*Skin Research and Technology 2011; **17**: 26–34*
Printed in Singapore · All rights reserved
doi: 10.1111/j.1600-0846.2010.00459.x

Skin Research and Technology

Electrodermal activity by DC potential and AC conductance measured simultaneously at the same skin site

Sverre Grimnes[1,2], Azar Jabbari[1], Ørjan G. Martinsen[1,2] and Christian Tronstad[2]

[1]*Department of Physics, University of Oslo, Oslo, Norway and* [2]*Department of Clinical and Biomedical Engineering, Oslo University Hospital, Rikshospitalet, Oslo, Norway*

Background: For a long time, DC conductance has been the most important parameter in electrodermal routine measurements. However, DC current flow polarizes the electrodes, electrolyzes the skin, disturbs the measurement of conductance by possible varying electromotive forces (EMFs) in the circuit, and impedes the registration of the skin endosomatic DC potential.
Methods: We therefore present a measuring system where DC current was replaced by a small AC current in a monopolar system, enabling the DC potential and AC conductance to be measured simultaneously at the same skin site.
Results: We have also found examples of skin potential (SP) response waveforms with diphasic sharp edges not appearing in the conductance waveforms. The potential responses were found to be more robust with respect to movement artifacts, and the instrumentation could discern whether the indifferent electrode actually was on an inactive skin site.
Conclusion: In order to study the generating mechanisms of EDA in detail, the SP must be measured without DC current flow and compared with AC conductance results.

Key words: sweat duct reabsorption – bioimpedance

Accepted for publication 4 June 2010

TWO IMPORTANT parameters in the electrodermal activity (EDA) tradition are skin conductance (SC) and skin potential (SP), even if the conductance parameter has been much more commonly used than the potential parameter (1, 2), (p. 178). Both parameters are sometimes used and compared, usually simultaneously contra-lateral (3) or in sequence (4). In the public recommendations on electrodermal measurements (5), resistance is not a recommended parameter but conductance is. In both cases, this implies that an exosomatic, continuous DC current flows through the electrodes and the skin. Even if such a system is simple and practical, it is not particularly suitable for research purposes: (a) DC current flow polarizes the electrodes and electrolyzes the skin, (b) the measurement of conductance is disturbed by possible varying electromotive forces (EMFs) in the circuit, and (c) skin endosomatic DC potential cannot be registered simultaneously with DC conductance because of the DC current used.

SC is largely determined by the low-conductivity stratum corneum shunted by the high but very variable conductance contribution of the sweat content in the sweat ducts in parallel (2), (p. 59) (6, 7). While SC mainly is a sweat duct filling parameter, the DC potential is a skin membrane parameter (8). Earlier results (1) have shown that the SC response (SCR) is preferred to the SP response (SPR) because the former has a simpler curve form, always with an initial rapid increase and a slower recovery. Many papers, such as Gaviria et al. (1), Lykken et al. (3), Venables and Martin (8), Venables & Sayer (9) and Yokota et al. (10), have presented results with both conductance and potential parameters and found this to be an interesting research area even without having the chance of measuring both parameters simultaneously at the same skin site. They pointed out different correlations between potential and conductance both with respect to responses and levels. It is clear that the variables may contain different information from sweat glands, sweat ducts, membranes, and epidermal responses.

We have looked more closely at the possibilities offered by modern electronic and computer

technology to see whether it is possible to measure more than one parameter simultaneously at one skin site. Measuring with the same electrode is important because of the often large skin site dependence of levels and response waveforms. In our laboratory, we have also developed an instrument able to measure single skin site AC conductance at four different placements simultaneously (11). We have found that the SCR amplitude for instance may be doubled at the hypothenar with respect to the thenar site and be fourfold as high on the long finger. This is in agreement with earlier findings (5). We now present a new methodology, enabling simultaneous and separate recordings of the two parameters by combining AC SC with SP in a novel way.

