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Psychogalvanic reflex and changes in electrical parameters of dry skin

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Abstract—*The change in electrical characteristics of the skin owing to the psychogalvanic reflex has been investigated. The importance of using parallel values of admittance data is underlined because sweat-duct conductivity is anatomically in parallel with the rest of the skin. The response has been found to be mainly conductive, but small capacitive changes can appear. The effect of conductive-film formation on the inside of the duct walls is discussed and emphasised. It is postulated that the dorsal side of the hand is as reflex-sensitive as palmar sites, but the lack of continuous sweat-gland activity and the conductive duct-wall films of dry skin often make the response disappear on non-palmar skin sites. GSR on non-palmar skin sites can be a source of error if not adequately considered because just a deep breath may double skin conductance in seconds. To explain the rapid, positive waves often seen in the skin-potential response a new theory based upon electrokinetic phenomena is proposed.*

Keywords—*Electrodermal response, Galvanic skin response, Psychogalvanic reflex, Skin impedance, Skin potential, Sweat glands*

1 Introduction

WANG (1958) reviewed the literature on what he called the galvanic skin reflex (GSR). EDELBERG and BURCH (1962) used the galvanic skin response (also GSR), but, in a more general description later, EDELBERG (1971) used the expression phasic response and more specifically the electrodermal response (EDR). Earlier, ROTHMAN (1954) discussed the terms, and, although not happy with it, retained the old description used by GILDEMEISTER (1915): the psychogalvanic reflex (PGR). The term 'response' therefore limits the scope to the change in e.g. electrical parameters of the skin as the result of a psychogalvanic reflex mechanism.

The main point in all these descriptions is the quick but transitory change in electrical characteristics of the skin evoked by a sudden stimulus such as a noise, drawing a deep breath, answering a question or moving a limb. The palmar skin of the hands (and soles of the feet) is unique in this respect; as we shall see, other sites do not show the reflex so distinctly.

An important factor in skin impedance (admittance) is the capacitance and conductance of the stratum corneum. This is composed of several layers of dead, keratinised cells through which the current must pass if there is no easier way via fluid-filled intercellular channels or sweat gland ducts. KUNO (1956) stressed the importance of a clear differentiation between thermal and mental sweating, and that palmar sweat secretion is more determined by 'emotional' than thermal factors. He pointed out that palmar sweating is continuous and, although diminished during sleep, it recovers at once after wakening. ROTHMAN (1954) emphasised that the differentiation is not clear-cut, and that the conductance of the palmar skin also depends to a certain extent on thermal stress. It is important to be aware of this when evaluating skin-conductance data. The person under test must undergo an adequate rest period before measurements are started to avoid the decrease in admittance owing to reduced physical activity.

The skin parameters of interst are d.c. potential, conductance and capacitance, and the changes in these caused by the reflex. Traditionally only the d.c. parameters have been used, but there are several reports on a.c. testing. A.C. involves capacitative current paths in addition to the d.c. paths. On the other hand, d.c. can have certain electrochemical and other effects which are absent with a.c. A method without such effects is the endosomatic skin-potential measurement performed virtually without current flow. The study of all these parameters can be of value not only in the study of the psychogalvanic reflex but also for shedding light on the more general problems of the electrical properties of the skin.

ROTHMAN (1954) indicated that the skin response is of a purely capacitive nature, whereas MCCLENDON and HEMINGWAY (1930), GRINGS (1953), FORBES and

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Landis (1935) and Takagi and Nakayama (1959) pointed out that there were changes in both capacitance and conductance. Yokota and Fujimori (1962) found, however, that the whole change was in conductance. Based on their results Montagu (1964) made a comparison between d.c. and 60 Hz a.c. results, and concluded to his own surprise that there was often a direct linear relationship between a.c. admittance and d.c. conductance, a result which could be in conflict with the condition of constant capacitance.

In an earlier paper Montagu (1958) pointed out that the change in d.c. potential did not exactly match the impedance change. Takagi and Nakayama (1959) also examined the d.c. potential waves and found that positive changes were not shown in the d.c. conductance waves. Edelberg (1968) presented a model of the skin-potential response.

In this paper further evidence is sought on the nature of the changes in the skin during the psychogalvanic reflex.

