ENGINEERING CONSIDERATIONS IN GSR RESEARCH

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Recent interest in the psychophysiologic study of subjects in unusual and remote environments, such as supersonic aircraft (19), high altitude balloons (2), satellites (8), and others (21, 23), has placed severe demands on the instrumentation used in these studies. The standard laboratory instruments used for detecting and recording such parameters as the electroencephalogram, electrocardiogram, galvanic skin resistance, and other phenomena, cannot meet the stringent space and power limitations levied on instrumentation in such vehicles. As a result, new miniaturized devices must be developed, often by companies previously inexperienced in the technics and requirements peculiar to bioelectronic devices.

The galvanic skin resistance, a parameter of psychophysiologic interest in stressful environments, would seem to have relatively simple instrumentation requirements; however, the design engineer must be familiar with the technical and practical details peculiar to the detection and recording of this phenomenon or the result may be an instrument which is technically able to measure resistance but totally unsatisfactory for measuring *skin* resistance under the conditions of the experiment.

This paper is a synopsis of the experiences at the USAF School of Aerospace Medicine and those reported in the recent literature concerning the critical methodological points involved in studying galvanic skin reflexes (or resistance, both aspects of the same phenomenon and abbreviated GSR) to assist the engineer and the natural scientist concerned with fabricating GSR recording apparatus.

The basic mechanism underlying the galvanic skin reflex is a relatively slow change in the permeability of two electrically distinct membranes, probably sweat glands and epidermal cells,

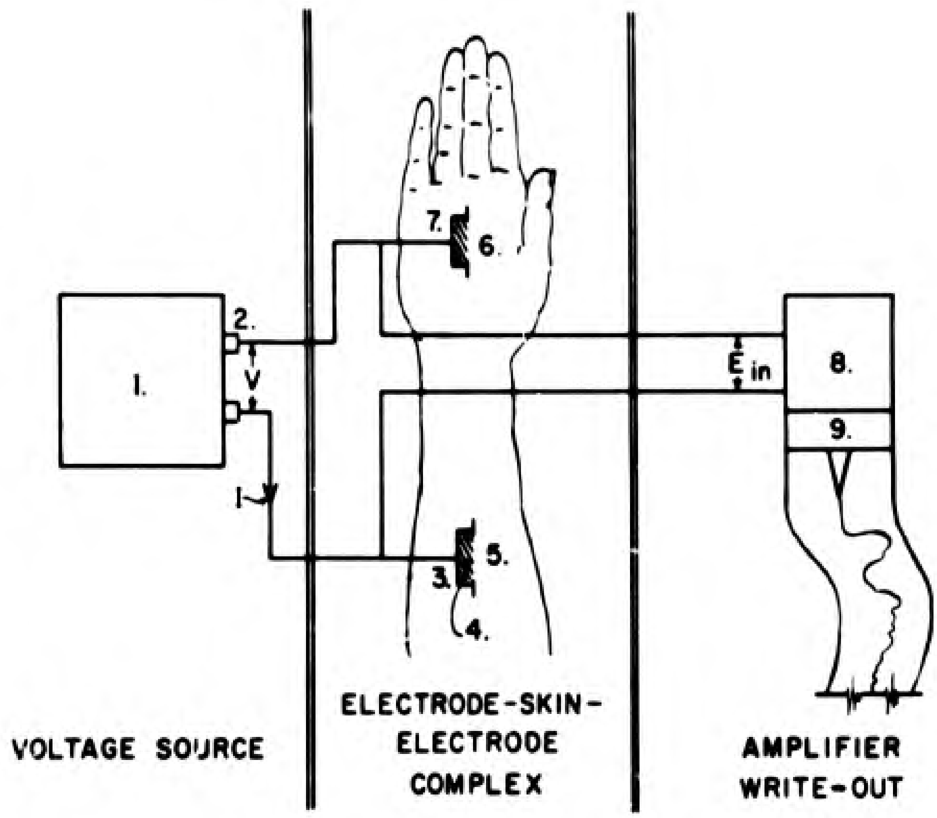


FIGURE 1

Essential components and fundamental relationship for the measurement of GSR: (1) voltage source; (2) current polarity; (3) electrodes; (4) contact medium; (5) reference site; (6) current density; (7) active site; (8) amplifier; (9) write-out.

located in the skin. Both steady state base permeability, which is a function of mental alertness, and small, short-term, transient changes (GSR's), which are a function of inner body and environmental stimuli, are modulated by nervous impulses emanating from the autonomic nervous system.

