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Methodology

Pre-Polarization Resistance of the Skin as Determined by the Single Square Voltage Pulse Method

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ABSTRACT

Use of a new microcomputer-based instrumentation system to record and analyze current waveforms produced by applying square voltage pulses of 0.5–3.5 V to the skin revealed that peak currents are considerably higher, and corresponding pre-polarization resistance values considerably lower, than previously supposed. However, in keeping with previous observations, we confirmed that the skin is an Ohm's Law conductor in its pre-polarization state and that the pre-polarization resistance of the skin is resolvable into two components, a localized resistance beneath each electrode and a non-localized (body core) resistance. In addition, a three-electrode method was devised to measure the localized resistance at any selected location (target site). Simple equivalent circuit simulations of the initial section of current waveforms are used to assess the degree of instrument-related peak current underestimation inherent even in this system. This preliminary study indicates the need for reassessment of the roles played by the various body tissues, particularly the epidermis, in determining the pre-polarization electrical character of the skin.

DESCRIPTORS: Square voltage pulse, Pre-polarization resistance, Electrical equivalent circuit.

The technique of applying square voltage pulses to the skin via surface electrodes and recording the resultant current waveform is finding increasing use in electrodermal research (Hozawa, 1928; Lykken, 1971; Melczer, 1976; van Boxtel, 1977). Prominent among its positive features are: a wide frequency range can be covered in a matter of seconds, the direction of current flow can be specified, the amount of charge transferred during each pulse can be regulated to ensure minimal disturbance to the living system under measurement, and most importantly, no *a priori* assumptions need be made concerning an equivalent circuit model for skin impedance (Lykken, 1971), a major drawback of the more commonly used impedance bridge technique.

In the present study, a fast-sampling digital wave memory device operating with an on-line microcomputer was used to facilitate observation of a "single event" phenomenon, namely, the recording and subsequent analysis of the skin current waveform produced in response to a single 1-ms square voltage pulse.

During investigation of the electrical properties of the skin using this system, we became aware of an important aspect of the square voltage pulse technique which seems to have been inadequately considered by many previous workers: the peak value of the current waveform is necessarily dependent upon the rise times of the pulse generator and the measuring device (usually an oscilloscope). If these frequency characteristics of the pulse generator/current detector system are overlooked, inaccurate peak current estimations may occur, leading to erroneous conclusions about the pre-polarization of the skin.

The observations in this paper are based upon the replication of several previous studies, and also upon the subsequent extension of these studies by using a more accurate single-pulse method to determine peak current.

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Method

Instrumentation

A schematic diagram of the instrumentation system used in this study to deliver square voltage pulses to the skin and subsequently record and analyze the resultant current waveforms is shown in Figure 1. The system is composed primarily of a pulse generator (special order upon specifications from our research group, Matsushita Electric Co., Osaka, Japan—circuit diagram available to interested parties upon request to authors), an electrode box, a fast-sampling digital wave memory (Model WM-852, NF Circuit Design Block Co., Yokohama, Japan), a microcomputer, a printer, and a chart recorder and/or an oscilloscope. A manual switch on the pulse generator triggers a single square voltage pulse along with a separate trigger pulse for other system units. The rise time of the square voltage pulse is less than 50 ns with the pulse height and pulse width being adjustable from 0.5–5.0 V, and 1 ms to 1 s respectively. The pulse is transmitted through a 50Ω coaxial cable terminated by a 50Ω precision resistor to minimize waveform distortion. The pulse height is adjusted to the desired value at this termination resistor. The voltage pulse across the resistor is then applied to a pair of target sites on the skin through surface electrodes via an electrode box which allows polarity reversal. The skin current signal is detected by a 100Ω precision resistor inserted in series with the skin current circuitry. The skin current signal thus detected is then fed to a fast-sampling digital wave memory which is initiated by the trigger pulse from the pulse generator and which carries out Analog to Digital (A/D) conversion at a given rate specified by the sampling time. The wave memory has a minimum sampling time of 50 ns and a memory configuration of 8 bit (data) × 1024 (words); the initial 20 words are used to determine the zero level in the pretrigger region and the remainder are used for sampling the current response waveform. After the A/D conversion, the digitized waveform is stored in the memory and can be read out at various speeds to enable it to be recorded on a chart recorder or displayed on an oscilloscope as desired. Figure 2 shows a typical skin current waveform observed. (*Note:* Due to the particular set-up of the recording system, this and the other chart recordings in this study read from right to left.)

The microcomputer, which is interfaced to the wave memory, then receives the digitized data for routine analysis. The system software allows determination of four parameters used to define the current response waveform. These are the peak or pre-polarization current (I_p), the initial time constant of the polarization process (τ_0), the total amount of electrical charge mobilized for the polarization process after Aμs of waveform sampling (Q_A), and the current level after Aμs of waveform sampling (I_A). Whether or not I_A is also the asymptotic current value depends upon the position and size of the electrodes as well as pulse duration and voltage. Following calculation, these four parameters are printed out. Figure 3 shows the definition of these parameters in diagrammatic form.

The internal resistance of the instrumentation system was determined by applying 1-ms square voltage pulses to series arrangements of standard precision resistors and the system. For the range of voltages and peak currents observed in this study, the effective internal resistance of the system was found to be 131 ± 10(SD)Ω.