2 Method

Measurements were performed with simultaneous recording of two or three parameters.

(*a*) D.C. potential or d.c. conductance

(*b*) A.C. conductance

(*c*) Capacitance.

The a.c. measurements were performed in the frequency range 0·5–5 000 Hz. The measuring electrode was applied on dry, i.e. unmoistened skin. The stratum corneum is not truly dry; it has a water content in balance with the humidity of the surrounding air (at skin temperature), plus a supply from sweat gland activity and insensible perspiration. Dry skin in this paper is defined as the state of the skin when no electrolyte or conductive gel has been applied, after an adequate stabilising period during which the subject relaxes so that his sweat gland activity has reached a stable minimum and GSR waves are not elicited at non-palmar skin sites (to be discussed in Section 4).

The following impedance components are physically in series:

(*a*) electrode polarisation impedance

(*b*) skin impedance (admittance)

(*c*) deeper-layer resistance

Skin admittance, however, is composed of components which physically/anatomically are in parallel: sweat-duct conductance, horn-cell admittance and electrostatic capacitance. It is obvious then that skin admittance should be studied with parallel representation, whereas e.g. the relationship between skin impedance and deep-layer resistance or electrode polarisation impedance should be studied with series representation. In spite of this most skin impedance studies have been done with series components. Gerstner and Gerbstädt (1949), for instance, studied voltage-amplitude dependence of skin impedance and found capacitance dependence from 0·1 v r.m.s., whereas recalculating the data to parallel values shows constant skin capacitance to 1·6 v r.m.s.

Rosendal (1940) measured electrode-polarisation impedance for different metals in electrolytes and found all values to be less than 1,000 Ω cm^2 at 10 Hz. For an AgCl electrode it is presumably less than 250 Ωcm^2, and for our electrode less than 500 Ω. Our electrode should therefore be considered 'nonpolarisable', with less than 1% contribution down to 50 kΩ skin impedance or up to 20 μS admittance at 10 Hz. A complicating factor is that our electrode was placed directly on the skin, so that the diffusion zone may have reached the skin. Therefore the electrode polarisation was also checked with conductance gel between the skin and the electrode. The immediate admittance level increased by a factor of up to 50%, but otherwise the results were unchanged. This is believed to be due to an area-increasing factor caused by the curvature of the skin, but a certain effect from a diffusion zone reaching the skin cannot be excluded. The use of different electrode metals made no difference except to d.c. potential. For d.c. potential stability it is believed to be important to use AgCl-covered electrodes, which have a well defined potential with respect to NaCl, in contrast to pure silver, stainless steel etc.

In a bridge, series and parallel representation is determined by the coupling used in the balancing arm. With a lock-in amplifier as used here, it can be shown that recording output of series or parallel components is determined by whether constant voltage or constant current is applied to the unknown impedance (admittance). Skin-admittance measurements have consequently been performed with a constant-applied-voltage circuit, which is shown in Fig. 1. The a.c. admittance was measured using a function generator and a lock-in amplifier (Princeton Applied Research, model 129), an instrument functioning as a combination of a phase-sensitive a.c. voltmeter and a filter.

A lock-in amplifier was chosen instead of a bridge to obtain a facility for recording rapid parameter changes. In addition, it has a large frequency range from 0·5 Hz to 100 kHz, and is especially suited to low-level measurements.

