

ORIGINAL RESEARCH

PRELIMINARY TESTING OF FLEXIBLE ELECTRODES FOR BIOSIGNAL MEASUREMENT: ABRASION RESISTANCE

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Abstract

With growing interest in monitoring the health status of a human has raised demands on measuring systems and devices. It is important to develop monitoring system with user friendly and comfortable interface. This applies not only to setup and control but also to wearing and manipulation. Therefore, the replacement of conventional metal, rubber and self-adhesive electrodes by electrodes with thin-film conductive layer is desirable. These electrodes combine good electrical properties altogether with comfortable wearability, ease of manipulation and low-cost fabrication. The indicated factors allow these electrodes to be used in commercial measuring systems and devices. Their applicability in long term measurements is subject to meeting additional requirements, such as chemical and mechanical resistance. Abrasion caused by rubbing the human skin during standard measurements might affect the functionality of the electrode. Four types of electrodes based on Au, ITO, Graphite filled polymer and PEDOT:PSS underwent series of testing of their abrasion resistance. A surface with specific roughness and pressure force was used. A change in amplitude of testing ECG signal was measured as a function of number of abrasion cycles for all electrodes.

Keywords

Conductive polymers, PEDOT:PSS, flexible electrodes, abrasion resistance, ECG

Introduction

In the last decades the length of human life dramatically increased. According to the World Health Organization (WHO), the number of people older than 60 years will rise over the next 30-40 years. Expected is an increase from 600 million in the year 2000 to almost 2 billion by the year 2050 [1]. Elderly people are more susceptible to various diseases that affect the heart, muscles, respiratory tract, etc. Careful monitoring of ECG and EMG biosignal, HRV monitoring, respirometry, etc. can help early diagnostics of variety of illnesses and provide an automatic notification to a doctor or nurse. To make this possible, it is necessary that we monitor the signals continuously, also during routine activities of the patient. This is important to obtain relevant data about people suffering from, for example, white coat hypertension. White coat hypertension (WCHT) is a phenomenon in which patients exhibit elevated blood pressure in a clinical setting but actually are normotensive. In a study realized by Helvacı and Seyhanlı from 438 randomly chosen consecutive patients almost 43 % were suffering WCHT [2]. There are many types of daily monitoring equipment available that help

to diagnose the WCHT but they still use rigid electrodes, long cables and heavy control units. These devices do not provide comfortable usage and can affect measured data. For these reasons we are trying to develop a monitoring system that eliminates all these discomforts. It uses a miniature precision ECG Holter, which can be placed around patient's neck. Conventional electrodes can be replaced by flexible ones. Flexible electrodes made of thin-film conductive material deposited on a flexible substrate offer good signal quality, while retaining low fabrication cost, wearability, and comfort during measurement. Flexible electrodes compared to rigid electrodes have substantially shorter life span during which they maintain stability and good signal quality thus may be considered disposable. Since rigid electrodes are reusable and can be washed and placed repeatedly, the value of the electrode is multiplied by its usable life. Hence, in relation to final price of the product, the fabrication of a flexible electrode should be relatively easy and low-cost to make it competitive with rigid electrodes.

Materials used as conductive layers were selected according to their availability and our previous work. This expedited the preparation of the individual

electrodes and we could quickly test their qualities in biosignal monitoring. We have chosen materials commonly used in electronics to form thin-film layers, which had the required electrical and mechanical properties, specifically gold and indium tin oxide (i.e. ITO). However, many recent studies are focused on highly conductive organic materials such as polyaniline, polypyrrole, and polythiophenes to offer cheaper and rapidly processable alternative. Other perspective organic conductive material is poly(3,4- ethylenedioxythiophene):(styrenesulfonic acid) (i.e. PEDOT:PSS), which can replace conventional metal electrodes. It can be applied to a substrate using deposition techniques such as spincoating or ink jet printing. Doping of PEDOT:PSS can dramatically increase its conductivity (to 100 Ohm/sq) [3]. The final material used for thin-film conductive layers was commercially available graphite-filled polymer.

