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APPROACHES ON MEASUREMENTS OF HUMAN SKIN ELECTRICAL RESISTANCE

BY

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Abstract. The paper starts with an overview of the applications related to the measurements of the galvanic skin response. There are synthetically presented the actual challenges in the domain of electrical safety, medical diagnose and evaluation and, respectively, electrostatic discharge. There are briefly analysed the different approaches and definitions focussed on the determination of the surface and volume resistance, the conversion formulae for computing the (characteristic) resistivity. It is argued the inseparable influence of different layers of human derma upon the realistic results of the measurements. After a synopsis of the electrodes used to sample signals from a surface, there are demonstrated the advantages of using silicon rubber electrodes, the here proposed completion. We communicate the design solutions for the practically realized electrodes, including the mounting, the geometrical dimensions and the transfer coefficients from concretely measured resistances to the surface (mainly) and volume resistivity. We have also here submitted our tested proposals for connecting the electrodes to measuring instrumentation, both for direct and comparative methods set-up. We conclude about the cautions that must be assumed in order to obtain truthful results. We performed a comparison between the results obtained by using the measuring configuration with two bracelet-type electrodes and the compact one, the repeatability being better for the concentric mount, essential advantage when dealing with relative measurements.

Key words: electrostatic discharge; human skin resistance.

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1. Overview on Practical Significances of the Galvanic Skin Response (GSR)

Even if the challenge of measuring the human (skin) resistance is older than one century, in the last ten years were encountered many novel approaches, aiming to connect the galvanic behaviour of the skin with treatment and diagnosis, without neglecting electrical safety or performance of the human operator in an environment where the accumulation of static charges and the following discharge could be critical.

From the very beginning, it is compulsory to underline the existence of two different types of "human electrical impedance", (Sutherland *et al*., 2005): the skin (surface) impedance, basically different from the internal one. The skin has many layers, at the very surface there is a thin structure of dead cells, deposed on a vivid but heterogeneous layer, (non homogenous and un-isotropic), presenting both resistance (nonlinear in voltage and time) and capacitance, (Sălceanu *et al*., 2013). This impedance decreases with frequency (capacitance acts as a frequency dependant shunt for the relatively high resistances). The impedance of the bulk body is basically resistive, the model being ready at hand: a phantom filled with saline at human body concentration.

The first measurements concerning the electric response of the body were propelled by the electrical safety, the question being still ruling, (Ichikawa, 2013). The generally accepted dangerous (lethal) limit for the electric current (50 mA crossing the vital parts for more than 2 s) could be, under specific condition, much lower. Without using protective devices, the statistics demonstrate a much higher rate of fatal accidents from June to September, mainly because the outdoor operators sweat and their skin resistance decrease. The item must be graduated, also considering that the two main standards in the electrical safety, IEEE Std 80 and IEC 479, have different definitions of acceptable body current and body resistance (Lee *et al*., 1999).

In the field of medical engineering, health care, monitoring and diagnose, the skin behaviour is essential from two points of view: the interface with various types of electrodes (not to be introduced undetermined contact resistance), respectively the intrinsic galvanic skin response as monitoring parameter.

For instance, the textile electrodes are a challenging alternative for the customary metal or graphite ones (Dozio *et al*., 2007). Not only they fit to body shape, but they significantly reduced the contact resistance to the human skin.