Electrodes

Silver-silver chloride electrodes (9mm or 20mm diameter; Unique Medical Co., Tokyo, Japan) were used, unless specified otherwise, with a viscous electrode paste consisting of sodium chloride (13.76g/100g of paste) and calcium chloride (18.35g/100g of paste) in a base consisting of water, calcium carbonate, bentonite and glycerin (Type 244A, Himezaki Shoten Co.,

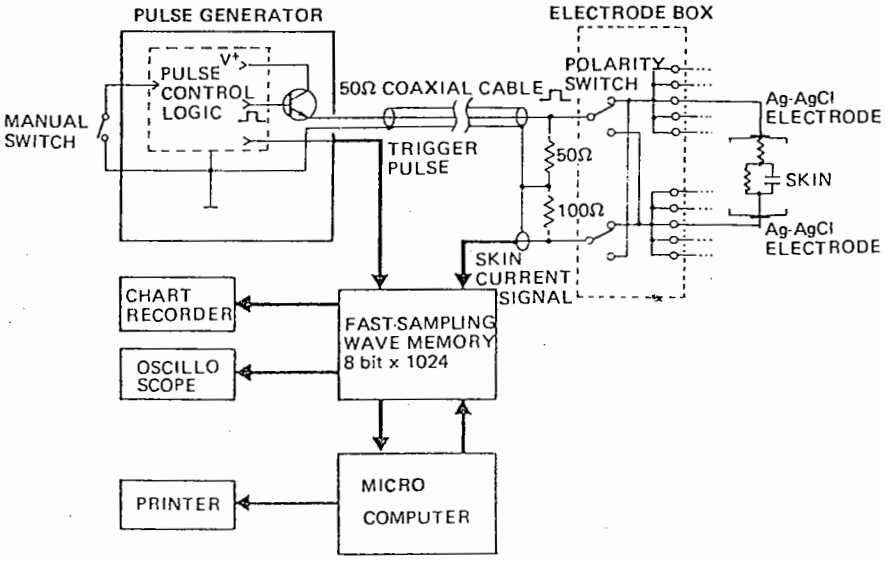

Figure 1. Schematic for the instrumentation system.

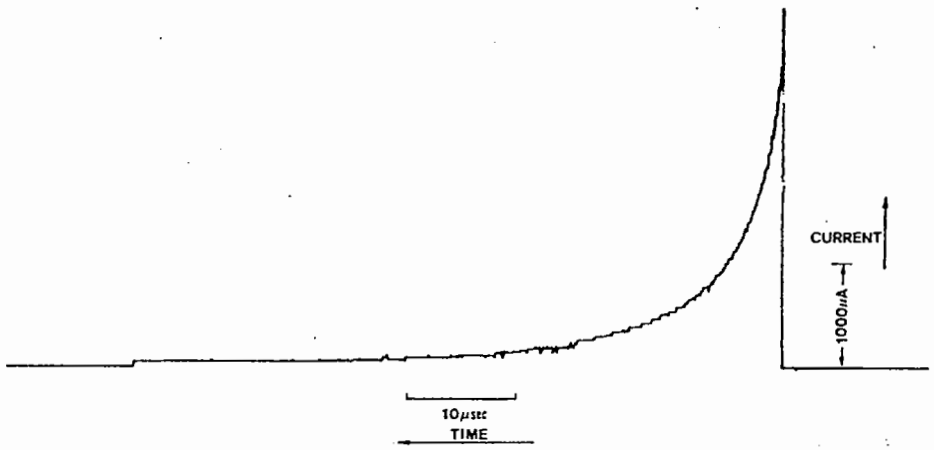

Figure 2. Chart recording of a skin current waveform produced in response to a 1-ms, 2.0 V square voltage pulse applied to the skin via surface electrodes. The electrodes were 1.77cm² area Ag/AgCl discs (see under heading ***Electrodes***) attached to the flexor surface of each forearm.

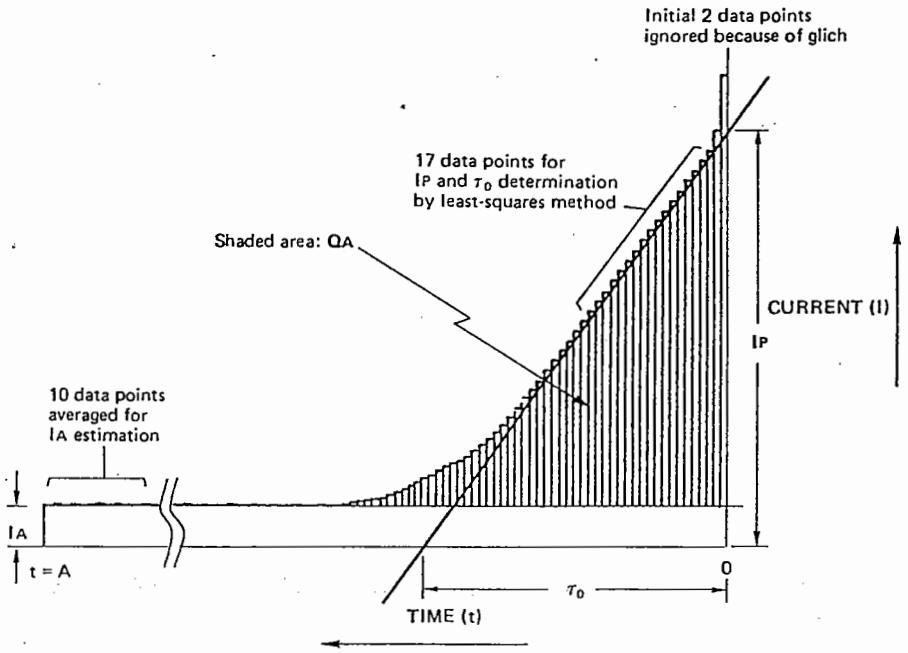

Figure 3. Parameters used to define the current response waveform.

