**Zbigniew MARSZALEK, Waclaw GAWEDZKI**

AGH University of Science and Technology, Department of Measurement and Electronics

doi:10.15199/48.2016.11.14

# Investigations of real conditions properties of the biomedical electrodes with integrated electrode contact quality monitoring system for recording electrocardiographic signals

***Abstract**. The results of investigations of the metrological properties of the system of 4 biomedical electrodes with the continuous control of the contact quality, are presented in the hereby paper. Investigations were performed under real conditions of measuring the electrocardiographic signals of humans, at the application of the typical ECG instrumentation. Due to the performed experiments the conformity of the electrocardiographic signals obtained by means of the standard gel electrodes glued to the body and the ones obtained by means of the electrodes with continuous control of the contact quality, was confirmed.*

***Streszczenie.** W artykule przedstawiono wyniki badań właściwości metrologicznych układu 4 elektrod do pomiaru sygnałów elektrokardiograficznych człowieka z ciągłą kontrolą stanu kontaktu, przy wykorzystaniu typowej aparatury EKG. Potwierdzono zgodność zapisów sygnałów EKG wykonanych za pomocą standardowych elektrod żelowych przyklejanych do ciała oraz przy zastosowaniu elektrod z ciągłą kontrolą stanu kontaktu. (**Badania właściwości układu elektrod biomedycznych z ciągłą kontrolą stanu kontaktu w rzeczywistych warunkach rejestracji sygnałów elektrokardiograficznych**).*

**Keywords:** biomedical electrode, contact quality, electrode-to-skin, impedance, ECG signals.
**Słowa kluczowe:** elektroda biomedyczna, stan kontaktu, elektroda-skóra, impedancja, sygnały EKG.

## Introduction

Very important and often applied electrodiagnostic examination is the electrocardiograph of heart operations (ECG). The proper recording of electrocardiographic signals requires ensuring the adequate contact of electrodes with the patient skin [1–3]. Biomedical electrodes are the interface for bioelectric signals between the patient skin and the measuring system. At the electrode contact with the skin the conductance change from ionic into electron occurs (contact between metal and electrolyte), which is accompanied by complicated physical and chemical processes [1, 4]. The contact impedance value is assumed as a measure of the quality of the electrode-to-skin contact. In order to assure the proper state of the contact the impedance value should be as small as possible. Various kinds of gels are applied in between the electrode and skin surface [1, 5]. For instance, during the long-term recording the electrocardiograph by the Holter's method, the standards concerning the maximum impedance value of the electrode-to-skin contact has to be satisfied (10 kΩ).

The applied, till now, control methods of the contact quality are based on measuring the contact impedance. The impedance value $|Z|$ is determined on the bases of measuring the current and voltage on the terminals of the measuring and reference electrode. According to publications [3, 5–10] it is related to the necessity of forcing the current flow through the patient body. Thus, the impedance cannot be determined during recording the bioelectric signals. Therefore the measurement of the contact impedance is performed before the ECG examination. The control of the contact quality during the examination requires interrupting of the ECG signals recording for the time of the impedance measuring.

In order to solve this problem the new method of determining the quality of the electrode-to-skin contact was proposed [11–13]. The new construction of the integrated biomedical electrode was shown. This electrode contains additional test electrodes, galvanically insulated from each other and from the skin, placed in the vicinity of the measuring electrode. The contact quality is determined on the basis of capacitance between the test electrodes. Test electrodes allow continuous monitoring measuring electrode's contact quality also during recording of ECG signals. The construction of such electrode, together with the integrated electronic capacitance-frequency converter, is presented in detail in [11,12]. The results of examinations of this electrode prototype carried out on the physical skin model are shown in [13]. The signal from the function generator simulating the electrocardiographic signal was used in experiments.

