Washable embroidered textile electrodes for long-term electrocardiography monitoring

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ABSTRACT

The improvement of human health condition is an important objective that remains relevant since the origin of human being. Currently, cardiovascular diseases are the first cause of death worldwide. For this reason, permanent real-time monitoring of heart activity (Electrocardiogram: ECG), its analysis and alerting of concerned person is a solution to decrease the death toll provoked by heart diseases. ECG signal of medical quality is necessary for permanent monitoring and accurate heart examining. It can be obtained from instrumented underwear only if it is equipped with high quality, flexible textile based electrodes guaranteeing low contact resistance between the skin and them. This work is therefore devoted to the design and test of wearable textile embroidered bands following defined protocol for ECG long-term monitoring. These bands were investigated in three configurations: band without any adding layer to protect lines between electrodes and the connector, band with lines protected by simple yarn, band with lines protected with thermoplastic polyurethane (TPU). Bands were worn around chest by healthy subjects in a sitting position and ECG signals were acquired by an Arduino-based device and assessed. Washability tests of connected underwear were carried out over 50 washing cycles in a domestic machine and by using a commercial detergent. Influence of encapsulation process on the electrical properties of textile electrodes during repetitive washing process has also been investigated and analyzed. All the ECG signals acquired and recorded have been reviewed by a cardiologist in order to validate their quality required for accurate diagnosis.

KEYWORDS

Embroidery, textile electrodes, washability, electrocardiography, signal quality

INTRODUCTION

Over the past few decades, there has been an exponential increase of wearable sensors that have revolutionized smart textile industry since the industry of electronic integration into garments has been grown [1,2]. With the increase in the general awareness of people regarding the use of smart textiles in health monitoring, more efforts are being involved to overcome problems related to their reliability and washability [3,4]to respond and adapt behaviour to them in an intelligent way and present a challenge in several fields today such as health, sport, automotive and aerospace. Electrically conductive textiles include conductive fibres, yarns, fabrics, and final products made from them. Often they are prerequisite to functioning smart textiles, and their quality determines durability, launderability, reusability and fibrous performances of smart textiles. Important part in smart textiles development has conductive polymers which are defined as organic polymers able to conduct electricity. They combine some of the mechanical features of plastics with the electrical properties typical for metals. The most attractive in a group of these polymers are polyaniline (PANI. Especially that the treatment of a wide critical diseases is not portable and require medically trained experts for their implementation [5]and an accurate heart examination can be obtained from instrumented underwear only if it is equipped with high-quality, flexible, textile-based electrodes guaranteeing low contact resistance with the skin. The main objective of this article is to develop reliable and washable ECG monitoring underwear able to record and wirelessly send an ECG signal in real time to a smart phone and further to a cloud. The article focuses on textile electrode design and production guaranteeing optimal contact impedance. Therefore, different types of textile fabrics were coated with modified poly(3,4-ethylenedioxythiophene.

Currently, lots of works have been done for the usage of smart textiles in medical industry for real time health monitoring and sports industry [6,7]. Health sector is still one of the big players in smart textile industry and reliability of the products used in this field is under discussion to make them acceptable for the market. These products, in future, will be used to integrate the routine checkup and comfortability of users with centralized data base [6]. Cardiovascular diseases are the first cause of lethal issues worldwide. To deal with this issue, real time heart monitoring and usage of smart textiles in inner garments got attraction [5]and an accurate heart examination can be obtained from instrumented underwear only if it is equipped with high-quality, flexible, textile-based electrodes guaranteeing low contact resistance with the skin. The main objective of this article is to develop reliable and washable ECG monitoring underwear able to record and wirelessly send an ECG signal in real time to a smart phone and further to a cloud. The article focuses on textile electrode design and production guaranteeing optimal contact impedance. Therefore, different types of textile fabrics were coated with modified poly(3,4-ethylenedioxythiophene.

ECG electrodes can be prepared by different techniques including conductive polymer, inkjet, screen printing and weaving / knitting etc [8–10]we unite graphene with ordinary textiles and report the development of graphene-clad, conductive textile electrodes for biosignal acquisition specifically in cardiac monitoring. The proposed electrode was prepared by dipping nylon fabric in reduced graphene oxide (rGO. But embroidering of electrodes were preferred because it is easy and less time consuming to produce embroidered electrodes and secondly, they are produced with same conductive threads used as connection yarns. Hence if conductive yarns are reliable and washable, both connection threads and electrodes will be reliable.