Himeji City, Japan). A less concentrated paste (0.05M NaCl in carboxymethylcellulose) was also tested. Electrodes with electrode paste were secured to skin sites masked by annular adhesive patches (8mm or 15mm internal diameter), the masking defining the effective area of the electrodes. For each study a stabilization period of 5 min or more was allowed for contact between the skin and electrode paste prior to measurement, and a time period of 30 s or more was allowed for electrical recovery between successive measurements. The electrode-electrode paste contribution to the pre-polarization resistance was determined by applying 1-ms wide square voltage pulses to series arrangements of standard precision resistors and paired electrodes separated by electrode paste and the appropriate-sized adhesive patch. For the range of voltages and peak current levels observed in this study, th average pre-polarization resistance values from th 1.77cm² area electrodes (20mm diameter disc ele trodes with 15mm diameter patches) and the 0.50cn electrodes (9mm diameter disc electrodes with 8mı diameter patches) were found to be 15 ± 5(SD)Ω an 38 ± 7(SD)Ω respectively.

Subjects

Nineteen normal male and female volunteer sul jects were involved in this study. A minimum of female and 2 male subjects participated in each of th *in vivo* experiments. The subjects were positioned t give the attached surface electrodes approximatel horizontal orientations. In some trials this meant tha the subjects were positioned in a prone or supine pc

sition, while in other trials a sitting position was used. Skin sites for investigation were specified in relation to, but generally not located at, acupuncture points chosen by reference to standard charts and anatomic reference points (Kinoshita, 1970). Skin sites were left untreated except for the trimming away of any surface hair with scissors. Most sites were non-palmar, but palmar placements were also examined for comparison purposes.

Results and Discussion

Dependence of Measured Peak Current on Sampling Time

The need to take into account the sampling time (frequency response) characteristics of the current detecting instrumentation as well as the rise time characteristics of the pulse generator can be readily appreciated from the examples shown in Figure 4. Figure 4-A shows the initial 11.0μs of a typical skin current response to a 1-ms square voltage pulse. In this example, electrodes with a 1.77cm^2 area were attached to the flexor surface of each forearm. Figure 4-B represents a reasonably accurate R-RC (parallel connection of a capacitor and resistor in series with a second resistor) equivalent circuit simulation of this same section of skin response. Although more accurate simulation circuits could be constructed by the inclusion of additional R, RC, and battery elements in series and in parallel (Lykken, 1971), the simple three-component model adequately serves to illustrate the following point. Namely, irrespective of whether peak currents are read directly from oscilloscope recordings as previous workers have done, or whether they are estimated using a linear extrapolation method as was done in our study, the measured peak height will show an apparent dependence on the sampling time (i.e. frequency characteristics) of the current detecting instrumentation. This becomes readily apparent by comparing Figure 4-B (sampling time 0.1μs) to Figures 4-C, D and E, which are current waveforms recorded from the same R-RC circuit but sampled

