and cerebrovascular diseases) has been increasing, resulting in frequent accidental sudden death. In order to understand the accumulation degree of chronic diseases, patients need to carry out long-term monitoring of physiological signals in the hospital, resulting in long registration and waiting time and crowded queue in the hospital (such as ECG, B-ultrasound and other monitoring departments). In order to alleviate this phenomenon, the new concept of modern medical treatment is to move the monitoring of chronic diseases from hospitals to communities and families. Patients monitor on demand at home, transmit physiological signals to hospitals through Internet of things technology, and doctors give diagnosis and treatment suggestions in time according to the signals. This idea has greatly promoted the research and development of wearable electronic clothing[1], and also promoted its application research in deep diving, military, aerospace, fire protection and other fields. Electronic clothing combines fabric and clothing technology, microelectronics technology, communication technology and cloud technology. It can monitor human physiological signals for a long time, give early warning before the occurrence of emergency conditions, and enable patients to be rescued at the first time.

As the sensing material of electronic clothing, the signal acquisition electrodes mostly adopt the adhesive electrodes (the core component is Ag/AgCl)

ARTICLE INFO
Received: April 16, 2021 | Accepted: May 18, 2021 | Available online: June 3, 2021

CITATION
Xiao X, Dong K, He W, et al. Research progress of fabric electrodes in wearable electronic clothing. Wearable Technology 2021; 2(2): 27–34.

in the early stage. During the detection, it is necessary to apply conductive paste between the electrodes and the skin. However, the conductive paste is easy to dry and is not suitable for long-term monitoring. Continuous use will also cause skin allergy, itching or inflammation[2].

Fabric electrodes is a kind of flexible dry electrodes which can monitor physiological signals for a long time. It uses fabric processing technology to process conductive materials into functional fabrics, which can collect the weak potential (bioelectrical signal) on the skin surface. Compared with wet electrodes, fabric electrodes are more suitable for monitoring physiological signals for a long time. This paper summarizes the research and development of material, structure and performance of fabric electrodes in wearable monitoring system, and analyzes the relationship between its comfort and monitoring signal stability.

2. Fabric electrodes material

The traditional Ag/AgCl gel electrodes is shown in **Figure 1.** Fabric electrodes can replace the traditional Ag/AgCl electrodes. Through wireless transmission technology, it can monitor physiological signals for wear, long-term, continuous and undisturbed. Compared with gel electrodes, the advantages of fabric electrodes are its wearability, softness, breathability, comfort and real time acquisition, as well as the good experience it brings to guardianship objects.

The materials of fabric electrodes can generally be divided into polarized metal, non-polarized metal, polymer coating metal, conductive polymer, nano silicone and carbon black[3]. At present, the research focuses include new conductive polymer (modified polymer polyimide), micro precious metal, graphene, modified conductive rubber, dry foam electrodes and so on. As far as the fabric electrodes is concerned, the new conductive polymer is the easiest to weave into the electrodes structure. At the same time, it has attracted people's attention because of its flexibility, light weight and strong weavability. According to different structures and preparation methods, conductive polymers can be divided into composite type, ionic type and structural type. The conductivity of the three structural types varies greatly due to different materials and structures[4].

Figure 1. Ag/AgCl electrodes and its fabric composite electrode.

In addition, compared with the current common porous carbon coated electrodes, polypyrrole/cotton fabric electrodes not only have incomparable flexibility and mechanical properties, but also has the characteristics of light weight, low cost and non-toxicity, and has high conductivity, which can meet the requirements of flexible wearable fabric electrodes. For example, Yue[5] used ordinary cotton fabric to prepare polypyrrole coated fabric through in-situ chemical polymerization (CP), vapor deposition polymerization (CVD) and interfacial polymerization. After repeated high-strength stretching, the polypyrrole coated fabric can still maintain high electrochemical properties, be suitable for stretching during human movement, and realize the softness and lightness of fabric electrodes. It can be applied to wearable monitoring electronic clothing.

Xin et al.[6] used the method of first chemical synthesis and then electrochemical plating to coat the polypyrrole conductive layer on the substrate of the fabric surface to prepare a fabric electrodes for ECG acquisition. This fabric electrode has good conductivity and good soft, breathable and moisture permeability. It can directly contact the skin surface of the monitoring object for long-term ECG acquisition.