New measuring method

SC need not be measured using a DC method; by using AC, the influence of all unknown or unstable EMFs of electrodes and tissue can be eliminated. EDA data can be recorded in the following way, from one skin site only:

A monopolar measuring system is selected and the DC+AC voltage of the electrode is measured using a usual voltmeter circuit. The AC voltage measured is proportional to the impedance of the electrode-skin tissue under the measuring electrode if a constant small-amplitude AC current is applied to the measuring electrode. Skin AC conductance values are calculated from the impedance values continuously and in real time. In this way, skin AC conductance and SP are measured simultaneously at the same skin site.

Monopolar electrode system

It is possible to find electrode types that are equally well suited for conductance and potential recording (5). For SP recording with a two-electrode system, one of the electrodes must be on an inactive skin site. For SC recording, the inactive electrode must also be indifferent meaning that it must have a much larger skin contact area than the active electrode.

The electrode system chosen (Fig. 1) was a small measuring electrode, together with a large indifferent electrode. Electrodes were commercial skin surface Ag–AgCl types. The measuring electrode (Arbo hydrogel, Covidien, Mansfield, MA, USA) was placed on the palm; the skin contact area was about 3 cm^2. A wet gel electrode (Ambu Blue Sensor, Ambu A/S, Ballerup, Denmark) was used as a part of the indifferent electrode and connected to a bath of physiological saline with the forearm immerged to a contact area of about 300 cm^2 (Fig. 1). The NaCl concentration of the saline is too high to be in accordance with the recommendations of Fowles et al. (5). This is not important for the present study, but will be a research topic in a planned study of sweat reabsorption processes in the ducts.

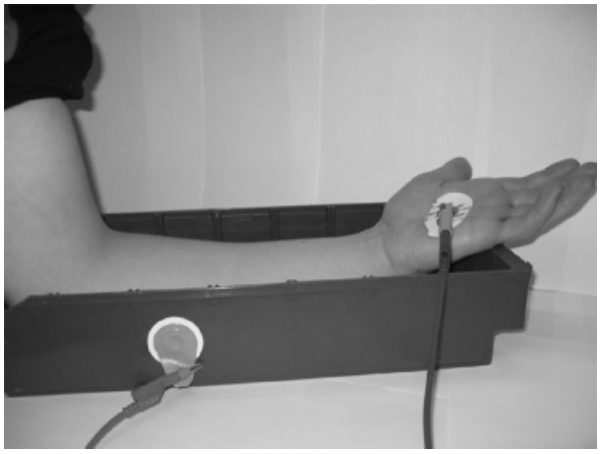

Fig. 1. Monopolar electrode system.

For an accurate measurement of the DC potential, the two electrodes were measured to have <1 mV generated DC voltage when connected directly together gel to saline.

No electrostatic shielding was used; on using such a large indifferent and grounded electrode, the signal noise on e.g. power line frequencies was reduced to a negligible level.

Measuring circuit

As shown in Fig. 2, the small monopolar measuring electrode records both the SP and the AC voltage generated by a constant-amplitude AC current supplied to the same electrode. The composite DC and AC signal was sent to a non-inverting DC-coupled operational amplifier circuit and amplified by 100. The amplifier was trimmed to a DC offset voltage <1 mV and the typical input DC bias current was 50 pA.

The output was further coupled to an analogue-to-digital (A/D) converter and a lock-in amplifier. This lock-in amplifier was used both as a signal source (22 Hz sine) and as a low–noise-phase-sensitive rectifier. The sine curve output was fixed at 2.5 V rms at 22 Hz and the large 100 MΩ resistor converted it to an AC current

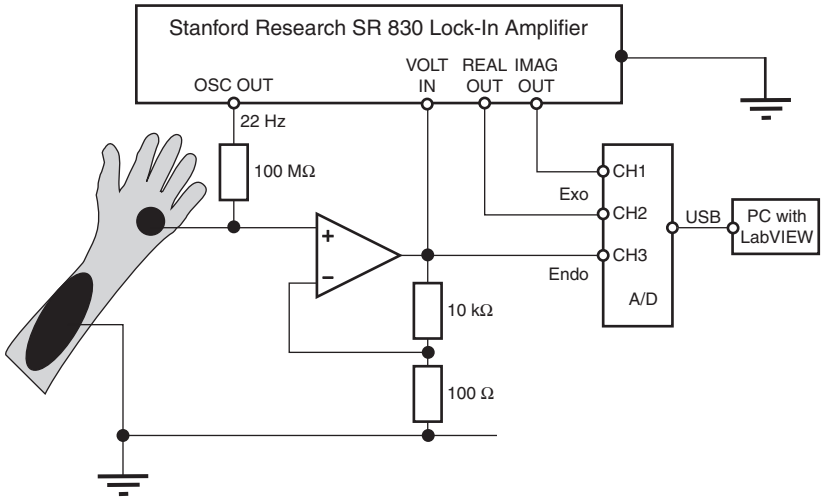

Fig. 2. Measuring system. The small electrode is the measuring electrode.