These electrodes permit the implementation of the measurement of the surface resistance distribution, a strong point for textile materials solution. The contact skin–electrode resistance is essential in the situation of dry, without gel application of electrodes, used for long-term investigations, mainly for the accurate design of the input stage of associated conditioners and/or amplifiers (Gniotek *et al*., 2011). The importance of an accurately measured contact resistance at the skin level is increased in the situations when the patient's surveillance is for a longer period, for instance, when is desired to monitor artificial organs implanted into the body (Okamoto *et al.*, 2013). Good perspectives are for titanium mesh electrode, providing stable mechanical contact (involving low and constant electrical resistance) to the skin. The next step is toward "intelligent clothes", a novel approach, aiming to embed the sensors into textiles, without paying the price of lower flexibility and wearability, the physician being able to continually survey the patient (in door), using wireless communication, (Maozhou *et al.*, 2007; Ibrahim *et al.*, 2009). As soon as the problem of measuring the skin-electrode resistance is solved, the next phase is to correctly insert this value in the diagnose process, allowing the sampling of the right, undisrupted biological signal. The value of the skin resistance is unanimously considered a physiological answer to a stressing event, (Abdullah *et al.*, 2012). In the peaceful state, the resistance offered by the skin could exceed 2 MΩ, while being reduced less than 300 kΩ when an emotional stress is applied. An "emotional, wearable, stress sensor" might be very useful, as many people do not realize their daily real level of stress, with considerable impact in their life. The decrease in skin resistance is caused by an augmented blood flow and perspiration, as physiological answers to the stress. More accurately, the resistance varies inversely proportional to the stress. The investigations related to the skin resistance could continue, in a larger framework, with the "polygraph", involving a higher resolution, due to other associated parameters (Sang *et al.*, 2005). The Galvanic Skin Response must be checked both for direct and alternative (50 Hz) current. It is compulsory to use line filters and switching in time domain, to reduce interferences and to separate ECG and GSR signals having the similar frequency range. The heart pulse and respiration rate are also important parameters indicating the stress or the discomfort.

A more detailed approach might be based on elementary active cells flexible placed on the skin, with a space resolution of a few cm^2 (Meffre *et al.*, 2006). The main parameters indicating a stressing situation have been chosen: skin resistance, potential and temperature, blood rate, ending with "on the spot" cardiac and respiratory frequency. Obviously, the thermal comfort of the human being is a composite indicator, simultaneously including the temperature and wetness (relative humidity) determination (Gerrett *et al.*, 2013). It is advisable to measure the local galvanic skin conductance (GSC) and local skin wettedness in different (up to 5 or 6) body segments. The degree of experienced discomfort seems to be related to the quantity of sweat on the skin, indirectly measured by the skin conductance at each selected part of the body.

Another field of interesting applications could be the measurement of electrical characteristics (resistance and capacitance) of biologically active points (BAP), known as acupuncture points (Prokhorov *et al.*, 2000). Comparing with the value registered in ordinary points of the skin, the resistance of BAP is lower and the capacitance is higher, being also not only quantitative, but qualitative differences between the associated impedance spectra. No doubt, the large dispersion of the *in vivo* impedance characteristics of the human body is also owed to the distributed presence of biologically active points.

The third main field where the skin resistance is a decisive parameter is the electrostatic charge accumulation on the human body followed by a possible discharge on sensitive equipment. Since the moment when the old Human Body Model was established, in order to bring at a common denominator the tests and measurements in the electrostatic charge–discharge domain, the importance of "human" resistance was clearly set up. The model proposed a value for Human Body Resistance (HBR) of 1.5 kΩ as discharging resistance from a 100 pF capacitance.

Aiming to impose heavier conditions for immunity tests, the EN 61000-4-2 standard specifies a lower (330 Ω) as discharging resistance from a 150 pF capacitance (higher stored energy on the capacitor and higher peak discharging current).

More or less, these values are just only generally accepted compromises, it is beyond any expectations that human electrical parameters to be quasi identical, (Sălceanu *et al*., 2013). Of practical importance is to establish a realistic divergence of them and to clarify to what extend these values have significant influences on the static charge–discharge events, from both points of view: the "operator" involved and the possible to be aggressed devices or components.

The encountered difficulty is mainly due to the *R-C* impedance character of the skin itself or of the whole body, both galvanic and capacitive components being influenced by the amplitude and the frequency of the applied voltage. Consequently, any useful attempt might determine both the skin resistance, R_S, serial with the "human capacitor" and global "leakage" body resistance to ground, R_L, parallel to the previously evoked capacitor.

What have we proposed for the here presented approach?

To respect the suitable safety and health regulations (chiefly, the applicability of regulatory limitations) and, obeying to this framework, to perform real measurements regarding the human resistance, both in d.c. and a.c. conditions. More over, we asses the differences between the standard and realistic values, in close connection with their practical impact on the disturbing potential of the electrostatic discharge current.

