Long-term ECG (electrocardiogram) measurement in patients with burns is a complicated problem since the overlapping of surface contact electrodes can lead to additional injuries. The possibility of ECG recording in patients with burns using capacitive electrodes was not proved, and there are no models of the electrode contact with a patient's body while rehabilitation means are used.

In this paper, the model of the contact between capacitive electrodes and the skin was modified and the circuit model of the contact: skin – bandages (saline solution) – film – active capacitive electrode, was described. The influence of the parameters of a capacitive electrode on the frequency response of the contact of an electrode with skin was assessed. It was found that contact capacitance is crucial to obtain a high-quality ECG signal. The parameters of the impedance of bandages, saline solution, a dielectric film were calculated, and their effect on the frequency response was studied. Based on the modified model, the frequency response of contact was modeled taking into consideration all the calculated parameters; it was found that the resulting frequency response of the contact corresponds to the frequency range of the ECG signal. Analysis of the calculations proves the possibility of using capacitive electrodes when applying various rehabilitation means. It was found that at a change in the impedance of the saline solution from 0.1 gigaohms to 1 gigaohm, the changes in the frequency response of the contact are not crucial for the final quality of the received signal.

All calculations were carried out by modeling in the Qucs environment (ngspice SPICE).

Simulation results can be used in the development of new types of capacitive electrocardiographic electrodes. The proposed model can be used to study other wound covers, as well as to model physiological processes when putting artificial skin and wound covers

***Keywords:** electrocardiography, capacitive electrodes, burn injury, biomedical electrodes, impedance modeling*

UDC 616.71
DOI: 10.15587/1729-4061.2021.228735

DEVELOPMENT OF A MODEL OF ELECTRIC IMPEDANCE IN THE CONTACT BETWEEN THE SKIN AND A CAPACITIVE ACTIVE ELECTRODE WHEN MEASURING ELECTROCARDIOGRAM IN COMBUSTIOLOGY

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Received date 03.03.2021
Accepted date 06.04.2021
Published date 22.04.2021

***How to Cite:** Savchuk, A. (2021). Development of a model of electric impedance in the contact between the skin and a capacitive active electrode when measuring electrocardiogram in combustiology. Eastern-European Journal of Enterprise Technologies, 2 (5 (110)), 32–38. doi: https://doi.org/10.15587/1729-4061.2021.228735*

1. Introduction

As of 2018, about 180 thousand people die in the world every year and on average more than 11 million people received burns and sought medical help [1]. Severe burns on large areas of skin (more than 10–30 %) cause a complex of pathological changes that occur in the organism in response to the influence of a thermal agent, which in turn causes the development of burn disease [2]. One of the methods for diagnosing the patient's condition after significant burns and the appearance of burn disease is the electrocardiogram (ECG) measurement.

At the first stages of burn disease, resuscitation measures are carried out when there are signs of disturbance of the vital functions of a patient's body. During this process, the vital indicators, in particular, ECG signs of the heart muscle pathology, are constantly monitored.

Intensive care is carried out after restoring the basic functions of the body and stabilizing the patient's condition. With successful stabilization of the main indicators, a patient can be transferred to the rehabilitation department to restore the damaged skin areas. Correct and complete reduction of the effect of burn disease on the general condition of the organism reduces the probability of complications in the rehabilitation process.

Atrioventricular, or atrial-ventricular blockages can manifest themselves in patients with burns after surgical and therapeutic procedures, as well as the appearance of myocarditis at the septicotoxemia stage [3].

The possibility of constant ECG monitoring in patients with extensive skin injuries enables the timely and effective reaction to the dynamics of pathological processes and, in general, on patient's passing all stages of burn disease. ECG measurement makes it possible to control, first of all, the pulse and heart rate, as well as to control partially the process of infusion-transfusion therapy and the existence of arrhythmia in a patient. At the stage of toxemia, there occur kidney and adestial function failure, which causes hyperkalemia in a patient, which in turn leads to heart rhythm disorders (bradycardia, asystolia, ventricle fibril). Most changes in the myocardium and pathological conditions of the heart can be diagnosed using the classical ECG method.

The relevance of the study is related to the fact that the use of capacitive electrodes will make it possible to detect pathologies in the work of the heart in the rehabilitation of patients with burns. The possibility of long-term ECG measurement allows diagnosing pathological processes of the cardiovascular system that can develop over time. Modeling the processes that occur during the contact between wound covers at burns and capacitive electrodes creates the prerequisites for the development of new systems of ECG registration for combustiology for use in clinical practice.

