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Progress on Fabric Electrodes Used in ECG Signals Monitoring

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Abstract

Wearable monitoring system is designed for skin stimulation of conductive adhesive, prolonged physiological monitoring and biocompatibility, whose core is fabric electrodes and it can feedback physiological status by analysis of abnormal electrocardiogram (ECG). Fabric electrode is a sensor to collect biological signals based on textile materials including signals acquisition, processing systems and information feedback platform and so on. In this paper, the design methods and classification of medical electrodes would be introduced. It also sorted out the principle of biological electrical signals, the design methods and characteristics of different material and different structure electrodes from the point of dry electrodes and wet electrodes. There are many methods that can be used to prepare fabric electrodes. They are mainly metal plating, conductive polymer coating, magnetron sputtering, gas phase deposition and impregnation. Besides, they select the appropriate substrate, conductive medium and composite way to get light fabric electrodes which have high conductivity, good conformability. From the perspective of biological signal acquisition by fabric electrodes, this paper also sorted out the influence and approaches of biological signals and the way to feedback the physiological condition of human. As a new generation of bio-signal acquisition material, fabric electrode has met the requirements of the development of modern medicine. Fabric electrode is different from traditional conductive materials in the characteristics of comfort, intelligence, convenience, accuracy and so on.

Keywords

Fabric Electrode, Biological Signals, Slide Artifacts, ECG

1. Development of Fabric Electrodes

Textile science is no longer a discipline just for clothing. With the accelerated pace of development of textile

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science and medical technology, more and more attention has been paid to medical textile and industrial textile research. Recently, the quality of life was seriously affected by cardiovascular disease, heart disease, chronic pneumonia and other diseases, and more researches about physiological condition monitoring were followed. A long-term monitoring system for old people's physiological state came into being, and health monitoring systems typically included signal acquisition, processing systems, signal contras and physiological state feedback platform. Textile materials have developed in electronic information technology very well which makes it the best choice to use intelligent fabric electrodes as sensors for monitoring system due to intelligence and flexibility. As a new generation of bio-signals acquisition sensor, fabric electrode met the requirements of modern materials like convenience, intelligence, accuracy and so on. It is different from traditional needle electrode which is prone to cause skin damage and has some other shortcomings. Fabric electrodes belong to the category of smart textiles in the electronic textile which is not just a simple conductive fabric. The smart fabric electrode consists of micro power, connecting member and signal path together to monitor the biological electrical signals. Fabric electrode is provided with high research value and social economic benefits by the great market demand in medical field.

Electrode is used as a sensor to collect biological signals which begin at an embedded motherboard. Georgia Institute of Technology embedded GTWM motherboard into clothing to detect life signs of wounded soldiers in 1996. GTWM wearable motherboard made of optical fibers concentrated human life, biological signals monitoring and signals processing functions into one. How to collect biological signals by wearable monitoring system and feedback accurate physiological state has been a hot topic in foreign countries in recent years. Researches have paid a great attention to the research of fabric electrodes. As shown in **Table 1**, MagIC project [1] of Polytechnic University of Milan, Italy used fabric electrode as an original information collection to monitor heart and lung function by acquiring biological electrical signals of breathing and temperature changes. Jacket monitoring system prepared by the EU WEALTHY project [2] used textile conductive wire, Bluetooth and GPRS technology to transmit and get feedback on dynamic bioelectric signals in mechanical movement. In addition to these projects, MyHeart project [3] of monitoring the elderly cardiovascular disease of Philips Research Europe, Vital Jacket plan of the University of Aveiro [4] and CHRONIOUS program [5] of Bremen University had also used a similar embedded technology to collect biological signals through embedding fabric electrodes in wearable clothes and transmitting signals by wires or wireless technology. The research of wearable body monitoring system has made great achievements in the monitoring of elderly breathing, body temperature and blood oxygen saturation. In addition, monitoring time of human physiological signals is short and further research is required.