Weder et al. [11] have developed an embroidered textile electrode from polyethylene terephthalate yarn plasma coated with silver and ultra-thin titanium layer on top for passivation. Those electrodes were embedded into a breast belt. However, they had to be moisturized with a very low amount of water vapor from an integrated reservoir. In our opinion, this moisturizing will be an issue for long-term use, because the reservoir has to be filled up regularly. The advantage of this approach is that the monitoring is possible at rest, as well as when the subject is moving.

The current challenge faced in developing wearable ECG sensors is washability. Our previous works [4,5,9] and an accurate heart examination can be obtained from instrumented underwear only if it is equipped with high-quality, flexible, textile-based electrodes guaranteeing low contact resistance with the skin. The main objective of this article is to develop reliable and washable ECG monitoring underwear able to record and wirelessly send an ECG signal in real time to a smart phone and further to a cloud. The article focuses on textile electrode design and production guaranteeing optimal contact impedance. Therefore, different types of textile fabrics were coated with modified poly(3,4-ethylenedioxythiophene explain the washability and reliability of textile electrodes by analyzing the performance of ECG signals after 50 washing cycles. In other research [12] different conductive threads behavior after washing was analyzed and concluded that washing have some severe effect on the conductivity of connection threads due to some mechanical forces acting during the washing process. In continuity with the previous work, this study is conducted to evaluate the performance of two different silver plated polyamide conductive yarns. Wearable textile bands for ECG long-term monitoring were produced by embroidering these conductive threads to make three electrodes with lines and connectors. Different protective methods of lines, that connect electrodes to connectors, were assessed and compared in order to determine the best one that can withstand in washing process. These methods include protection with a thermoplastic polyurethane film (TPU) and protection by a nonconductive yarn (simple yarn) and without any protective treatment. Washability tests of connected underwear were carried out over 50 washing cycles in a domestic machine and by using a commercial detergent. Influence of encapsulation process on the electrical properties of textile electrodes during repetitive washing process has also been investigated and analyzed by (i) calculating the resistances of lines that connect electrodes to connectors, (ii) computing of signal-to-noise ratio (SNR) and spectral power densities of ECG signals.

EXPERIMENTAL

Materials and Methods

The patterns of electrodes and lines were designed on the software BASE PAC8 provided by SZK Company (Germany) as shown in Figure 1.

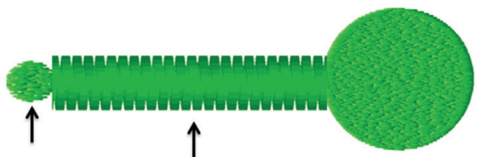

Figure 1. The pattern of electrodes

Two type of silver plated polyamide conductive threads were used: Statex-Shieldex 117f17 2-ply HC+B and Madeira HC-40 to embroider bands on a plain cotton fabric by using embroidery machine (ZSK, Germany). Embroidery machine was preferred to normal stitching machine due to better stitch quality and availability of vast range of design possibilities. Conductive lines between ECG electrode and connector were assessed up to 50 washing cycles, protottected by nonconductive yarn embroidered on the of the top of conductive lines (Figure 2), without any protection (Figure 3), protected by a thermoplastic polyurethane film (TPU) (Figure 4). The TPU protection film (BEMIS, United Kingdom) was attached by using a heated press at 140°C for 20 seconds.

The washing process was carried out with a commercial detergent (X.TRA Total, Roubaix, France) in a domestic washing machine (Miele, Paris, France). Each washing cycle comprised 35 min at 40 °C with 30 mL of detergent and a total machine load of 2.5 kg. The drying spinning speed was 600 rpm. Household washing machine was preferred on laboratory washing machine because if these products will be commercialized, ultimately they will be washed in available washing machines.

Samples were dried in controlled conditions (20 ±2 °C and 65 ± 5 % R.H) for 24 hours before each measurement. Change in resistance (Ri/Ro) in conductive lines was measured after washing. Digital multi meter was used for measurements.