2. Literature review and problem statement

The possibility of using capacitive electrodes to measure ECG was proved by the authors in paper [4]. In research [5], the authors developed and described the system of ECG registration based on compact capacitive electrodes, which are manufactured according to the technology of PCB production. The authors note that the ECG signal can be affected by motion artifacts that bring characteristic noises into the resulting signal. This feature of capacitive electrodes is not an obstacle to measuring ECG in patients with extensive burns since rehabilitation is usually carried out in the hospital and a patient rarely moves during rehabilitation. Paper [6] deals with the dependence of input noises of capacitive electrodes from a distance to the skin surface in the frequency range of 1–100 Hz. It was experimentally found that even at a distance of 3.2 mm, the root mean square value of the noise amplitude does not exceed 17 μV. If we take into consideration the above-mentioned features of rehabilitation of patients with burns and the features of capacitive electrodes identified by the authors, we can assume that it is possible to measure the ECG parameters even through several layers of a dry gauze bandage. It is important to note that in study [4], synchronous recordings of ECG signals were made using contact Ag/AgCl, dry gilded electrodes, and various types of capacitive electrodes. Capacitive electrodes have been shown to be used to measure ECG on a par with classic contact electrodes. When using capacitive electrodes in case of burns, these studies do not provide an answer about the possibility of using capacitive electrodes in the process of rehabilitation of patients with burns and the use of wound covers. In paper [4], the possibility of creating wireless systems based on capacitive electrodes, which greatly simplifies the rehabilitation of patients with burns, was established. In papers [4–6], the authors do not indicate any ways or methods of using such electrodes in the rehabilitation of patients with burns.

ECG monitoring when using capacitive electrodes is studied in research [7], but the use of capacitive electrodes for long-term ECG measurements in patients with burns was not described. It is important to note that the presence of bandages, saline solutions, and antiseptic preparations can significantly affect the quality and reliability of the measured ECG by capacitive electrodes, so it is necessary to assess the impact for further research. Each component makes its characteristic contribution to the measured ECG signal and may have certain dynamics of changes in these parameters during long-term measurements. The impact of each factor is not obvious and requires additional research since such modeling has not been fully carried out before.

The models of contact of capacitive electrodes and a human body are described in article [8], which deals with the connection of a different number of electrodes and the use of grounding electrodes and basic electrodes (withdrawal from the left leg). These models focus on the electrical topologies of biopotential amplifiers but do not determine the possibility of using such electrodes at burns. Study [7] examined the models of electrical impedance between the equivalent EPC source in the human body and an electrode for classic Ag/AgCl, dry and capacitive electrodes, but did not take into consideration the possible existence of dielectric films.

Patients with burns usually need ECG monitoring throughout the entire treatment period, but the existence of permanent bandages and severe skin injuries does not make it possible to register ECG for a certain period to monitor changes in the patient's state. All procedures carried out in the rehabilitation of patients with burns were determined in paper [2], but do not describe the methodology for the long-term ECG registration in patients with extensive chest burns.

At burns, the procedure of covering bandages with films is often used to speed up the healing process of wounds. Special wound covers, which may include dielectric coatings and additional solutions, are used [9], but the methods and means for long-term ECG measurement are not described in this work.

Electrical models of the contact when using bandages, saline solution, and dielectric films have not been studied. In addition, the methods for registration and daily monitoring of patients with chest burns using the 12-wire ECG were not described. Dependences on the parameters of capacitive electrodes are still being studied, but most of them have already been explored and described in articles [7, 8]. The models take into consideration the elements that can distort the signal form, as well as additive noise that occurs due to physical processes in various materials, but this is not enough for full modeling.

Therefore, there are grounds to believe that it is advisable to conduct a study of the model, which will take into consideration the effect of bandages, saline solution, and dielectric films on the contact.

3. The aim and objectives of the study

The aim of this study is to develop a model of contact of capacitive electrodes with skin to increase the effectiveness of ECG measurement in combustiology by numerical modeling of the impedance of the electrical contact in the presence of wound covers of various kinds. This will make it possible to use the model and its parameters in the development and design of new systems of ECG registration and analysis for combustiology based on capacitive electrodes.