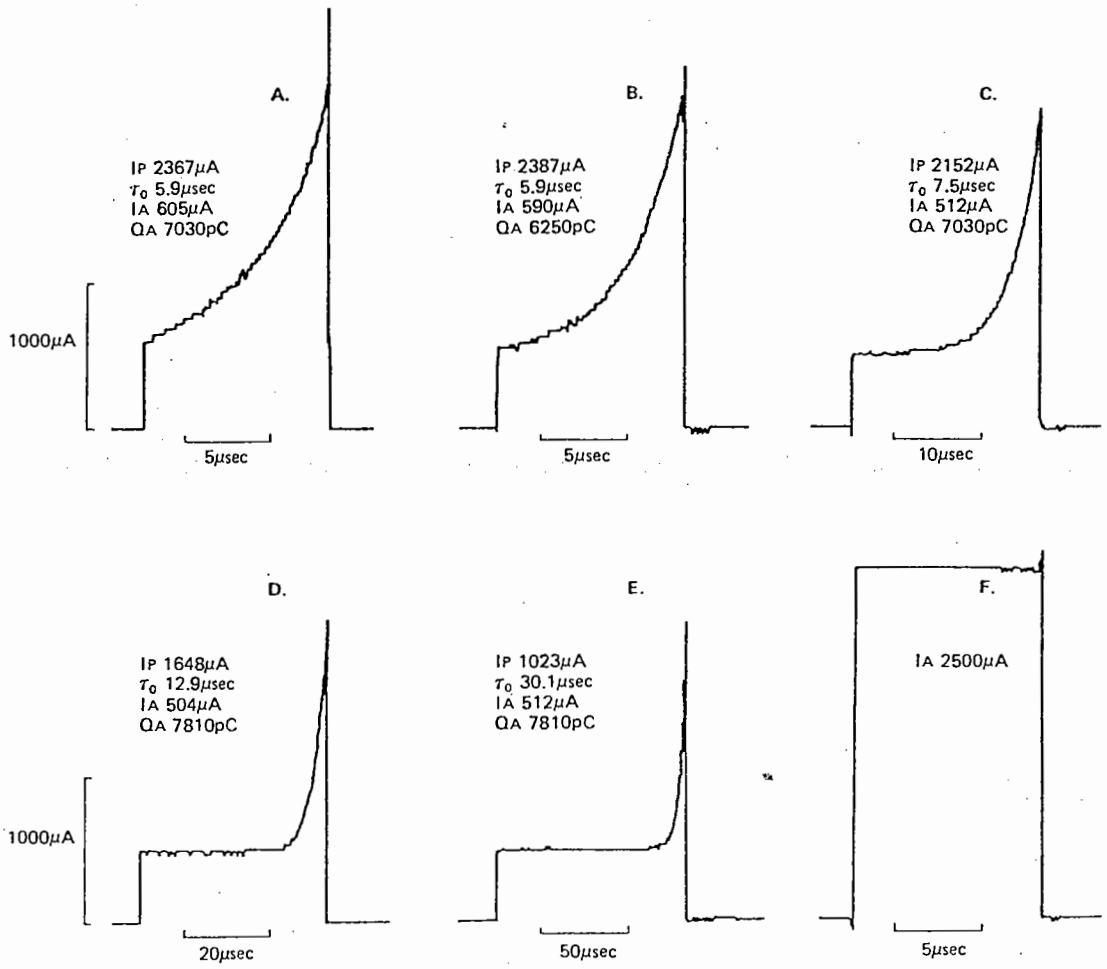

Figure 4. Current waveforms produced by the application of 1-ms, 2.0 V square voltage pulses to the skin (A) to a simple R-RC equivalent circuit (B-E) and to the isolated series resistor element of the equivalent circuit (F). Figures A, B and F were recorded at sampling times of 0.1 μs, while Figures C, D and E were recorded at sampling times of 0.2 μs, 0.5 μs, and 1.0 μs, respectively.

with progressively longer sampling times. The theoretical peak current of the R-RC current response, however, is dependent solely on the magnitude of the series resistor (at a particular voltage) and so can be determined from the current level of the approximately square current waveform recorded across this resistor in isolation as shown in Figure 4-F. It should be noted that due to software limitations, the peak current (I_p) of such square-like current waveforms cannot be correctly calculated; therefore, the current level (I_A) at A = 11μs is used instead as a measure of the waveform current level. This theoretical peak current can then be used to assess the degree of underestimation of the peak current measured at any particular sampling time. In the case of the 0.1μs sampling time (the sampling time used throughout the remainder of this paper), the peak current level of the R-RC current response, and by inference that of the skin current response that it simulates (Figure 4-A), is underestimated by about 4.5%. Figure 5 shows the relationship between the measured peak current and the sampling time in graphic form.

Failure to adequately consider the sampling time (frequency response) limitation of their pulse generator/current detector systems has led many previous workers using this pulse technique to overestimate the pre-polarization resistance corresponding to these peak currents and, consequently, to overestimate the resistance contributions from the various body tissues. Therefore, in the remaining studies cited in this paper, measuring conditions (sampling time, electrode area, inter-electrode distance, etc.) were chosen so as to limit the degree of these peak current underestimations. In addition, when deemed necessary, theoretical peak current estimations (made on the basis of R-RC simulations as described above) were made for selected sets of measurements to check the general validity of the results.

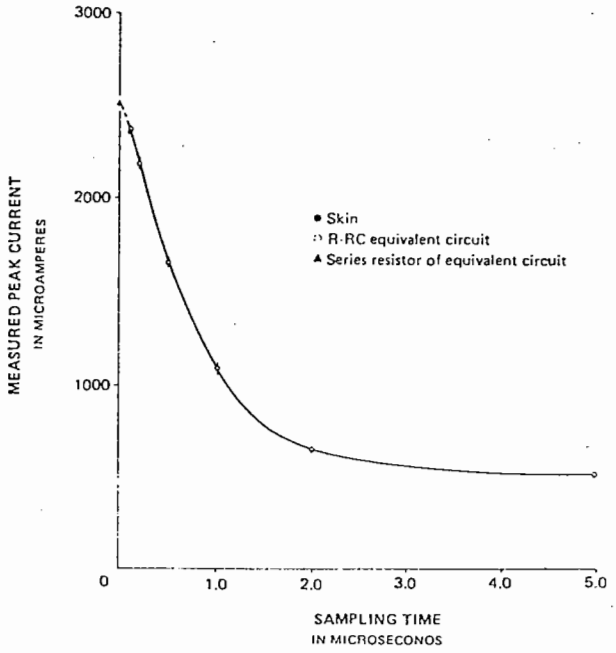

Figure 5. Measured peak current - sampling time relationship. Each point is the average of 4 determinations except that of the skin which is a single measurement. Vertical bars are plus and minus one average deviation.

Effect of Electrode Polarity on Peak Current

Knowing if a particular current response parameter shows dependence on the direction of the current flow is fundamental to the use of the pulse technique. The following study, involving 4 subjects, was made to investigate the effect of electrode polarity on the peak current level.

In order to optimize any influence current direction may have on peak current levels, square voltage pulses were applied to the skin through a small (0.50cm²) area electrode used in conjunction with an electrode cluster almost 18 times as large (5 × 1.77cm²) in area. The small electrode was attached to a site on the flexor surface[1] of the left forearm and the large electrode to the region centered around the homologous site on the right forearm.