2. Generation Principles and Characteristics of Fabric Electrodes and Biological Signals

2.1. Characteristics of Fabric Electrodes

Body weak electric current is called biological electric current which results from heart beats, muscle contraction and other actions. Human body composed of cell membrane is a kind of semi-permeable membrane. The principle of cell membrane is that only a certain kind of ions can go through it in a certain state which results in a potential difference between inside and outside of cell membrane. Fabric electrode could be essentially regarded as an interface because of achieving ions transformed between skin surface and wires to analyze electrical current. Biological signals passed through tissues and fluids surrounding the heart to the conductive skin surface and formed a weak potential difference. Electromyography signal is a kind of weak physiological signal caused by mechanical heart beat. The cell membrane of human body is similar to a semi-permeable membrane.

2.2. Generation Principles and Characteristics of Biological Signals

The principle of semi-permeable membrane is that only a certain kind of ions can go through it in a certain state. It's known that there are a series of physiological and chemical changes in the body when a man is in motion. At different potentials, the cell membranes have a different permeability for sodium ions (Na^+) and potassium (K^+). That is to say, when the cell is at resting potential, membrane permeability for potassium (K^+) is greater than sodium ions (Na^+), making potassium ions move to the extracellular, and the membrane potential outside is higher than the membrane potential inside, forming a negative potential inside but positive outside. Instead, when the

Table 1. Research status of fabric electrodes.

Project title	Basic component	Communication mode	Measurement object	Medical applications
MagIC	Vest with sensors embedded/portable circuit board	Bluetooth technology	ECG/breathing/ temperature	Record the signal of cardiopulmonary function and daily activities
WEALTHY	Vest with sensors embedded	Conductive yarn/ Bluetooth technology/GPRS	ECG /breathing/ Temperature/EMG signals/ mechanical activity	Monitoring the recovery of elderly chronic disease
MyHeart	Chest belt with sensors embedded/PDA	Conductive yarn/ Bluetooth technology/ GPRS	ECG/other important signals/mechanical activity	Prevention of cardiovascular disease in elderly
Vital Jacket	Vest with sensors embedded/PDA/PC	Conductive yarn/ Bluetooth technology/ GPRS	ECG/breathing/temperature/ mechanical activity /oxygen saturation	The elderly physiological signs monitoring
CHRONIOUS	T-shirt with sensors embedded/PDA/PC	Conductive yarn/ Bluetooth technology/ GPRS	ECG/other important signals/mechanical activity	Elderly chronic disease prevention

cell is at action potential, membrane permeability for sodium ions (Na^+) is greater than potassium (K^+), making sodium ions (Na^+) continuously transfer to the intracellular, and the membrane potential outside is lower than the membrane potential inside, forming a negative potential outside but positive inside [6]. Biological signals have some characteristics as followed.

1) Signal is weak. Biological electrical signals are generated by the difference of random ion concentration inside and outside of human cell. The signal collected must be gone through a relative larger common-mode rejection and higher amplification circuit. In addition, biological signals can be affected by motion artifact and noise and it also needs to be amplified step by step. Electricity and magnetism are inseparable. Bioelectrical signals captured by fabric electrode are susceptible to being affected by current source, especially the electromagnetic waves around 50 Hz frequency. Biological signal in power frequency noise is random and it could easily drown out the pure electric signal. Therefore, electromagnetic frequency closed system reducing the wire length method has to be used to reduce the power frequency noise to acquire relatively pure signal. Due to the influence of external electric field and electromagnetic field, there is some potential on the body surface of patients. This kind of induced potential is bonded to passing through electrodes to the preamplifier to form interference signals. It usually presents 50 Hz frequency interference which can be controlled by increasing the amplifier's common-mode rejection ratio in laboratory conditions.

2) Noise processing. Because the skin friction noise and electromagnetic impact of external environment can't be ignored, biological signals collected must be passed through low pass and high pass filtering process to gather accurate electromyography signals. On the other side, baseline drift caused by human respiration and the circuit connection between fabric electrode and skin would make a great influence on electrical biological signals. Baseline drift could make the band offset the original position and affect the accuracy of low frequency ECG signals. Therefore, in order to obtain a certain output signal, the treatment of electrical signals through amplifier has very strict requirements.