To accomplish the aim, the following tasks have been set:

– to modify the model of the contact of capacitive electrodes with skin, taking into consideration the saline solution, gauze bandages, and a polyethylene dielectric film;

– to calculate the effect of the input resistance of the electrode and capacitance of the contact of the capacitive electrode with skin on the frequency response of the contact;

– to calculate the parameters of impedances of saline solution, gauze bandages, and a polyethylene dielectric film for the new model and conduct numerical modeling of the frequency response of contact;

– to assess the effect of drying of saline solution on the frequency response of the developed model of the contact.

4. Materials and methods to study the influence of contact between a capacitive electrode and skin

Since the scheme of the contact can be replaced with standard electric elements, its modeling can be carried out using common computer automated design (CAD) systems. Most electrical circuit simulators are constructed on SPICE software (USA), intended to simulate static and dynamic processes in linear and nonlinear electrical circuits. Electrical circuits were modeled using the Qucs V0.019 program (ngspice SPICE engine)

4. 1. Standard (classic) model of the active capacitive electrode of the buffer cascade type

Fig. 1 shows the electrical model of the capacitive electrode of the buffer amplifier type [8], where C_{in} is the input capacitance of the operating amplifier, R_{in} is the input resistance of the operating amplifier. The following parameters are responsible for the properties of a dielectric film: C_d is the capacitance of the dielectric film, R_d is the resistance of a dielectric film, C_c is the capacitance of the skin-dielectric contact, R_c is the resistance of the contacts of the dielectric with skin.

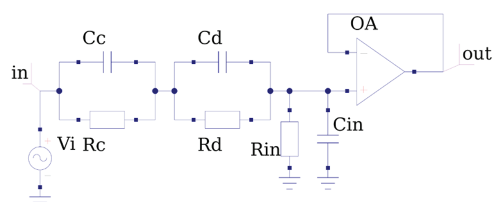

Fig. 1. Circuit of the electric model of capacitive electrode considering the impedance of skin-electrode, and resistance of dielectric (electrode coating)

The parameters R_d and R_c are calculated from the following formula of resistance of current conductor:

$$R = \frac{\rho \cdot S}{D}, \quad (1)$$

where R is the conductor resistance, Ohm; ρ is the specific resistance, Ohm·m; S is the area of the electrode, m^2; D is the thickness of conducting material, m.

The specific resistance of the dielectric coating of the electrode can be taken from tables [10], area $S=S_{Cd}$. Thickness $D=D_{Rd}$ corresponds to the thickness of the dielectric coating of the electrode, thickness D_{Rc} corresponds to the distributed electric resistance of the skin-dielectric contact. The distributed electric resistance of the contact is usually by 5–10 orders of magnitude lower than the resistance of a dielectric film, so it may not be taken into account in the electric model.

The contact capacitance is calculated from the following formula of a flat capacitor:

$$C = \frac{\varepsilon \cdot \varepsilon_0 \cdot S}{d}, \quad (2)$$

where ε is the dielectric permeability of the material between the overlays; ε_0 is the dielectric permeability of vacuum, F/м; S is the area of the electrode, m^2; d is the distance between overlays, m.

R_{in} and C_{in} consider input resistance and capacitance of the operating amplifier, as well as the topology of the structure of capacitive electrodes, but they are not separated as components in the model. Comprehensive electric capacitance C_{in}, which depends on the topology, can be measured directly by a device, or its parameters can be taken from the experimental research.

In the new model, impedance of the skin-electrode $Z_c(C_c\|R_c)$ contact changes and becomes more complicated to take into consideration the effects of the means used in the rehabilitation of patients with burns.

4. 2. Modification of the model of capacitive electrode considering rehabilitation means

The proposed model takes into consideration the influence of bandages moistened with saline solution or solutions of antiseptic drugs, as well as covering with dielectric films to accelerate the healing of burn wounds. Dielectric coating is also taken into consideration for full modeling of various specialized bandages: sterile adsorption bandages for the removal of exudate from burn wounds, which may contain dielectric materials (plastic, silicone or have a spongy structure) on the backside. Fig. 2 shows the structure of the new model and electrical parameters, which take into account the rehabilitation means listed above.

