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PHYSICO-MATHEMATICAL BASIS OF THE BIOLOGICAL IMPEDANCE STUDY — CASE OF THE ELECTRODERMAL ACTIVITY

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ФИЗИКО-МАТЕМАТИЧЕСКИЕ ОСНОВЫ ИЗМЕРЕНИЙ БИОЛОГИЧЕСКОГО ИМПЕДАНСА ПРИ ИССЛЕДОВАНИИ ЭЛЕКТРОДЕРМАЛЬНОЙ АКТИВНОСТИ

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В исследовании исходили из необходимости определения зависимости реографических показателей от объемного тока крови. Установлено, что вариабельность относительной величины объемного тока крови прямо пропорционально зависит от вариабельности показателей импеданса ($\Delta Z/Z$) в сегменте тканей тела, которые подлежат исследованию. Вместе с тем, наблюдается обратная пропорциональная зависимость вариабельности объемного тока крови от натурального логарифма общего импеданса (lnZ).

Ключевые слова: электродермальная активность, формула Кубичека, измерение импеданса, электроплетизмография.

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Physical laws are reliable means of data processing techniques and particularly in medical engineering. Specifically, biological objects demand a deep analysis of some regularly used formulas and defined conditions, the lack of which will nurse some doubt as for the effectiveness of the formulae particularly used in rheography. The basic formulas used in bioimpedance measurements are considered in this work. The insufficiency in the expression of blood volume change as a function of total resistance (or biological impedance) relative to variation is being considered, while new expressions are being proposed. For instance, it has been demonstrated that the relative blood volume variation $\Delta V/V$ is directly proportional to the relative impedance variation ($\Delta Z/Z$) within the body segment under investigation and inversely proportional to the natural logarithm of the total impedance of the segment (lnZ).

Key words: Electrodermal activity, Kubicek's formula, Impedance measurement, Electroplethysmography.

Introduction

The electromagnetic fields theory and methods of electric field analysis enable creating powerful non-invasive methods for the investigation of the activity of the heart, brain, skin, muscle, etc. by *potential measurement* (Electrocardiogram (ECG), Electromyogram (EMG), Electrooculogram (EOG), Electrogastrogram (EGG), Electrodermal Activity (EDA) by TARCHANOV [1] etc., or by *impedance measurement* (Electroplethysmogram (EPG), EDA) by FERE [2] etc. The development of the latter group created powerful technical basis, methods and relatively simple mathematical process for calculating hemodynamic parameters [3–6] or the activity of sweat glands. It has been demonstrated by Fowles that the electrodermal response (EDR) is associated with the activity of sweat glands. A direct correlation exists between EDR and the activity of sweat gland. There are no EDR signals without the activity of sweat glands [7]. Concerning the impedance measurements, the mathematical formulas used are based on the laws of solid state of physic (for instance, Ohm's law) applicable for certain defined conditions which are met always proper to biological objects. The case of biological objects is considered with enough precautions regarding the application of this law. That is why some authors do not trust the formulaes used in Electroplethysmography while others consider them as only useful for predicting hemodynamic parameters. In this article, a review of Ohm's law will be made while an update will be proposed in the first instance. Secondly, the application conditions of this law will be specified in biomedical engineering and finally the basic formulas for impedance measurements will be reviewed.

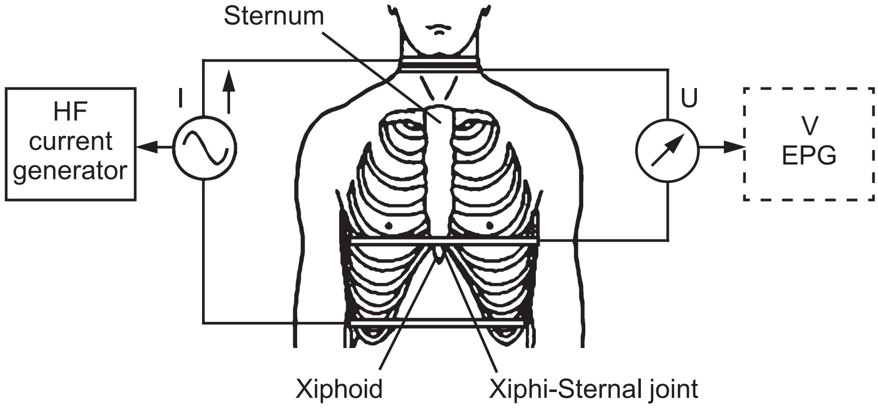

Fig. 1. Electropletysmography measurement of cardiac impedance
Note. The impedance of the thorax is measured longitudinally by four electrodes band. A pair of external electrodes (an electrode is placed around the abdomen and other placed around the upper part of the neck). A pair of internal electrodes (an electrode is placed around the thorax at the level of the articulation between the xiphoid and the sternum, called the xiphoid articulation, and the other around the lower part of the neck). Source [15], reproduction.