ECG measurements were performed by a SHIELD-EKG-EMG card from OLIMEX. The OLIMEX card was configured using an Arduino, and data analysis was processed using MATLAB (R2013a). Signals were filtered by a Butterworth passband filter (0.05–100 Hz) and Notch filter at 50 Hz to remove, respectively, motion artifacts and power line noises. The recording was carried out for around 40 s with subjects wearing bands around chest and sitting to avoid motion artifacts. Measurements were carried out without any skin preparation at the electrodes sites, and performed immediately after installing the bands.

The signal recorded is obtained from the Lead I corresponding to the voltage between the left arm (LA) electrode and the right arm (RA) electrode. The quality of ECG signals was assessed by calculating signal-to-noise-ratio (SNR) which is the ratio between filtered signal and the original noisy signal [13].

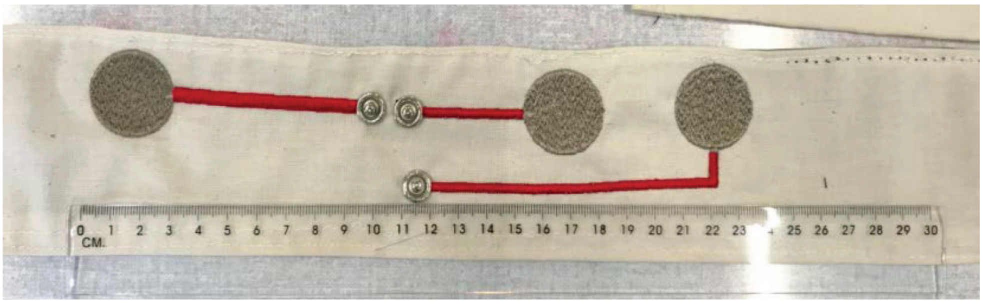

Figure 2. Band with lines protected by nonconductive yarn (red yarn)

Figure 3. Band without any protection

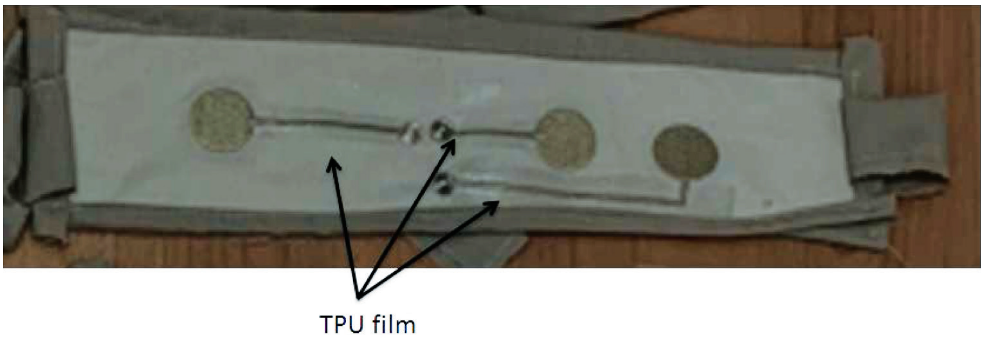

Figure 4. Band with lines protected TPU film

RESULTS AND DISCUSSION

Figures 5 and 6, illustrate variations of Ri/Ro during 50 washing cycles for both silver-plated yarns (Shieldex and Madeira), where Ro is the resistance of conductive lines before washing and Ri is the resistance after the i-th washing cycle. For all yarns, the resistance increases linearly as a function of the number of washing cycles, but with different slopes. For Madeira conductive yarn (Figure 5), protective coating with simple yarn seemed to save it from mechanical stresses during washing process. When we compare Ri/Ro while using TPU film and without any coating, the results are almost same, meaning that TPU film indeed is not protecting the conductive yarn layer. Moreover, whatever the type of protection, Ri/Ro increases slowly and with low standard deviations that means that Madeira yarn is homogenous and stable compared to Shieldex conductive yarn (Figure 6). The same as for Madeira yarn, simple yarn protection is proved to be the best one to protect the Shieldex conductive lines from damages exerted in the washing machine. However, TPU protection seemed to damage Shieldex yarn. In fact, Shieldex yarn has conductive silver plate coating on the outer side of yarn plies only. But in Madeira yarn, each filament in the ply is separately coated with silver. Consequently, for Shieldex yarn, the protruding fibers on its surface are more damaged during the application of TPU film at high temperature (140°C for 20 s) and hence resistance increased after repetitive washing cycles.