supply of 25 nA coupled to the measuring electrode. The AC voltage is then proportional to the impedance of the electrode and the skin beneath. The lock-in amplifier output supplies the signal in two channels: the AC resistance R and the AC reactance X. These two signals are coupled to the A/D converter, and in software, transformed to conductance G (and susceptance B, which is not used in this application) as shown in the following paragraph. A lock-in amplifier was chosen because it is especially efficient in picking up small signals in the presence of noise. The input and output terminals were referenced to the power line ground as shown in Fig. 2. See (12) for more circuit details.

Signal conditioning

The circuit of Fig. 2 measures the complex impedance Z (13); see Appendix C for details. AC conductance G must therefore be calculated from the impedance parameters measured:

$$G = \frac{R}{R^2 + X^2} \quad [\mathrm{S}] \qquad (1)$$

All calculations and signal processing were performed by LabVIEW version 7.1. In this program, the composite signal from the measuring electrode was filtered in order to obtain the DC potential without the 22 Hz AC component. DC voltage is graphically presented in the diagrams (Figs. 3–6) with increasing negative potentials and increasing AC conductance pointing upwards.

Results

The new instrumentation was tested, with the authors as the test subjects. The test subjects were measured sitting relaxed in a chair with one forearm immersed in the bath. A response was elicited by one deep breath or other stimuli as noted.

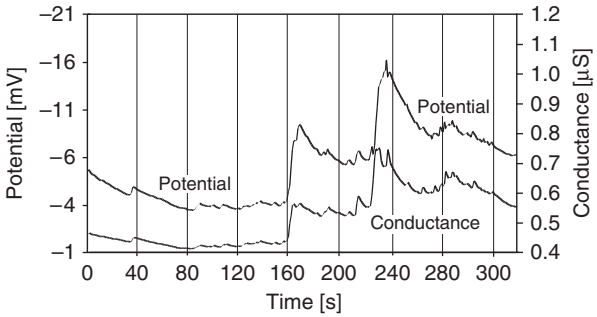

Fig. 3. Potential and AC conductance curves highly correlated.

A few representative results are given as examples of performance. Some preliminary results and interpretations have already been presented (12, 14). In general, the potential and AC conductance responses are clear and noise free and well suited for a detailed examination.

Example: highly correlated potential and AC conductance curves

The results shown in Fig. 3 are those obtained from a male test subject (age 46). The test subject relaxes in the chair from 0 to 159 s, and then takes deep breaths at times 159 and 233 s. From 272 to 300 s, small-talk, afterwards complete relaxation in sitting position. The SP and SC signals are highly correlated both with respect to level (slow changes) and response. The small response at 38s was non-specific (could not be associated with an identifiable external stimulus).

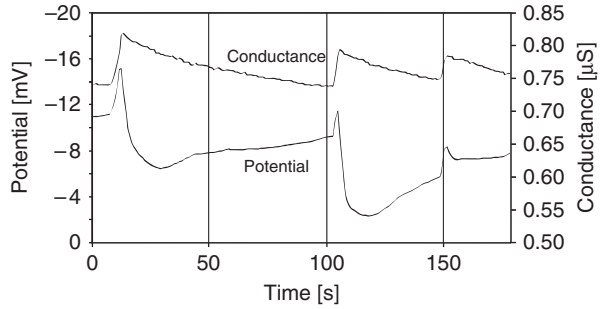

Fig. 4. Diphasic potential curve.