The results of investigations of the correctness of the electrocardiographic signals recording, when the developed biomedical electrodes with the continuous control of the contact quality are applied, are presented in the hereby paper. One of the applied, in practice, connection system of four electrodes, the so-called Einthoven system, was used. Measurements were performed by means of the typical ECG instrumentation. Signals recorded by the investigated integrated electrodes (with a continuous contact control) and the reference electrodes were compared. As the reference electrodes the classic glued to skin standard electrodes, without the contact quality control were used.

## Purpose and subject of investigations

The purpose of the investigations was to determine metrological properties of the system of 4 electrodes with the continuous control of the contact quality. Investigations were carried out by means of the typical ECG equipment and under real conditions of measuring the electrocardiographic signals of a human.

Each – being tested – biomedical electrode (Fig. 1) contains two measuring elements. The first element, basic one, constitutes the measuring ECG electrode, intended for measuring the electrocardiographic signals. The second measuring element constitute test electrodes, galvanically insulated from the patient skin, between which the capacitance is measured. The measured capacitance value depends on the impedance of the electrode-to-skin contact, which was shown in [13]. Due to a small capacitance value of test electrodes the measuring system is susceptible to the influence of the connecting cables capacitance. Therefore in a direct vicinity of test electrodes the capacitance-frequency converter, $C/f$ (Fig. 1), was used. In effect, the converter of the contact impedance into frequency of a monotonically growing characteristics was obtained [11–13].

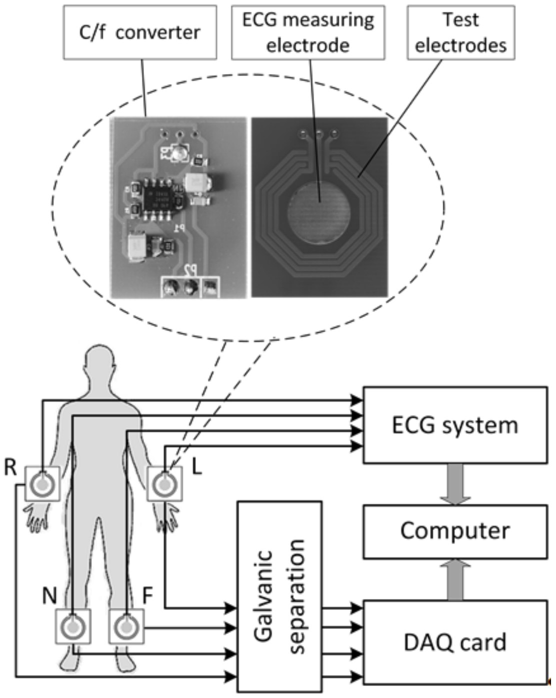


Fig.1. Block diagram of the measurement system (the electrode is shown an enlargement)

**Contact quality control system**
Integrated electrode consists of (Fig. 1):

- measuring electrode, intended for measuring electrocardiographic signals,

and the control system of the measuring electrode contact quality, which contains:

- two test electrodes to control the contact with the skin,
- capacitance-to-frequency converter C/f.

The aim of this converter is to convert the signal obtained from test electrodes in such a way as it will be possible to determine on its basis whether the impedance value of the integrated electrode-to-skin contact is the proper one. The scheme of the converter *C/f* [14] is shown in Figure 2. Conditions of selecting system elements, results of simulation investigations performed in the MicroCap program as well as the way of galvanic separation of signal and supply path, are discussed in paper [13].

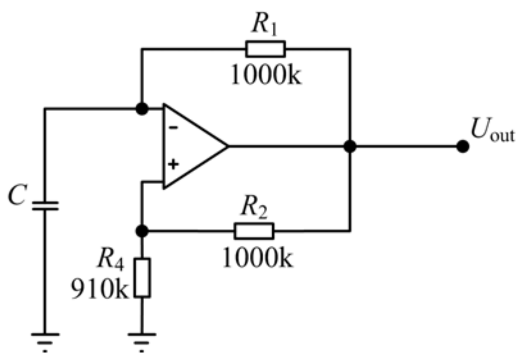


Fig.2. Electric scheme of the capacitance-frequency converter *C/f*

For the needs of investigations the 4-channel supplying-separating system was prepared. The galvanic barrier for the output frequency signal was realised by using the transoptor ACPL-W611 of the AVAGO Company of a maximal impulse voltage 15 kV. The galvanic separation of the supply system was done by using the converter DC/DC, TME0505S type of the Traco Power Company, of the insulation voltage 1 kV.