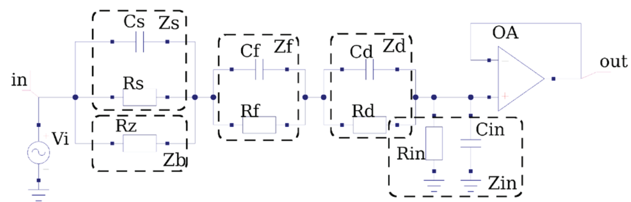

Fig. 2. The circuit of the developed electric model of the capacitive electrode considering parameters of the active capacitive electrode R_{in} and C_{in} and resistance of dielectric Z_d, bandages Z_b, saline solution Z_s, dielectric film Z_d on electrode coating Z_f

The new elements of the circuit include parallel connection of impedance of bandages Z_b (R_z) and impedance of saline solution or antiseptic solutions Z_s, which is taken into account in the model as R_s and C_s. The model also considers the impedance of the dielectric film Z_f, expressed by parameters C_f and R_f. The elements of the capacitive electrode, like in the classic circuit are taken into consideration as a sequential connection of dielectric coating with equivalent impedance Z_d, determined from parameters R_d and C_d, as well as input impedance Z_{in} (R_{in} and C_{in}). Model parameters Z_d and Z_{in} remain unchanged but involve take into consideration the input impedance of the buffer cascade to obtain the frequency response of the entire tract of the active electrode and the formed contact between the electrode and skin. It is believed that the capacitive electrode fits without any air gaps, and space is completely filled with saline solution or a solution of antiseptic preparations in saline, so additional parasitic parameters are not taken into consideration in the model. The model is implemented in the software environment Qucs V0.019 (ngspice SPICE engine) (Germany).

5. Results of studying the calculation and modeling of the contact

5. 1. Model of an active capacitive electrode of the buffer cascade type

To calculate the parameters of the model, a capacitive electrode with an input buffer based on the operating amplifier AD8603 [11] was used. The view of the capacitive electrode is shown in Fig. 3.

The capacitive active electrode was developed by the author of this paper for previous studies. The capacitive electrode consists of two operational amplifiers, one of which is used as an input buffer with a low input current. The output operating amplifier is an active high-frequency filter of 1 order with a cut frequency of 500 Hz. The amplification factor of the amplification cascade in the range of 0.1–200 Hz was selected at the level of 26 dB.

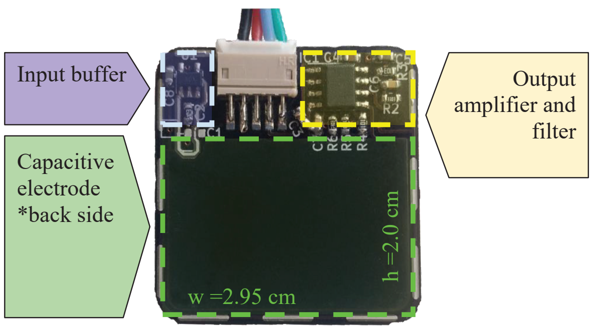

Fig. 3. General view of the prototype of the capacitive electrode for electrocardiogram measuring in combustiology

The design of this capacitive electrode involves shielding, placing all analog components, as well as placing a copper electrode on the backside of the PCB.

After digitization using the ADC (analog-digital converter) ADS1115 [12] with a frequency of 860 Hz, it is transmitted to the computer using a microcontroller.

The dimensions of the capacitive electrode itself, which directly ensures the electric capacitance connection with the skin surface, are shown in green color. The designated dimensions of the capacitive electrode are: $w=0.0295$ m and $h=0.02$ m, the area of the developed prototype of the electrode $S=w\cdot h=0.0295\text{ m}\cdot 0.02\text{ m}=0.00059\text{ m}^2=5.9\text{ cm}^2$. The input buffer cascade is highlighted in violet, and the output cascade of amplification and previous analog filtration is highlighted in yellow. The base of the capacitive electrode is the PCB made of FR4, a two-sided copper coating of 35 microns and lacquer coating with the thickness of the dielectric of the PCB of 0.02 mm. The capacitive electrode was made according to the standard technology of PCB production.

The input capacitance of a buffer amplifier for AD8603 $C_{in}=2.5$ pF. The input impedance of the buffer amplifier in the ECG frequency range is larger than 2.5 gigaohms without taking into consideration the parasitic parameters of the PCB.

5. 2. Calculation of the influence of the amplifier/buffer parameters on the frequency response of the capacitive electrode

Based on the model of the active capacitive electrode of the buffer amplifier type, it should be determined how the input parameters of the amplifier affect the received signal. At the skin-electrode contact, significant changes in the input parameters of the capacitive electrode can occur, which in turn will have an effect on the frequency response of the entire buffer tract. There are grounds to believe that an increase in the distance from skin to the electrode will decrease the contact capacitance and it will be impossible to neglect any longer the influence of other parameters at a certain value of electric capacitance of the electrode. The processes described above will lead to distortion of the measured ECG signal and, as a result, to the low diagnostic value of such measurement. That is why it is necessary to consider the effect of each component on the frequency response of the electrode in order to separate the effect of each of them on the input signal. To do this, we will model the frequency response at a change in input resistance and at a change in the electrical capacitance of the electrode.