After allowing a stabilization period of 19 min, 38 successive 1-ms, 2.0 V square voltage pulses alternating in polarity were applied to the skin at intervals of 30 s. The small electrode had a positive polarity for the initial pulse in 2 subjects, and in 2 other subjects this electrode began the sequence with a negative polarity. The peak values from the current responses to these 38 pulses were subsequently analyzed by Student's *t* test for any significant difference with respect to electrode polarity. For all 4 subjects, no significant difference ($p > .10$) was found for the influence of current direction on the peak current. In subsequent experiments, therefore, peak current measurements derived from the application of square voltage pulses of opposite polarities were pooled to give an average result.

Variation of Peak Current with Voltage

Using the square voltage pulse technique, Lykken (1971) found that when peak currents were converted into terms of resistance—the pre-polarization resistance—this resistance remained essentially constant over the voltage range from 0.2–10 V. Because we used a different method for peak current determination, we re-investigated the pre-polarization voltage-current characteristics of the skin.

[1]At, or slightly superior to, acupuncture point HC4.

For 4 subjects, a 1.77cm² electrode was attached to the flexor surface of each forearm. After allowing a 5-min stabilization period, current waveforms were recorded in response to the application of 1-ms square voltage pulses to the skin. Voltages were applied in increments of 0.5 V from 0.5–3.5 V, in ascending and descending series, with pulses of both polarities being recorded at each voltage setting. Thus a total of 4 recordings were made for each voltage. Analysis of the data by the least squares method revealed a very clear linear relationship between peak current and voltage for each subject (correlation, $r = .9989$–$.9998$), with the lines passing approximately through the origin. A similar finding was also obtained ($r = .9998$) for another trial in which the electrode on the left forearm site was re-located to a site on the medial surface[2] of the right leg. These results imply that, over the range of voltages and peak current levels observed in this study, and in agreement with previous findings, the skin in its pre-polarization state obeys Ohm's Law.

The Two-Component Model of Pre-Polarization Resistance—The Electrodes-in-Parallel Method

According to the original model proposed by Lykken (1971) and later supported by van Boxtel (1977), the pre-polarization resistance of the skin can be resolved into two types of components: a component localized in the skin beneath the electrodes and a non-localized component representing the body core resistance between the electrodes. We repeated the work of Lykken using our new method for peak current determination. For 8 subjects, sets of four 1.77cm² electrodes were attached in cluster form to homologous sites on the left and right lower arms. For each subject, current waveforms were recorded in response to the application of 1-ms, 2.0 V square voltage pulses to various combinations of 1 × 1, 2 × 2, 3 × 3, and 4 × 4 electrodes. The order of measurement was 1 × 1 combinations first, followed by 2 × 2, 3 × 3, and 4 × 4 combinations, followed in turn by the same sequence in the reverse but using opposite electrode polarities. Each peak current measurement was converted into terms of pre-polarization resistance ($R = V/I_p$) and, after the 131Ω internal resistance of the system was subtracted, average pre-polarization resistance values for the 1 × 1, 2 × 2, 3 × 3, and 4 × 4 electrode combinations were calculated. Thus, if we assume that the resistance of a single unit of skin beneath each electrode is approximately the same for all sites (given by R_s), and that there is a body core resistance between the left and right forearm sites (given by R_c), then we can write the total pre-polarization resistance for the 1 × 1 and 2 × 2 electrode combinations as $2R_s + R_c$ and $R_s + R_c$, respectively. From these two equations we can thus solve for R_s and R_c. The average R_s and R_c values from the 8 subjects are shown in Table 1. Values in parentheses have been corrected for sampling time dependence using R-RC simulations as described previously. For each subject, comparison of the measured resistances for the 3 × 3 and 4 × 4 combinations showed close agreement (within 2%) to the corresponding resistances predicted using the 1 × 1 and 2 × 2 derived average R_s and R_c values. These agreements provide support for the original two-component model of pre-polarization resistance.

An important feature of these results is that each of the average R_s values at the forearm sites (all are lower than 200Ω/1.77cm²) is less than one-tenth the R_s value (1873Ω/2.42cm²) implicit in the study by Lykken (1971). This large discrepancy is almost certainly not attributable to subject variation or to differences in electrode pressure on the skin (Swanson & Webster, 1974). Neither does electrode paste

Table 1

Average localized ($\bar{R}_s$) and body core ($\bar{R}_c$) pre-polarization resistance values between homologous forearm and palmar sites

Electrode Sites	Subject	Sex	Age (yrs)	$\bar{R}_s$ (Ω/1.77 cm²)	$\bar{R}_c$ (Ω/1.77 cm²)
Left and Right Forearms—Flexor Surfaces[a]	1	F	55	165 ± 16[e] (150 ± 15)[f]	373 ± 21 (363 ± 20)
Same as above	2	M	31	107 ± 31	305 ± 39
Same as above (with CMC paste)[b]	3	F	28	182 ± 17	413 ± 23
Same as above (with CMC paste)	4	M	32	121 ± 19	363 ± 26
Left and Right Forearms—Extensor Surfaces[c]	5	F	54	196 ± 26	361 ± 31
Same as above	6	M	24	130 ± 7	299 ± 9
Left and Right Palms[d]	7	F	58	118 ± 24	658 ± 32
Same as above	8	M	19	127 ± 21	532 ± 31

[a]Electrode clusters centered at, or slightly superior to, acupuncture point HC4.