The dependence joining the rectangular signal frequency – generated by the converter – with the value of converted capacitance *C,* has a form [14]:

$$f = \frac{1}{2 \cdot \ln\left(\frac{2R_4 + R_2}{R_2}\right) \cdot R_1 \cdot C} \qquad (1)$$

where: $R_2$ and $R_4$ – resistors determining the voltage threshold levels of hysteresis, $C$ – capacitance of test electrode, $R_1$ – resistor determining a capacitor charging time $C$ (time constant $R_1C$), it means the range of frequency changes (1) for the determined range of capacity changes.

On the basis of dependence (1), at taking into account the values of parameters of electronic elements (acc. to Fig. 2), the diagram of the frequency dependence on the test electrodes capacitance was made (Fig. 3). Two, empirically determined, threshold values of the contact quality are marked in the diagram by dashed lines. These threshold values divide:

- good contact G zone and the transient zone of uncertain contact T,
- transient zone of uncertain contact T and the poor contact P zone.

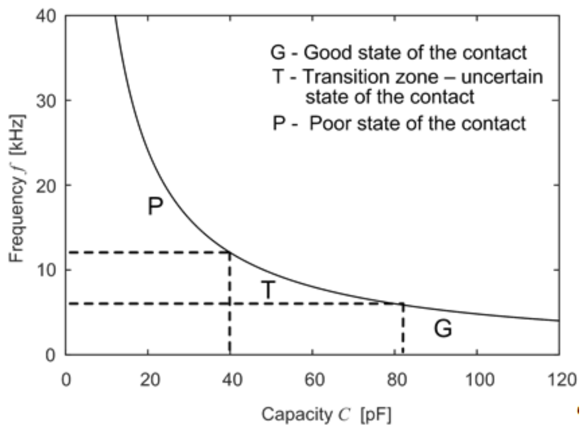


Fig.3. Characteristics of the frequency $f$ (1) as the capacitance function $C$ of the test electrode. Dashed lines are marking empirically determined thresholds between contact quality: good G, poor P and uncertain T

Threshold values of individual contact zones are listed in Table 1.

Table 1. Threshold values determining contact zones qualities

| Zone | Frequency $f$ [kHz] | Capacity $C$ [pF] |
|---|---|---|
| Good | $f \leq 5.7$ | $C \geq 83$ |
| Transition | $12 > f > 5.7$ | $83 > C > 39.5$ |
| Poor | $f \geq 12$ | $C \leq 39.5$ |

The threshold values of frequency and test electrodes capacitance presented in Table 1 and in Figure 3 are only valid for the developed prototype electrode. The selection of other parameter values of converter electronic elements *C/f* or a different project of the test electrodes system (Fig. 1), will cause different threshold values. Specially essential is the choice of shape and dimensions of test electrodes. The investigation results of the influence of the number of test electrodes rings, their width and mutual distances on the initial capacitance and sensitivity of the converter *C/f,* are presented in paper [11].

## Experiments and their results

Laboratory experiments were performed in two stages. The first one, at gluing standard electrodes to the skin, without a continuous control of the contact quality, was aimed at obtaining the reference signal. In the second stage the investigated electrodes were applied.

The block diagram of the stand for recording ECG signals using the system of the biomedical electrodes with a continuous control of the contact quality, is shown in Figure 1. The dipole limb drains (Einthoven) were applied. Four electrodes of this drain were placed on the patient body (Fig. 1):

- electrode R – right hand,
- electrode L – left hand,
- electrode F – left shin,
- electrode N – right shin (the so-called reference point).