3) Large difference in signals. The difference of bioelectricity is great. As we know, people of different ages have different metabolisms. The ion concentrations and temperature are not equal inside and outside of cell membrane. Studies have shown that human skin has some small potential difference, this potential difference is related to human mechanical movement. When the fabric electrode collecting biological signals, the accuracy would be disorganized and affected by skin surface. On the other side, human mechanical movement makes the skin extrusion and stretching deformation, but the fabric electrode could not be completely deformed with the skin and sliding artifact could be caused by skin-electrode interface due to the relative sliding friction. Thus, the biological signal is very complex which needs high-pass filter technology, low-pass filter technology, 50 Hz notch filter and other professional signal processing technology [7]-[9].

3. Different Kinds of Electrodes

Impedance and frequency characteristics of human epidermal tissue should be taken into consideration before studying human physiological state through collecting biological signals. The level of the potential difference and impedance is one of the most important factors to determine the selection of electrodes. From a biological point of view, human skin can be regarded as a pure resistance for its good conductivity. The cuticle thin insulating film acts as a medium between the two electrode plates of capacity consisting of dermal tissue and electrode plate which determines the skin impedance magnitude. The sweat caused by longtime mechanical activity would increase the degree of fit between human skin and fabric electrode and decrease the impedance caused by gap air between the electrode and skin. Fabric electrode can not seamlessly fit the skin. The gap air between the electrode and skin would also affect the conductivity which can be seen as an equivalent circuit of resistors and capacitors in parallel [10] [11].

As shown in **Figure 1**, electrodes can be divided into insertion electrodes and surface electrodes and surface electrodes can be divided into dry electrodes and wet electrodes. At the state of rest, there are a certain number of positive ions inside of cardiac muscle cell and the same amount of negative ions outside. When the cardiac muscle cells get a certain extent of stimulus, the permeability of cardiac muscle cell would change and the positive ions would rush into or exhaust from the cell membrane and form an electric potential difference. The electric potential difference is the foundation of electrode collecting biological signals. Needle electrode is a typical insertion electrode, which collects every moving part signal by inserting it into the human skin. Although the signal acquisition method can accurately collect biological signals, it needs not only high operation requirements, but also can cause severe harm to human body.

3.1. The Characteristics of Dry Electrodes

The study of dry electrode has caused more and more attention in recent years. Dry electrode is different from wet electrode, which needn't apply conductive adhesive to improve conductivity but it can also cause great motion artifacts and noise by skin friction. Biological signals acquired by dry electrode must be filtered by buffer amplifier circuit and transformed from high impedance input into low impedance input to reduce interference noise and motion artifact. In a word, the design of fabric electrode needs considering every step of process including selection of materials, structure of fabric and conductive way of biological signals. Fabric electrode could be easy to fix in clothes or elastic bands to make patients comfortable. This kind of flexible electrode has the advantages of breathability, moisture permeability, soft and biological compatibility. Hongyi Zhai [12] *et al.* use wearable fabric electrodes made of silver-plated fabric to acquire ECG to combine it with classic ECG after signal conditioning and micro-processing device and get abnormality ECG eventually.

3.1.1. The Affects of Different Fabric Structure

Fabric organizational structure not only affected the firm level between conductive materials and fabric-base materials but also the adhesion of conductive materials. At the same time, structure can also make some influences on the stability of signal acquisition and the comfort of wear clothing. Besides the size and the stability of fabric electrodes, fabric organizational structure directly affects the degree of fitting between the electrode and skin, especially the side contacting with human. Almost all fabric organizational structures have been selected as fabric electrode materials like weaving, knitting, embroidery, jacquard fabric and non-woven fabric, but it remains many problems about structure which needs future researches. 1) Woven fabric electrode. Yarns should be weaved into plain woven fabric on a loom first, then plated with a metal surface on the sample, it would be very hard for us to guarantee good surface uniformity of conductive metal and surface morphology everywhere. To some extent, requirements of metallization technology are very strict because the degree of surface uniformity of conductive metal would affect the degree of chlorination irregularity directly. Dandan Tao [13] *et al.*

