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Comfortable textile-based electrocardiogram systems for very long-term monitoring

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Introduction

Recent advances in miniaturization of electrocardiogram (ECG) devices, as well as mobile computing, have fostered a dramatic growth of interest in wearable ECG sensor technology. The interest for comfortable textile-based ECG systems originates from the need for monitoring patients over extensive periods of time and reinforces the "doctor is always with you" paradigm since the usual clinical or hospital monitoring of the electrocardiogram provides only a brief window on the status of the patient.

Very long-term monitoring ECG systems allow for serial comparisons of long segments of data, which provide robust characterization of the electric cardiac activity data. This approach provides much more information than the traditional, short-term 12-lead ECG and provides a tool to study the dynamics of heart rate variability, restitution, the dynamics of repolarization and trends. This is due not only to the tremendous increase in research devoted to this area in the past few years but also to the large number of companies that have recently started investing aggressively in the development of wearable ECG products for clinical applications [1].

Electroactive fabrics and fibre sensors

Promising developments in non-contact sensor technology, material processing, device design and system configuration have enabled the scientific and industrial community to focus their efforts on the creation of smart textiles. In fact, all components of wearable ECG systems (sensors, electronics and power sources) can be made from polymeric materials, to be woven directly into textile structures (sensing micro-fibres) or printed or applied onto fabrics (flexible electronics) [2]. In particular, intrinsic sensing, dielectric or conductive properties, lightness, flexibility and the relative low cost of many electroactive polymers make them potentially suitable materials for the manufacture of such systems [3]. The use of "intelligent materials" has enabled the design and production of a new generation of garments with distributed sensors and electrodes [4, 5]. Biopotential Fiber Sensors (BFS) significantly reduce the size of the ECG sensors, eliminate the need for pastes and gels by the introduction of new sensor materials and eliminate the patient cables. A typical BFS sensor assembly combines the functions of the sensor itself, a lead wire and a patient cable. Wearable comfortable systems permit the patients to perform all daily activities with minimal training and no discomfort [5, 6].

A comfortable, skin contacting "sensor shirt" was implemented using carbon loaded elastomeric (CLR) piezo-resistive fabric sensors, used to monitor respiration trace (RT), and conductive fabrics, used as electrodes to detect ECG signals [7].

To record the ECG signals, two different square-shaped fabrics (1 × 1 cm) were used: the first was made with steel threads wound round acrylic yarns, the second with a layer of acrylic/cotton fabric coupled with a layer containing stainless steel threads. In order to assess their performance, the signal originating from an Ag/AgCl electrode (Red Dot by 3M) was recorded simultaneously with the signal detected by the fabric electrode [8].

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Non-contact ECG sensor systems

The desire to replace wet ECG electrodes prompted research towards the development of non-contact sensors that are not physically attached to the skin. These work by sensing the electric field created by the displacement currents in the body. These are referred to in the literature as insulated, capacitive or impedance probes [9].

Early applications included the development of a non-contact biopotential sensor for neonatal monitoring. A thin silk fabric was used as an insulator between the skin and the sensor [10]. Progress in the development of low noise Giga Ohm impedance probes further enabled research activities in the field of non-contact biopotential sensors [11]. Lee et al. [12] reported the development of miniature insulated biopotential sensors for military applications. These can measure electric potential on the skin without an electrical contact and with very low capacitive coupling. This has been made possible by the combination of an innovative circuit design and the use of a new, low dielectric material. Capacitively-coupled, non-contact sensors (CCNS) enable through-clothing measurements. The CCNS utilizes high impedance, low noise probe technology that measures low frequency electric potentials in free space, i.e., without physical contact to the body. The process of electrogram recording through a cotton shirt is shown in Figure 1.

Figure 1. Recording of electrocardiogram signals from capacitively-coupled, non-contact sensor (CCNS) through a cotton T-shirt.

CCNSs produce signals morphologically very similar to the electrocardiogram recorded from the standard Ag-AgCl electrodes, as shown in Figure 2.

The first version of the CCNS biopotential sensor, including all amplification electronics, is shown in Figure 3.