For some fabric electrodes, the composite structure of conductive materials and conventional fabric materials is mostly used, or the conductive materials are attached to the yarn or printed and dyed to the fabric through various coating processes. The materials used in the composite structure of the latter include base materials and conductive materials. Common base fiber materials include animal and plant fibers and some chemical fibers. Acrylic and polypropylene fibers in chemical fibers are not suitable as substrates because of their poor moisture absorption, comfort and dimensional stability; The polyester fiber and its fabric in the chemical fiber have good wrinkle resistance, good elasticity, wear resistance, poor moisture absorption, easy washing and quick drying, and are not easy to moth and mildew. On the contrary, it is suitable to be used as the base material of conductive fabric. Also suitable for base materials are nylon filament, viscose yarn, cotton, carbon nanotube, polyethylene, polyamide and other fibers[7]. For the materials of conductive parts, they need to be selected according to the base materials. For example, nylon filament is generally silver plated, viscose yarn is generally made of core spun yarn with 30% stainless steel filament, conductive fabric is copper plated, polyester is blended with stainless steel wire, carbon nanotube is coated with Ag/AgCl, polyethylene is deposited with titanium and copper, polyamide and other chemical fibers are silver plated, etc.[8]

3. Fabric electrodes structure

Fabric electrodes mostly adopt the interleaving structure of conductive materials and conventional fabric materials, or attach conductive materials to yarns or printed and dyed fabrics through various coating processes, so as to form various types of fabric electrodes.

3.1. Common fabric electrodes assembly forms

The properties of the fabric electrodes are different according to the manufacturing method and structure. Catrysse et al.[9] used stainless steel filaments to make knitted structure electrodes as shown in **Figure 2**. The advantage of the electrodes is that it does not stimulate the skin and can be integrated into the clothing. The disadvantage is that the interface between the fabric and the skin has a large impedance, resulting in too weak or unstable ECG signal acquisition. In addition, knitted fabrics are prone to curling and de edging in the manufacturing process, and have large deformation in the use process. When stressed, the resistivity will also change, resulting in the instability of ECG signal.

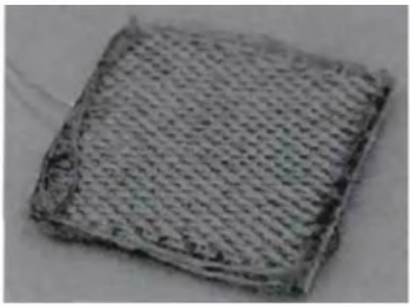


Figure 2. Soft electrodes made by steel fiber knitted fabric.

Huang[10] laid the carbon fiber lead wire on the conductive hydrogel, and then pressed the three parts by pressing the non-woven fabric. A disposable ECG monitoring electrodes was invented. He et al.[11] developed a non-contact ECG sensor and its wearable multi-channel ECG sampling underwear. In the underwear, a three-dimensional shielding cavity is formed through a hole, a shielding ring and a shielding layer, which can collect excellent ECG signals under the interference of daily electromagnetic environment.

Cai et al.[12] designed a new type of ECG monitoring electrodes. The conductive elastomer is placed in the concave cavity of the anti-mucous membrane, and the surface is connected with the sensing electrodes. The conductive elastomer uses a protruding sponge block to impregnate the conductive paste. Compared with the traditional coating conductive paste, its cost is reduced and its conductivity is improved. Qu and others[13] invented a new conductive hydrogel electrodes material, which is mainly composed of polymer and deionized water, electrolyte, water retaining agent and so on. It shows excellent biocompatibility, strong adhesion to skin, good environmental stability and excellent electrical conductivity.

Chen et al.[14] took graphene as the substrate, placed the metal seed layer between the metal electrodes and the flexible graphene substrate, and the electrodes lead is connected to the metal electrodes on the flexible substrate. The electrodes are arranged coronally, which increases the contact area with the skin and enhances the stability of ECG acquisition; At the same time, because its texture is soft and flexible, it can adapt to people of different shapes. Wu et al.[15] invented a similar electrodes structure. At the same time, several electrodes are connected in series, which are directly used for skin dressing, and complete the test and monitoring of 12 leads at one time.