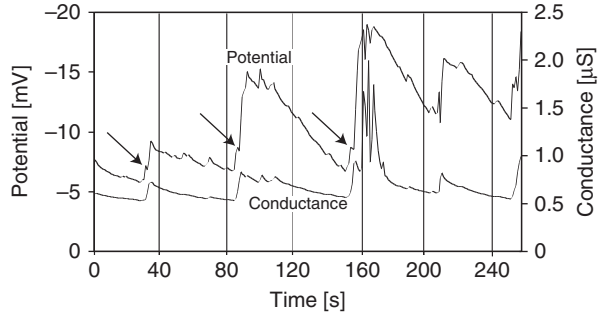

Fig. 5. Small diphasic skin potential responses (SPRs) similar to those seen in Fig. 4 are discernible (arrows). Movement artifact noise is more pronounced in the AC conductance curve.

Example: large-amplitude diphasic potential curve
Fig. 4 shows the results from a male test subject (age 67). The first response was from moving the legs while sitting, the second elicited by a surprise, and the third by laughter. Figure 4 shows typical uniform SCR waveforms but a high variability of a second wave in each SPR, a diphasic waveform with quick potential reversals.

Example: Small-amplitude diphasic potential responses, potential curve less sensitive to movement artifacts
Figure 5 shows the results from the same subject as that shown in Fig. 3 (male, age 46). The first response was non-specific. The second was from a deep breath, the third from a needle prick in the finger and the test subject's movements in the chair and the fourth from a deep breath. The movement artifacts at the time of around 165 s were more pronounced in the conductance curve.

Regarding the potential reversal waveform positions shown in Fig. 4, a close inspection of Fig. 5 reveals small notches corresponding to the potential reversal process also in this example as indicated by the arrows. In general, the potential

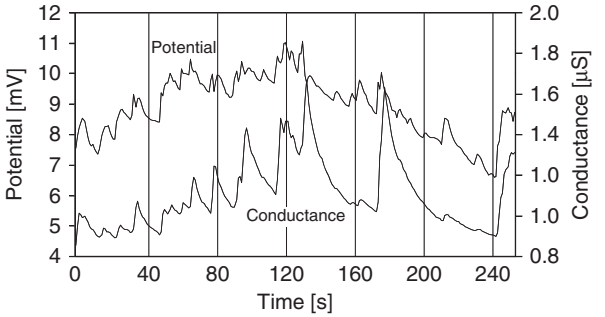

Fig. 6. Skin potential (SP) and skin conductance (SC) weakly correlated.

waveform shows many small responses not present in the conductance signal.

Example: Indifferent electrode on active skin site
Figure 6 shows the result from a female subject (age 29) during conversation (left part) and relaxation (right part). In the left part, the SC and SP do not follow the same pattern, and in the right part, the SCR are few and with a large amplitude, while the SPRs are small and SPL decreases linearly. The potential waveform shows many small responses not present in the conductance signal. Some of the potential responses start or peak slightly earlier than the conductance responses.

Discussion

Our results show that it is possible to measure the SP and skin AC conductance separately but simultaneously in a low-noise system. The routinely used DC method of measuring SC has properties, which makes it less attractive for electrodermal research. This is well illustrated by the problem of choosing the applied DC voltage level. According to the recommendations of Fowles et al. (5), the SCL range is reported to be from 2 to 100 µ℧/cm^2. With the recommended applied constant voltage 0.5 V DC, this corresponds to a DC current flow up to 50 µA/cm^2 [Eq. (A1): $I = UG$]. The lower the applied DC voltage, the larger the contribution from the other EMFs of the circuit, the epidermis itself being one of them with possible variations of tens of millivolt. Gradually, the measured parameter is no longer a calibrated DC conductance but represents a mixture of SP and SC, and the higher the applied DC voltage, the larger the DC current, inducing new side effects (non-linearity, electrode drift, skin DC potential affected, increased

skin irritation). 0.5 V therefore represents a compromise proven to be practical in well-standardized situations but not very well suited for research when for instance different electrode metals are chosen for mechanical strength.

The problem with DC current flow and the ambivalence between the SP and skin DC conductance parameters has followed the electrodermal measurements right from the start. Both Tarchanoff (15) and Féré (16) measured DC currents using a galvanometer, and the results were a function both of potentials and of DC resistance/conductance.