This work is focused on comparison of 4 types of electrodes made of different conductive materials and their abrasion resistance. We simulated mechanical stress nascent through friction electrodes on the skin and how this stress affects measured ECG signal generated by ECG simulator. Thin-film flexible electrodes were based on following materials: (i) metal, (ii) transparent conductive oxide, (iii) polymer with graphite filling, and (iv) organic conductive polymer. Mutual comparison of selected electrodes demonstrates capabilities to serve as an alternative to bulk rigid electrodes.

Methods

Electrode fabrication

To verify the mechanical resistance of thin-film conductive layer to abrasion, we prepared a set of electrodes which have undergone testing. Electrodes were produced with contact on a bottom side made of commercially available conductive adhesive and a copper wire. Thin-film conductive layer was prepared with approximately 3 mm offset from the edges of flexible substrate (as shown in Fig. 1). To provide suitable material comparison electrodes were made of four different materials: (i) gold, (ii) ITO, (iii) graphite-filled polymer, and (iv) PEDOT:PSS. All above materials were chosen with regard to their properties and availability. We tried to combine variety of types of materials: inorganic, organic, transparent, composites, polymers, and metals. A short overview of properties of selected materials is shown in Tab.1.

Polyester foils (2.5 cm × 5.0 cm) were used as substrates for conductive flexible electrodes. Gold film (100 nm thick) was fabricated by vacuum evaporation using Ni adhesion layer (5 nm thick) through the shadow mask in vacuum of 8×10^{-6} Pa or better and exhibited sheet resistance of about 0.6 Ω /sq. Transparent ITO film (provided by VisionTek Systems, UK) with thickness of 100 nm achieved sheet resistance of 100 Ω /sq. Graphite-

filled polymer film (Bare Conductive, UK) was fabricated by doctor blade technique with dry film thickness of 50 μ m and sheet resistance of 120 Ω /sq. The PEDOT:PSS films were fabricated from 1 wt% aqueous solution (from Heraeus, Germany), where sorbitol was added to the solution (4 wt%) to increase the conductivity. PEDOT:PSS solution was filtered through 0.22 μ m syringe filters to remove insoluble particles, deposited on a substrate by spincoating (2000 rpm), and subsequently annealed at 200 °C for 5 min in order to

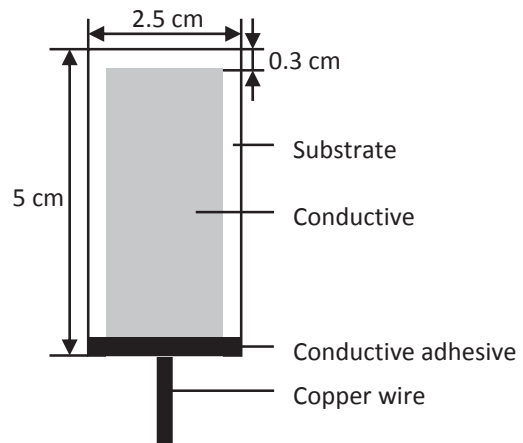


Fig. 1: Electrode geometry and composition.

remove water from the layer. Fabricated films were 100 nm thick and exhibited sheet resistance of 100 Ω /sq.

Tab. 1: Properties of electrode materials.

| Electrode material | Transparency | Sheet resistance (Ω /sq) | Fabrication costs (EUR/electrode) |
|-------------------------|--------------|----------------------------------|-----------------------------------|
| Gold | No | 0.6 | 6.1 |
| ITO | Yes | 100 | 0.9 |
| Graphite-filled polymer | No | 120 | 0.4 |
| PEDOT:PSS | Yes | 100 | 0.4 |

Testing method and process

There is a standard for testing ECG electrodes [4], but that require testing wide range of parameters like biocompatibility, shelf life, adhesive performance, etc. For preliminary testing of selected materials we have used simpler but non-standard method to determine the effect of mechanical stress on the signal measured by flexible electrodes. We had to create a test station, i.e. ECG patient simulator. This setup consists of ECG signal generator based on programmable system on a chip by Cypress semiconductor, a voltage divider and electrodes simulating human skin surface. The generated signal designed by Matlab software package was used to test the electrodes (as shown in Fig. 2). ECG measurement was