Zieba et al.[16] designed a wearable system for ECG monitoring. As shown in **Figure 3**, the electrodes of the system is woven fabric of silver plated wire, and the interior of the electrodes is filled with elastic sponge.

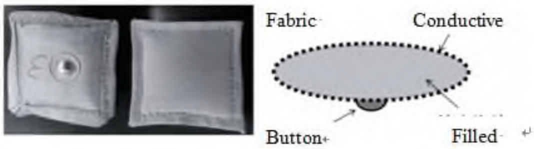


Figure 3. Electrodes model of woven fabric.

The electrodes in **Figure 3** can be well attached to the skin. The silver plated yarn improves the information conductivity of the electrodes and will not stimulate the skin if worn for a long time.

According to the weaving method, the conductive fabric of fabric electrodes can be divided into four structural forms: woven, knitted, nonwoven and other fabrics. **Figure 4** shows the fabric morphology of different fabric electrodes.

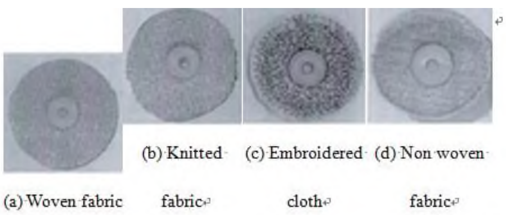


Figure 4. Fabric electrodes.

3.2. Fabric electrodes of woven structure

The fabric electrodes of woven structure is made of warp and weft conductive yarn, which has stable structure and high uniformity and consistency. Guo[17] used silver plated polyester filament as the conductive fiber of woven structure, wrapped sponge in the fabric of woven structure, and used sponge elasticity to ensure full contact between conductive cloth and skin; at the same time, hard sponge and support pad are applied to the outer ring to further improve the support force of fabric electrodes and slow down the impact in the wearing process. The structure and real object of fabric electrodes are shown in **Figure 5** and **Figure 6.**

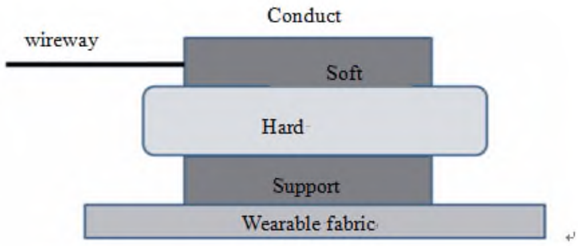


Figure 5. Structure illustration of a woven electrodes.

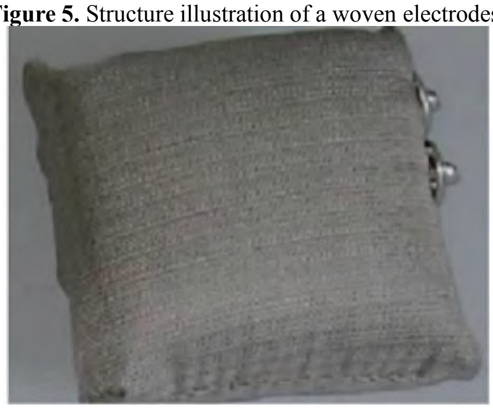


Figure 6. A real woven electrodes.

In addition, the fabric electrodes of woven structure can be made by coating conductive materials with woven fabric as the bottom layer. For example, Zhang[18] compounded polypyrole/cotton fabric ECG electrodes through electrochemical polymerization to measure the ECG signal of human body in static state. Li et al.[19] studied the effects of different woven structure parameters on the electrical conductivity of polypyrrole fabrics. Using 37 tex polyester cotton staple yarn, four kinds of plain fabric, through-hole fabric and 1/3 right twill fabric with different weft density were prepared by changing the crimp speed and weft density of the loom. The conductive materials were compounded on the fabric by chemical oxidation synthesis. It is found that the greater the weft density or linear density of the fabric, the smaller the surface specific resistance of the fabric and the stronger the conductivity; When the critical value is exceeded, the conductivity will decrease.