Our new instrument uses an exosomatic AC current source of 25 nA that has three orders of magnitude lower amplitude than the DC levels reported above. In addition, it is a 22 Hz sine curve without the DC component and therefore a strongly reduced ability to generate electrolysis. The DC bias current for the amplifier is typically 50 pA, which is six orders of magnitude lower than the current used in the DC method.

Fowles et al. (5) pointed out that SC measurements are best performed using a bipolar electrode system with both electrodes at an active skin site preferably belonging to the same dermatome. Such considerations are unnecessary with our monopolar conductance method as only one skin site is measured. They also wrote: "It is essential to monitor electrodes for changes in bias potentials and for polarization." This is certainly good advice, but we believe that the need for such controls will be less with the new method.

According to Fowles et al (5), a disadvantage of the AC method is that the capacitive properties of the skin add to the DC conductance values, resulting in too high conductance readings. As shown in Eq. (A2), Appendix C, the skin capacitance contribution is proportional to the measuring frequency. By using a low measuring frequency (e.g. below 40 Hz) and phase-sensitive rectification, the skin capacitance contribution is reduced to negligible values.

SP measurements need an inactive skin site. Our results indicate that by measuring SC simultaneously, it is possible to assess to what extent the indifferent electrode placement actually is an inactive skin area. Figure 3 shows a result where the responses start or peak simultaneously, indicating that the indifferent skin site at that time was inactive. Figure 6 shows the result with some of the potential responses starting or peaking slightly earlier than the conductance responses. One possible reason for this is that even if the large indifferent electrode makes the conductance measurement monopolar, it does not do so for the potential measurement. One large and one small electrode do not make a potential registration monopolar; it is a function of the degree of passiveness of the presumed inactive skin site. Figure 6 shows a result where the SPR started earlier than the SCR, indicating that the indifferent skin at that time was active, and as it is proximal to the measuring electrode, the SPR started earlier.

Our method therefore may assess whether the indifferent electrode actually is on an inactive skin site.

Our indifferent electrode (Fig. 1) was large and not very practical. We are currently developing a refinement of the circuit of Fig. 2, where the large indifferent electrode is replaced by two control electrodes. This will make the circuit more easy to use, and the necessary inactive skin area may be much smaller.

Our results (Fig. 5) show that SP is a more robust parameter than SC because it is less dependent on the constancy of the electrode skin contact area. Movement artifacts therefore tend to be more pronounced in SC than in SP curves.

We found the rise times to be about 2 s, which is in accordance with data from Venables and Christie (7), Table 1.4, and presumably corresponds roughly to the gland activity duration. The recovery period ($t/2$) was about 40 s, which is much longer than the data presented by Venables and Christie (7). The reason for this is presumably the different contact electrolyte concentration already mentioned influencing the emptying process of the ducts.

In the literature, published method descriptions sometimes have been unclear with respect to the measurement method used. Presumably, neither Goadby and Goadby (17), Venables and Christie (7), figure 1.4 nor Shirai et al. (18) presented SP and SC waveforms obtained simultaneously with one measuring electrode. Wilcott (19) made the well-known statement: "As it is of course not possible to record the two types (SP and SC, authors remark) of bioelectrical activity from the same skin area simultaneously, they were recorded alternately from different skin areas."

Montagu (20) and Grimnes (21) performed measurements on the same skin site simultaneously. Montagu (20) used a monopolar electrode system and capacitor-coupled 60 Hz sine signal to the active electrode, and the corresponding AC

voltage was capacitor coupled to the impedance measuring amplifier. The DC amplifier was directly coupled to the electrodes. Grimnes (21) used a controlled voltage monopolar circuit with a blocking capacitor between the measuring electrode and the current reading shunt. Both these circuits had the disadvantage that the measuring electrode must supply the necessary charge/discharge current to the blocking capacitor(s) with changing DC voltages. This also introduced a time constant determined by the capacitance and the measuring electrode resistance.