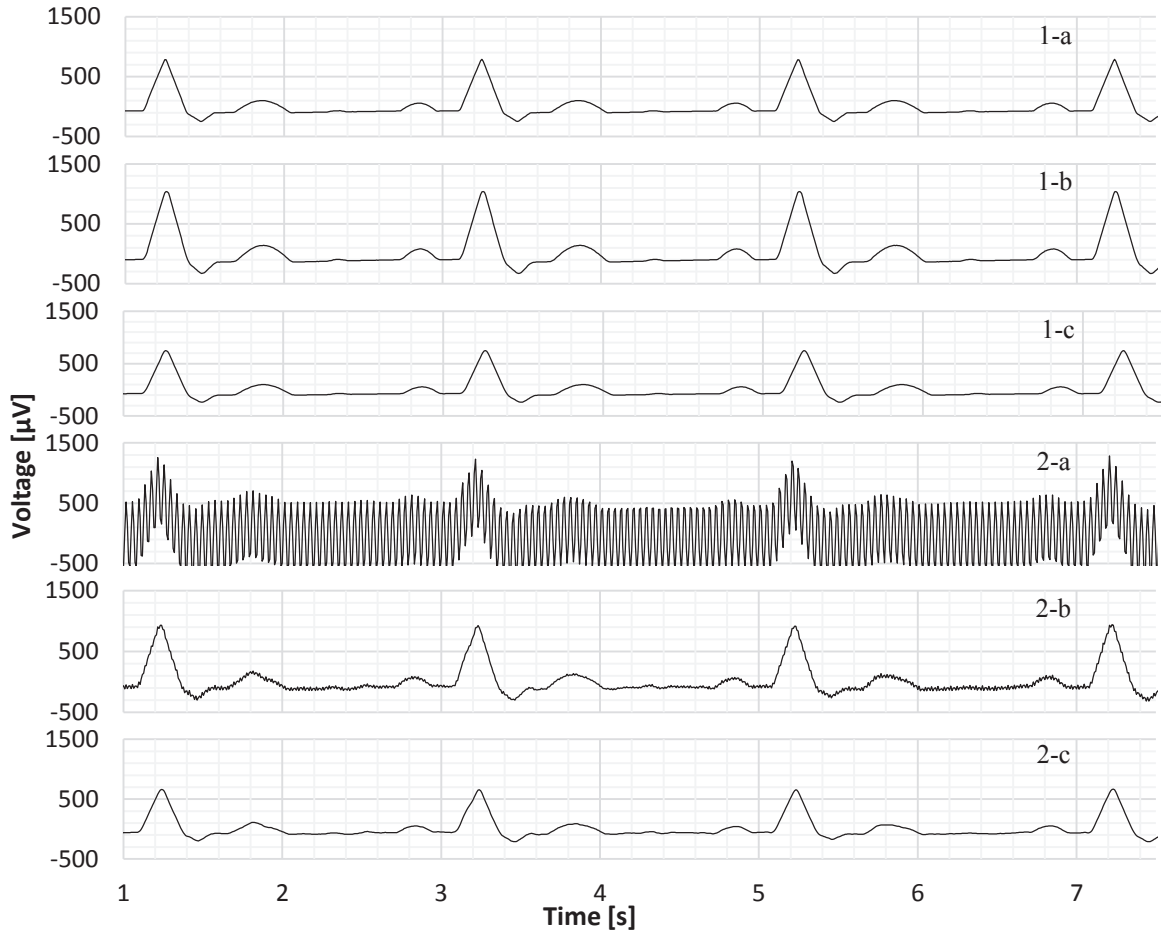


Fig. 2 Comparison of measured signal with initial conditions (1) and after 50 abrasion cycles (2). In both cases graph a shows unmodified original signal, graph b shows signal with FIR filter applied, and graph c shows floating average of original signal.

performed by mini ECG holter developed at our institute [5]. To simulate friction between skin surface and electrodes, we have created an abrasion tool, which consisted of a plate made of acetal copolymer (i. e. POMC), dimensions of 4 x 5 cm, and a filter paper KA 4 (from PAPIRKA Perštejn s.r.o., CZ) attached to bottom side. The plate was created with a pocket for two 100 g weights to achieve better balance.

