SMART MATTRESS TOPPER WITH ENHANCED HYGIENIC PROPERTIES FOR ECG MEASUREMENT AND DETECTION OF POSITION

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Abstract: *The contribution focuses on technical solution and confirmation of functionality of a prototype of a smart mattress topper with enhanced hygienic properties, designed for monitoring of human bio-medicinal data in real time. It involves integration of progressive technologies in a form of low-temperature atmospheric-pressure plasma, application of nanotechnologies in a form of an antimicrobial nanosol and integrated sensing system for monitoring electrical activity of the heart (ECG) and position of a lying person. The sensing system consists of a set of active ECG capacitive textile electrodes with incorporated microelectronics, capacitive sensors for detection of presence and position of a lying person, passive DRL electrode, data, control and communication elements integrated into construction of the mattress topper with an own mobile application. Functionality of prototype of the mattress topper will be demonstrated by measurement of ECG and position of a lying person by means of a patient simulator as well as a real person.*

Keywords: *smart topper, antimicrobial nanosol, low-temperature plasma, ECG, position detection.*

1 INTRODUCTION

Cardiovascular diseases belong among leading causes of death in Europe and they are responsible for more than 50 % of all deaths [1]. The cardiovascular diseases can be indicated, but mainly reduced by a soon diagnostics, suitable disease management, rehabilitation and prevention [2]. Electrocardiogram (ECG) sensing represents a traditional diagnostic method often used to monitor human health and diagnose potential cardiovascular diseases. The conventional method of ECG sensing uses electrodes and electro-conductive gel in direct contact with skin surface of an examined person. A special feature of this type of measurement is high quality of measured signal due to low transfer resistance between the electrode and the skin (when using an electro-conductive gel). On the other hand, long-term measurement is uncomfortable and can cause allergic skin reaction in some cases. In recent years, capacitive sensing of ECG signal avoiding direct conductive contact between the electrode and the skin of an examined person is being developed. This unconventional method of capacitive sensing has been successfully integrated e.g. into office arm-chairs, car seats or beds [3, 4]. Decubital ulcers (bed sores) arise frequently in immobile, usually older, long-term lying patients and/or patients with a diagnose requiring monitoring of their health condition in a bed. This primarily concerns the lesions caused by circulatory insufficiency due to pressure applied on the affected place between a bone and a base, when insufficient congestion takes place. Therefore, prevention of genesis of decubital ulcers is identification of position and regular displacement of a lying patient.

The developed original proposal of a prototype of smart mattress topper „ECG-SmartSheet“ with enhanced hygienic properties designed for monitoring of human biomedical data in real time constitutes a system of unobtrusive long-term monitoring electric activity of the heart (ECG) and position of a lying person over the day and/or during sleep. An efficient and advanced design of a smart mattress system is involved. Progressive technologies used on elaboration of the project included:

- plasma finish: activation of the surface by low-temperature plasma under atmospheric pressure aimed at achievement of improved adhesion of the functional nano-coating on the textile material used as basic material for development of the mattress topper;
- nanotechnologies: application of antimicrobial nanosol with incorporated nano-particles on the plasma activated textile surface aimed at creation of nano-structured surface with high adhesion to achieve functional hygienic properties of the mattress topper;

- smart technologies: integration of a system of active textile capacitive ECG electrodes with incorporated microelectronics, power, data, control and communication components into construction layers of the mattress topper using innovative antimicrobial (AMB) nano-coated textile material, customized algorithms and mobile application.

2 TECHNOLOGIES AND MATERIALS

The mattress topper consists of a protective removable shell and a core consisting of several internal layers on which functional components of the sensing system are placed. The sensory part of the mattress topper consists of active textile ECG capacitive electrodes with incorporated microelectronics, designed to monitor electric activity of the heart (ECG) and textile sensors designed to detect presence and position of a lying person, made on a base of electro-conductive textiles. A customized application developed for readily available imaging equipment allows assessment of the sensed data in real time.