Conclusion

The traditional DC measuring method was recommended in 1981 (5). However, this popular method presupposes continuous DC current flow and cannot separate conductance and potential waveforms. In order to study the generating mechanisms of EDA in detail, the SP must be measured without DC current flow and compared with the AC conductance results. This is enabled by utilization of modern instrumentation solutions such as phase-sensitive rectification, real-time signal processing and conversion of variables. We have presented novel methodology for measuring SP and skin AC conductance activities selectively and simultaneously with only one measuring electrode. The method has sufficiently low noise to discern small response waves. The performance examples showed that sometimes the potential and conductance signals were highly correlated. In other cases, an SPR had no corresponding SCR and visa versa, indicating that they may be generated by different mechanisms. Even if the DC method certainly has advantages in routine work, new methods must be considered for future electrodermal research.

References

1. Gaviria B, Coyne L, Thetford PE. Correlation of skin potential and skin resistance measures. Psychophysiology 1969; 5: 465–477.
2. Boucsein W. Electrodermal activity. New York: Plenum Press, 1992.
3. Lykken DT, Miller RD, Strahan RF. Some properties of skin conductance and potential. Psychophysiology 1968; 5: 253–268.
4. Edelberg R, Burch NR. Skin resistance and galvanic skin response. Arch Gen Psychiatry 1962; 7: 163–169.
5. Fowles DC, Christie MJ, Edelberg R, Grings WW, Lykken DT, Venables PH. Committee report: publication recommendations for electrodermal measurements. Psychophysiology 1981; 18: 232–239.
6. Edelberg R. Biopotentials from the skin surface: the hydration effect. Ann NY Acad Sci 1968; 148: 252–262.
7. Venables PH, Christie MJ. Electrodermal activity. In: Martin I, Venables PH, eds: Techniques in Psychophysiology. New York: John Wiley, 1980.
8. Venables PH, Martin I. The relation of palmar sweat gland activity to level of skin potential and conductance. Psychophysiology 1967; 3: 302–311.
9. Venables PH, Sayer E. On the measurement of the level of skin potential. Br J Psychol 1963; 54: 251–260.
10. Yokota T, Takahashi T, Kondo M, Fujimori B. Studies of the diphasic wave form of the galvanic skin reflex. EEG Clin Neurophysiol 1959; 11: 687–696.
11. Tronstad C, Gjein GE, Grimnes S, Martinsen ØG, Krogstad A-L, Fosse E. Electrical measurement of sweat activity. Physiol Meas 2008; 29: S407–S415.
12. Jabbari A. Mechanisms behind endogenous and exogenous electrodermal response (in Norwegian). Master thesis, Department of Physics, University of Oslo, 2006.
13. Grimnes S, Martinsen ØG. Bioimpedance and bioelectricity basics, 2nd edn. Amsterdam: Elsevier, 2008.
14. Jabbari A, Grimnes S, Martinsen ØG. Electrodermal response – correlation between potential and conductance. IFMBE Proc 2007; 17: 747–750.
15. Tarchanoff J. Ueber de gavanischen Erscheinungen in der Haut des Menschen bei Reizungen der Sinnesorgane und bei verschiedenen formen der psychischen Tätigkeit. Pflug Arch 1890; 46: 46–55.
16. Féré C. Note sur des modifications de la resistance electrique sous l'influance des excitations sensorielles et des emotions. C R Soc Biol (Paris) 1888; 5: 217–219.
17. Goadby K, Goadby H. Simultaneous photographic records of the potential and resistance effects of the psycho-emotive response. J Physiol 1936; 83: 11–13.
18. Shirai K, Yamamoto Y, Nakamura T, Kusuhara T. Formative mechanism of skin potential activity and relationships between skin potential and skin impedance. IFMBE Proc 2006; 14: 2573–2576.
19. Wilcott RC. Correlation of skin resistance and potential. J Comp Physiol Psychol 1958; 51: 691–696.
20. Montagu JD. A comparison of AC skin resistance and skin potential changes. J Neurol Neurosurg Psychiatr 1958; 21: 119–128.
21. Grimnes S. Psychogalvanic reflex and changes in electrical parameters of dry skin. Med Biol Eng Comput 1982; 20: 734–740.
22. Grimnes S. Skin impedance and electro-osmosis in the human epidermis. Med Biol Eng Comput 1983; 21: 739–749.