Model parameters for 10 different values of input resistance R_{in} are evenly distributed in the range from 1 gigaohm to 10 gigaohms. Fig. 4 shows the results of modeling the frequency response of the circuit (Fig. 1) with the corresponding parameters described above.

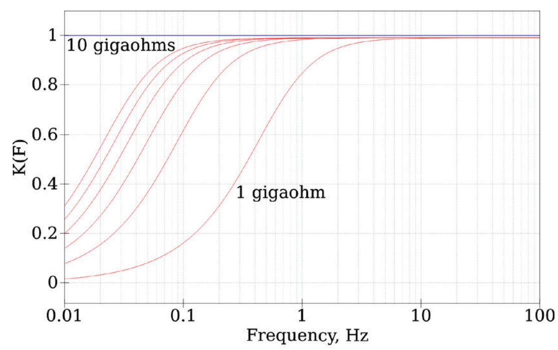

Fig. 4. The frequency response of the buffer with the variable of input resistance R_{in} beginning with 1 gigaohm to 10 gigaohms with the pitch of 2 gigaohm

The chart shows that the input impedance of the buffer amplifier affects only the low-frequency characteristics of the formed analog filter. At an increase in input impedance, the frequency characteristic of the high-frequency filter shifts towards lower frequencies that are not typical of the ECG spectrum [13] and therefore may not be taken into consideration at measuring.

At the input impedance of less than 2 gigaohms, the frequency characteristics of the cascade begin to significantly affect the input signal, so the high input impedance of the selected amplifier makes it possible to minimize distortion of the low-frequency characteristics of the ECG signal [14].

In addition, a very important parameter of the capacitive electrode is the capacitance of the contact skin-electrode, which depends on the parameters of the dielectric coating of the electrode, the distance from skin to the electrode. That is why, it is important to take into consideration the minimum capacitance of the skin-electrode contact, in which ECG registration is still possible without significant distortion. Fig. 5 shows the results of modeling of the capacitance contact of the ideal voltage source and electrode capacitance with different values of electric capacitance formed by the dielectric, which covers the copper electrode.

The selected range of a change in contact capacitance makes it possible to estimate the lower threshold of capacitance, at which the capacitive electrode significantly impairs the frequency characteristics of the contact. From the graph in Fig. 5, it can be seen that when contact capacitance is below 30 pF, the capacitive electrode significantly distorts the resulting signal and, accordingly, cannot be used to measure the ECG. An increase in capacitance of more than 30 pF improves the reproduction of amplitude characteristics of the contact in the range of 1–100 Hz and indicates the extension of the low-frequency signal range from 0.5 Hz at 30 pF to 0.05 Hz at 300 pF.

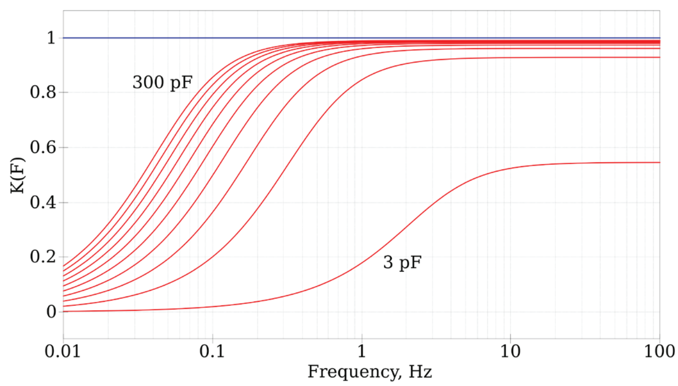

Fig. 5. Frequency response of the input amplifier of the capacitive electrode with the variable of electrical capacitance C_s of the skin-electrode contact starting from 3 pF to 300 pF with the pitch of 30 pF

5. 3. Calculation of model parameters and their impact on the frequency response of the contact