2.1 Construction of the mattress topper

Shell of the mattress topper consists of an upholstery fabric pre-finished by activation of its surface structure using low-temperature atmospheric-pressure plasma and subsequently finished by an antimicrobial nanosol imparting hygienic properties to the mattress topper during its long-term use. Permanency of the antimicrobial nanofinish on the surface of the upholstery fabric has been evaluated after 20 washing cycles performed using 4N process according to STN EN ISO 6330 and its antibacterial efficiency has been evaluated according to AATCC TM 100 and expressed as a percentage of bacterial reduction of Staphylococcus aureus. The achieved bacterial reduction after 20 washing cycles was on a level of 50% (bacteriostatic efficiency). A positive influence of the pretreatment by activation of the surface of the upholstery fabric using low-temperature plasma on enhancement of affinity of the antimicrobial coating to the surface of the upholstery fabric has been demonstrated by bacterial reduction, which was higher by about 35% in comparison with an upholstery fabric finished by the antimicrobial nanosol under the same conditions without activation of the textile surface by low-temperature plasma.

On a face side of the surface of the shell of the mattress topper there is a set of active ECG capacitive textile electrodes with incorporated microelectronics and a reference active ECG capacitive textile electrode for monitoring heart activity, creating an eight-lead system of ECG measurement. On the shell of the topper there is also a passive textile DRL electrode to repress technical artefacts, primary interference from the electrical network. Electronics of the ECG electrodes is placed on a flexible circuit board and it is conductively connected with the textile sensor. Connection of the electrodes is terminated by a power take-off connector, connected to the control unit.

In construction of the core of the mattress topper there are pressure capacitive textile sensors for detection of presence and position of a lying person. The pressure sensors are connected by an electro-conductive sewing thread. Between the pressure sensors there is a dielectric, which on change of the pressure changes its thickness and this way capacity of the pressure sensors changes as well. The pressure sensors allow to monitor not only presence of a patient in the bed, but also distribution of pressure on the topper and monitor this way the most vulnerable places of human body for the purpose of positioning a long-term lying patient. The pressure sensors are connected with the circuit board by a connector connecting the conductors conducting signal further to the sensing unit which passes the information to the control unit.

The control unit captures signals from the electrodes, performs their further analog processing, digitizing of the data and their transfer to a computer by means of universal serial bus (USB). A basic element of the control unit is an eight-canal integrated circuit, analog-digital (AD) convertor with internal reference and adjustable amplification, sampling frequency and microcontroller ensuring communication with a personal computer. A prototype mobile application has been developed for analysis, evaluation, display and storage of the sensed data as well as for display of a position. It monitors actual state of the patent in real time.

The active ECG capacitive textile electrodes and passive pressure capacitive textile sensors have been made from electro-conductive fabrics with electric resistivity of 1.5 Ω/10 cm, creating their sensing part. An advantage of the textile electrodes is a pleasant feel, elasticity and ability to adapt to contours of a human body what enhances comfort of a man during his stay in bed and ECG measurement. The electrical conductivity of the fabrics used to prepare the textile sensors and electrodes ensures functionality of the whole sensing system integrated into construction of the mattress topper. Influence of washing and mechanical abrasion on change of the surface electric resistance and electric conductivity of the electro-conductive textiles has been evaluated after 20 washing cycles using 4N process. Functionality of the fabrics designed for sensing of ECG and position of a person has been confirmed. The electric resistance of the fabrics increased after 50 000 abrasions to a level of 19 Ω/10 cm, whereby the fabrics preserved their appearance without significant changes. Tests for human-ecological properties of the applied electro-conductive textile materials have been performed according to test methods of the international association OEKO-TEX® to confirm health safety and health protection of a consumer: determination of forbidden disperse dyestuffs classified as allergenic, carcinogenic and other forbidden dyestuffs, determination of extractable heavy metals, determination of total quantity of lead (Pb) and cadmium (Cd), determination of total quantity of silver, determination of polycyclic aromatic hydrocarbons (PAH), determination of phenol, chlorinated phenols and orthophenylphenol (OPP) and determination of pH of water extract. No presence of health harmful substance has been determined in the applied electro-conductive textiles. The determined quantities have been under detect limit and they meet the required limit concentrations of harmful substances for textiles and clothing products for children up to 3 years of age, for direct and indirect contact with the skin according to the technical requirements of the standard STN 80 0055 and the international OEKO-TEX® Standard 201.

2.2 Capacitive measurement of ECG

The principle of capacitive ECG sensing is that the active ECG textile electrode constitutes one plate of a plate condenser and surface of human skin constitutes the second plate of the plate condenser. A dielectric layer is placed between these two plates; the most frequently this layer is a layer of cotton clothing in which a lying person is dressed during measurement. Capacity of such a condenser is calculated according to the formula 1:

$$C = \varepsilon_0 \varepsilon_r \frac{S}{d} \tag{1}$$

where *S* is surface of condenser plate, *d* is distance between the condenser plates, ε_0 is permittivity of vacuum and ε_r is dielectric permittivity.