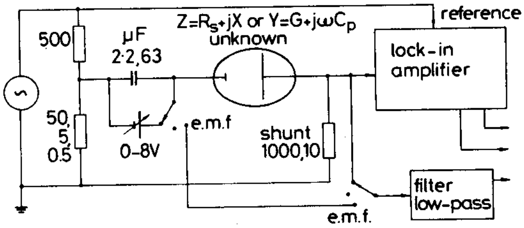

Fig. 1 *Details of circuit*

All data given here were taken with a current level of less than 100 nA cm^{-2} (except direct current with applied d.c. potential). Responses were fed into a 2-channel strip-chart recorder (slow changes) or a 3-channel storage oscilloscope plug-in system (Tektronix, model 7633). D.C. potential measurements were made via a high-input impedance ($>$ 10,000 MΩ) preamplifier and a lowpass filter (Krohn-Hite, model 3750) to remove the a.c. components. Dry electrodes covered by a hard surface of AgCl were used as measuring electrodes. They were taken from commercial pregelled e.c.g. electrodes (3M model 2246). They had a diameter of 8·5 mm and a contact area of 0·56 cm^2. The measuring electrode was fixed to one end of a 0·5 m plexiglas rod, the other end of which hung freely from a string. Thus, the arm could be moved slightly without affecting the electrode-skin contact. The electrode rested on the skin with a pressure of about 5 kPa. On ordinary soft skin and during the procedures described here, the increase in admittance was less than 5% when the pressure was increased to 25 kPa. A large flexible nickel plate 16 × 8 cm coated with conductive gel placed on the forearm was used as reference electrode. The skin impedance under this reference electrode was measured with a 3-electrode arrangement and found to be about 1,000 Ω at 10 Hz. The results shown in Fig. 6 were made with the pregelled e.c.g. electrode mentioned above used as reference electrode.

The reflex was elicited by a deep breath or raising the arm without the electrode. The subject sat in an ordinary office chair, relaxing until the parameters were stable, which could take 15–60 min. Room temperature was 20–23°C and relative humidity 40–50%. The site of the measuring electrode was changed after the stabilising period, and each time the frequency was changed. The area of the muscular ball of the thumb (thenar eminence) was used, or the dorsal side of the hand when so indicated. Just before the electrode was put on the skin the area was moistened by being breathed on to get stable results as quickly as possible. The nomenclature of the Society for Psychophysiological Research (VENABLES and CHRISTIE 1973) has been used: skin admittance response (SYR), skin conductance response (SCR).

3 Results

Fig. 2 shows the admittance response for four different frequencies. The time constant of the lock-in amplifier output was (1 + 0·3) s. A series-capacitor of 63 μF (Fig. 1) was used; at 5 kHz the 10 Ω shunt resistor was used.

It is evident that the capacitance response was small compared with the conductance response. At 500 Hz, for instance, the relative amplitude *RA* of the capacitance wave was only about 2%, whereas that of conductance was about 25%.

From Fig. 2 it is also clear that the relative amplitude of the conductance waves diminished as the frequency increased. Even if the reflex intensities cannot be considered equal, the trend was clear: *RA* = 50%, 25%, 25%, 12% in increasing frequency order.

Fig. 2 shows small capacitance waves at all frequencies. They are examples of maximal response and may be smaller or virtually absent, particularly in non-palmar sites. It is a matter of amplification whether they are discernible.

At each frequency on Fig. 2 the admittance is drawn with a common zero point of conductance and susceptance, to give a correct visual impression of the relative magnitudes of the waves. Fig. 3 shows a typical response in more detail with an expanded capacitance scale. It can be seen that the increase in capacitance was delayed with respect to the increase in conductance by 2 s or more. Sometimes a negative capacitance wave appeared, as shown at 20 Hz on Fig. 2 and on Fig. 3; this is simultaneous with the leading