The electrode area $S=S_s=S_b=S_d$ for all parameters is the same and equals 5.9 cm^2. The thickness of the layer between the capacitive electrode and skin is considered to be equal for impedances of saline solution and gauze bandages and can be measured experimentally using a slide gauge and is equal to the thickness of 8 layers of a gauze bandage $D=D_s=D_b=1$ mm. Taking electrical specific resistance of saline solution calculated in the previous section as equal to $\rho_s=1.3\cdot10^{-3}$ Ohm·m, the area of the electrode, and the thickness of the layer according to the formula of the capacitance of a flat capacitor, we obtain electrical resistance. After the calculation, we obtain the impedance of saline solution $R_s=Z_s=2.2\cdot10^{-3}$ Ohm for the given model. The impedance of saline solution does not depend on frequency within the frequency range that is characteristic of the ECG signal. The electric capacitance of gauze bandages C_b according to formula (2) of the capacitance of the capacitor is equal to $C_b=5.2$ pF. Knowing specific resistance of cotton equal to $\rho_b=10^{18}$ Ohm·m, it is possible to calculate the electric resistance of a gauze bandage R_b, which is after corresponding calculations from formula (1) is equal to $R_b=1.7\cdot10^{18}$ Ohm.

The electric resistance of a polyethylene film is also calculated from formula (1). The specific resistance of a polyethylene film is taken from proper tables and is equal to $\rho_f=10^{12}$–10^{13} Ohm·m, thus, the resistance of a polyethylene film is equal to $R_f=1.7\cdot10^{13}$ Ohm. To determine the electric capacitance of a polyethylene film, it is necessary to take from the corresponding tables [10] the value of relative dielectric permeability for polyethylene that is equal to $\varepsilon_f=3.5$ at a frequency of 50 Hz. The thickness of one layer of polyethylene film, which is used when putting bandages does not exceed 9 microns. Having substituted the appropriate parameters in the formula for the capacitance of a flat capacitor (2), when using one layer of a polyethylene film, we obtain electric capacitance of the polyethylene plastic $C_f=2.03$ nF.

For the new model, the following unknown parameters of the electrical circuit were calculated:

– $Z_s=2.2\cdot10^{-3}$ Ohm – electric impedance of saline solution;

– $C_b=5.2\cdot10^{-12}$ F – electric capacitance of dry gauze bandages;

– $R_b=1.7\cdot10^{18}$ Ohm – electric resistance of dry gauze bandages;

– $C_f=2.03\cdot10^{-9}$ F – electric capacitance of a polyethylene dielectric film;

– $R_f=1.7\cdot10^{13}$ Ohm – electric resistance of a polyethylene dielectric film.

Using the parameters calculated above and the proposed model, one can calculate the frequency response of the contact. Fig. 6 shows the results of modeling the contact: skin – bandages – saline solution – polyethylene film – capacitive electrode.

The calculated frequency response of the contact makes it possible to evaluate the amplitudes of the ECG signal in the low-frequency range. The frequency response chart shows that the limit frequency, at which the amplitude begins to fall by 3 dB, is equal to 0.06 Hz, which makes it possible to conclude that the developed model of the contact allows the possibility of measuring the ECG in the presence of the above materials between the skin and the electrode.

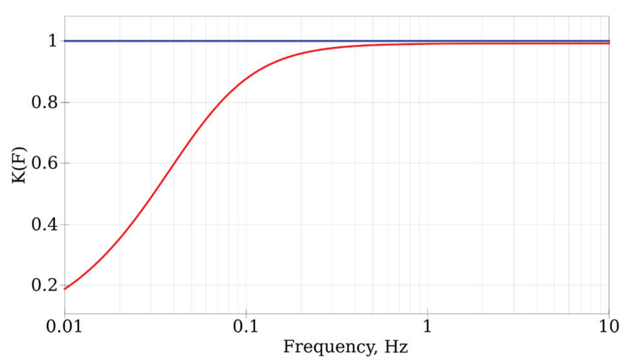

Fig. 6. Frequency response of the contact: skin — bandages (saline solution) — a film — capacitive electrode in a frequency range from 10 MHz to 100 Hz

5. 4. Modeling a change in the impedance of saline solution at drying

Evaporation of water from saline solution leads to an increase in the NaCl concentration in the solution, which in turn increases ion conductivity and, accordingly, decreases the specific resistance of the sample. According to the calculations carried out above, the impedance of saline solution Z_s with a concentration of 0.9 % NaCl does not exceed 2.2 megaohms. The impedance of this section of the circuit is by 12 orders of magnitude lower than the input impedance of the operating amplifier, but it must be taken into consideration in the new model, as it can vary in a wide range.