Zhang et al.[20] designed a flexible wireless bioelectric electrodes, including conductive layer, adhesive layer, flexible layer and conductive part of woven structure. The conductive part passes through the flexible layer and adhesive layer and is connected with the conductive layer. The conductive layer is woven by several conductive yarns in woven structure, the woven conductive fabric is adhered to the adhesive layer, and the signal collection and transmitting device is placed on the flexible layer and connected with the conductive part, This design avoids the wear of the conductive layer on the yarn surface in the process of fabric shuttle, ensures that the electrodes has good conductivity, reduces the attenuation of signal and increases the wearability of flexible electrodes.

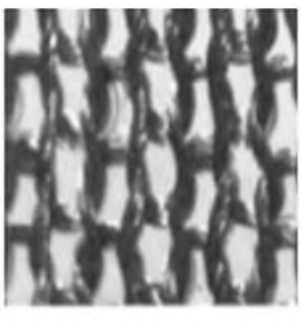
The fabric electrodes of woven structure can also be obtained by jacquard process. The jacquard structure of the jacquard weaving machine of the Korean University[21] uses the physiological signal of the jacquard weaving machine of the Korean university to detect the tissue of the human body. The fabric uses 82.5 dtex/36 F and s twisted polyester filament as warp yarn, silver plated yarn as weft yarn to make the bottom layer, and then silver plated yarn weaves the sensing layer on the bottom layer, so that the silver plated yarn becomes a double-layer structure. The fabric electrodes size of the woven jacquard structure is 50 mm×50 mm.

3.3. Fabric electrodes of knitted structure

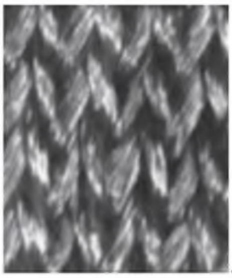
In the process of using knitted fabrics, due to repeated stretching, there will be problems such as looseness and deformation, fuzzing and hook wire, so the signal acquisition of this kind of fabric electrodes will also be affected. In addition, when weaving the knitted electrodes, the fabric can be coated with conductive materials, or the fabric electrodes can be obtained by weaving conductive yarn with other materials.

Yang et al.[22] developed a kind of knitted wool flexible ECG electrodes, which overcomes the problems that the existing flexible fabric ECG electrodes cannot contact with the skin stably and the contact impedance increases due to the growth of stratum corneum, and can effectively avoid the skin allergy caused by conductive paste.

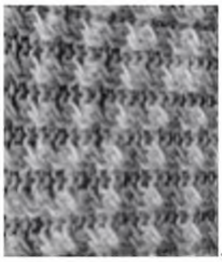
Liu[23] used coated carbon fiber and its conductive composite silk thread, selected weft flat weave and 1+1 rib structure to make fabric electrodes with knitted structure. It is found that the stability of 1+1 rib structure is better than that of weft flat structure; However, when simulating the washing process, it is found that with the increase of washing times, the overall resistance increases, and the change of resistance becomes more and more unstable. Wang et al.[24] prepared four kinds of fabric electrodes as shown in **Figure 7** by weft knitting. Comparing the sensitivity of four kinds of fabric electrodes to collect physiological signals, it is found that the signal sensitivity of vertical stripe double rib knitted fabric is higher than that of horizontal stripe double rib knitted fabric, and higher than that of silver plated yarn weft flat knitted fabric; From the repeatability of double rib resistance, it can meet the requirements of sensor repeatability and stability, and can be used to develop monitoring devices for heartbeat, respiration and cardiopulmonary function.



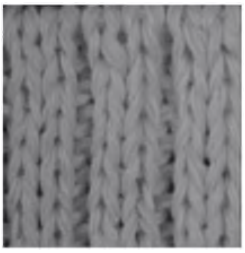
(a) Silver plated yarn weft flat knitted fabric



(b) Silver plated yarn spandex double yarn interwoven weft flat knitted fabric



(c) Silver plated yarn and wool yarn horizontal double rib knitted fabric (1, 2-way wool yarn, 3, 4-way silver plated yarn)



(d) Double rib knitted fabric with vertical stripes of plated yarn and wool yarn (1 and 3 are wool yarn, 2 and 4 are silver plated yarn)

Figure 7. Four knitted structure of fabric electrodes.