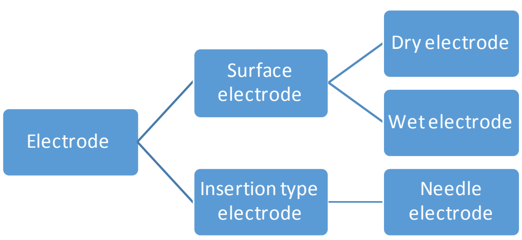

Figure 1. Classification of electrodes.

made conductive silver paste and fabric into an woven fabric electrode which is fixed by elastic belt, and used as a collecting element of EMG signals during mechanical movement. On one hand, warps and wefts consist of woven fabric together and the knot points of fabric can be seen as resistors when the woven fabric is used as a fabric electrode. On the other hand, some capacitive characters would be produced between the space portions of fabric electrode. In a word, plain woven fabric could not only be regarded as a sample resistor or a capacitor, but it's also an electronic component consisting of resistors and capacitors. With the impact of common capacitors and resistors together, the woven fabric electrode would receive different quality signals in different frequencies or different pressures. 2) Knitted fabric electrode. Silver plated yarns could be usually chosen as basic materials manufactured into a three-dimensional cylindrical knitted fabric electrode on a hosiery knitter then cut into a desired shape sample. Coil structure determined an unstable fabric structure and was easy to deform, so the program of conductive metallization is unfeasible for knitted fabric electrode. From the point of service life, unstable dimensional and discontinuous conductive metal is the reason that knitted fabric electrode is not as good as woven fabric electrode. However, knitted fabric electrode can fit human skin better and deform with it. Finally, this feature of good elasticity could reduce the noise impact caused by relative friction between skin and electrode [14].

These structures have many advantages and disadvantages. First, not only woven fabrics have a stable warp and weft structure but the production process is very complex. Secondly, knitting fabric is more convenient than woven fabric but the size of coil structure is unstable because the yarn is easy to slide. Similarly, embroidery fabric is very convenient to design because of the unique structure. Non-woven fabric electrode has the same characteristic but the structure is not as stable as embroidery fabric for its unique structure between fibers. All in all, weaving, knitting and embroidery organizational structure are all popular organizational structures for fabric electrode.

3.1.2. Properties of Different Fabric Electrodes

1) Metal fabric electrodes. Metal fabric electrodes can be designed in the way of disposing conductive metal inside the fabric or yarn surface for transferring electrical signals. It is not suitable for fabric electrode because the metal thread couldn't meet the requirements of washable and anti-wrinkle. Recently, metal conductive fibers stretched from metal yarns are usually used to blend with common yarns, which can not only solve the problems of metal threads but it can also output more simple electrical signals. Metal conductive yarns have good conductivity, heat resistance and also have certain strength. In view of the above features, metal conductive is more suitable for ECG electrodes to transform the ion current on skin surface into an electron current in wire. It also has some shortcomings, although such an electrode retains the degree of fabric softness, the metal fibers can result in skin tingling easily if the implantation skill is not good. Metal materials can also be used as a dense conductive metal layer on the surface of fabric by magnetron sputtering or vapor deposition methods. Metalized fiber blended fabric electrode depends on the principle of "silver mirror reaction" to form a layer of silver on the surface of fibers by redox reactions and blend with other fibers to weave into fabric electrodes. In addition to the electrodes for ECG, such conductive fabrics can also be used as radiation materials for the excellent electromagnetic radiation protection. Binbin Yue and Xin Ding [15] plate gold film on fabrics by magnetron sputtering, then deal with acetonitrile solution, which containing toluene sulfonic acid and polypyrrole monomer to obtained the polypyrrole composite conductive fabric electrodes by chemical polymerization method polymerization methods. Fabric electrode prepared by this process has the characteristics of a uniform coating, strong adhesion, washable and so on.

