Final Report

THE ELECTRICAL CHARACTERISTICS OF SURFACE ELECTRODES FOR ELECTROCARDIOGRAPHY

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TABLE OF CONTENTS

I. INTRODUCTION

The purpose of the experimental and theoretical study, which is described in this report, has been to determine and describe some of the properties of the present surface electrodes which are used for monitoring physiological processes of human subjects in the dynamic environment.

The properties of electrodes are poorly known, or at least not known in sufficiently useful form to be used in the design of proper electronic instrumentation or signal conditioners for use in our space program. Consequently, waveform recognitions in conjunction with electrodes is very much limited to a primitive stage. The approach to electrode design remains entirely empirical, and the comparison between different types of electrodes for the same purpose remains a matter of personal judgment based on experience.

The objective of this study has been to determine the equivalent circuit of a typical set of surface electrodes in contact with human skin. In a continuing program, it is planned to further investigate the equivalent circuit with the motive of learning how it varies under different environmental and subject conditions and of accounting for the generation of the motion artifact. As a final result, it will be sought to obtain a fundamental understanding of electrode theory in terms of physics, electrical engineering, and physiological principles.

II. BIOELECTRODES

Bioelectrodes can be subdivided into two classes: body surface electrodes and implanted electrodes. Body surface electrodes are those which do not themselves penetrate the skin, while implanted electrodes, as the name implies, pass through the outer layers of the skin to make direct contact with body tissue. Implanted electrodes have the advantage of avoiding the problem of conduction through the outer layer of skin, since they make direct connection with the tissue which has a greater conductivity than the skin itself. However the implanted electrode is not without its disadvantages. There is of course the discomfort of implanting the electrode. There is also the danger of tissue destruction by the electrode material when long periods of monitoring are necessary. Copper electrodes, for example, which produce no noticeable ill effects in an hour's use, result in notable destruction of tissue when used to observe biological activity for a period of several weeks. Stainless steel electrodes do not show this deleterious effect.

When the implanted electrode is used as a path for a stimulating signal, another problem arises. Since generally higher current densities are involved in stimulation than in detection, which is accomplished through a high input impedance amplifier, there is the possibility that the electrode will plate itself out on the tissue, and thus dissipate itself in a relatively short period of time.

The body surface electrodes on the other hand do not encounter tissue directly. They may be attached directly to the skin, but are generally linked to the skin by an electrolytic jelly which provides a good contact with the skin. The external electrode in either case results in additional complexity since it then involves the electrode-skin interface, or the electrode-electrolyte and electrolyte-skin junctions. Thus the analysis of the body surface electrode is more difficult and such a configuration is also subject to a greater number of perturbing influences than the implant.

The implanted electrode generally takes the form of a thin wire with a pointed end, or it may actually consist of a wire attached to a needle. A common needle type is the bi-polar, concentric-needle, electrode which consists of a simple stainless steel hypodermic needle containing an insulated wire in its barrel.

Body surface electrodes consist generally of an insulated wire lead attached to a metallic plate which is encompassed in an insulating material. Generally the metal plate is recessed in the insulating material, and contact with the skin is made through an electrolytic gel. However some electrodes have been constructed so that the metal projects out of the insulator and thus makes a closer contact with the skin (such as those used at the Rancho Los Amigos Hospital in Los Angeles). An insulated wire with bared tip has also been used as an electrode with a glue base paste to hold it fast and provide connection with the skin. All three types appear to yield comparable results, and at this point it is more a matter of choice accompanied by suitable application technique.

III. APPLICATION OF BODY SURFACE ELECTRODES

The problems of discomfort and of physiological damage are not by any means foreign to body surface electrodes. Attachment of such electrodes is generally preceded by what is termed "skin preparation". This may take the form of a brisk cleansing with a solvent such as acetone, or the rubbing in of electrode paste. Sometimes the skin is abraded through the use of a solvent-soaked surgical sponge, or the application of sandpaper to the area. Scarification can be accomplished with the electrode paste through the inclusion of some ground glass, which when applied results in minute scratches on the skin which afford a direct path to the tissue. In some cases the skin is pricked to provide this contact.