3.4. Fabric electrodes of nonwoven structure

Nonwoven structural materials have good mechanical properties such as breaking strength and breaking elongation, short production process and low cost, so they are widely used. Xu et al.[25] used magnetron sputtering to form a layer of deposited nano silver film on the surface of nonwovens, so that nonwovens can conduct electricity and be used to manufacture fabric sensors. The nano silver film of the fabric has good combination with the substrate, and the film has the characteristics of high purity, good compactness, uniform film formation and no chemical pollution of the fabric electrodes.

Ninane et al.[26] designed a nonwoven fabric electrodes, which can monitor human physiological signals for a long time. This electrodes adopt multi-layer three-dimensional structure, has superior hydrophilicity, can store a certain amount of solution, leach and wet the contact surface between skin and electrodes during extrusion, and reduces the impedance of the interface between electrodes and skin. Kang et al.[27] formed conductive lines and conductive layers on the surface of nonwovens by hand drawing or screen printing, and prepared nonwovens active electrodes. The results show that this kind of active electrodes have improved air permeability and more flexible skin adhesion design.

3.5. Fabric electrodes with embroidery structure

It is more flexible and convenient to weave fabric electrodes by embroidery. Peng Xiaohui et al. [28] embroidered silver plated fiber to produce fabric electrodes according to the designed structure, and used it as a pressure sensor for respiratory monitoring. In addition, in order to improve the sensitivity and repeatability of the sensor, the contact resistance can be connected in series and silica gel can be coated at the contact point, as shown in **Figure 8**. In the manufacturing process, 11.1 tex silver plated filament yarn is selected to be twisted into sensing materials (18 pieces/strand, two strands twisted, strand twist 8 twist/dm), which are sewn at 6 cm×6 cm polyester base cloth. Experiments show that the electrodes have the feasibility of physiological signal acquisition.

Figure 8. Embroided fabric electrodes covered with silica gel.

Zhang et al.[29] used Ag/AgCl composite yarn prepared by silver plated yarn electroplating as sensing material, and adopted the structure of embroidered Terry to prepare a circular fabric electrodes with Terry height of 3 cm, needle pitch of 1 mm and diameter of 3 cm. The utility model has the advantages that the terry structure can pass through the body hair, the skin adhesion is better, the physiological signals can be measured more accurately, and there is no need to process the skin in the process of use. In addition, in the process of connecting the fabric electrodes with the outside, the electrodes buckle is nailed in the middle of the fabric electrodes, and the male buckle is connected with the female buckle to realize the detachability of the electrodes.

4. Conclusions

Compared with traditional medical electrodes, fabric electrodes have the characteristics of softness, air permeability, stability, comfort and long-term wearability from the perspective of material and structure. Therefore, they play a more and more important role in the application of human physiological signal monitoring[30]. With the rapid development of microelectronics and information technology, fabric sensing will become a research hotspot of life and health materials and technology.

Conflict of interest

The authors declare no conflict of interest.