2) Poly fabric electrode. Polymer fabric electrode. Xiaolan Fu [16] *et al*. from Donghua University selected polyaniline and metal composites materials as an intermediate flexible conductive layer. Under ultrasound conditions, they use polyester as base materials to prepare polyaniline polymer/Cu composite conductive fabric with a chemical coating method. The reasons why conductive poly can be used for fabric electrodes can be explained from three aspects, namely field emission effect, percolation and tunneling effect [17]. 1) Field emission effect. According to the field emission effect, as long as ions of different potential with a certain charge close enough, electrons can leap over the intermediate insulating layer to the adjacent ion and generate a current, then non-contact-conductive is achieved. 2) Percolation. Based on percolation, as long as the concentration of charged particles in a conductive polymer is high enough and the distance between conductive particles is in nanometer range, the electrons can form current. 3) Tunneling effect. Tunnel theory holds that when the thickness of isolation layer between ions is less than 10nm, an electron tunnel could be formed by electrons to produce electron

flow. These three theories supported the reason why polymer can be used to prepare conductive layer fabric electrodes.

3.2. The Characteristics of Wet Electrodes

Wet electrode is a kind of electrode with conductive adhesive. Conductive adhesive is made of high concentration negative ions electrolyte. These materials can improve the electrical conductivity of the skin surface and reduce the error of biological signals but it may cause skin irritation like skin allergy or itchy in prolonged exposure because the chemical properties of adhesive would damage human skin. Electrode with conductive adhesive is not suitable for long time monitor as conductive adhesive would volatilize in the process of use and affect the signal quality. As the most common bioelectricity measuring wet electrode in clinical medicine, metal plate electrode connects human skin and induces surface bio-potential with metal conductive materials. The structure of metal plate electrode is very simple. A layer of conductive adhesive or sponge mat impregnated with electrolyte should be used to pad the vacancy to improve the contact area between the skin and electrode. In some cases, electrolyte conductive materials were used to improve the conductive ability and surface smooth performance. Wet electrode conductive adhesive is usually attached with an electrochemically-treated silver chloride coating on the side of contacting with the surface of skin. There is a lead wire welded on the back of metal plat electrode and insulation materials such as polyvinyl chloride and epoxy resin used as connecting materials to protect lead wires and the electrode. This kind of electrode was usually used to record electrocardiogram signals on the patient's chest with the layer of electrolyte in shot time. Besides electrocardiogram (EEG), wet electrode can also record electromyography signals (EMG) and electroencephalogram (EEG) although hurting human skin in long time monitoring. Moreover, wet electrode made of stainless steel materials with good corrosion resistance is better than dry electrode in a short time. Stainless steel materials would be corroded by sweat and cause electrochemical noise which can be solved by plating a layer of film [18].

4. Feedback Physical Condition by Classic ECG

Normal ECG performance reflects normal human physiological characteristics. As shown in **Figure 2**, biological signals collected by fabric electrodes will be compared with classic ECG after filtering and amplifying processing. Any erratic performance appeared in psychical condition would appear in one band of classic signals. This performance provides a good basis for arrhythmia, cardiac tumors, heart disease and so on.

To improve the fabric electrodes can meet the requirements of medical electrodes. Sun Jiaxing [19] *et al.* acquired ECG signals by carbon nano tube fabric electrodes and compared them with standard ECG signals. In a