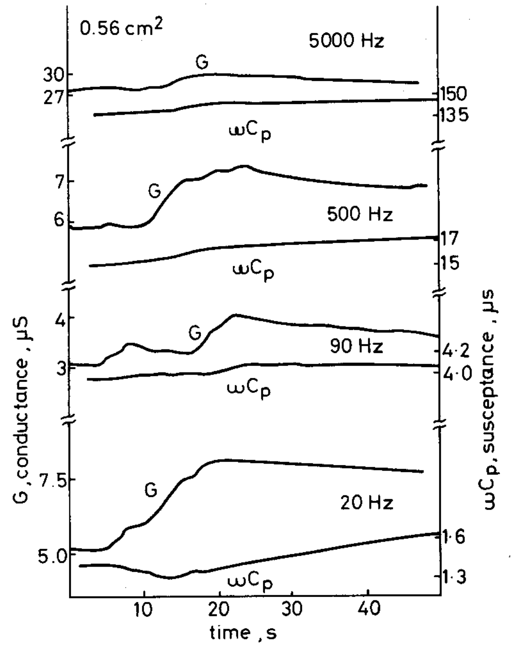

Fig. 2 *SYR from thenar eminence at four different frequencies*

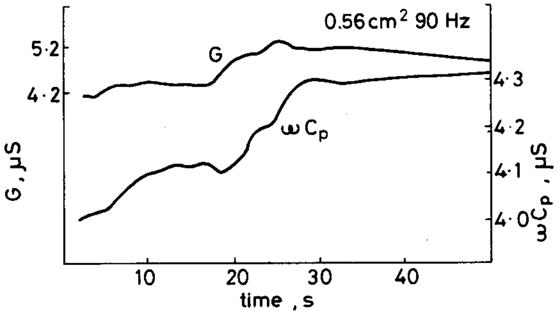

Fig. 3 *SYR with expanded capacitance scale*

edge of the conductance wave.

Fig. 4 shows a trend recording from the dorsal side of the hand from the moment the subject sat down. For about 10 min conductance was very GSR-responsive; it could be suddenly doubled just by a deep breath or changing position in the chair. After this period conductance decayed to low values, and in the end GSR was absent. No quick decrease in the leading edge of the conductance waveforms was ever observed.

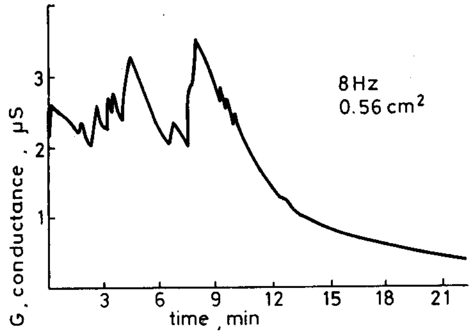

Fig. 4 *Trend recording of a.c. conductance from dorsal side of the hand*

Fig. 5 shows the results with and without application of −3 V polarising d.c. potential. No capacitance waves were seen, but both conductance level and rate of baseline increase was higher with −3 V applied.

Fig. 6 shows the simultaneous recording of skin potential and conductance waves. Upward deflection of e.m.f. indicates less negative, i.e. positive waves. The 2·2 μF capacitor of Fig. 1 was used to decrease the time constant of this capacitance and the cell impedance. This introduces a certain phase error, which, however, has negligible influence on the conductance waveshapes.

4 Discussion

A response wave always has a rather quickly increasing leading edge, and often a slower trailing edge. This is in accordance with the description by KUNO (1956) of sweat secretion and reabsorption. The lack of rapidly decreasing leading edges means that there can be no rupture of the sweat column as it disappears back down the duct. From the gradual decrease shown in Fig. 4 it is evident that the sweat must leave a d.c. conductive film on the inside of the duct walls. The decrease of conductance of these films progresses until a low basic level of 10–100 nS cm^{-2} is reached (THOMAS and KORR, 1957).

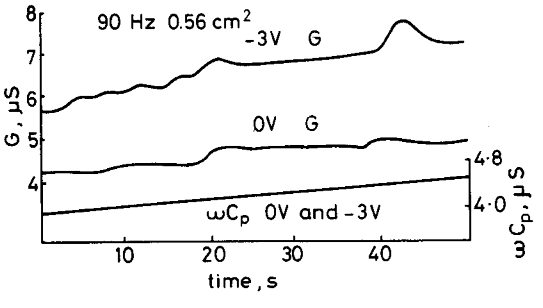

Fig. 5 *SYR with and without applied d.c. polarising potential*

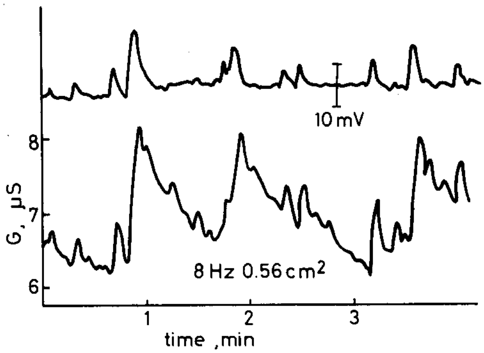

Fig. 6 *GSR of a.c. conductance and endosomatic e.m.f.*

If such a film exists in a duct, the simple rise and fall of the sweat meniscus contributes to the conductance wave. This is, presumably, the case with palmar skin where sweat gland activity is high. However, on other skin sites a basic level can be attained where the duct walls have reached such a state of dryness that sweat must be expelled right to the surface to contribute to a wave.