The apparatus used to detect this phenomenon, usually in terms of electrical resistance (a measure inversely related to membrane permeability), may be formalized as follows (see figure 1):

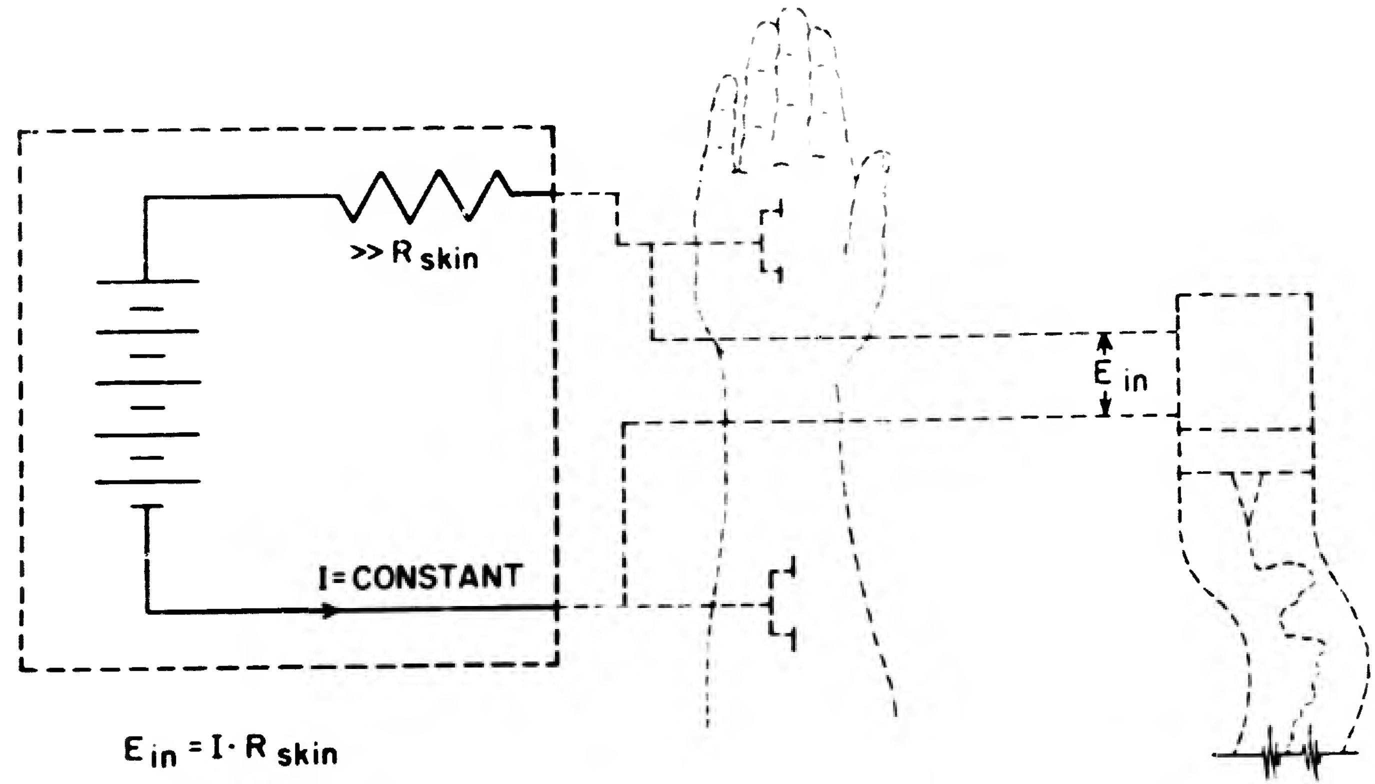
A *voltage source* provides a current of constant or alternating *polarity* to a pair of electrodes, making contact with the skin through an *electrolytic* gel or solution.

One of the electrodes contacts an area of skin known as the *reference site*, which maintains a relatively constant potential against which the potential of an *active site* may be measured.

The potential difference between the reference and active sites is a function of the membrane permeability and *current density* through the skin of the active site. The potential is detected by an *amplifier*, which may simply reproduce or perform various analytic operations on the absolute value and variations of the potential difference between reference and active sites. The amplified signal is then displayed by some means of *write-out*. The design characteristics pertinent to each of these 9 elements of GSR detection circuitry will be discussed.