One abrasion cycle was defined as a swipe of the abrasion tool from one edge of the electrode to the opposite by entire width of the tool. Measuring the impact of abrasion on signal quality was carried out after placing the electrodes on dry ECG simulator and covering them with 500 g weight. During the measurement, the electrodes had static position, herefore motion artifacts did not affect the relevance of individual electrodes comparison.

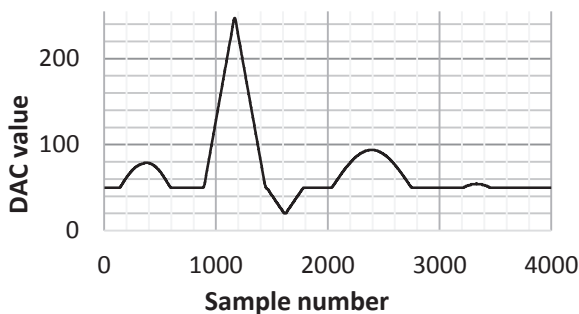


Fig. 3: Simulated ECG signal by Matlab.

Results and Discussion

During the measurement, we found out that despite the fact that we used measuring system isolated from AC power, altogether with reducing conductivity of electrodes we measured a not negligible 50 Hz noise. This problem can be seen also in professional ECG measurement devices. In our case the noise is caused by decrease of electrode conductivity. It can be eliminated using right leg drive electrode. It was necessary to filter the signal. A comparison of different filtering techniques can be seen in Fig. 3. These graphs show that the FIR filter significantly amplifies the signal and do not reduce

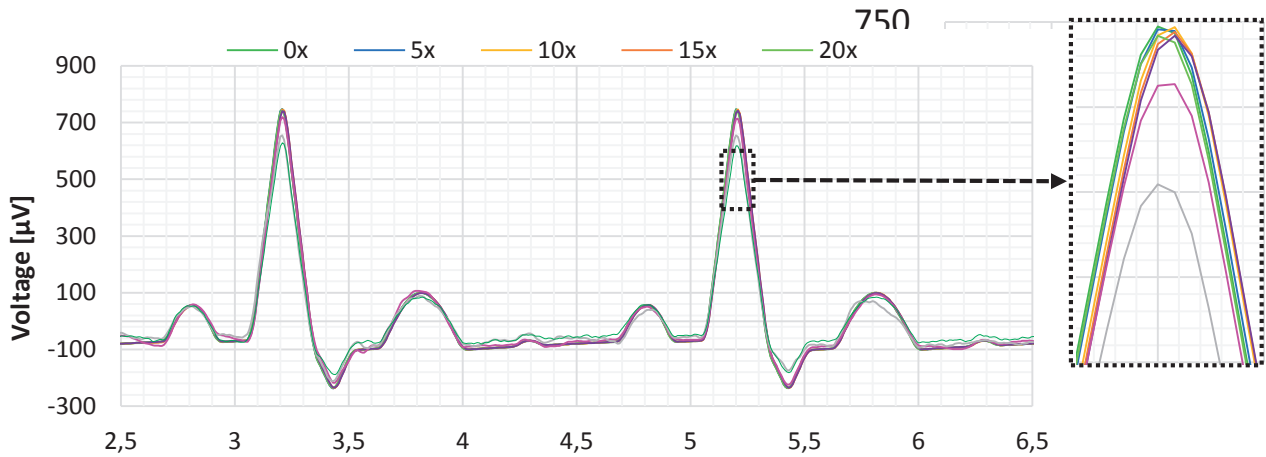


Fig. 5: Direct comparison of data measured on PEDOT:PSS electrode as a function of number of abrasion cycles.