The clear existence of reflex waves only in the stabilisation period on dorsal hand sites is in agreement with YOKOTA *et al.* (1959) who found no waves at low room temperature, but almost 100% responsiveness at temperatures greater than 30°C. There seems, therefore, to be no difference between dorsal and palmar skin with respect to nerve supply. The difference is that the palmar sweat glands are perpetually active at ordinary room temperature, and thus response sensitive, whereas on dorsal skin the basal sweating can be too small to give response except to very large stimuli.

Fig. 4 shows that during the first 10 min just a deep breath or movement of a limb could double skin conductance values in some seconds. Thereafter conductance decreased to 1/10th in about 10 min. The two effects are, of course, important to consider in the choice of a low-frequency (< 1000 Hz) skin-impedance measuring method. BLANK and FINESINGER (1946) studied skin d.c. conductance as a function of exercise, and GOUGEROT and CHANTEUR (1951), ALMASI and SCHMITT (1970) mentioned possible effects of GSR. The two effects have not, however, been mentioned in dry-electrode low-frequency impedance measurements reported by GEDDES and VALENTINUZZI (1973) and BERGEY *et al.*

(1971) nor results with wet electrodes reported by ASK *et al.* (1979), ROSENDAL (1940), and YAMAMOTO and YAMAMOTO (1977).

The delayed increase in capacitance must be due to an increased supply of electrolyte to both the distal parts of the sweat ducts and to the surface of the skin. The results of MCCLENDON and HEMINGWAY (1930) were obtained with the fingers dipped in electrolyte, and so their increase in capacitance must therefore have been a pure duct effect. In the deeper part of the duct the conductive film can be in contact with vascular parts of the dermis by capacitive/resistive coupling through the duct walls. When sweat is rising in the duct the resistive sweat column first shunts these capacitive connections, then fills the part of the duct which passes the stratum corneum. Whether there will be negative capacitance waves or not is accordingly dependent on the height of the sweat columns prior to a wave.

Such an explanation supports the idea that the psychogalvanic reflex mechanism is basically a change in d.c., and therefore also low-frequency a.c., conductance. Thus the term 'galvanic' seems adequate.

Fig. 5 showed that skin conductance was very dependent on a negative polarising potential, whereas skin capacitance was not. Because the capacitance is a property of the cell membranes of the skin, dominated by the stratum corneum, this indicates that the effect is on the sweat gland ducts and not on the cells of the stratum corneum.

The results are in agreement with the results of MCCLENDON and HEMINGWAY (1930), who found an *RA* of 2% in capacitance and 12% in conductance. They did not find any delay, but their bridge method did not allow them to discover such rapid differences.

The results of FORBES and LANDIS (1935) are not necessarily in conflict with ours, because they used series-equivalent values of resistance and capacitance. If their values are recalculated to parallel, their capacitance waves diminish, and the missing resistance waves appear with a larger relative amplitude than the capacitance waves. At the highest frequencies (5–10 kHz), however, their waves are too small to allow close interpretation.

The results of GRINGS (1953) and TAKAGI and NAKAYAMA (1959) are in agreement with ours. YOKOTA and FUJIMORI (1962) did not find any capacitance waves. Their method of plotting an arc in the imaginary plane, however, is indirect and too crude to make the small capacitance waves appear. The method of MONTAGU (1964) is also a very indirect one for separation of capacitive and resistive terms; his results can be interpreted as a disproof of the condition of constant capacitance.

As the frequency is increased the admittance of the stratum corneum becomes more and more important. This is a stable admittance not very dependent on sweat gland response. It is therefore clear (Fig. 2) that the sensitivity decreases with increasing frequency. There does not seem to be additional information in the a.c. conductance waves except for the delay mentioned. The a.c. method cannot generally be recommended for any reason other than that it obviates the need for a d.c. polarising potential. Such a potential has an effect on the baseline progress of conductance, but it also influences the waveforms and is thus a more decisive and interesting parameter than a.c. frequency.