The basic ECG signals I, II and III were recorded by means of the standard ECG system.

Between the first three electrodes R, L and F the potential differences were measured (in mV):

- drain I – potential difference between electrodes: L – R („left hand" – „right hand"),
- drain II – potential difference between electrodes F – R („left shin" – „right hand"),
- drain III – potential difference between electrodes F – L („left shin" – „left hand").

Output signals of the converter *C/f*, describing the contact quality, were transformed by means of multi-channel measuring card NI 6341 [15–17]. Frequency values were measured in the real time by means of measuring card counters. Several experiments with 'dry' and 'wet' electrodes, applying the gel improving contact, were performed.

The ECG records, obtained when applying standard gel electrodes ECG – Ag/AgCl glued to the skin, without the contact quality control (reference notation), are presented in Figure 4.

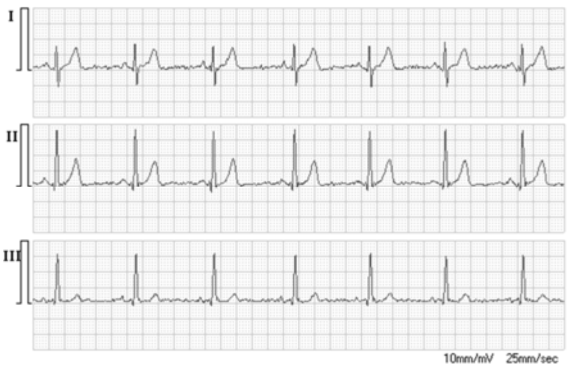


Fig.4. Recorded ECG signals when the standard electrodes were used (reference notation)

All recorded signals I, II and III are in agreement with the typical ECG records. Voltage scales and recording velocities are given in the lower part of the diagram.

Examples of ECG signals, recorded by means of the investigated electrodes with the continuous contact quality control, are presented in Figure 5a. All electrodes which adhered to the skin were in the 'dry' contact state (gel decreasing the contact impedance was not applied). Frequency signals as the time function supplying information on the contact quality of electrodes R, L, F and N are presented in the additional diagram in Figure 5b. Electrodes R, F and N – adhering all the time to the skin – have a good contact quality, generated signal frequency is of a value of 5.7 kHz (Table 1 and Fig. 3). Electrode L had a good contact quality in the initial phase (before 22nd s) and in the final phase (after 24th s) of the signal ECG recording. In between the 22nd and 24th second of the recording (Fig. 5b), the electrode L down-pressing to the body was decreased. This caused worsening of the electrode contact quality during the recording and a significant increase of the frequency generated by the control system of the electrode L contact quality, as well as disturbed signals of ECG I (L–R) and III (F–L) (Fig. 5a).

After restoring the good contact quality of electrode L in the 24th second, the ECG signals became the proper one again.

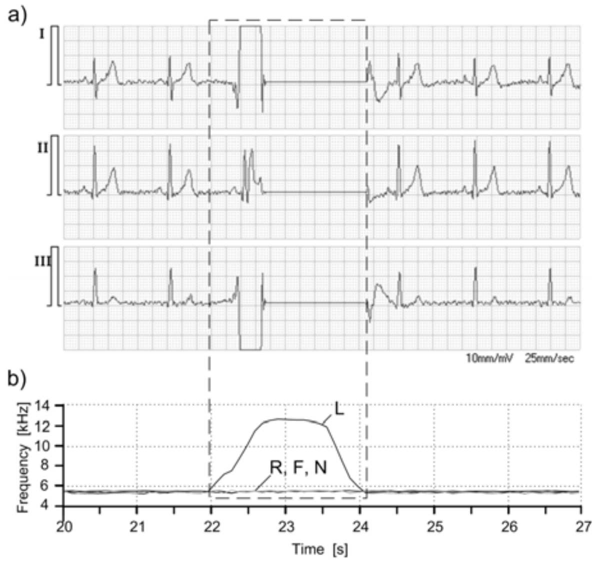


Fig.5. Recorded signals for electrodes in the 'dry' contact state: a) EKG – when the investigated electrodes with the continuous contact quality control are applied, b) frequencies supplying information on the contact quality of the investigated electrodes (R, L, F and N)