If surface of an electrode is 25 cm^2, dielectric material is a cotton fabric with 0,5 mm thickness and 2.077 permittivity [5], capacity of the plate condenser will be approximately 92 pF. The active ECG electrode incorporates a low-noise operational amplifier in connection of a voltage tracker. Static charge of the condenser is discharged by means of R resistor. Combination of C condenser with R resistor creates a filter whose limit frequency is calculated according to the formula 2:

$$f_c = \frac{1}{2\pi RC} \tag{2}$$

If value of the resistor will be 2 GΩ, then the cut off frequency of the filter will be 0.87 Hz. Such a filter will enable to remove unacceptable biological artefact caused by breathing.

2.3 Position sensing

Hardware and software modules have been developed to detect presence and position of a lying person. Result of sensing presence of a person in a bed using a method of measurement capacity between two pressure capacitive sensors can be shown in two ways:

a) curve representing sensed capacity in real time for a pushed sensor (Figure 1b) and/or a non-pushed sensor (Figure 1a).

b) using a color map (color squares), representing a more sophisticated method to display change of pressure by presence of a person lying in a bed.

Data obtained by measurement can be transformed to „pictures“ where the individual cells will represent pressure intensity. Innovative algorithms known from recognition of a picture and software developed for the purpose of data monitoring and data capture from the sensors in real time are used in the developed module. After starting the measurement the measured values are recorded and at the same time level of pressing the sensor is shown in graphical form by means of colors. Each square in the map represents one sensor and capacity is represented by coloring the square. Unloaded (non-pushed) sensor is represented by blue color and pushed sensor by yellow color. Such a color map displays position of a patient in a bed. Pressure sensors of matrix 2x2 sensors in „quiescent“ condition are shown in Figure 2a, from which is can be seen on the base of the color map, that the sensors are not loaded. In Figure 2b one square is yellow; it means that the sensor in left upper corner was pressed. In Figure 2c it can be seen a case when the right lower sensor was pressed. After completion of the measurement it is possible to store the data for subsequent use when training the innovative algorithms for detection of position of a man.

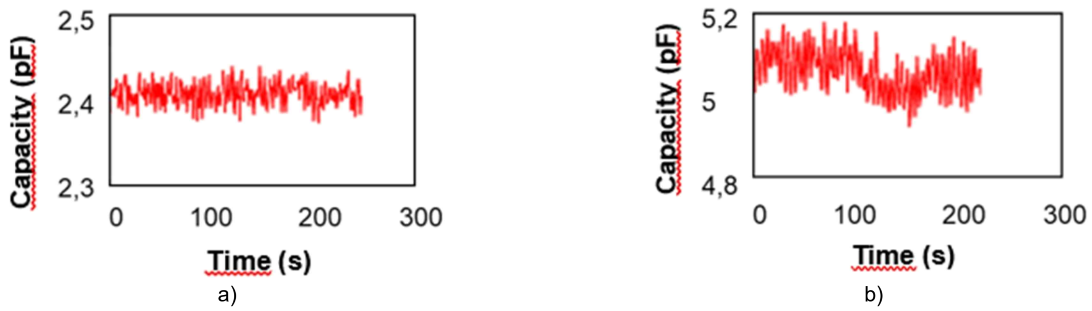
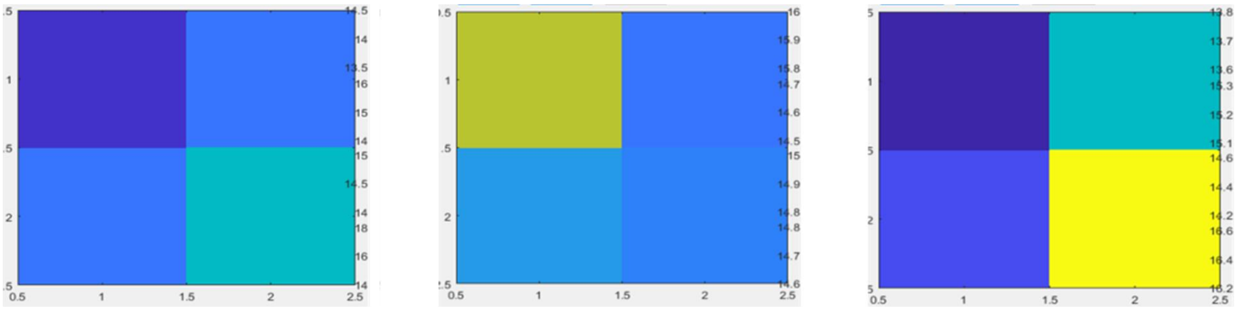