Appendix A: Some characteristic properties of AC and DC conductance methods

The advantages with the present DC conductance technique are as follows:

- Well-established clinical practice.
- Simple concept, skin capacitance does not intervene.
- Large amount of reference data found in the literature.

The disadvantages with the present DC conductance technique are as follows:

- Recommended technique (5) allows a continuous DC current flow up to $50\,\mu A/cm^2$.
- DC currents may change the EMF generated in the circuit, in the electrodes (polarization properties and bias voltage) and in the skin (electro-osmosis and sweat duct filling (22), membrane potentials, skin electrolysis and irritation).
- Uses bipolar electrodes and the results originate from two different skin sites. However, electrodes and skin sites are not equal, and one does not know the individual contribution of each electrode.
- Less suitable for physiological research.

The advantages with the proposed AC conductance technique are as follows:

- Enables measurement of AC conductance and potentials at the same skin site simultaneously.
- No DC current flow, less stringent requirements for the electrode technique.
- Not necessary to monitor electrode bias potentials or polarization during use.
- No influence from changing EMFs in the circuit.
- Measures at one single skin site.
- No skin irritation created by DC currents.
- Very suitable for physiological research.

The disadvantages with the proposed AC conductance technique are:

- More complicated measuring system and more parameters must be understood and controlled.
- Much less reference data found in the literature.

Appendix B: Terminology

Venables and Christie (7) proposed a terminology that we follow. It is based on a clear distinction between levels and responses: skin potential level (SPL), skin potential response (SPR), skin conductance level (SCL), and conductance response (SCR). In their terminology, skin conductance (SC) means DC conductance. Skin potential is obtained with a DC-coupled potential measuring circuit. SPR are sometimes high-pass filtered so that only responses and not levels are recorded.

Fowles et al. (5) formed a committee presenting recommendations for electrodermal measurements. Accordingly, we use SC as the preferred parameter to resistance but implicitly also including skin resistance when necessary for historical or other special reasons.

SC may be measured with DC or AC, and so this must therefore be specified. However, as in the present tradition, conductance implicitly means DC conductance (5), and AC conductance must be explicitly pointed out when used. Also, AC conductance may be measured either by phase-sensitive or -insensitive rectification. With phase-insensitive rectification, the modulus of admittance is measured [Eq. (A4)], with the capacitive part included. This is therefore no pure conductance method and cannot be called an AC conductance method. The term AC conductance means conductance measured only using a phase-sensitive rectification method.

Skin capacitance must be measured using an AC method, and so this need not be explicitly specified. However, it is very important to state whether it is series or parallel capacitance [Eqs. (A2)–(A5)].

Appendix C: Potential and conductance parameters

The new AC technology is more complicated than the traditional DC method, even if the DC method also has its pitfalls due to poorly defined EMFs. In order to give interested readers a chance to increase their knowledge about AC and DC electrodermal methods, we have added a few basic remarks and equations important for understanding not only the AC technology but also the DC method used so much. More basic descriptions of bioimpedance and bioelectricity can be found in Grimnes and Martinsen (13).

Potential

Potential is actually a potential difference between two electrodes. Both the electrodes (metal and contact electrolyte included) and the epidermis under the electrodes contribute to the result. The method is endosomatic because no sensing current is sent through the electrodes, and accordingly, the electrodes are not polarized. The electrodes cannot be a bipolar pair in the same dermatome. The response potential may then be the same on both electrodes and the potential difference response more or less canceled. The electrode system must be monopolar in the sense that one electrode is the measuring electrode and

the other electrode is in contact with inactive skin. Potential responses are then measured relative to this electrode. The electrode may have a large potential level without being on active skin due e.g. to the use of different electrode metals. The size of the skin contact area has no influence. The potential has no true zero value and both positive and negative values are measured.

Conductance

Conductance is a quantity dominated by the properties of the epidermis and sweat ducts under two electrodes. A sensing current must be sent through the electrodes in order to measure conductance; the method is exosomatic. The electrodes may be a bipolar pair on the same dermatome or a monopolar system with a measuring and an indifferent electrode. Indifferent means that the electrode has a much larger skin contact area than the measuring electrode so that the small electrode conductance dominates, being in series with the indifferent electrode conductance. The conductance has a true zero value and no negative values.