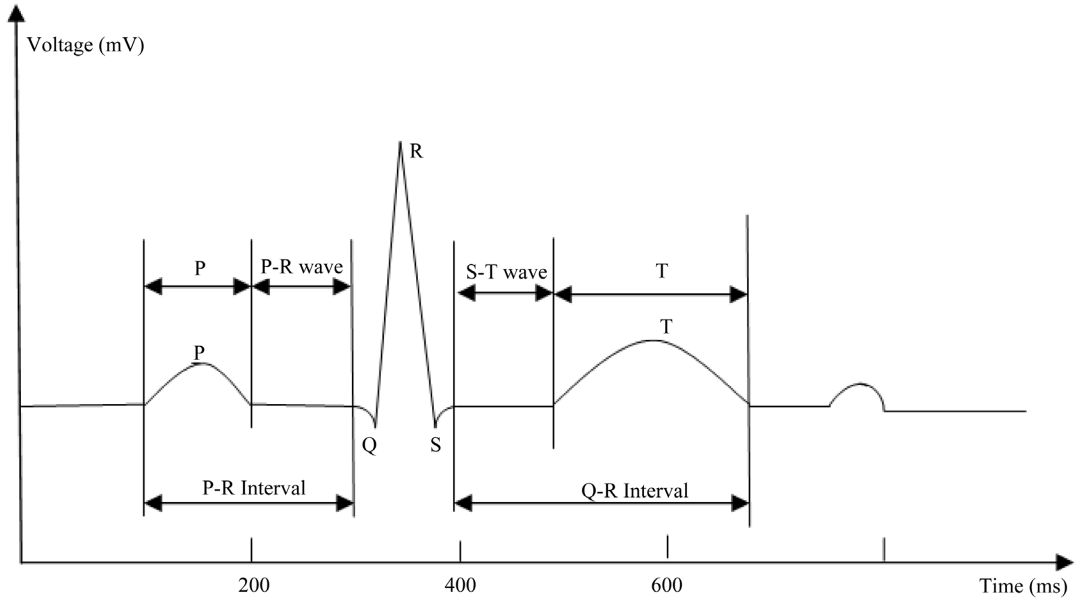

Figure 2. Classic electrocardiogram.

Table 2. Parameters of electrocardiogram.

Type of wave	Cycle	Amplitude	Source
P-wave	0.06 - 0.11	0.05 - 0.25	Produce left and right atrium signal
Q-wave	<0.03 - 0.04	<R 1/2 - 1/4	Deliver left and right atrium signal
R-wave	-	<2.5	Deliver left and right atrium signal
S-wave	0.06 - 0.11	-	Deliver left and right atrium signal
T-wave	0.05 - 0.25	0.1 - 1.5	Electric potential of ventricular repolarization
P-wave	0.06 - 0.14	Coplanar with the baseline	Between P-wave and QRS-weave
PR interval	0.12 - 0.20	-	Deliver to ventricular
ST-wave	0.05 - 0.15	Line	Process of ventricular restoration
QT interval	<0.4	-	process of ventricular repolarization

stationary state, PR interval, QRS interval and QT interval change little, the amplitude of Q-wave and S-wave and the error rate of characteristic waves are larger. Under the motion of standing, walking and jogging, PR interval is reduced and the error rate of characteristic waves is much larger. But the QRS interval and QT interval change little and the quality of signals remains clear.

Resting potential and action potential in medicine are known as polarization and depolarization. A classic electrocardiographic includes not only P-waves produced by atria depolarization, QRS-waves produced by ventricular depolarization, T-waves produced by rapid ventricular repolarization and so on. At the moment of atria depolarization, the beating heart could produce biological signals of P-waves. QRS-waves can also be produced by ventricular depolarization. T-waves, PR segment, ST segment, PR interval and ST interval can appear at the time of rapid ventricular repolarization. Classic ECG can accurately reflect the changes of biological signals and provide a reference for medical treatment [20]-[23]. Every band corresponds to a kind of mechanical moment of ventricular or atria as shown in **Table 2**.

5. Conclusion

The development of fabric electrodes not only solved the problem that the skin was damaged by inserting traditional needle electrode, but also solved the problem of skin irritation caused by conductive gel on surface electrode. Different from traditional electrode, fabric electrode has many advantages of inner and outer. The characteristics of comfortable, breathable, and non-irritating properties of textile materials are greatly favored by many researchers. It is in accord with the requirements of medical and health field oriented toward miniaturization, intelligence and convenience, and fabric electrode has become one of the hottest researches among researchers in this area. As every coin has two sides, fabric electrode is not perfect because the biological signals acquired by fabric electrode need future processing. The selections of structure and materials are the most important factors. For the biological signals collected, how to filter the noise, how to reduce sliding artifacts and other problems are the other hot issues needed to be resolved for fabric electrodes. In a word, fabric electrode as a kind of dry electrode could meet the modernization medical needs. There will be a great market demand of fabric electrode. Therefore, fabric electrode has a high research value and it will also bring social and economic benefits.

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