VOLTAGE SOURCE

The simplest and most straightforward way to detect changes in the ionic permeability of the cells of the skin responsible for the GSR is to pass a known constant current through two electrodes attached to the skin and measure the IR (current times resistance) drop in voltage across the electrodes. This voltage is readily expressed as skin resistance (fig. 2). The physical mechanism underlying this resistance is considerably different from the mechanism in a carbon resistor, for example, but under most conditions the skin behaves like a variable resistor in parallel with a variable capacitor. If the current through the electrodes is held constant by placing them in series with a relatively large resistance, the potential difference across the electrodes will be directly proportional to the skin resistance plus electrode resistance. The magnitude of the voltage source and value of the series resistance will be determined by the selected current strength and the highest anticipated skin resistance under the various experimental circumstances. The resistance of the electrode-skin-electrode complex will vary inversely with the area of electrical contact with the skin. For measurements within 5% accuracy limits, the series



$$E_{in} = I \cdot R_{skin}$$
$$I = \text{CONSTANT}$$
$$E_{in} \approx R_{skin}$$

FIGURE 2

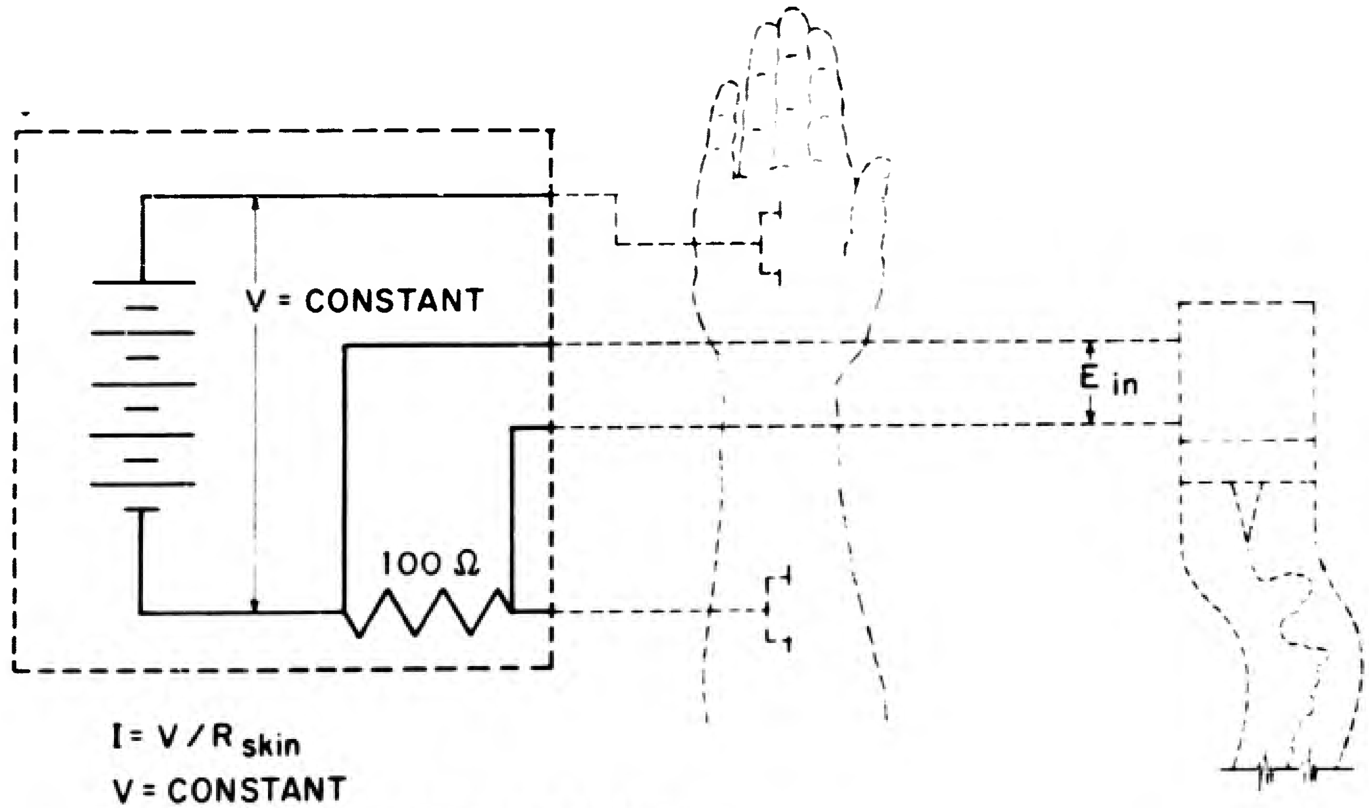
Basic circuitry required for the constant current measurement of GSR.

resistor should have a value twenty times greater than the highest expected electrode-skin-electrode complex resistance.

Psychologists (9) have found that the inverse relationship between GSR amplitude and base resistance can be linearized by expressing their results in units of conductance rather than resistance. This conversion may be accomplished automatically by holding the potential across the electrode-skin-electrode complex constant and measuring the current variations (fig. 3). The parameters of this circuit must be such that the current through the skin does not fall below 3 μa./cm.^{2}; otherwise, the current generated by the electromotive force associated with the variations in membrane permeability will introduce spurious signals during the determination of lower conductance values (4).