Figure 1 Capacitive curves: a) non-pushed sensor, capacity about 12.4 pF; b) pushed sensor, capacity about 15.1 pF



a) b) c)

Figure 2 Color map representing: a) non-pushed sensors; b) pushed left upper sensor; c) loaded right down sensor

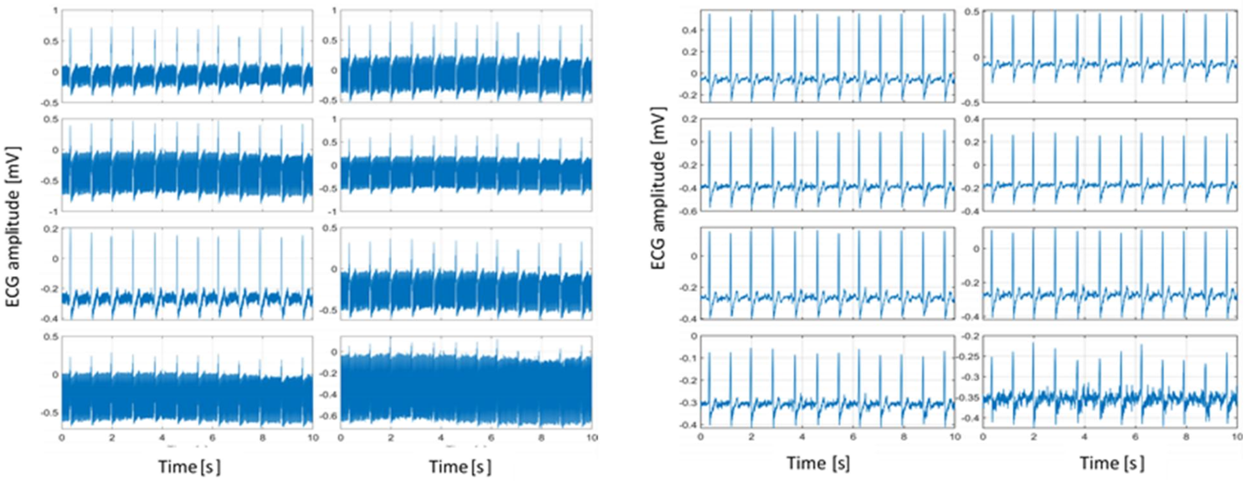
3 RESULTS AND DISCUSSION

Functionality of the cover of the mattress topper has been evaluated on a person lying on his back for 1 hour (Figure 3).

Figure 3 A proband lying on the developed mattress topper

The subject wore nightdress made from cotton fiber. Sampling frequency was adjusted to 250 Hz. Amplification was adjusted to value 6 for all channels with the exception of channel No. 2 and No. 3. Signal in these channels exceeded the range on amplification 6 and therefore amplification in these channels was reduced to 4. DRL circuit was active and signal for DRL circuit was derived from all input channels. Raw ECG record is shown in Figure 4. The channels are arranged in lines, i.e. channels No. 1 and No. 2 are shown in the first line. It is obvious from the figure that signals in the channels are influenced by noise differently and show also different offset. This phenomenon is caused by local differences in distribution of electrical potential on the skin, accumulation of static charge and different pressure of the electrodes.

Although DRL circuit has been used and electronics of the active electrodes have been shielded, the output signals comprise considerable noise on the frequency of 50 Hz as it is evident from the power spectral density (PSD) in Figure 5. A narrow band notch filter for 50 Hz, applied to all channels, has been proposed to reduce the noise. ECG record after application of the filter is shown in Figure 4b. The main problem is electrostatic charge and movement artefacts. The movement artefact causes saturation of the operational amplifier inputs and it can take even several seconds until the signal has been stabilized again. Solution of this problem consists in application of a special electronic circuit grounding temporarily inputs of the operational amplifier as soon as a signal gets outside the measuring range [6].



a) b)

Figure 4 Eight-channel ECG record measured from the cover of the mattress topper: a) raw, b) filtered