In order to assess how a change of impedance affects the frequency characteristics of the contact and at what value the ECG signal begins to be distorted, the frequency response of the circuit at five different values of the impedance of saline solution were modeled. The fequency response of this model at a change in impedance for modeling was selected in the range of 100 megaohms – 1 gigaohm with the pitch of 225 megaohms and shown in Fig. 7.

It was determined that during long-term measurements, only the impedance of saline solution can have a significant effect on the signal. Taking into consideration the above, the performed modeling of the frequency response with a deterioration in the impedance of the saline solution up to 1 gigaohm proves that even at incorrect putting of electrodes, the frequency response of the contact electrodes must not distort the ECG signal.

In general, the conducted modeling assesses the effects of each element of the model on the frequency response of the contact: skin – bandages (saline solution) – a film – a capacitive electrode. It was found that the input resistance of the buffer should not be lower than 2 gigaohms for this type and design of the electrode so that the low-frequency range (less than 0.1 Hz) of the signal was not distorted. The obtained data revealed that input resistance does not affect the amplitude component of the ECG signal, and the main effect is made by the capacitance of the contact: skin – the electrode C_c, which should not be lower than 90 pF. Further decrease in the contact capacitance C_c worsens the low-frequency characteristics of the signal and can also significantly reduce the amplitude of the ECG signal in the characteristic frequency range of 0.5–40 Hz.

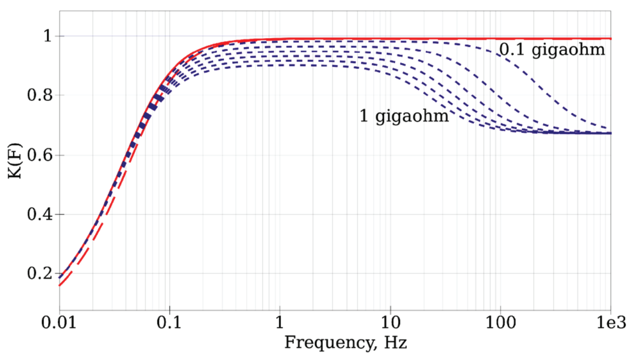

Fig. 7. Frequency response of the model at the values of the impedance of saline solution from 0.1 gigaohms to 1 gigaohm with the pitch of 225 megaohms

Modeling the contact: skin – bandages (saline solution) – film – capacitive electrode proves that the frequency response of the system will not affect the measured ECG signal. The obtained results show that within the entire range of ECG signals (0.5–40 Hz), the signal amplitude decreases by less than 1 % and only at a frequency of 90 MHz decreases by 20 %.

It was found that a decrease in the conductivity of the saline solution, for example, due to drying, begins to affect the frequency response of the system only at the values of electrical resistance of more than 2 megaohms and virtually does not affect the low-frequency component of the ECG signal.

6. Discussion of results of studying and modeling the contact between a capacitive electrode and the skin for ECG measuring in the presence of means of rehabilitation after burns

The modification of the model (Fig. 1) of the contact of capacitive electrodes with skin was proposed. This is important because the presence of various materials can distort the signal and even lead to a misinterpretation of the ECG signal. The unreliability of measurement results reduces the diagnostic value of the measured ECG for high-quality diagnosing of a patient. The proposed modification of the model (Fig. 2) took into consideration the presence of bandages of saline solution and polyethylene film in the contact.

The calculated frequency response, shown in Fig. 5, demonstrates how important the contact capacitance is since a decrease in capacitance below 30 pF significantly decreases the lower threshold of frequency and signal amplitude. Such distortions are unacceptable in clinical practice and should be signaled using additional contact control systems, as this may affect the interpretation of the result and making a diagnosis by a doctor. The effect on the frequency response at a change in the input resistance (Fig. 5) of the amplifier is less critical and does not depend on the method of putting electrodes. Input resistance with this type of capacitive electrode depends only on the choice of input buffer/amplifier and the PCB topology, so it can be leveled at the stage of the development of the capacitive electrode.

Calculation of the parameters of the model showed that at the calculated area of the electrode of 5.9 cm^2 and the thickness of a gauze bandage impregnated by the saline solution of 1 mm, the impedance of such a contact is equal to the impedance of saline solution $Z_b=Z_s=2.2\cdot10^{-3}$ Ohm and in the more general case can be simplified to the impedance of saline solution. In turn, the existence in the contact structure of saline solution increases the frequency range of frequency response of contact, which positively affects the frequency characteristics of the contact in general and reduces the effect of the distance between the skin and the electrode on the frequency response of the system. An important feature of capacitive electrodes is the possibility to register the signal even through dielectric films, but this feature was not taken into consideration when modeling classic electrodes [7, 8]. Modeling of the contact in the presence of bandages covered with one layer of polyethylene film with a thickness of 9 microns shows that the total frequency response of the contact of the model (Fig. 6) retains all the properties of the capacitive electrode. In turn, the existence of the dielectric contact makes it impossible to use classical gel and dry electrodes for ECG, since such application was not described in the relevant literature [2].