[b]Electrode paste consisting of sodium chloride (0.05M) in a sodium carboxymethylcellulose (CMC) base (4.3g/100g of paste), prepared according to the method of Woodrough, Canti, and Watson (1975), used instead of Himazaki Type 244A paste.

[c]Electrode clusters centered at, or slightly superior to, acupuncture point TH8.

[d]Electrode clusters centered slightly superior to acupuncture point HC8.

[e]Average deviation.

[f]Parenthetic values have been corrected for sampling time.

[2]At acupuncture point GB38.

composition seem to account for this difference, as seen in Table 1 where average R_s values at forearm sites remain of the same order of magnitude when a .05M NaCl paste (approximately isomotic with sweat) is substituted for the Himazaki Type 244A paste containing sodium chloride and calcium chloride concentrations more than forty times greater than this. This table also shows that palmar sites have R_s values that are of the same order as non-palmar. We therefore directly attribute the lower R_s values obtained in this study to our more accurate instrumentation for peak current determination. Even with the sampling time of 0.1μs which we used, R_s and R_c values tend to be overestimated. However, as exemplified in Subject No. 1 in Table 1, the overestimations under these conditions are very slight. Thus, in the light of these new findings, a reassessment is needed of the contributions made by various tissues of the body, particularly the epidermal strata, to the pre-polarization resistance of the skin.

The Two-Component Model of Pre-Polarization Resistance—Comparison of the Electrodes-in-Parallel Method with the Three-Electrode Method

Although the electrodes-in-parallel method is useful in that it provides an overall estimate of the localized pre-polarization resistance for single units of skin over neighboring and homologous sites, its applications are particularly limited because it does not enable determination of the actual localized resistance values at each individual site. Therefore, a new method was developed to ascertain localized resistance values at each site. However, this method is once again based on the two-component model of pre-polarization resistance, and in a series of 4 trials the results are compared to those obtained independently using the electrodes-in-parallel method. This second method is referred to as the three-electrode method.

In the three-electrode method, a reference electrode is placed on either side of the test electrode in such a way that the three electrodes are approximately co-linear along the surface of the body. Under this arrangement it would seem reasonable to assume that the three sites share a common body core-pathway. Thus, the localized pre-polarization resistance at the test electrode can be estimated by subtracting the pre-polarization resistance between the two reference electrodes from the sum of the pre-polarization resistances between each reference electrode and the test electrode, and then dividing the total by two, as is illustrated in Figure 6.

The electrode placements on one male subject (Subject No. 1) are shown in Figure 7-A. The localized pre-polarization resistances were determined for the six 0.50cm² test electrode sites (a, b, c, and a′, b′, c′, in circles in Figure 7-A). Using a systematic measurement order (1 × 1 combinations first, followed by 2 × 2 and 3 × 3 combinations, followed in turn by the same sequence in reverse but using opposite electrode polarities), the average localized pre-polarization resistance over the test electrode sites was determined by the electrodes-in-parallel method (between the homologous test electrodes) and the localized resistance at each individual test site was determined by the three-electrode method. Furthermore, in the latter procedure, three independent estimates were made for the resistance at each test site by employing three sets of widely spaced 1.77cm² reference electrodes in combined pairs on both the left and right sides of the body (1–2, 3–4, 5–6 on the left side, and 1′–2′, 3′–4′, 5′–6′ on the right side, shown in circles in Figure 7-A). Figure 7-B shows the relationship between the test electrode locations and the localized pre-polarization resistances corresponding to the different reference electrode pairs employed.

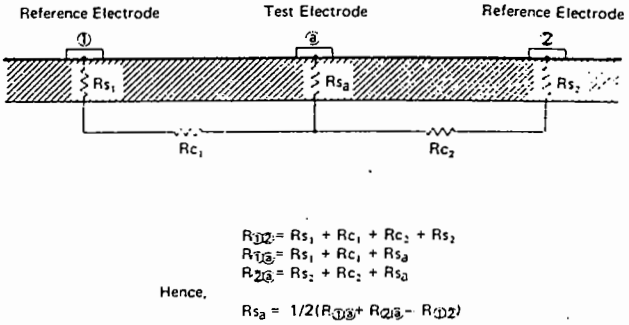

Figure 6. The three-electrode method of estimation of localized pre-polarization resistance at a selected test site.

The above trial is useful in illustrating points common to all 4 trials: First, it has been found that the calculated localized pre-polarization resistances at the test sites are essentially independent of the specific locations of the reference electrodes along the line passing through the test electrodes.[3] Second, even nearby sites on apparently similar skin regions can show appreciable differences in localized pre-polarization resistance, as in the case of sites b′ and c′ which display a difference in resistance of more than 13% ($\sim$40Ω/300Ω) over a distance of only 20mm. Third, fairly good agreement exists between the localized pre-polarization resistance value (324 ± 26Ω/0.50cm²) obtained from the electrodes-

[3]More specifically, there appears to be a general tendency for the calculated localized pre-polarization resistance to show some slight decrease with decreasing distance between the reference electrodes. The reason for this tendency in unknown at present.