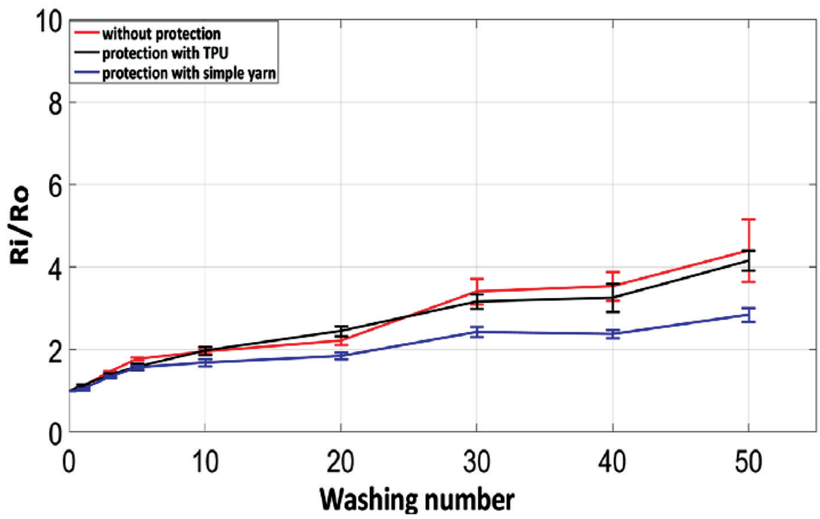

Figure 5. Madeira

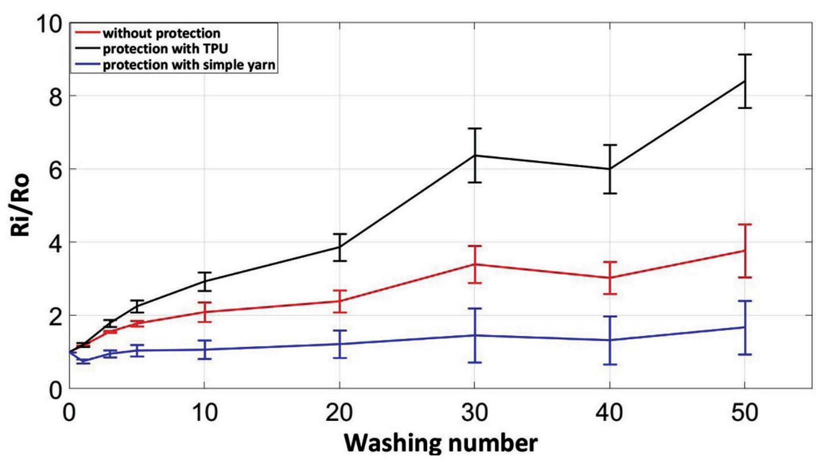

Figure 6. Shieldex

In order to determine the effect of the difference protections on the quality of washed bands, ECG signals were recorded before and after 50 washing cycles. High quality signal means that there is no missing P, Q, R, S and T waves. They provide useful information for cardiologists to interpret. Figures 7, 8 and Figure 9, show electrocardiograms before and after washing recorded by bands without any protection, protected by TPU film and those protected by nonconductive yarn. For all ECG signals recorded by the two types of conductive yarns (Shieldex and Madeira), cardiac waves were clearly identified: P wave which correspond to atrial depolarization, QRS complex corresponding to ventricle depolarization and T wave corresponding to the repolarization of the ventricle. After 50 washing, ECG signals were contaminated by noise, especially for bands protected with TPU film (Table 1).
In fact, before washing the bands with TPU film had the best SNR, as the heated press increased the contact between fibers. However, these bands are more sensitive to washing process because of the high set-up temperature of TPU installation (140°C). Moreover, according to Table 1, protection with simple yarn seemed