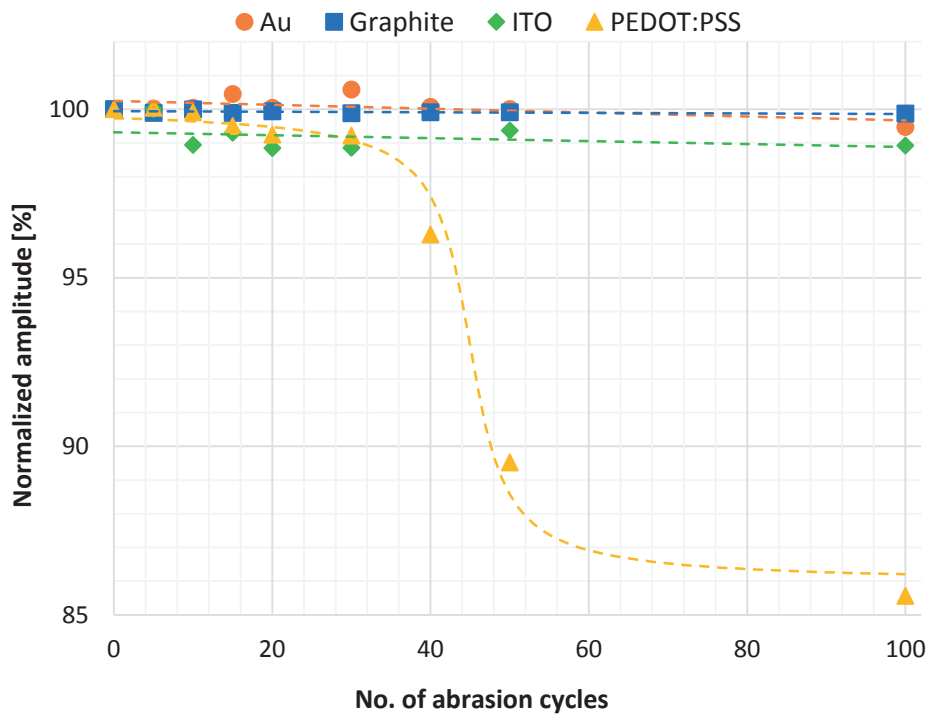


Fig. 3: Dependence of normalized amplitude on the number of abrasion cycles.

all the noise. On the other hand, the method of floating average with period of 5 samples proved its ability to be used for signal processing.

We compared processed data in a direct way (Fig. 4). It is obvious that measured signals have significant changes in its amplitude but not in its shape. Due to this fact we could normalize amplitude values by the initial value and make a comparison of individual electrodes on the basis of amplitude decrease, depending on the number of abrasion cycles (Fig. 5). All the materials resisted almost half of performed abrasion cycles without significant change in signal quality. In further cycles, deep scratches in sub-micron thin layer of PEDOT:PSS

started connecting and cutting off large areas of conductive material. This phenomenon greatly reduces the amplitude of testing ECG signal.

Conclusion

This work deals with possible replacement of conventional ECG electrodes used in measuring systems and devices for continuous measurement. We compared different types of conductive thin-film layers on a flexible substrate. Selected organic and inorganic materials were tested for their abrasion resistance. As

expected, the thicker layers were more resistant, but surprisingly only 100 nm thin layer of PEDOT:PSS could resist comparably well. After half of the cycles amplitude decrease was less than 10 % and after whole test the decrease was nearly 15 %. This points out the possibility of using PEDOT:PSS based electrodes for daily monitoring of ECG. Further tests can demonstrate the possibility of using it in long-term monitoring. Whereas the polymers, as well as PEDOT:PSS, offer low-cost and easy fabrication process, they have the potential to replace rigid electrodes for measuring ECG signals in many cases. In our future work we will focus on PEDOT:PSS as a conductive material and we will pass all necessary experiments for standardization process.

Acknowledgement

This work has been supported by the Scientific Grant Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic and of the Slovak Academy of Sciences under contract no. VEGA 1/1177/12 and Slovak Research and Development Agency under the contract no. APVV-0865-11 and contract no. APVV-0819-12.

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