2. Fixing the Framework and the Terms of Our Attempt

Basically, we determine a resistance by performing the ratio between a voltage applied to the selected test points and the resulting current.

The difficulties appear when it is desired a high accuracy measurement, in the extremities of the domain: low resistance (high conductance materials), respective high resistance (insulating materials).

In this paper we present our attempts focussed on the human resistance, in consequence we are interested in the determination of higher spectrum of electrical resistance, the so called *insulation resistance*.

The total current is the amount of the current established through the surface paths, respective through volume (bulk) paths, other words, it is a composite result. If we want to obtain a conclusive result about the "insulation" assured by a material, it is compulsory to perform both surface and volume resistance measurements, with different positions of application for the electrodes. No doubt, the surface, respectively volume current paths cannot be totally separated, but according to the position of the electrodes, the measured resistance is in the main that of a surface, respective of a volume pathway. The most advisable configuration is with three specific, particular electrodes, with the possibility of inter-changing their role, from guard electrode to active, guarded electrode and *vice versa*.

So, the measured insulation resistance is the combined result of the surface resistance, R_S, (calculated by the current predominantly rated in the thin surface layer, including moisture) and the volume resistance, R_V, (calculated by the current mainly settled through the "bulk" body).

If we need to compare the (insulating) materials from the point of view of their electrical resistance, we need to apply to their resistivity.

The surface resistivity, ρ_S, is defined as the potential gradient, having the same direction as the current settled along the surface, divided by this current, all related to the unit. Dealing with surfaces, the unit, Ω, is associated the immaterial "square". Explicitly, the surface resistivity is numerically equal to the surface resistance of that specific material, measured by a "square" configuration: the length of the two "linear" electrodes is equal with the distance between them. This is the "etymologic" explanation of the sometimes used "Ω/square" unit, even if the dimensional unit for surface resistivity is just Ω.

Complementary, the volume resistivity, ρ_V, is the potential gradient (having the same direction as the settled current in the material) divided by the current density. The unit in the metric system is Ω.m. Clearly, it would be extremely difficult to prepare a cubic sample with the dimension of one meter. More easier is to measure the volume resistance between the opposite faces of the 1 cm^3, cut from the evaluated material, numerically equal with volume resistivity, but now expressed in Ω.cm. The ρ_V expressed in Ω.cm, is 100 times greater than expressed in Ω.m.

3. A Good Compromise: Electrodes from Silicone Rubber

Dealing with measurements on humans, focussed on specific, local parts of the body, there are some requirements compulsory to be fulfilled, most of them regarding the signal acquiring electrodes. They must be made from a "gentle" toward the skin material, not introducing contact and/or contamination errors, being corrosion resistant in the environment of the test and having the adequate, well known dimensions, essential when we convert the value of the measured resistance to the characteristic resistivity of a certain material, (ASTM Standard, 1999).

From the large diversity of electrodes, we had to choose the most passable ones, starting from the previous stipulations.

A pin inserted in a hole having the adequate dimensions represents a usual type of electrode for rigid, flat samples, providing an intimate contact, influenced by roughness of the surfaces having electric contact: the (metallic) pin and, respectively, the hole in the measured insulating material. The method is recommended for the materials that might be used with binding-posts (for instance, frontal panel). Anyway, due to the influence of the conductance of the intrinsic contact, the reproducibility of the experimental set-up is quite low. For a sample long and thin (like a tape or a strip), the electrical contact of the electrode could be assured by a system of two flat pieces (usually from brass or copper), tight by two opposite screws and nuts.