Electrodermal phenomena can be detected by the use of alternating current sources; however, our experience is similar to that reported by others (6, 7, 17). Both base resistance and galvanic skin reflexes decrease rapidly with frequencies above 1 kc. per second and are essentially constant above 10 kc. per second.

The electromotive force associated with changes in skin resistance may be detected without using an external current and is referred to as the endosomatic GSR because the current originates in the body (fig. 4), as opposed to exosomatic GSR or resistance measurements where the current is drawn from an external source. This technic obviates many of the problems such as electrode polarization, regulation of constant current density, and maintenance of a constant contact area, which plague methods utilizing passage of current. Unfortunately, the correlation between this aspect of GSR phenomena and the resistance, or "exosomatic" component, is poorly defined and not exactly equivalent. No consistent correlation has been demonstrated between base resistance and base potential difference (7, 24). Furthermore, the endosomatic reflexes may be mono-, di-, or even triphasic as compared to the consistently monophasic exosomatic reflex.



$I = V / R_{skin}$

$V = \text{CONSTANT}$

$I \approx 1 / R_{skin} \approx$ SKIN CONDUCTANCE

FIGURE 3

Basic circuitry required for the constant voltage measurement of GSR.

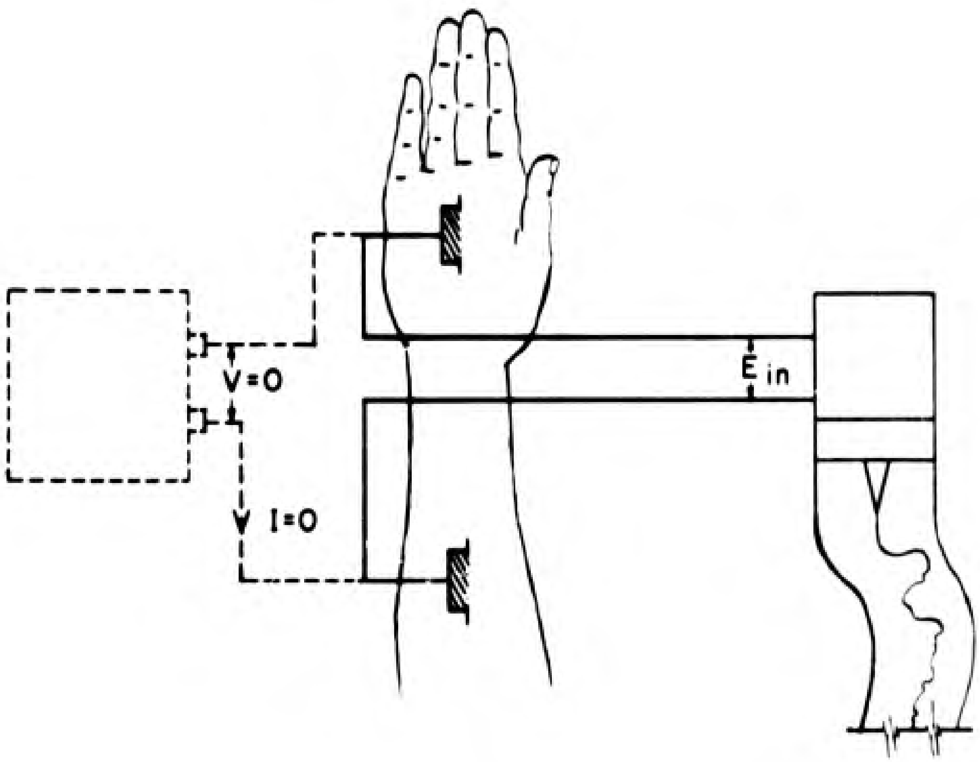


FIGURE 4

Basic circuitry required for the endosomatic measurement of GSR.

CURRENT POLARITY

Little consideration has been given to the polarity of the exosomatic current in most of the methodologic descriptions found in the literature. Fortunately, the polarity of the active site has a negligible effect on the data obtained for base resistance and GSR amplitude, if the current density is low and the usual electrolytes such as sodium chloride and potassium chloride are used in the contact medium.

Edelberg et al. (4) found that under conditions of low current density (8 μa./cm.^{2}), the active site polarity did not influence the values obtained for base resistance and GSR amplitude when chlorides of small cations were bathing the active skin. Conversely, calcium and aluminum ions were found to augment GSR amplitude under anodal currents. Sulfates gave similar results under cathodal currents, and high anodal current densities (greater than 11 μa./cm.^{2}) gave base resistance values larger than those found under cathodal currents, regardless of the electrolyte composition of the contact medium.