References

1. Chang F, Yin J, Zhang H, et al. The research and expectation on wearable health monitoring system. Chinese Journal of Medical Instrumentation 2015; 39(1): 40–43.
2. Qin L, Li M, Li G, et al. Preparation and evaluation of flexible silver/silver chloride EEG electrodes. Journal of Analytical Science 2016; 32(4): 445–450.
3. Hoffmann K, Ruff R (editors). Flexible Dry Surface-Electrodes for ECG Long-term Monitoring. France: 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society; 2007. p. 5740–5742.
4. Liu M. Research on conductivity and response performance of intelligent flexible sensor [PhD Thesis]. Shanghai: Donghua University; 2009.
5. Yue B. Study on polypyrrole coated fabric for stretchable supercapacitor electrode [PhD Thesis]. Shanghai: Donghua University; 2013.
6. Ding X, Zhou Y, Zhang J, et al. (inventors). A Preparation Method of Textile Electrode for Testing ECG Signal. CHN patent. 103,462,602b. 2015 Jul. 8.
7. Lu L, Zhang H, Xie G. Research progress of the textile-structured flexible ECG electrodes. Synthetic Fiber in China 2015; 44(11): 34–38.
8. Meng Y, Zheng G, Dai M. The research of wearable ECG signal collection electrodes. Journal of Tianjin University of Technology 2014; 30(5): 22–25.
9. Catrysse M, Puers R, Hertleer C. Towards the integration of textile sensors in a wireless monitoring suit. Sensors and Actuatorsa Physical 2004; 114(2–3): 302–311.
10. Huang G (inventor). Production Method of Disposable ECG Monitoring Electrode Using Carbon Fiber Lead Wire. CHN patent. 103,239,226a. 2013 Aug. 14.
11. He J, Lei Y, Chang L, et al. (inventors). Contactless ECG Sensor and Wearable Multi-channel ECG Sampling Underwear. CHN patent. 205,268,157u. 2016 Jun. 1.
12. Cai R, Zhang J, Hu S, et al. (inventors). An ECG Monitoring Electrode. CHN patent. 204,072,086u. 2015 Jan. 7.
13. Qu B (inventor). A Conductive Hydrogel and Conductive Hydrogel Membrane and Its Preparation Method.CHN patent. 105,153,359A. 2015 Dec.16.
14. Chen J, Meng Y, Li Z, et al. (inventors). Graphene Based Flexible Coronary ECG Electrode and Its Preparation Method. CHN patent. 102,920,452a. 2015 Feb. 13.
15. Wu W (inventor). A Portable ECG Electrode. CHN patent. 103,222,865b. 2015 Jan. 21.
16. Zieba J, Frydrysiak M, Tesiorowski L. Textronic clothing to ECG measurement. Medical Measurements and Applications Proceedings (MeMeA) 2011; 1(2): 559–563.
17. Guo W. Research and implementation of wearable human physiological parameter detection system [PhD Thesis]. Changchun: Jilin University; 2012.
18. Zhang J. Development of polypyrrole/cotton fabric ECG electrode [Phd Thesis]. Shanghai: Donghua University; 2014. p. 19–29.
19. Li H. Study on the influence of fabric structure parameters on the conductivity of conductive fabric [PhD Thesis]. Shanghai: Donghua University; 2014.
20. Zhang H, Liu G (inventors). A Flexible Wireless Bioelectric Electrode System. CHN patent. 204,207,743u. 2015 Mar. 18.
21. Song H, Lee J, Kang D. Textile electrodes of jacquard woven fabrics for bio-signal measurement. Journal of the Textile Institute 2010; 101(8): 758–770.
22. Yang X, Zhou Y, Dai X, et al. (inventors). An Embroidered Villus Flexible ECG electrode. CHN patent. 104,523,267a. 2015 Apr. 22.
23. Liu T. Carbon fiber coated conductive knitted fabric

[PhD Thesis]. Hangzhou: Zhejiang University of Technology; 2011.
24. Wang J, Long H. Research on flexible sensors based on knitted fabric with conductive fiber. China Textile Leader 2011; (5):76–79.
25. Xu F, Wei Q, Meng L. Conductivity of silver-coated non-woven fabric deposited by magnetron sputtering. New Chemical Materials 2012; 40(6): 105–107.
26. Ninane C (inventor). Textile Electrode. EU patent. EU10169351. 3. 2010 Jul. 13.
27. Kang T. Textile-embedded sensors for wearable physio-logical monitoring systems [PhD Thesis]. Ra-leigh: North Carolina State University; 2006. p. 1–7.
28. Peng X, Yang X, Hu J. Study on respiration monitoring Piezo-Resistive sensors based on embroidery. Journal of Donghua University (Natural Science) 2014; 40(6): 712–717.
29. Zhang H, Li W, Tao X (editors). Textile-structured human body surface bio-potential signal acquisition electrode. Shanghai: 4th International Congress on Image and Signal Processing. Shanghai: Donghua University; 2011. p. 2792–2797.
30. Yue S, Wang M, Guo F, et al. Present status of wearable wireless ECG. Biomedical Engineering and Clinical 2006; 10(4): 262–264.