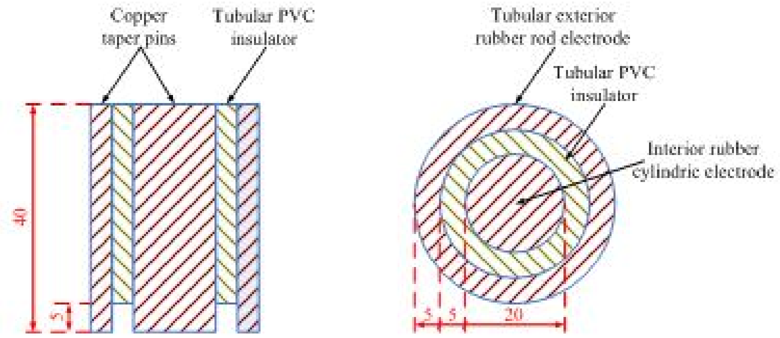
The conductive paint is a large-spread solution, with many varieties of drying, just in the free space or at a reasonable baking-temperature. Its main advantage is the allowance for the sample to be conditioned (due to their porous nature) even after the paint application, mainly essential for studies regarding the resistance–relative humidity dependence. If it is necessary, the same technique (using complementary masks), but with the deposition of insulating paints, might be applied for delimitating the electrodes, by painting a gap between. A close related solution is provided by evaporating a specific metal or just by applying a very thin (tens of μm) metal foil. The attention should be paid to the adhesive, not producing "wrinkles" of the foil or chemical corrosion of the specimen under test.

Metallic flat electrodes are the best option for testing (at various temperatures) materials that are compressible and flexible, but accepting pressure of hundreds of kPa to ensure good intimate electric contact. The most advantageous geometry of these flat electrodes is the circular one, but when dealing with thin layers, stripes or tapes, the rectangular structure could be a better option.

The colloidal graphite (dispersed in non-corrosive liquids) is an outspread solution in an environment that not absorbs water very fast, while the measurement itself and the previous conditioning could be done in a dry atmosphere.

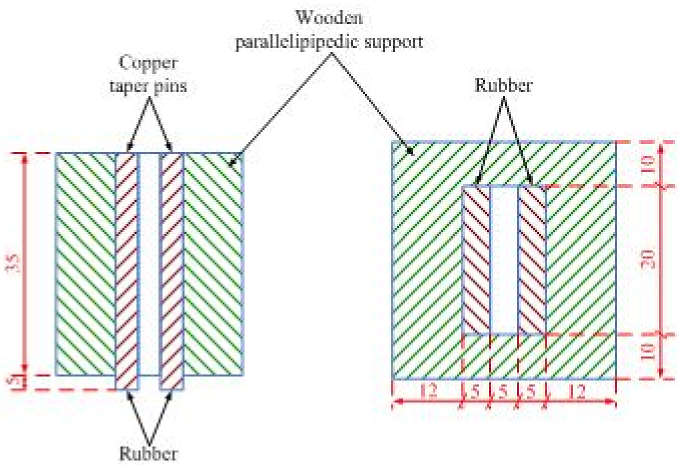
We decided that a very flexible, affordable, non-intrusive and workable out solution is that provided by the conducting rubber. There are many arguments for applying this solution on human–skin resistance measurements. First of all, the application of these rubber electrodes is not painful for the subject (even when decent pressure is applied) and allows many comparative measurements, from different zones, not interfering with any conditioning requirements for the skin.

We have designed two different samples for measuring the surface resistance-resistivity of human skin, using a circular geometry (Fig. 1) and a parallel one (other words, the opposite sides of a square) (Fig. 2) for the pair of electrodes made from conducting silicon rubber. The main advantage of these approaches is that of mobility, allowing fast measurements in many points of interest.



a *b*

Fig. 1 – Design values for the configuration with two concentric electrodes made from silicone rubber: *a* – longitudinal section; *b* – transversal section.



a *b*

Fig. 2 – Design values for the configuration with two linear, parallel electrodes made from silicone rubber: *a* – longitudinal section; *b* – transversal section.

The electrodes are connected by two copper taper pins to the voltage supply of the measuring circuit.

The overall dimensions, in mm, of the electrodes-enclosures are presented in the Figs. 1 and 2. While the length, height and width of the mounts are generally informative, of metrological importance are only the effective average face to face (mutual) perimeter of the electrodes, *P*, and the relative distance, *d*, between the same electrodes (the so called *gap*, where is placed the "material" to be measured), for the specific arrangement employed.