SKIN ELECTRODES

In selecting and preparing the skin electrodes, one must exercise different degrees of care depending on whether one is measuring GSR only, GSR and base resistance, or endosomatic potentials.

Edelberg and Burch (5) have compared several reversible and nonreversible electrodes as to fitness for the different methods mentioned. They found that simple metal plates made of iron, lead, or zinc are adequate for short-term GSR-only investigations—that is, when only GSR amplitude data are of interest and not base resistance. Other metals, such as stainless steel and aluminum, are unsatisfactory because of high random noise levels. Solder, copper, and silver were reported to be characterized by undesirable slow wave artifacts.

Reversible electrodes must be used when direct current is passed for long periods of times, as in continuous monitoring of base resistance, to prevent errors due to polarization potentials. Unfortunately, reversible electrodes are only *relatively* reversible, and unwanted polarization potentials causing erroneously high base-resistance data will develop if they are used in a d.c. circuit for more than a few hours. Gradual loss of the anodized coating occurring at the cathodal electrode can eventually convert the system to a nonreversible state with concomitant high polarization potentials. Using a minimum current density and making the cathodal electrode large relative to the anode are solutions Edelberg and Burch (5) have suggested for this problem. A four-pole electrode system described by Barnett (1) and others and recently modified by Lykken (11) permits the detection of the potential difference, but not polarization potentials, created by current passed by separate but concentric electrodes.

Endosomatic GSR and base potential measurements are not complicated by this problem. The bioelectric signal for the galvanic skin reflex is only a few millivolts, and extremely stable electrodes which will maintain a potential difference of less than 1 mv. during the experiment are required. The papers by O'Connell et al. (15, 16) may be consulted for their evaluation of reversible electrodes and their methods for making extremely stable silver-silver chloride electrodes. Lykken (11) has reported that zinc-zinc sulfate electrodes were the best and most easily prepared reversible electrode; however, their use for study of skin resistance seems undesirable in light of the report by Edelberg and Burch (5) that zinc salts potentiate the GSR amplitude by more than 100%.

Of equal importance to the electrical characteristics in the fabrication of GSR electrodes is their physical configuration. The skin must be masked or the electrode affixed to the skin in such a way that the area of active skin under the electrode is maintained constant. Otherwise, a known, carefully controlled current density cannot be obtained. The contact paste must not be allowed to dry or extend beyond the selected, known area of skin for the same reasons.

A Lucite cup electrode was developed in the Aviation Medicine Department and used for long-term GSR and base resistance studies (fig. 5). The wide flange, beveled back, and shallow cup reduce the chance of accidentally dislodging the electrode from the skin. A silver chloride anodized disc of silver is glued to the bottom of the cup, and the lead connection and unanodized back of the disc are sealed from contact with the electrolyte-containing medium placed in the cup. Eastman 910 adhesive, applied to the flange, quickly and firmly fixes the electrode to the skin and forms an innocuous, constant area, nondrying electrode which adheres firmly but can be removed quickly and easily. Use of Davol cement (No. 262) or donut-shaped discs of Stomaseal cut to the size of the electrode flange is also a useful technic for sealing the electrodes to the skin.