EDELBERG (1971) reported that different electrolytes can have a large effect on the response wave amplitudes. This can have at least three explanations.

(*a*) The electrolytes can contribute to the formation of a conductive film within semi-filled sweat ducts, so that more ducts contribute to the overall response.

(*b*) They can influence the d.c. potential in the distal part of the duct, which in turn is supposed to influence sweat secretion (SULZBERGER *et al.*, 1950).

(*c*) They can change the double layer formed at the interface sweat/duct wall and therefore change electrokinetic parameters, (see later).

EDELBERG (1968) proposed a model based on variations in the series resistance of two separate e.m.f. sources. The positive e.m.f. waves, as seen in Fig. 6, would then correspond to an increased conductance of the skin itself, because the duct's negative e.m.f. is the largest. It is hard to explain how the skin conductance could increase so suddenly. It is true, as EDELBERG (1971) pointed out, that the positive wave is often preceded by a short, small negative wave and followed by a negative wave, so that the progress is triphasic. It can be seen from Fig. 6 that a positive wave was of rather short duration and that there were periods of little e.m.f. activity while the conductance decreased. We also know that the positive waves do not change the shape of the conductance waves. Previous investigations agree that diphasic waves are related to large responses, YOKOTA *et al.* (1959). In the light of this another hypothesis is proposed.

REIN (1924) reported that water in the skin moves towards the cathode as the result of an electro-osmotic process. This means that the central part of the sweat in the duct should be positively charged with respect to the walls. GILMER (1942) also reported the process of electro-osmotic staining and that a positive electrode pushes a dye solution down the sweat ducts. There are, however, four electrokinetic effects (CASTELLAN, 1971). The reciprocal effect of the electro-osmosis is the streaming potential effect. If a cathode attracts water, then, inversely, the water should bring a positive charge to the opening when propelled up the duct by the gland-secretion pressure. From this, the amplitude of the positive wave should be proportional to the velocity by which the liquid passes the duct. As soon as the sweat reaches the electrode, the positive charge is discharged. When the secretion stops, the contribution disappears. However, there is still liquid-film contact with the negative sweat-duct for some time and the moistening effect of the surface will also prevail. This can, therefore, also explain the biphasic and triphasic character of the waves. The hypothesis is also consistent with the report of TAKAGI and NAKAYAMA (1959) that small positive waves persisted even if the epidermis was removed.

5 Conclusions

(*a*) The examination of sweat-duct influence cannot be done without also recording the parallel values of skin impedance, i.e. the admittance of the skin.

(*b*) During the psychogalvanic reflex the dominant response is a sudden increase in conductance. Small capacitance waves can also appear, but, particularly at non palmar sites, they may be negligible.

(*c*) The importance of duct-wall liquid-film conductance is underlined. On palmar and plantar sites it is believed to contribute all the time (except during sleep); on other sites the residual film conductance will reach very low values when physical activity has been low. In the first case just the rise and fall of the sweat meniscus contributes to the waves; in the latter case sweat must be expelled to the surface to contribute. The small capacitance waves are believed to be a cell-membrane effect.

(*d*) Non-palmar sites provide a good reflex response when the sweat glands have recently been active and important duct-wall conductivity exists. It is therefore postulated that the sensitivity to a reflex mechanism is rather equal for dorsal and palmar sides of the hand, the only difference being that the palmar sweat glands have a perpetually higher activity level less dependent on thermal factors.

(*e*) In ordinary skin-impedance measurement procedures it is important to be aware of possible GSR on all skin sites, just a deep breath of the subject under test may double conductance in some seconds. On non-palmar sites this can be circumvented by measuring on 'dry' skin.

(*f*) A polarising d.c. potential of less than -3 V has little influence on skin capacitance. The large effect on conductance must therefore be due to a change in sweat-duct conductance.

(*g*) The sensitivity of the d.c. conductance to a certain reflex intensity is larger than that of the a.c. conductance. The sensitivity is more reduced the higher the frequency used. The advantage of a.c. methods is mainly to obviate the effect of a d.c. polarising potential.

(*h*) The skin-potential response was not in accordance with accepted theories. A new explanation based upon the electrokinetic streaming-potential effect is proposed for the rapid positive waves often found.

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