Why? Because the ratio between the perimeter and the gap is the transfer coefficient from the effective measured resistance to the calculated resistivity

$$\rho_S = \frac{P}{d} R, \ [\Omega/\text{square}], \tag{1}$$

For the arrangement presented in Fig. 1, the value of the converting ratio is

$$\frac{P}{d} = \frac{2\pi R_{\text{average}}}{d_{\text{gap}}} = \frac{2\pi (R_{\text{int}} + d_{\text{gap}}/2)}{d_{\text{gap}}} = \frac{2\pi \times 12.5}{5} = 15.7. \tag{2}$$

For the arrangement presented in Fig. 2, the calculation is simpler

$$\frac{P}{d} = \frac{20}{5} = 4. \tag{3}$$

Even if we weren't successful in producing a rectangular pair of electrodes, due to our technological limitations, we also considered this option. Considering the rectangle with the length *L* and the width *l*, while the distance between electrodes is *d*, the effective perimeter could be calculated with the relation

$$P = 2\left(L + l + 2d\right). \tag{4}$$

For other electrode arrangements it is possible to convert the measured resistance to volume resistivity by multiplying with a coefficient that is the ratio between the effective mutual, face to face, area of the electrodes and the distance between them, other words, the thickness of the sample

$$\rho_V = \frac{\text{Mutual area}}{\text{Thickness}} R = \frac{A}{d} R, \ [\Omega \cdot \text{m}]. \tag{5}$$

A technical desire is to improve the electrical contact between the skin and the electrodes. When we use bracelet (clip) electrodes, placed at significant distances between them, the simplest solution is provided by a non-sensitizing, non-abrasive, bacteriostatic gel electrode. In this situation we measure an insulating resistance (partly surface, partly volume), without having the possibility of converting the result in resistivity. This solution is not suited for a rigid mounting, with well established, little distance between the measuring electrodes, as the gel could introduce a shunt to "measured" skin resistance. We shall discuss the main cautions that must be implemented in the next section.

4. Recommended Set-up: Comparative Results

For many samples of specific materials, prepared for surface and/or volume resistance measurements, a three electrodes arrangement is preferred. The third electrode is a guard one, collecting all the undesired low eddy or stray currents, wanting not to interfere with the metrological one.

Usually, one electrode is always active, being connected to the voltage source, while the other two inter-change: one is the guard and the other is the "common" or *vice-versa*. Dealing with human skin, it is quite impossible to apply a guard electrode at the required, adequate point for any performed test. On the other side, due to the low values of the established current, it is strongly advisable to use shielded, coaxial cable, providing a significant reduction in the general, electric noise, in the very surroundings of the experiment. It is mandatory not to establish a "common mode loop". In consequence, the two electrodes are connected to the core lead of two different coaxial cables, while their shields, finished with about 1 cm from the main, warm lead, are all together connected at a single point, the common of the ammeter-voltmeter set-up (Fig. 3).

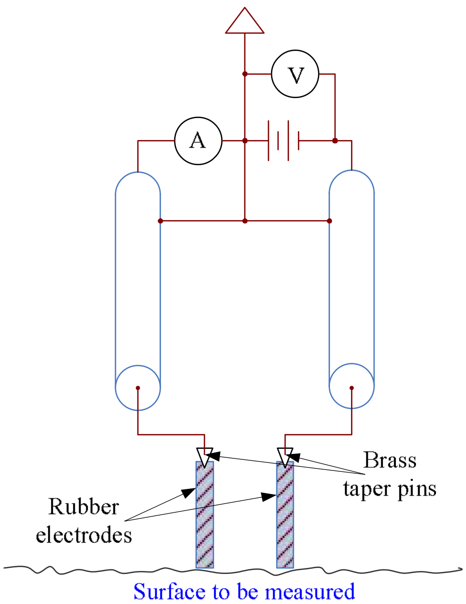


Fig. 3 – Connections of the two measuring electrodes to the instrumentation.

