Peculiarities of noncontact cardiac signal registration

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Abstract. The goal of actual research was to test the possibility of electrocardiogram registration through the layer of dielectric material and compare the received signal with the electrocardiogram recordings obtained through resistive contact between skin and electrodes. Several prototypes of the devices for electric cardiac signal registration were designed, assembled and tested. The comparison among recorded electrocardiograms is performed. Differences between cardiac signal recordings obtained by means of the ohmic contact and through capacitive link over dielectric environment are demonstrated.

1. Introduction
One of the relevant problems in biomedical and electronic engineering is electric cardiac signal (ECS) registration through dielectric environment such as clothing. The motivation of research in this field is to increase the number of patients coming through electrophysiological observation per unit of time thanks to decreasing the amount of work for electrodes installation: the classic contact electrocardiogram (ECG) registration devices require the maintenance of stable low-resistance contact, which leads to the necessity of conductive gel application, requires the using of suction cap electrodes (with the alternative in flat electrodes for single use) and long wires. These circumstances restrict the area of use of contact ECG systems to the clinical monitoring. Application of the contact ECG devices in the camp conditions, in smart clothing and wearable accessories is quite limited. Despite that, the minimal bill of materials in electronic circuit of the simplest contact ECG device includes just one instrumentation amplifier, several operational amplifiers and sufficient number of passive components. Also the contact ECG systems were successfully approbated during decades of manufacturing and operation for biomedical purposes.

There are many lab prototypes and very few industrially produced noncontact ECG registration devices which can record the ECS through dielectric layer between skin and sensor surface. The ideal noncontact ECG registration device shouldn’t have any resistive contact with the patient’s body: all electric conductors of the device should be isolated with at least one dielectric layer.

2. Problem definition
When developing an ECG registration system, an engineer has to deal with signals in the millivolt scale [1]. The frequency band of the ECS is limited to several hundred Hertz, in practice all useful information is enclosed in a band from 0.05 Hz to 100 Hz. Overlapping with the frequency of mains power line, ECS is sensitive to the corresponding 50/60 Hz interference, thus special attention is paid to the methods of mains hum reduction in the field of ECG registration. In addition to mains hum, there are several factors that complicate the development of any ECG monitoring system:
- noise generated by the electrode-skin contact;
- patient’s movements affecting the resistance of electrode-skin contact;
- electromagnetic interference from various electronic equipment;
- electric potentials generated by muscle activity – electromyographic (EMG) artefacts.

The experiments show that the last of the factors is the most significant and hard-to-remove: the cardiac muscle contractions and the activity of musculoskeletal system are phenomena of the same nature. In this regard, one of the possible methods to eliminate the influence of EMG artefacts on the quality of the resulting ECG is a simple rejection of ECS data at the time of high muscle activity. An accelerometer can be used to identify the peak EMG activity moments.

Analysis of papers [2-4], devoted to the development of systems for noncontact ECG registration, leads to the following conclusion: the noncontact technique deals with extremely high impedance of the signal source. The signal is coming through the skin-electrode capacitance of several pF to the front-end amplifier. Thus, the noncontact ECS measurement requires the direct current (DC) biasing of the signal inputs using a circuit with ultra-high ohmic resistance. The front-end amplifier should have ultra-low input leakage currents.

In ideal conditions that ensure the minimum impact of electromagnetic interferences, in particular mains hum, the noncontact ECS registration system is fairly feasible [5][6]. Herewith the distance to the electrodes may be quite long (at least centimeters), or the electrodes can be separated from the surface of the skin with several layers of cotton fabric. However the stability of noncontact ECG monitoring technique in the real world filled with electromagnetic disturbances is under discussion.