Objective

The main objective in this work is to make a thorough review of the conditions of use of the laws of physics in engineering and particularly in medical engineering. To do this, we will:

— review Ohm's law in plethysmography and electrodermal activity;

— accentuate the weakness of the application of this law in the field of medical engineering;

— develop a new version of the application of this immutable law.

Problem

Measuring biological impedance reveals relative results when based on the current expression used in the calculation of hemodynamic parameters in rheography (fig. 1). Analysis demonstrates the need for an adjustment in the fundamental formulas based on Ohm's law and which are used in biological impedance measurements. Indeed, the voltage fall U(V) on a conductor, through which a current runs is directly proportional to the resistance R(Ω) of the conductor and the intensity I(A) of this current.

$$U(V) = RI \quad (1)$$

The resistance R is an electrical property characteristic of the conductor, fig. 2, *a,* which depends on its geometric shape (dimensions), its homogeneity and its nature. This relationship is summarized in the following formula for every conductor and every shape:

$$R = \int \rho dl/ds \quad (2)$$

In this formula:

— ρ (Ωm) is the resistivity (specific resistance) of the material of the conductor and depends on some parameters as electron charge, carrier concentration, velocity, temperature, the charge of the conductor etc.;

— *s* (m^2) is the cross section of the conductor;

— *l* (m) is the length of the conductor.

When those parameters are constant in a solid conductor of length L defined as not very large, then the resistivity can be assumed to be constant with a relative uncertainty very low or negligible. Then the specific resistance is also constant.

Under these conditions, the formula of resistance can take the following simple form

$$R = \rho L/s = \rho L^2/sL \quad (3)$$

or

$$R = \rho L^2/V, \quad (4)$$

where V (m^3) = *sL* is the volume of the conductor.

The formula (4) is basical and is widely used in bioimpedance measurement. It was considered to be true and applicable to biological objects because of the early concept that human organism is electrically homogeneous. But this concept was later considered vague and/or only partially true [8], since it has been found that specific resistance of different tissues within human organism varies in large limits (as shown in the table 1) and together with the current frequency. Thus, it was found that the specific resistance (resistivity) of blood varies between 120Ω·cm and 180Ω·cm at current frequency of 500 Hz and between 118Ω·cm and 149Ω·cm at current frequency of 2.5 MHz. The conclusion was that the human organism is "relatively" homogeneously conductable. The same result was achieved by Nyboer [4]. Some years ago, Furthermore, Swanson confirmed that blood conductivity varies with the blood viscosity in blood vessels [14]. In spite of these results it has been accepted that certain average value of the blood specific resistance, which allows Ohm's law to be viable when measuring blood resistance or impedance. The blood specific resistance is still a function of the hematocrit. All that shows the relative character of the results when the expression (1) is used for the calculation of the hemodynamic parameters in rheography. Based on this analysis, an adjustment seems to be necessary in the fundamental formulas used in biological impedance measurements.

Table 1

The Resistivities of Some Tissues in the Body

Tissue	ρ[Ωm]	Remarks
Brain	2.2 6.8 5.8	gray matter white matter average
Cerebro-spinal fluid	0.7	
Blood	1.6	Hct = *45*
Plasma	0.7	
Heart muscle	2.5 5.6	longitudinal transverse
Skeletal muscle	1.9 13.2	longitudinal transverse
Liver	7	—
Lung	11.2 21.7	—
Fat	25	—
Bone	177 15 158 215	longitudinal circumferential radial (at 100 kHz)

Note. With Hct = Hematocrit (%). Source: [9–13].

Materials and Methods

They are based on the reformulation of basic expressions of rheography. In order to get more accurate and convenient rheumatics expressions, the calculation of parameters, data analysis and the blood resistance in a given body segment should be considered to be parallel with the resistance of the remainder of that segment (fig. 2, *a, b, c, d*).

In that figure, R_0 and R are the total resistance of the segment at moment t_0 (respectively at moment t), Rb, Rt and ΔRb are respectively blood resistance, the resistance of the remainder tissues of the segment and the variation in blood resistance following the change ΔV in the blood volume V.

Within the segment the variation in the total resistance is noted ΔR as:

$$\Delta R = R - R_0 \quad (5)$$

From fig. 2, we have:

$$\Delta Rb = -RR_0/\Delta R \text{ [21–23]} \quad (6)$$

Rb is the resistance of the blood.