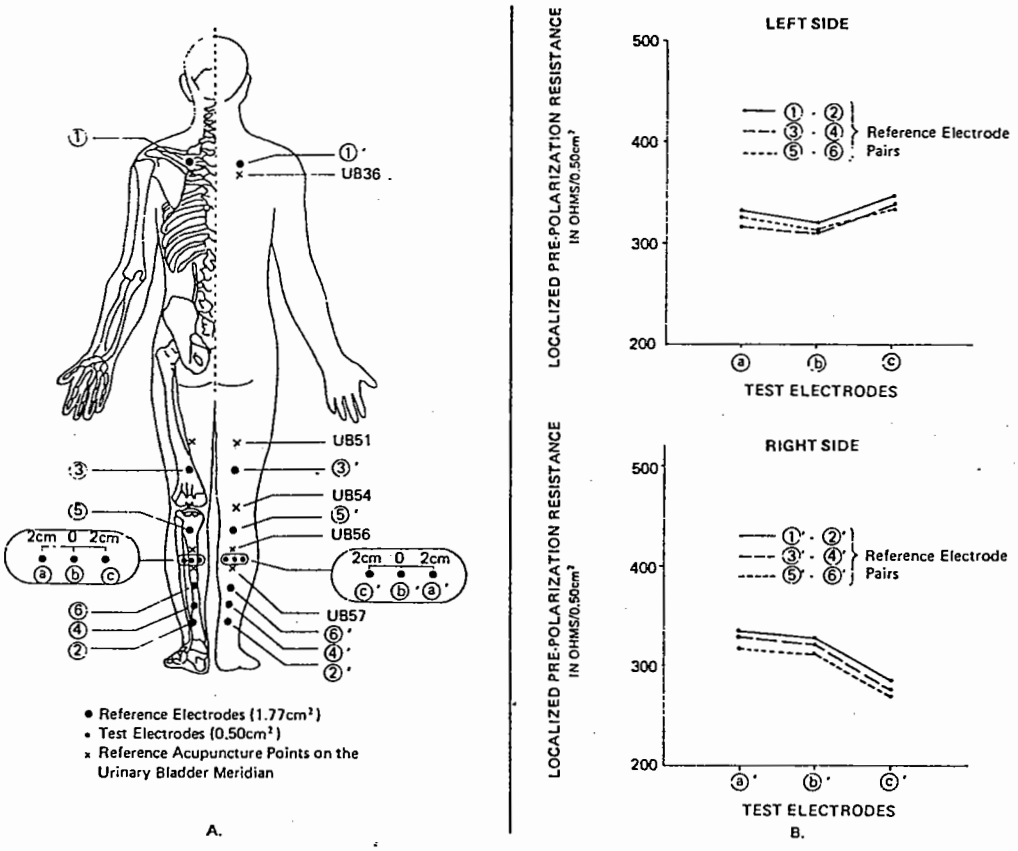

Figure 7. A. Reference and test electrode locations for one subject (Subject No. 1) during comparison of the electrodes-in-parallel method to the three-electrode method. **B.** The localized pre-polarization resistance at each of the left and right test electrode sites corresponding to each of the three pairs of bilateral reference electrodes used.

in-parallel method and the average resistance value ($319 \pm 15\Omega/0.50cm^2$) obtained by averaging the 18 individual values gained from the three-electrode method and shown plotted in Figure 7-B. Comparisons between these same two sets of resistance values for the other 3 trials are given in Table 2. It should be noted that each of these values is subject to slight overestimation due to the dependence of the measured peak current on the sampling time, as was discussed previously. For example, application of sampling time corrections (using R-RC simulations) to a measurement set randomly selected from the three-electrode study of Subject No. 2 revealed a pre-polarization underestimation of about 7%. In any case, the consistency between these essentially independent methods provides further support for the underlying rationale of both methods, namely, that the pre-polarization resistance of

Table 2

Comparison between average localized pre-polarization resistance ($\bar{R}_s$) values obtained from the Electrodes-in-Parallel (E-in-P) Method and the Three-Electrode (3-E) Method

Test Electrode Locations	Extreme Range of Reference Electrodes	Subject	Sex	Age (yrs)	$\bar{R}_s$ from E-in-P Method (Ω/0.50 cm²)	$\bar{R}_s$ from 3-E Method (Ω/0.50 cm²)
Left and Right Lower Legs—Flexor Surfaces[a]	Lower Leg–Upper Back[a]	1	M	23	324±26[d]	319±15
Same as above	Same as above	2	F	50	394±44	416±19
Left and Right Forearms—Flexor Surfaces[b]	Forearm–Upper Arm[c]	3	M	34	320±37	316±15
Same as above	Same as above	4	F	44	445±37	471±42

[a]See Figure 7-A.
[b]Electrodes positioned slightly superior to acupuncture point HC4.
[c]Acupuncture points on the Heart Constrictor Meridian used as reference sites for electrode positions.
[d]Average deviation.

the skin can be resolved into two types of components, a localized resistance and a non-localized (body core) resistance.