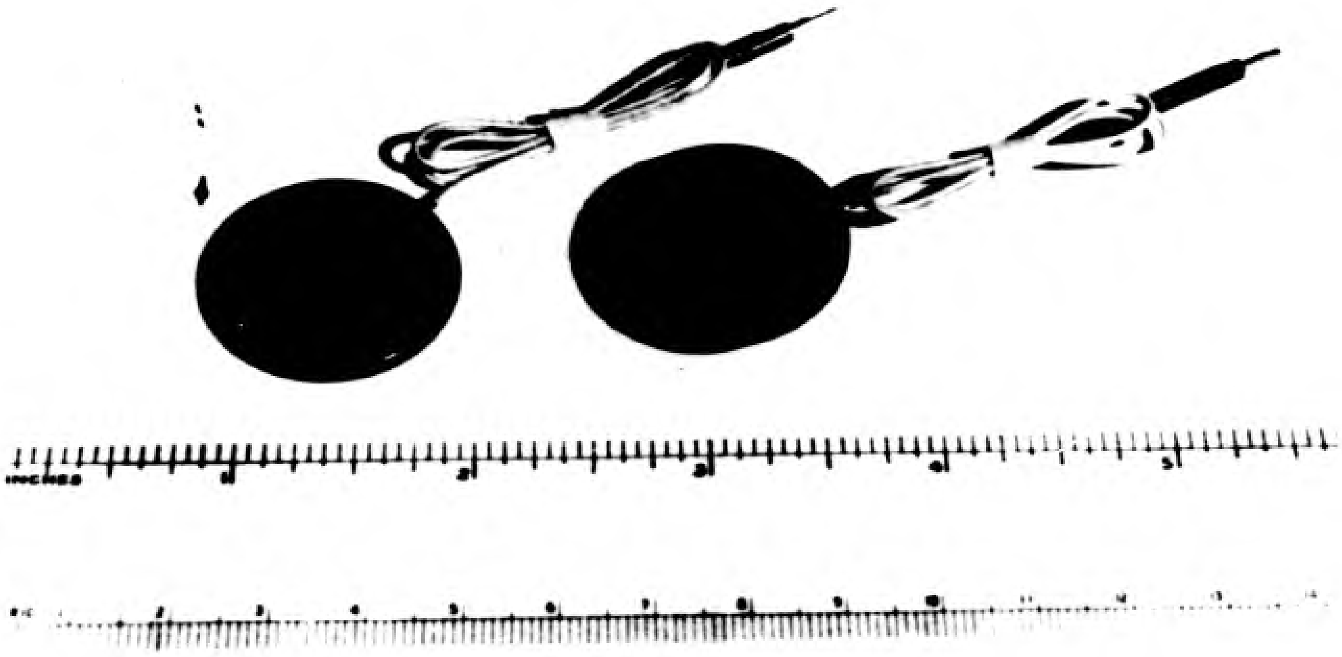


FIGURE 5

GSR electrode cups illustrating the plastic cap as it fits on the skin (left-hand unit) and as seen from the under side (right-hand unit).

CONTACT MEDIUM

For all types of GSR studies, care must be used in the selection of the composition and concentration of components used in preparing an electrically conducting liquid paste or gel which makes contact between the metal electrode and skin.

Edelberg et al. (4) have reported dramatic augmentation of GSR amplitude by 1 *M* lithium chloride, aluminum chloride, calcium chloride, ammonium chloride, and potassium sulfate. In all cases except aluminum chloride, GSR augmentation was accompanied by a reduction in base resistance. One molar potassium chloride, detergents, dilute alkali, and acids caused reduction in both GSR amplitude and base resistance. In light of these and other findings, Edelberg and Burch (5) suggested, as an inert contact medium, the use of a starch paste made of 0.05 *N* sodium chloride solution which provides a salt concentration approximating that of sweat, according to Rothman (20).

REFERENCE SITE

In most GSR studies it is desirable to have one electrode affixed to an area of skin which does not exhibit GSR phenomenon and has a constant, low resistance. A large plate electrode applied to an inactive area such as the upper arm satisfies most of these requirements; however, in our experience, such an electrode is cumbersome, difficult to keep moist, and hard to prevent from sliding down the arm when used on an active subject. Pricking the skin with a hypodermic needle before applying the electrodes is a quick, painless method of obtaining a constant low resistance. Care must be exercised when using this method, however; in our experience, a prick by a No. 26 gage hypodermic needle carried through to subcutaneous depths by slow application of the needle perpendicular to the skin will seal over, causing an increase in resistance within about 45 minutes. Equally effective without penetrating the dermis is the "skin drilling" technic described by Shackel (22). Figure 6 demonstrates this technic as used in the Aviation Medicine Department. The gentle application of a No. 6 dental bur with a hand tool quickly removes the upper layers of

FIGURE 6

Use of hand tool to remove surface squamous epithelial cells for preparing a cutaneous electrode site.

dead epithelial cells, creating a low resistance contact with the wet, viable underlying tissues. The method is painless and requires seconds to complete; it needs only an electrode large enough to cover the desquamated area and consistently provides an inactive site with 1,000 ohms' resistance or less for periods greater than 24 hours. When used for endosomatic GSR studies, Edelberg (3) advises masking from electrical contact the skin immediately surrounding the drilled reference site to guard against average potential variations of the reference site.

As in all reference sites used in skin resistance measurements, an area of skin must be used which does not have a large potential difference vs. the active site.

CURRENT DENSITY

The passage of current through the cells responsible for electrodermal phenomenon might readily be expected to alter the bioelectric characteristic of those cells, and this question has been the subject of several investigations. Landis and Forbes (10) in 1933, Grings (7) in 1953, and Edelberg et al. (4) in 1960 generally agreed that the current voltage relationship for skin deviates significantly from the linearity above 10 μa. cm.^{2} Edelberg et al. found a depression in GSR amplitude associated with currents above this value, which persisted for several minutes after return to values below 10 μa. cm.^{2} A value of 8 μa. cm.^{2} was recommended by Edelberg and Burch (5) in a later report. Lykken (11) found a linear relationship between current and voltage through the skin, but his results cannot be compared accurately because he reported total current, not current density, and did not mention how large was the area of electrical contact with the skin in these measurements. The size of the electrodes reported elsewhere in Lykken's report would indicate that his lowest current values were well within the range of current densities associated with injury of the active membrane, as described by Edelberg et al. As stated before, the endosomatic current establishes lower limits of current density when a constant voltage method is used.