With reference to the expression (4) we obtain:

$$\Delta Rb = \rho L^2/\Delta V \quad (7)$$

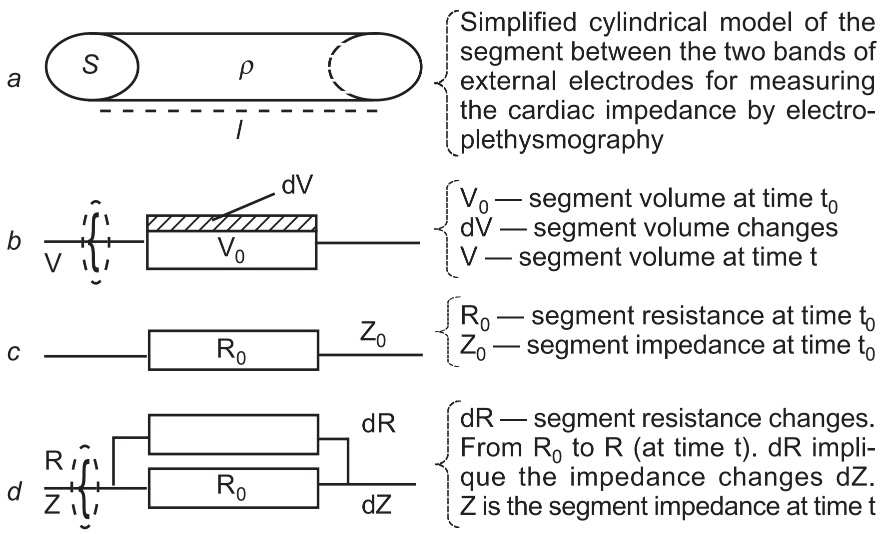

Fig. 2. Electric models of the body part under investigation

Note. R_0 and R are the segment total resistances with the blood at time t_0 and t. R_b, R_t and ΔR_b are respectively the blood resistance, other tissues in the segment and with changes of the blood resistance in accordance with changes in the blood volume.

Since only the blood volume has varied in the segment, the change in volume of the segment is also the change in blood volume thus:

$$\Delta V = \Delta Vb \quad (8)$$

It follows:

$$\Delta V = -\rho L^2/R_0 \cdot \Delta R/R \quad (9)$$

In case of elementary change in blood volume dV, we get

$$dV = -\rho L^2/R_0 \cdot dR/R \quad (10)$$

A solution of the expression (10) is

$$V = -\rho L_2/R_0 \cdot ln(k{\cdot}R) \quad (11)$$

In this expression k is a coefficient (k normalizer in Siemens or 1/Ω), which expresses the constant of integration.

From the expressions (9) and (11) we get:

$$\Delta V/V = (\Delta R/R) \times \times 1/ln(k{\cdot}R) \quad (12)$$

We note that this result is widely different from the usually used expression and that the discrepancy is certainly not noticed because of the approximations used in Electroplethysmogram (EPG).

Results

Application to electrodermal activity by FERE: Electrodermal activity (EDA or EDF) is a signal recorded at the surface of the skin and which reflects the psychophysiological state of the body. This activity can be recorded either as a potential (TARHANOFF method) or as a change in impedance (Method FERE). We use the skin series equivalent model — FERE model (fig. 3). It has been shown that only tissue resistivity is required and that the effect of electromagnetic propagation can be neglected [16; 18], except for a respiratory inductance plethysmography [19].

Since the series equivalent model is used and since the presence of inductance is not yet accepted by numerous authors, between the impedance Z and the active resistance R we have the following relation:

$$Z = R(1 + 1/(RC\omega)^2)^{1/2} = = \eta R \quad (13)$$

C is the capacity of the tissues within the segment. Since in bioimpedance measurements (EPG, EDA etc.) changes in active resistance R and in capacity C are small (absent some per cent) (Nyboer 1970), η is almost constant and may be calculated for each rheography and the body segment. Due to the reason explained above it may be accepted that the measured impedance Z is proportional to the active resistance R, thus:

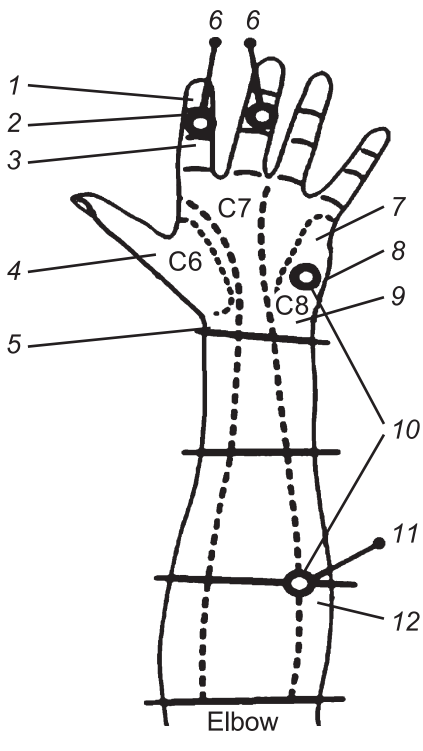

Fig. 3. Electrodes locations on the palm for measurement the resistance and potential of the skin. (Venables et Christie, 1980). Reproduction. Source [17]: *1* — distal phalanx; *2* — medial phalanx; *3* — proximal phalanx; *4* — thenar eminence; *5* — crease; *6* — bipolar placement (SC measurement); *7* — hepothenar eminence; *8* — active electrode; *9* — dermatomal distribution; *10* — unipolar placement (SC measurement); *11* — reference electrode; 12 — abraded site

$$|Z| = \eta R \quad (14)$$

The frequency f is related to the pulsation ω by the equation $\omega = 2\pi f$. Because the rheography works at a fixed frequency (selective), we can not expect the change in ω which could give rise to changes in η. Therefore $\Delta Z/Z = (\Delta R / R){\cdot}(\Delta\eta/\eta)$.

From the expression (14) we may get:

$$\Delta Z/Z = \Delta R/R \quad (15)$$

In expression (12) when we replace ΔR/R by ΔZ/Z and we make a proper calibration of the measuring instrument, we obtain:

$$\Delta V/V = (\Delta Z/Z) \times \times 1/ln(k/\eta)Z) \quad (16)$$

The ratio k/η can be reduced to the unit from the calibration of the meter. Thus the final formula becomes:

$$\Delta V/V = (\Delta Z/Z) \cdot 1/ln(Z) \quad (17)$$

Analysis Discussion & Perspectives

This last formulation (17) is based on skin abrasion and can be used safely in all measurements of biological impedance variations related to changes in various flowing objects in the body (such as blood, lymph, sweat, etc.). This is helpful because the skin impedance varies for each individual and depends primarily on: the skin temperature, the surface and contact pressure, contact tension (force), the moisture condition and sweating of the skin, the time of passage of the electrical current, physiological state, the morphology of the individual and the contact points on the body.

We note that expression (12) is widely different from the usually used expression while the discrepancy remains certainly not noticed because of the approximations used in Electroplethysmogram (EPG).

It is necessary to have here a short discussion: in expression (4) ρ is the blood resistivity, the resistance R must be the blood resistance, so that V represents the blood volume, but in expression (12) R is the total resistance of the segment. All the formulas above concern only active resistance. However, current measurement is never a direct current because of the danger due to the faradic effect. So, in reality, it is rather the total resistance. However, many authors toggle from the active resistance to complex resistance (the impedance), replacing R by Z! This requires a prior adjustment.

In impedance, the influence of plethysmography capacitance is reduced to minimum value by skin abrasion and the use of high frequencies (20 KHz to 200 KHz), but nonetheless the measured quantity is indeed impedance since reactive components are not completely cancelled.

The ratio k/η deserves special attention and can be reduced to the unit from the calibration of the meter. If k/η <1> k/η? In reality, the value to be assigned will depend on the scope and measurement conditions in each clinical specialty.

Regarding impedance, we want to know if the resistivity of the blood is not a function of other parameters in addition to the Hematocrit. Furthermore, we will also have to make an experimental phase to justify the approach.

In our opinion the results should provide further details in the calculation of cardiac parameters such as: cardiac output, heart rate, maximum frequency theoretical intracardiac hemodynamic, corrected QT interval, mean arterial pressure, cardiovascular risk, and valve area.

Conclusion

There are some difficulties in using certain formulas in the theory and practice of plethysmography (EPG) and in their applications to other biological impedance measurements (such as Electrodermal Activity). This shows the limitations and shortcomings of these formulas.

This work shows some inadequacy in the basic formulaes used in impedance rheography measurement while at the same time proposing solutions without the aforementioned discrepancies. The proposed formulas are based on reliable physical basis, but they may not be considered as the final correction in the wide range (largely used formulas), but simply as a step in the research of universal solution to the insufficiency.

This formula contains two parameters, still undetermined *k* and *h* but with the practical conditions on the current frequency of measures for *h* and on the calibration of the meter for *k*.

Concluding therefore, our conclusion is a challenge to the engineers to determine these parameters, and more still, to the physicists who are looking for conditions, on which physical laws of matter could be based on medical objects.

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