3. Results and Discussion

Several prototypes for contact and noncontact ECG registration were assembled on the printed circuit boards (PCB). All circuitry and electrodes are located on the same PCB for better mains hum elimination. First prototype (figure 1) has tinned electrodes without any covering; second and third devices have a layer of solder mask on the electrodes. Each prototype has three electrodes: two sensors and one so called driven right leg (DRL) electrode. The difference of potentials between sensors is amplified and recorded by means of a sound card inside a laptop. The DRL electrode is used for common-mode suppression. The assembled devices are supplied through USB port of the laptop. The laptop is powered by internal lithium-ion battery and disconnected from the mains power line during ECG registration. The PCB is placed on the left side of the thorax during the experiment. The appearance of the prototypes and obtained ECS recordings are shown below.

![Figure 1](image-url)

Figure 1. Top layer (a) and bottom layer (b) of the first PCB with uncovered electrodes.

The top layer of the first prototype’s PCB has active shielding over sensing electrodes. The bottom layer contains several isolated areas: sensing electrodes on the left side and on the right side, DRL electrode at the centre. The linear dimensions of the PCB are 64.2 mm (length) by 36.7 mm (width). ECG recorded by first prototype through direct contact between skin and electrodes is shown in figure 2.
Figure 2. ECG recorded through direct contact with the skin. The DRL driver gain is -10. No filtration applied.

ECG obtained through the layer of cotton textile is presented in figure 3. The DRL electrode has direct contact to the body through right hand touch. Since the direct skin-sensor contact is absent, the signal to noise ratio is considerably decreasing.

Figure 3. ECG recorded through the layer of cotton fabric. The DRL driver gain is -200. The 50 Hz notch and 100 Hz lowpass digital filters are applied.

The second prototype’s PCB has solder mask covering on the electrodes. Long accordion-like tracks connected to the reference voltage source (half-supply voltage) are added to the sensors to create the DC biasing through leakage currents. The appearance of the PCB is shown in figure 4. The recorded ECGs are presented in figures 5, 6, 7. The 50 Hz notch and 100 Hz lowpass digital filters are applied to the received ECS.
Figure 4. Top layer (a) and bottom layer (b) of the second PCB with solder mask covered electrodes.

Figure 5. ECG recorded through the solder mask. The DRL electrode has direct contact to the body through right hand touch. The DRL driver gain is -10.

Figure 6. ECG recorded through the solder mask. All electrodes are capacitively coupled to the body through the solder mask. The DRL driver gain is -1000.
Figure 7. ECG recorded through the layer of cotton fabric and the solder mask. The DRL electrode has direct contact to the body through right hand touch. The DRL driver gain is -1000.

In the third prototype the DRL circuitry and accordion-like tracks are unified (figure 8). The DRL signal consists of the DC reference voltage plus the inverted and amplified common-mode. Obtained ECGs are shown in figures 9, 10. The hum notch and 100 Hz lowpass digital filters are applied.

Figure 8. Top layer (a) and bottom layer (b) of the third PCB with solder mask covered electrodes.

Figure 9. ECG recorded through the solder mask. All electrodes are capacitively coupled to the body. The DRL driver gain is -1000.
Figure 10. ECG recorded through the layer of cotton fabric and the solder mask. The DRL electrode has direct contact to the body through right hand touch. The DRL driver gain is $-10^0$.

4. Conclusion
Presented signal recordings are promising for further research in direction of increasing the signal to noise ratio to improve the quality of noncontact ECS registration technique. Obtained ECGs prove that the noncontact registration system can be put into practice and should have quite stable operation. This system will utilize generally available electronics and hence it will be sold by low cost. The reliability of the noncontact ECG technique depends on several conditions:

- the surface of each electrode should be at least 500 mm$^2$;
- the DRL electrode is directly connected to any limb of the patient or capacitively coupled to the body through an electrode with large surface of several thousand mm$^2$. This electrode can be manufactured as a part of clothing or furniture items.

One of the hindrances for noncontact ECS registration is the patient movements, especially for continuous ECG monitoring outside the clinic. As it stated above, this problem can be resolved with the use of microelectromechanical accelerometer indicating the moments of peak motion activity. The spoiled ECG data recorded in these moments can be simply put out of consideration. Also the mains hum should be deeply rejected by means of hardware notch filter [7] or by using 24-bit analog to digital converter [8][9] (32-bit ideally) and adaptive filtration algorithms.

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