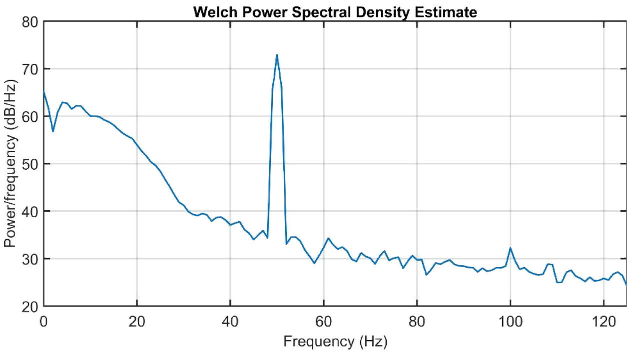


Figure 5 Power spectral density (PSD) of the channel No. 1

The measured signals clearly show visible course of the ECG signal, suitable for subsequent analysis. Although not all canals are without disturbing arfefacts, incidence of these artefacts in some canals does not represent any risk from a viewpoint of determination of diagnosis as the applied algorithm selects for the needs of diagnosis only the canal with the best signal quality.

A graphical display of results from measurement of capacity using colour map (colour squares) was selected to measure position of a lying person on a prototype of the mattress topper (Figure 6).

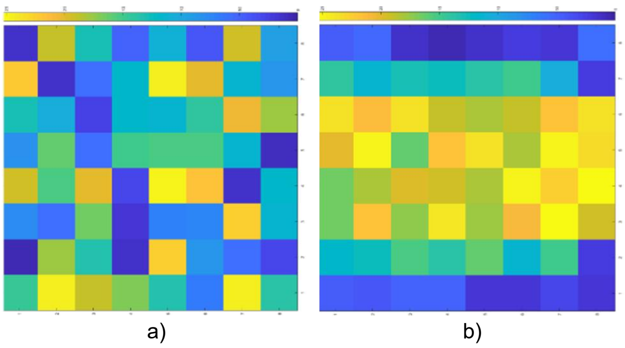


Figure 6 Detail of colour map of the matrix of sensors of position: a) without shielding; b) with shielding

From a viewpoint of monitoring position of a patient it is not necessary to know concrete value of capacity but only its change. Each square in the map represents one sensor and capacity is represented by colouring the square. Unloaded (unpushed) sensor is represented by blue colour and loaded sensor by yellow colour. Influence of shielding on measurement and values of capacities sensed using the sensors is shown in Figure 6a, when measurement was performed without shielding and in Figure 6b, where measurement was performed with an applied shielding layer. Shielding layer of the electroconductive fabric has been inserted between shell of the mattress topper and the passive pressure capacitive textile sensors. While from results measured without shielding it is not possible to identify unambiguously a lying person (influence of spurious capacities), after introduction of a shielding layer to the construction of the mattress significant improvement is visible which allows identification of area of a lying person and distribution of pressure cause by weight of a body on the topper.

4 CONCLUSION

The matter of prevention of cardiovascular diseases is very actual, important and necessary not only in the Slovak Republic but world-wide at present. The proposed prototype of smart mattress topper “ECG-SmartSheet“ with enhanced hygienic properties, designed for monitoring of bio-medicinal human data in real time ensures ECG monitoring of a patient on capacitive principle in lying position as well as detection of presence and position of a lying patient in a bed. It is a conjunction of progressive technologies for textile finishing such as plasma treatment and nanotechnologies with application of smart technologies such as smart systems for biodata collection with subsequent positive impact on socio-health aspects of social and demographic development. The smart topper „EKG-SmartSheet“ is a functional system of contactless and unobtrusive long-term monitoring of human vital functions in health service establishments or in the domestic environment. Sensing bio-potentials using textile electrodes prepared from electro-conductive textiles is a progressive solution of measurement of ECG signal without direct contact with human skin. The method of contactless measurement of ECG signal becomes an alternative of common Ag/AgCl electrodes used at present in health service establishments. The textile electrodes act as dry electrodes allowing measurement of ECG signal without electrolyte gel or adhesives. Besides, application of textile material with antimicrobial nano-coating with plasma application ensures permanently enhanced functional hygienic properties during the long-term use even after 20 washing cycles and/or after multiple abrasion of the surface of electro-conductive textiles in the form of textile sensors and/or ECG electrodes. Besides, from a viewpoint of materials used in the construction of mattress topper, health safety and maximal protection of consumer health has been confirmed according to the test methods of the international association OEKO-TEX® Standard and technical requirements of the standard STN 80 0055.

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