The efficiency of the system of the continuous contact quality control for 'dry' electrodes, was in this way confirmed. The lack of interaction between the system of the contact quality control and the system of recording ECG signals was also confirmed. As the result of the performed experiments and the analysis of the obtained results the conformity of the recording of the electrocardiographic signals obtained by means of the standard gel electrodes glued to the body (Fig. 4) and by means of "dry' electrodes with the continuous contact quality control (Fig. 5a), was found.

Examples of the ECG signals recorded by means of the investigated electrodes with the continuous contact quality control are presented in Figure 6a. All electrodes were in the 'wet' contact state with the skin after applying gel decreasing the contact impedance. The frequency waveforms as the time function, supplying information concerning the contact quality of electrodes R, L, F and N, are presented in the additional diagram in Figure 5b. All these electrodes have a good contact quality – the generated signal frequency is of a value of 5.5 kHz (Table 1 and Fig. 3).

In a similar fashion as for 'dry' electrodes the efficiency of the system of the continuous contact quality control was confirmed for 'wet' electrodes. The lack of interactions between the system of the contact quality control and the system of signal ECG recording was also confirmed. On the basis of the analysis of the recorded signals the conformity of the recording of the electrocardiographic signals obtained by means of the standard gel electrodes glued to the body (Fig. 4) and by means of "wet' electrodes with the continuous contact quality control (Fig. 6a), was found.

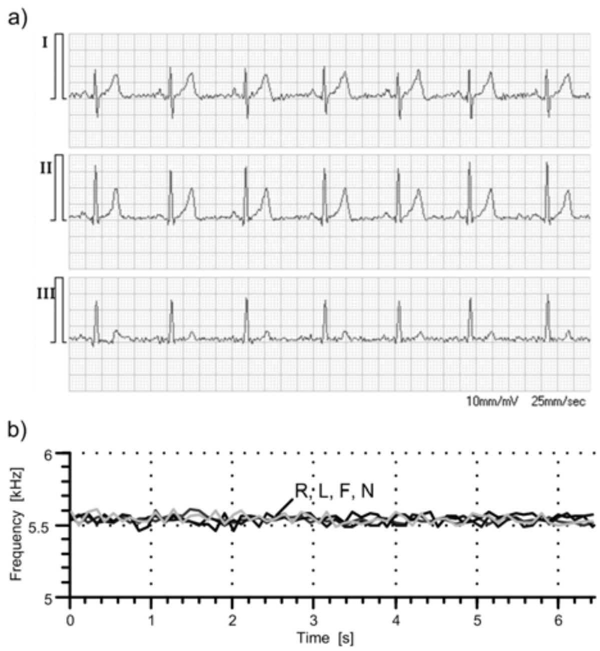


Fig.6. Recorded signal for electrodes in the 'wet' contact state: a) EKG – when the investigated electrodes with the continuous contact quality control are applied, b) frequencies supplying information concerning contact quality of the investigated electrodes (R, L, F and N)

**Conclusions**

On the basis of the performed experiments the written below conclusions can be formulated.

- The investigated electrodes with the continuous contact quality control allow for the proper recording of electrocardiographic signals.
- ECG signals recorded by means of the integrated electrodes are in conformity with the signals recorded by means of the reference gel electrodes.
- The control system of the contact quality of the investigated electrodes allows the continuous monitoring of the electrode-to-skin contact correctness.
- A high sensitivity of the contact quality control system to the changes of the contact impedance values was found.
- The control system of the contact quality was not disturbing the ECG signals recording.
- A possibility of the continuous control of the electrodes contact quality is specially essential in case of long-term recording of ECG signals (e.g. Holter's method).
- The proposed integrated electrodes, properly adjusted, can find applications in measuring another electrodiagnostic signals.