ACTIVE SITE

The important considerations of electrode contact area, contact medium composition, and current density have already been discussed. Care must be taken in preparation of the active site for electrode application. Wiping with acetone to lower resistance and provide a better gluing surface by removal of skin secretions seems to have no deleterious effect; however, washing the skin with detergents, abrading it with sandpaper, or vigorous rubbing could be expected to injure the bioelectrically active cells. Pressure on an active site has been found to depress the amplitude of GSR's, and the marked effect of active site temperature on reactivity and base resistance has been demonstrated by Maulsby and Edelberg (14).

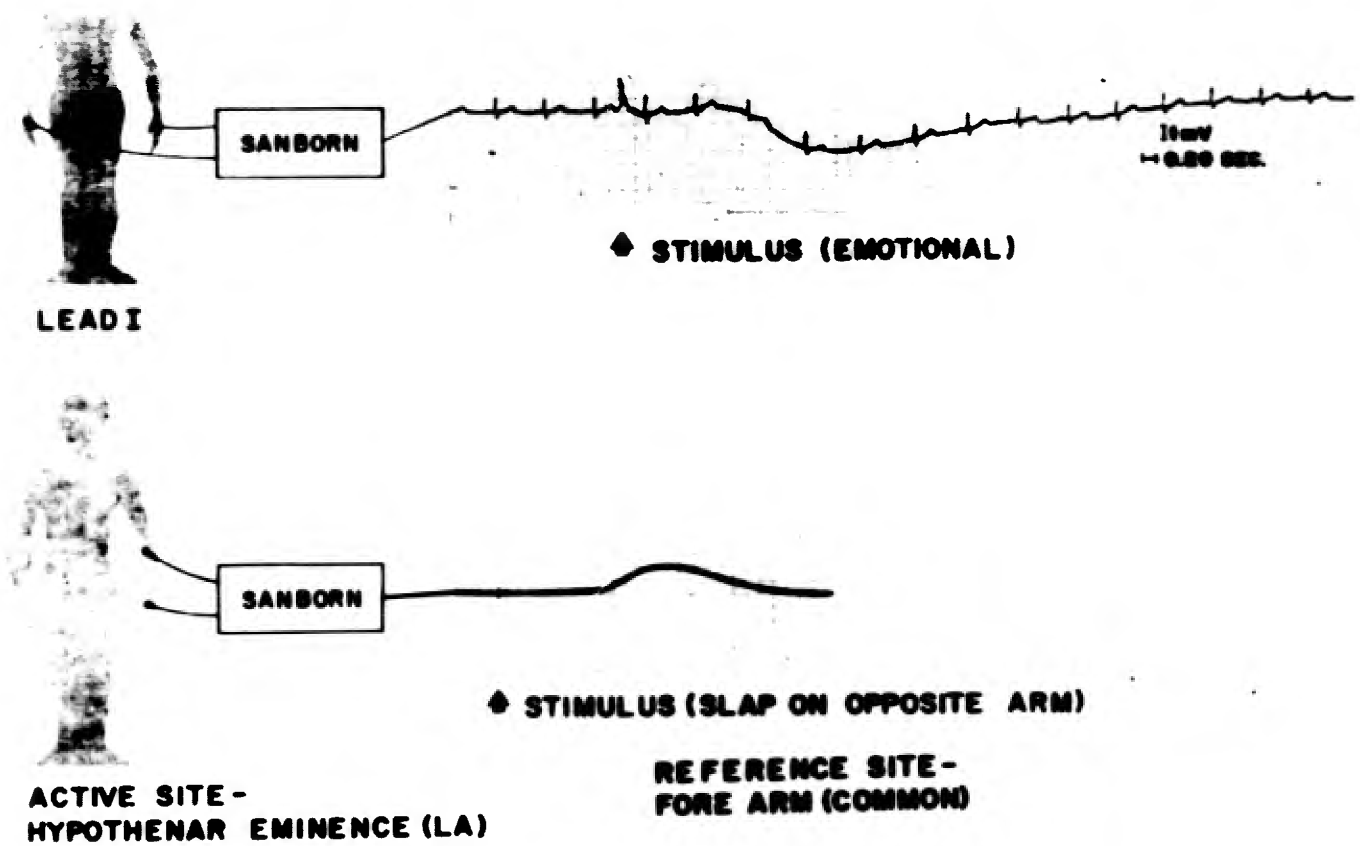
AMPLIFYING SYSTEM

The gain requirements for an amplifier used in studying electrodermal phenomena are governed primarily by the method selected for detecting GSR activity. The signal level of the IR drop method is a direct function of the current density through the active site. When no excitation is used, the endosomatic GSR activity is characterized by 1 to 5 mv. variations on a base potential difference which may range from 1 to 100 mv. Parenthetically, an ordinary ECG machine will register endosomatic GSR's accurately if the coupling networks have a time constant of 6 seconds. Many commercial machines have time constants of only 3 seconds and must be modified if absolute amplitude and waveform data are of interest. Figure 7 depicts endosomatic GSR's obtained on a standard, portable, direct-writing ECG machine. The upper tracing was obtained in the usual lead 1 configuration. The lower tracing was taken with electrodes placed on the forearm and palm of one arm. The apparent reversal of polarity between the two tracings was caused by the selection of leads.

Direct current amplification is necessary for base resistance or base potential measurements, but often capacitative coupling and higher gain are preferable to study the galvanic skin reflexes without being bothered by baseline shifts due to changes in base resistance or potential. Prior to the development of stable low level d.c. amplifiers with output zero suppression capabilities,

FIGURE 7

Comparison of a GSR observed on a standard Sanborn ECG machine (seen as a baseline deviation of the clinical ECG record) and as seen on another channel of the same machine at the same amplification when the leads are connected to GSR electrodes in the configuration normally used for observing GSR.


SANBORN
STIMULUS (EMOTIONAL)
LEAD I
SANBORN
STIMULUS (SLAP ON OPPOSITE ARM)
ACTIVE SITE -
HYPOTHENAR EMINENCE (LA)
REFERENCE SITE -
FORE ARM (COMMON)

Wheatstone bridge circuits were used to balance out the base resistance. Although instruments exist which will automatically, and noisily, maintain such a bridge in balance (Fels Dermometer), a preferred method would seem to be to record base resistance and GSR's on separate but parallel channels, the former d.c. coupled and the latter a.c. coupled with the appropriate time constant (18). Input impedances of 10 to 20 megohms are desirable to prevent loading and attenuation of GSR amplitude when base resistance becomes high.