For proper measurements, we used both direct and comparative methods. For very low currents, there is required high sensitivity equipment, as electrometer, galvanometer or other ammeter, but with a very good d.c.

amplifier incorporated. It is possible to apply a calculating facility inside the device, in order to directly display the value of the resistance, expressed in ohms or of the resistivity, expressed in Ω/square. We compared the acquired results with this set-up with those presented by Sălceanu *et al.*, (2013), where we used bracelet contact electrodes. Obviously, the volunteer was the same for both experiments (male, 87 kg weight and 179 cm height, usually dry skin) and so were the points of measurement and the excitation d.c. or a.c. (50 Hz) voltages. The comparative results for the same part of the body are inside a margin lower than 17%. Moreover, the repeatability of the results is better when using circular electrode configuration, mainly due to the decrease of the disturbing currents, the design being more compact.

5. Conclusions

We have developed and tested two practical configurations of silicon rubber electrodes for mobile, multi-points measurements on the *in vivo* resistance and associated resistivity of human skin. The results might present interest in medical diagnosis or in the falsehood detection, in electrical safety domain and in the attempts of reducing the risk represented by the electrostatic discharge events. There were presented the advantages of using silicon rubber electrodes (the here proposed completion) by comparison with other solutions. We communicate the design solutions for the practically realized electrodes, including the mounting, the geometrical dimensions and the transfer coefficients from concretely measured resistances to the surface (mainly) and volume resistivity. We also here submitted our tested proposals for connecting the electrodes to measuring instrumentation, both for direct and comparative methods set-up. We concluded about the cautions that must be assumed in order to obtain truthful results, so supporting the acquired advantage of a guarded configuration, while the two electrodes are connected to the core lead of two different coaxial cables, with their shields finished with about 1 cm from the hot point connection, paying attention not to establish a common mode loop.

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ABORDĂRI PRIVIND MĂSURAREA REZISTENŢEI ELECTRICE A PIELII UMANE

(Rezumat)

Lucrarea debutează cu o sinteză a aplicaţiilor pe care le are măsurarea răspunsului galvanic al pielii umane. Sunt prezentate preocupări actuale privind folosirea metodelor şi rezultatelor obţinute, atât în domeniul siguranţei electrice, al diagnozei (în special, diagnosticarea stării de stress) şi supravegherii medicale, dar şi al acumulărilor, respectiv descărcărilor de sarcini electrostatice produse de pe corpul operatorului uman. Sunt succint analizate diferitele abordări şi definiţii ale rezistenţei de suprafaţă, respectiv de volum, completate cu formule de conversie de la o rezistenţă (locală) la rezistivitate (caracteristică de material). Este argumentată influenţa diferitelor straturi ale dermei asupra rezultatelor măsurătorilor. După o trecere în revistă a principalelor tipuri de electrozi utilizabili pentru prelevarea unor semnale electrice de pe o anume suprafaţă, sunt prezentate avantajele constructive şi funcţionale ale utilizării cauciucului siliconic, material din care am putut realiza o probă de măsură. Sunt prezentate desene şi dimensiuni de gabarit cu soluţii practice de realizare a probei, dar şi cu calculul coeficienţilor de conversie rezistenţă-rezistivitate (de suprafaţă). De asemenea sunt prezentate soluţiile de zgomot redus, de conectare a electrozilor din proba la aparatura de măsurare (ansamblu voltmetru–ampermetru–sursă sau punte). Rezultatele obţinute cu această configuraţie compactă (rezistenţe de suprafaţă măsurate în sau între diverse regiuni), au fost comparate cu cele furnizate de utilizarea montajului clasic, cu doi electrozi brăţară diferiţi. Pentru rigoarea comparării, determinările s-au efectuat asupra aceluiaşi voluntar, în acelaşi ambient şi în aceleaşi (aproximativ) regiuni ale corpului. Rezultatele au variat într-o marjă acceptabilă, mai mică de 17%. Un avantaj incontestabil al utilizării probei compacte propuse îl reprezintă o mult mai bună repetabilitate, cu impact în cazul măsurărilor relative, raportate la o referinţă determinată în aceleaşi condiţii. De asemenea, soluţia compactă propusă conferă o mai bună imunitate, mai ales la perturbaţiile produse de diverşi curenţi paraziţi.