*This research was financed by resources for statutory activities of the Department of Metrology and Electronics, AGH University of Science and Technology.*

***Authors**: dr inż. Zbigniew Marszalek, AGH University of Science and Technology, Department of Measurement and Electronics, Av. Mickiewicza 30, 30-059 Krakow, E-mail: antic@agh.edu.pl; dr inż. Waclaw Gawedzki, AGH University of Science and Technology, Department of Measurement and Electronics, Av. Mickiewicza 30, 30-059 Krakow, E-mail: waga@agh.edu.pl*

REFERENCES

[1] Augustyniak P., Przetwarzanie sygnałów elektrodiagnostycznych, *Uczelniane Wydawnictwa Naukowo-Dydaktyczne AGH*, Kraków, (2001)
[2] Huclova S., Erni D., Froehlich J., Modeling and validation of dielectric properties of human skin in the MHz region focusing on skin layer morphology and material composition, *J. Phys. D: Appl. Phys.*, 45 (2012), 025301
[3] Lin Ch.-T., Liao L.-D., Liu Y.H., Wang I-J., Lin B.S., Chang J.Y., Novel dry Polymer foam electrodes for long-term EEG measurement, *IEEE Transactions on Biomedical Engineering*, vol. 58 (2011), no 5, 1200-1207
[4] Pilawski A. (red.), Podstawy Biofizyki, *PZWL*, 1977
[5] McAdams E.T., Jossinet J., Lackermeier A., Risacher F., Factors affecting electrode-gel-skin interface impedance in electrical impedance tomography, *Medical & Biological Engineering & Computing,* 34 (1996), 397-408.
[6] Chi M. Y., Jung T.-P., Cauwenberghs G., Dry-Contact and noncontact biopotential electrodes: Methodological review, *IEEE Reviews in Biomedical Engineering*, vol.3 (2010), 106-119
[7] Ichida S., et al., Biomedical electrode, *Patent WO 2014*/ 007307 (2014)
[8] Livnech A., Granov E., Granov I., Biomedical electrode assembly, *Patent WO 2013/* 121415 (2013)
[9] Netherly S.G., Knudson O.B., Method and apparatus for controlling contact of biomedical electrodes with patient skin, *Patent US 2001*/ 6171304 B1 (2001)
[10] Herlerkson E.C., ECG electrode contact quality measurement system, *Patent US 2011*/ 8086300 B2 (2011)
[11] Marszałek Z., Gawędzki W., Nowa metoda monitoringu stanu kontaktu elektrody biomedycznej ze skórą pacjenta, *Przegląd Elektrotechniczny*, 5 (2014), 94-97
[12] Marszałek Z., Gawędzki W., Sposób monitorowania stanu kontaktu elektrody biomedycznej ze skórą pacjenta. Zgłoszenie wynalazku PL 406862, *Biuletyn UP RP,* nr 15 (2015), 3
[13] Marszałek Z., Gawędzki W., i in.: Badania wpływu układu monitorowania stanu kontaktu elektrody biomedycznej ze skórą pacjenta na mierzony sygnał elektrokardiograficzny. *Przegląd Elektrotechniczny*, nr 5 (2015), 72-75
[14] Marcos C., Sanchez Pena J., Torres J., Isidro Santos J., Temperature-frequency converter using a liquid crystal cell as a sensing element, *Sensors*, no. 3 (2012), 3204-3214
[15] Gawędzki W., Pomiary elektryczne wielkości nieelektrycznych. *Wydawnictwa AGH*, Kraków (2010)
[16] NI 6341 DAQ Card, User's Manual (2007) www.ni.com
[17] NI LabVIEW 2015 Development Systems, www.ni.com