A noninvasive, zero-prep-time, biopotential shirt system utilizing CCNS was developed for use

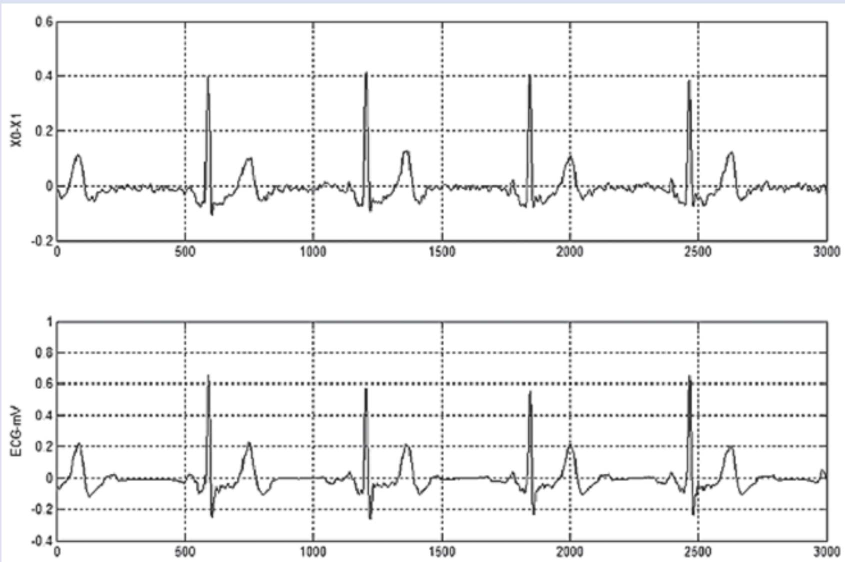

Figure 2. Capacitively-coupled, non-contact sensor (CCNS) produced electrocardiogram (top tracing) compared to electrocardiograms obtained from the Ag-AgCl electrodes in frontal plane (lower panel).

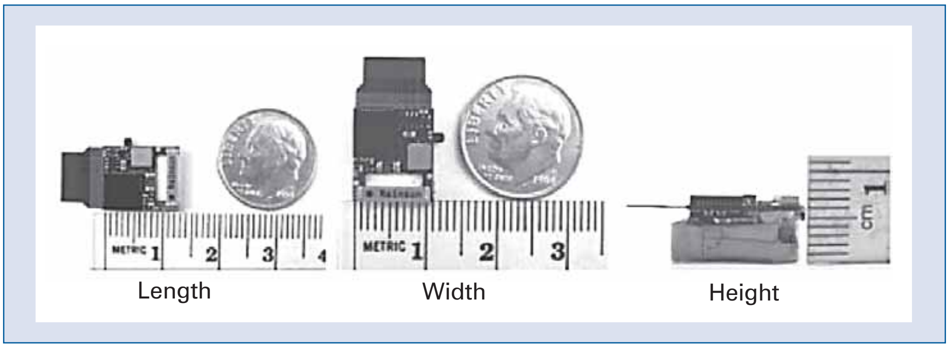

Figure 3. The capacitively-coupled, non-contact sensor (CCNS) assembly (13 mm × 11 mm × 7 mm).

Figure 4. A prototype sensor shirt for real-time measurement of the electrocardiogram.

by firefighters and is shown in Figure 4. The shirt offers the first non-contact system of its kind, allowing instantaneous electrocardiogram signal collection.

Conclusions

Comfortable textile-based ECG sensors and systems have evolved to the point that they can be considered ready for clinical application. The most promising clinical application appears to be very long-term atrial fibrillation monitoring. Stable trends showing a growth in the use of this technology suggest that soon such systems will be part of routine clinical evaluations. They will typically rely on wireless, miniature ECG sensors enclosed in patches or bandages or in items that can be worn such as personal jewellery or underwear. Other potential applications of wearable ECG devices may include:
- patterns altered by disease;
- patterns altered by drugs;
- monitoring changes in the course of the disease;
- monitoring rhythm and morphology changes due to pharmacological agents.

Practical textile-based ECG systems have the potential to become relatively non-obtrusive devices that allow physicians to overcome the limitations of ambulatory technology and provide a response to the need for monitoring individuals over weeks or even months or years.

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