What then are the anatomical locations of each of these resistances? Van Boxtel (1977) concluded that the localized component is primarily attributable to the stratum corneum; Lykken (1971), on the other hand, suggested that other tissue, possibly located in the lower epidermis, may also make an important contribution. If either of these is the case, then it is not readily clear why, except for the palmar sites, the average localized pre-polarization resistance ($\overline{R}_s$) at a particular site on a female subject is appreciably greater than that at the same site on a male subject (see Tables 1 and 2). Certainly the involvement of sub-epidermal tissue(s), some of which are known to display distinctive male-female characteristics (particularly the subcutaneous tissue), cannot be immediately ruled out. In fact, this statement seems even more valid when it is noted in Table 1 that the average non-localized pre-polarization resistance ($\overline{R}_c$) between homologous sites (including between palmar sites) on a female subject is considerably greater than that between the same homologous sites on a male subject. When electrodes are very close together, surface pathways are thought to be important (Edelberg, 1977; Tagami et al., 1980). However, as in this study, when electrodes are well-separated, it is generally considered (Burger & van Milaan, 1943; Edelberg, 1977; van Boxtel, 1977) that the non-localized resistance resides primarily in "deeper tissues." Details of the precise anatomical locations and factors determining these pre-polarization resistances, both localized and non-localized, must await further investigation.

Conclusions

Peak levels of current waveforms produced in response to applied square voltage pulses show no apparent dependence on the polarity of the pulse, and, under the conditions used in our experiments, remained essentially unchanged for periods of more than one hour. Furthermore, as previously found, the voltage-peak current characteristics of the skin imply that the skin is an Ohm's Law conductor in its pre-polarization state.

In agreement with previous work (Lykken, 1971; van Boxtel, 1977), the pre-polarization resistance of the skin is found to be resolvable into two components, a localized resistance and a non-localized (body core) resistance. However, upon careful consideration of the sampling time (frequency response) characteristics of the pulse generator/current detector system, the values of these two resistances are found to be appreciably lower than previously supposed. Reassessment of the roles played by the various body tissues, particularly the epidermis, in determining the pre-polarization electrical character of the skin is therefore called for. Simple three-component (R-RC) equivalent circuit simulations of the initial rapidly decreasing section of current response waveforms are useful in providing estimates of the degree of accuracy in peak current determination.

Based on the two-component model of skin pre-polarization resistance, a three-electrode method was devised to determine the localized pre-polarization resistance of any selected target site. Preliminary results suggest that even nearby sites on apparently uniform skin regions can display unexpectedly large pre-polarization resistance differences.

There is a good deal of evidence in the available literature to suggest that other commonly measured electrical characteristics of the skin such as DC potential (Woodrough, Canti, & Watson, 1975), DC resistance (Richter, Woodruff, & Eaton, 1943; Yamamoto & Yamamoto, 1981), and AC impedance (Reichmanis, Marino, & Becker, 1977) can also display marked differences over short distances. It therefore seems advisable to accurately define the sites of electrode placement during electrodermal research. A convenient body surface reference system, and the one used in this study, is the acupuncture meridian-acupoint system (Kinoshita, 1970), which specifies sites in relation to anatomical landmarks and, moreover, takes into account variations in body size.

REFERENCES

Burger, H.C., & van Milaan, J.B. (1943). Measurements of the specific resistance of the human body to direct current. *Acta Medica Scandinavica, 114*, 584–607.

Edelberg, R. (1977). Relation of electrical properties of skin to structure and physiologic state. *The Journal of Investigative Dermatology, 69*, 324–327.

Hozawa, S. (1928). Studien uber die Polarisation der Haut. *Pfluegers Archiv für die Gesamte Physiologie, 219*, 111–158.

Kinoshita, H. (1970). *Illustration of acupoints*. Tokyo: Ido-No-Nippon-Sha.

Lykken, D.T. (1971). Square-wave analysis of skin impedance. *Psychophysiology, 7*, 262–275.

Melczer, N. (1976). Electrometric studies in skin cancer. In R. Andrade, S.L. Gumport, G.L. Popkin, & T.T. Rees (Eds.), *Cancer of the skin* (pp. 293–313). Philadelphia: Saunders Co.

Reichmanis, M., Marino, A.A., & Becker, R.O. (1977).

Laplace plane analysis of transient impedance between acupuncture points Li-4 and Li-12. *IEEE Transactions On Biomedical Engineering, BME-24,* 402–405.

Richter, C.P., Woodruff, B.G., & Eaton, B.C. (1943). Hand and foot patterns of low electrical skin resistance: Their anatomical and neurological significance. *Journal of Neurophysiology, 6,* 417–424.

Swanson, D.K., & Webster, J.G. (1974). A model for skin-electrode impedance. In H.A. Miller & D.C. Harrison (Eds.), *Biomedical electrode technology, theory and practice* (pp. 117–128). New York & London: Academic Press.

Tagami, H., Masatoshi, O., Iwatsuki, K., Kanamaru, Y., Yamada, M., & Ichijo, B. (1980). Evaluation of the skin surface hydration *in vivo* by electrical measurement. *The Journal of Investigative Dermatology, 75,* 500–507.

van Boxtel, A. (1977). Skin resistance during square-wave electrical pulses of 1 to 10mA. *Medical and Biological Engineering and Computing, 15,* 679–687.

Woodrough, R.E., Canti, G., & Watson, B.W. (1975). Electrical potential difference between basal cell carcinoma, benign inflammatory lesions and normal tissue. *British Journal of Dermatology, 92,* 1–7.

Yamamoto, T., & Yamamoto, Y. (1981). Measurement of the skin impedance map of human body surface. *Proceedings of Vth International Conference on Electrical Bio-impedance* (pp. 209–212). Tokyo: Business Center for Academic Societies.

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