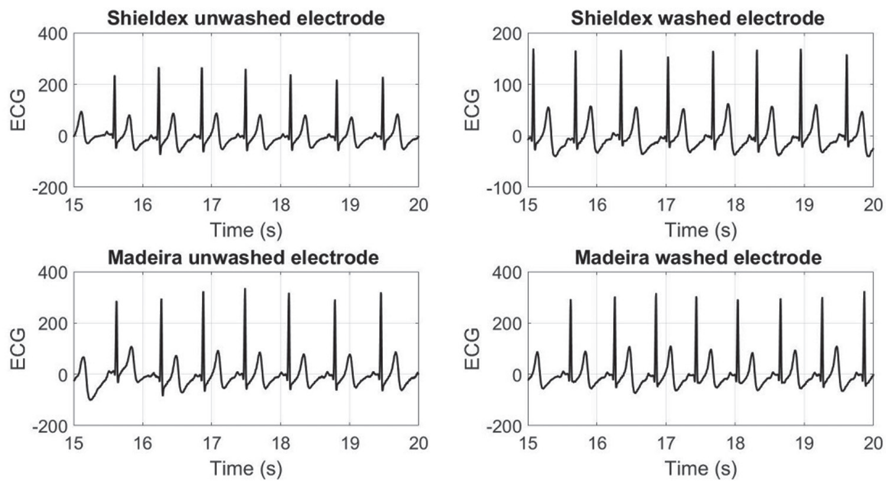

Figure 7. ECG signlas of bands without protection

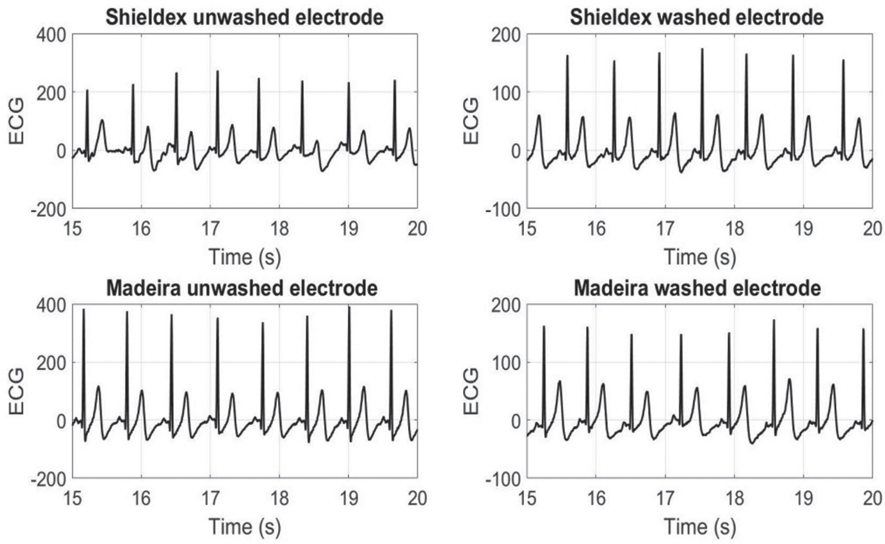

Figure 8. ECG signlas of bands protected by TPU layer

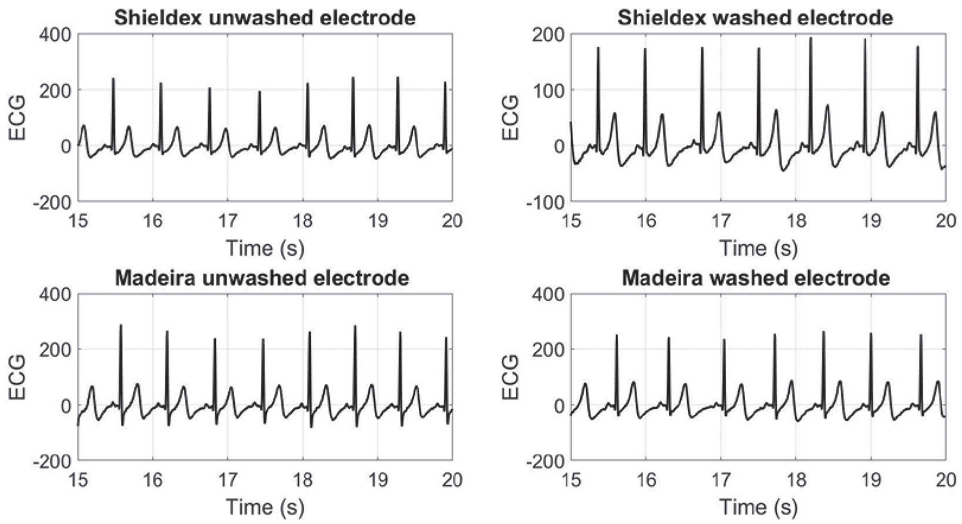

Figure 9. ECG signlas of bands protected by nonconductive yarn

to be the best solution for Madeira yarn since the SNR kept the same value after 50 washing cycles. For all types of bands made by Shieldex yarn, the SNR decreased strongly after repetitive washing meaning that Shieldex is more sensitive to washing than Madeira. Which again justify the fact that Shieldex yarn has conductive silver plate coating on the outer side of yarn plies only in contrast to Madeira yarn that has each filament separately coated with silver.

Table 1. Signal to-noise-ratio obtained by bands

	SNR (dB) Shieldex		SNR (dB) Madeira	
	Before washing	After washing	Before washing	After washing
Band without protection	37,7734 ± 2.6112	23,8203± 2.5025	35,1584 ± 3.2544	34,2087 ± 2.2285
Band with TPU protection	40,1633 ± 1.0169	20,2333 ± 6.0148	38.0609 ± 1.3876	35,0674 ± 1.2070
Band with nonconductive yarn protection	39,4139 ± 1.9619	21,2734 ± 2.6165	34,2131± 1.4018	34,1637 ± 1.4645

In order to confirm the influence of washing on ECG signal quality, the power spectral densities have also been evaluated. Figures 10, 11 and Figure 12 show that the density in the important frequency domain (<5 Hz) has not been strongly degraded [14]4-ethylenedioxythiophene. Moreover, after 50 cycles of washing, the power spectral density decreased from unwashed bands except band made by Madeira conductive yarn protected by nonconductive yarn (Figure 12b) when there is not obviously difference between the signal from unwashed and from 50 washing cycle bands. The significant decrease in signal quality after repetitive washing can be explained by mechanical stresses exerted in the laundry machine. Moreover water temperature and detergent lead to damages of fibers and small fractures which affect negatively the adhesion between silver coating and polyamide yarn and therefore electrical conductivity of embroidered electrodes. The TPU film used here is not a good solution to protect lines and the best choice is to use Madeira yarn protected by nonconductive yarn.

Zaman *et al* [15] explained the change in resistance after repetitive washing cycles and concluded that electrical resistance increased gradually as a function of washing cycles because of mechanical damages. Tao et al [12] used two techniques to protect the e-textile systems including TPU or latex protection. They concluded that TPU protection was not up to the mark when investigated after certain number of washing cycles and several connection points were damaged.

(a) (b)

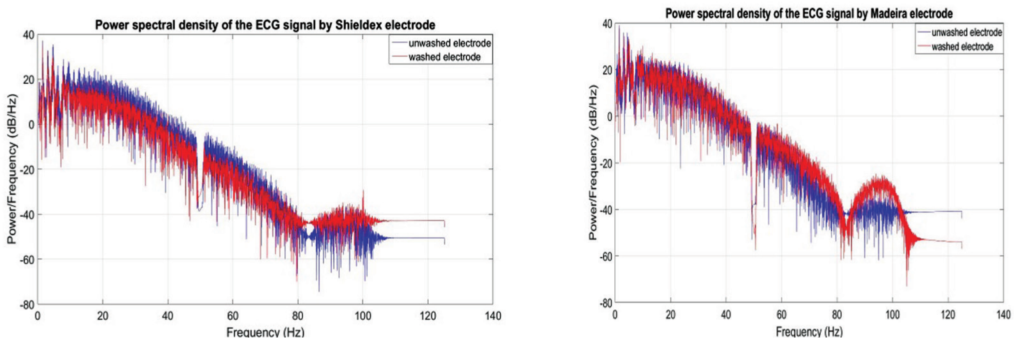

Figure 10. Power spectral densities of ECG signal measured from brands without protection (a) Shieldex; (b) Madeira