DC conductance

Ohm's law for DC cases is

$$G = I/U \text{ or } I = \text{GU} \qquad \text{(A1)}$$

where G is the DC conductance [S (℧)] and I is the measured DC current (A). The problem with Eq. (A1) is U, the total voltage of the circuit. If U is constant and known, Eq. (A1) is simple and linear and the values of G are calibrated.

However, U is the algebraic sum of all voltage sources in the circuit: (a) the exosomatic applied electromotive force EMF (V), (b) the membrane EMFs of the skin, (c) the half-cell potentials of the electrodes determined by electrode surfaces and the types of contact electrolyte. If the EMF of any of these sources are unknown and a function of DC current and time [Eq. (A1)] is not linear any more, DC conductance cannot be measured unambiguously. Skin membrane potentials are e.g. due to different ionic activities (concentrations) on each side of the membranes, and a DC current will change these concentrations and therefore influence the membrane potentials. Also, electrolysis may occur at the electrode metal, affecting both electrode polarization and the skin.

AC conductance, impedance, and admittance using sine curves

Strictly speaking, impedance and admittance are only defined with one waveform, the sine, which is the only waveform containing only one frequency. Ohm's law for AC cases is:

$$Y = G + jB = G + j\omega C_\text{p} = i/u \quad \text{(S)} \qquad \text{(A2)}$$

where Y (with bold character) is the complex admittance (S), G the AC conductance (S), j is the imaginary unit, B is the susceptance (S), ω is the angular frequency $2\pi f$, where f is the measuring frequency (Hz), C_p is skin parallel capacitance (F), u is the exosomatic constant amplitude sine voltage, and i is the measured sine current and a complex quantity because it is phase shifted with respect to u. The introduction of a capacitor C_p introduces a time lag in the circuit, a phase shift, and therefore admittance is a complex quantity. The time aspect is necessary because it takes time to charge or discharge a capacitor.

Equation (A2) is more complicated than Eq. (A1). Skin capacitance C_p is a new parameter, and so is the measuring frequency f. It is still of interest for our purpose to avoid the use of DC current flow and have the additional advantage of being able to measure electrode DC potential undisturbed.

The phase shift φ is

$$\varphi = \text{arctg}(\omega C_\text{p}/G) \quad (^\circ) \qquad \text{(A3)}$$

The modulus of admittance is

$$Y = \sqrt{G^2 + (\omega C_\text{p})^2} \quad \text{(S)} \qquad \text{(A4)}$$

The modulus can be measured using a phase-insensitive rectifier method. The separation of AC conductance and skin capacitance can be obtained using a phase-sensitive rectifier circuit. If the skin capacitance and measuring frequency are sufficiently small, Eq. (A4) shows that the conductance G can also be determined using a phase-insensitive method.

The circuit of Fig. 2 measures complex impedance Z:

$$Z = R + jX = R + j/\omega C_\text{s} = u/i \quad [\Omega] \qquad \text{(A5)}$$

where R is the AC resistance (Ω), X the reactance (Ω), C_s the skin series capacitance (F), i is the constant amplitude applied sine current and u the measured complex potential.

Admittance Y is the inverse of impedance Z

$$Y = 1/Z \quad \text{(S)} \qquad \text{(A6)}$$

AC conductance G can be found from the two measured impedance parameters resistance R and reactance $X = 1/\omega C_s$

$$G = \frac{R}{R^2 + X^2} \quad (\mathrm{S}) \qquad (A7)$$

The skin parallel capacitance C_p is not the same as the skin series capacitance C_s. As the epidermis capacitance is physically in parallel with the sweat ducts, C_s is not a preferred parameter even if it has been used. In our paper, skin capacitance was measured but only used for calculating the AC conductance G with Eq. (A7).

Address:
Ørjan G. Martinsen
Department of Physics
University of Oslo
P.O.Box 1048
Blindern
NO-0316 Oslo
Norway
Tel:+47 2285 6474
Fax:+47 2285 6422
e-mail: *ogm@fys.uio.no*