In addition, stability and reproducibility of the result at long-term measurements are important in clinical practice since this makes it possible to enhance the diagnostic value of the electrocardiographic method of assessing the heart work. To prove this requirement, a study of the effect of saline solution drying on the frequency response of the contact was carried out (Fig. 7). We studied only the influence of saline solution as a base for antiseptics, but in clinical practice, other antiseptics based on other substances, the conductivity of which may differ from the conductivity of the saline solution, are often used.

In general, long-term measurements in patients with extensive burns are not carried out just because of the lack of a reliable and convenient method of registration of the ECG of such patients. In this regard, long-term monitoring studies of the ECG of patients with burns are rarely carried out, which makes it impossible to methodically collect a large amount of data for analysis. The lack of such databases of the ECG of patients with burns makes it difficult to develop the methods of diagnosis based on statistical processing and analysis of slow changes in the heart function during the rehabilitation of patients with burns. Therefore, the creation of the systems of long-term measurement of the ECG of patients with burns is a promising area of research.

Additional studies of the contact of capacitive electrodes with other materials involve the exploration of the influence of wound healing processes and a frequent change of bandages on the signal obtained using capacitive electrodes. It is also necessary to study the influence of special wound covers during the ECG registration with the use of capacitive electrodes. The main wound covers include sponges made of natural polymers (collagen, chitosan, alginic acids, cellulose derivatives), hydrogel and hydrocolloid covers, bio-compatible materials capable of dissolving, and various types of xenoskin [15–17].

7. Conclusions

1. The electric model of the contact: skin – bandages (saline solution) – film – capacitive electrode was proposed and ana-

lyzed. This model takes into consideration electrical impedance of saline solution, the electrical capacitance of dry gauze bandages, the electrical resistance of gauze bandages, the electrical capacitance of a polyethylene dielectric film and electrical resistance of a polyethylene film. The main difference between the developed model and standard models of capacitive electrodes is the consideration of bandages soaked in saline solution and covered with a polyethylene film. This model makes it possible to evaluate the possibility of using capacitive electrodes to measure the ECG in the rehabilitation of patients with burns.

2. When modeling the influence of the main parameters of the capacitive electrode, it was determined that for the used type of capacitive electrodes the contact capacitance should be more than 30 pF, and the input resistance of the amplifier should be more than 2 gigaohms. It was found that with a decrease in the input resistance of less than 2 gigaohms and a decrease in input capacitance of less than 10 pF, the frequency characteristics of the input cascade begin to significantly distort the ECG signal.

3. The unknown parameters of the contact components such as impedance of the saline solution, impedance of gauze bandages, impedance of a dielectric film, and the frequency response of the new model were calculated (Fig. 6). It was found that the electric impedance of saline solution for the electrode area of 5.9 cm^2 and the contact thickness of 1 mm is equal to Z_s=2.2 megaohms. The electric capacitance of dry gauze bandages at the same parameters of distance and area is equal to C_b=5.2 pF, and electric resistance R_b is more than 10^{18} Ohm. The electric capacitance of a dielectric film is equal to 2.03 nF and its electric resistance R_f=1.7·10^{13} Ohm.

4. To assess the possibility of using capacitive electrodes for long-term ECG measurement, modeling of the contact frequency response, which considered the process of drying the saline solution, was performed. In modeling, a narrow range of changes in resistance of saline solution was chosen: 1 gigaohm – 0.1 gigaohm. A decrease in resistance lower than 0.1 gigaohm significantly improves the contact characteristics. Modeling showed that even a significant increase in resistance of saline solution does not lead to dramatic changes in the frequency response of the contact, and therefore has no effect on the characteristics of the received ECG signal. The calculated parameters of the contact for the new model made it possible to model the contact taking into consideration bandages, saline solution, and a film, and evaluate the frequency response of the contact. The conducted study proved that capacitive electrodes can be used in combustiology to control the vital function of a patient's organism during rehabilitation after a burn injury.

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