(a) (b)

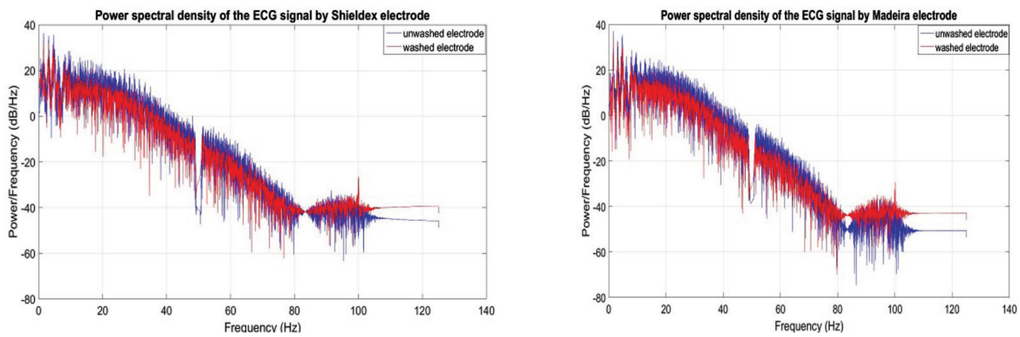

Figure 11. Power spectral densities of ECG signal measured from brands with TPU (a) Shieldex; (b) Madeira

(a) (b)

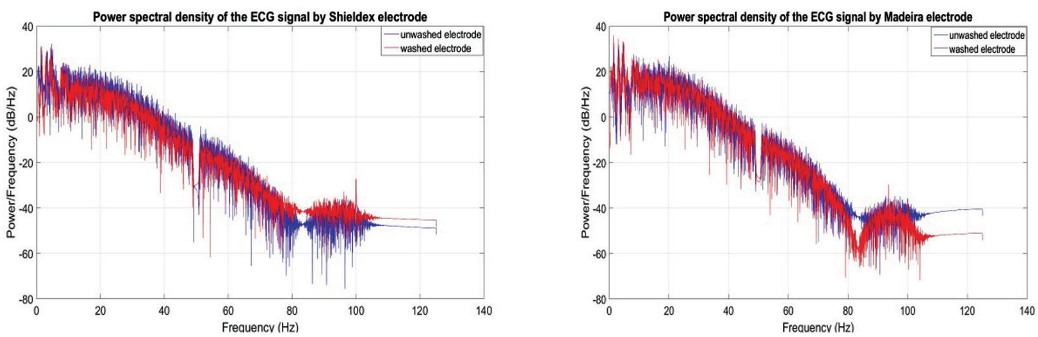

Figure 12. Power spectral densities of ECG signal measured from brands with simple yarn (a) Shieldex; (b) Madeira

CONCLUSION

This study was developed to assess the performance of embroidered bands for ECG long term monitoring. Two different types of yarns with two different protection types were used in this experiments and effect of washing on ECG signal quality was examined. For all ECG signals recorded by the two types of conductive yarns (Shieldex and Madeira), cardiac waves were clearly identified. In comparison of both yarns, shieldex yarn seemed to be more sensitive to damage by washing forces than Madeira yarn. This is because each ply in Madeira yarn is separately silver coated while in case of Shieldex, only the outer side of yarn is silver coated. Results revealed that non-conductive yarn embroidered on the top of conductive thread layer has clear advantage on TPU protection. TPU protection was applied at high temperature (140°C) which affects the quality of adhesion between silver layer and polyamide surface in conductive yarn after washing. Moreover water temperature and detergent lead to damages of fibers and small fractures which affect negatively the adhesion between silver coating and polyamide yarn and therefore electrical conductivity of embroidered electrodes. The TPU film used here is not a good solution to protect lines. Nonconductive yarn protected the inner conductive yarn from surface damage during washing and also from the effect of detergent. Consequently, according to our results, the best choice is to use Madeira yarn protected by nonconductive yarn to make bands.

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