When a constant voltage circuit such as the one described by Lykken (12) is used, these high impedance requirements do not obtain, since the signal is developed by the current variations passing through a 100-ohm resistor. If one preferred to use a constant current method, but wanted to analyze the data in units of conductance, an amplifier could be constructed to give an output voltage inversely proportional to the input voltage, similar to that described by Marko et al. (13).

WRITE-OUT

The frequency response characteristics of GSR write-out galvanometers are not demanding since the reflex has an onset-to-peak rise time greater than 1 second. (Return to baseline may take approximately 20 seconds if another GSR does not intervene.) GSR data are usually reported in units of resistance or conductance (ohms or mhos). However, the absolute value obtained in a skin resistance measurement is inversely dependent on the area of electrical contact with the skin, and unless this area is reported, data from different laboratories cannot be compared. It is proposed that data should be presented in units of specific resistance or specific conductance to permit a more accurate description of the phenomenon and facilitate comparison of data. Use of these units would demand that the area of electrical contact with the skin and current density be carefully controlled.

If the current is expressed in terms of current density, and resistance is expressed in terms of specific resistance, the recording galvanometer can be calibrated in units of specific resistance, provided current density is held constant (fig. 8). In practicality,

$$I = (\text{CURRENT DENSITY})(\text{AREA}) \qquad R = \frac{\text{SPECIFIC RESISTANCE}}{\text{AREA}}$$

$$I = D_I \cdot A \qquad R = \frac{r_{sp.}}{A}$$

$$E = I \cdot R$$

$$E = (D_I \cdot A)\left(\frac{r_{sp.}}{A}\right) = D_I \cdot r_{sp.}$$

$$D_I = \text{CONSTANT}$$

$$E \approx r_{sp.}$$

FIGURE 8

Relationships that are used in the derivation of the specific skin resistance calibration.

this calibration may be accomplished by using a total current of unit area density when calibrating with a standard resistance, and then changing the total current to the appropriate value required to maintain the selected current density through the active skin. For example, if a current density of 8 μa. cm.^{2} is used with a site of 2 cm.^{2} area, one would calibrate with a total current of 8 μa./cm.^{2} and then change the total current to 16 μa. when the electrode-skin-electrode complex is substituted for the calibration resistors. The current density through the skin would be 8 μa./cm.^{2}, and the galvanometer deflection may then be read directly in ohm-cm.^{2} units. Similar considerations hold true for specific conductance units.

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