After the area of application has been cleaned and dried and some provision made for the penetration through the skin to the tissue, electrolytic paste is applied to the metallic plate in the electrode, which is then pressed to the skin so that the metal-electrolyte and electrolyte-skin interfaces are in complete contact. The electrodes are then generally held in place by some adhesive or a suction cup.

In the present study, the skin was prepared by briskly rubbing the surface with a tooth brush which was saturated with electrode paste. This technique resulted in a satisfactory electrode-skin contact with a minimum of discomfort and physiological damage.

IV. MECHANISMS OF CONDUCTION

In examining the flow of current through the electrode-skin-electrode system, three separate regions must be considered. First there is the electrode skin interface (with the jelly considered as part of the electrode structure). The electrode acts as a transducer for the bioelectric signal which consists of a flow of ions. The epidermis itself, the outer layer of skin of 0.1 mm average thickness, is a poor conductor and offers a large resistive barrier to current flow. It consists of three layers. The (exterior) horny layer is easily penetrated by ions, molecules and even molecular aggregates. However, this is followed by a thin layer, the stratum lucidium, which screens out anions but passes cations. The stratum lucidium is followed by the Malaphigian layer which presents no further barrier to current flow. The channel of conduction through the stratum lucidium apparently consists of the eccrine sweat glands, as studies have shown the absence of a galvanic skin response in subjects whose sweat glands are mainly apocrine rather than eccrine.

Of course if the epidermis is removed during the preparation of the skin, the resistance of the skin-electrode interface is greatly reduced since contact is then made with the inner layer of skin, the derma. Once to the derma the current flow is carried by a third structure -- cell, tissue, and fluid.

Studies have shown that passive biological tissue can be represented by a stationary, lumped, linear, bilateral network. The biological tissue consists of a group of cells, surrounded by an intercellular fluid. The fluid has been found to be highly conductive, while the cell membrane can be represented by a large resistance in parallel with a capacitor. Intracellular low-resistance fluid is also present within the cell. An equivalent circuit for the electrical representation of a frog muscle was obtained by Fatt (Ref. 1) consisting of a resistor in parallel with two resistor capacitor series legs. The equivalent circuit shows that there are distinct regions in the impedance vs. frequency plot, where R_b, R_a, and R_i, dominate.

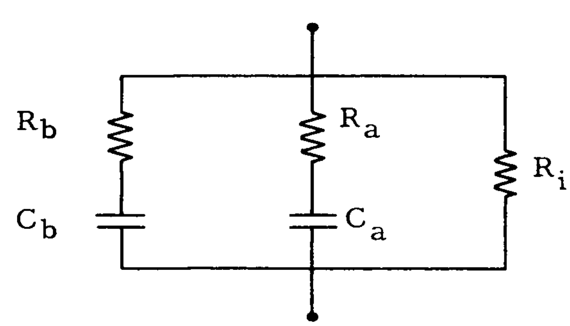

Figure 1. Fatt's Circuit

V. CHARACTERISTICS OF BIOELECTRODES

Other authors have shown that the electrical characteristics of the body surface type electrodes result from the mechanisms of conduction explained previously (Cf. Refs. 1, 2, and 3). As noted above, there exists a large resistance due to the skin electrode interface. Removal of this layer results in a much smaller resistive component in series with the tissue, which also implies better contact with the inner tissue. This situation in turn implies less variance of impedance due to loss of effective contacting area; since the electrode contact is better to begin with, small changes in contact area have less effect. It has been shown by Roman (Ref. 2) that over a narrow frequency range the skin-electrode combination can be approximated by an RC-parallel combination (0.1 to 100 Hz.). It has also been shown that resistance is a function primarily of skin preparation as implied above, but for a given type of preparation it varies inversely with the area of the electrodes (the area effectively in contact with the skin). Similarly the capacitive component of the skin electrode impedance is directly dependent on the area of the electrodes and the variation is extremely linear (Ref. 2).

Distance between the electrodes has been found to have little effect on the observed impedance. This result suggests that tissue conduction plays a relatively insignificant role in the determination of current flow through the system, i.e., that tissue impedance is small.

VI. VOLTAGE LEVEL OF ELECTRODE IMPEDANCE MEASUREMENTS

The electrical properties of human skin and tissue are such that the impedance is not constant as a function of voltage. This fact implies that if one wishes to determine the impedance of surface electrodes in contact with human skin, it is first necessary to specify the voltage level at which the impedance is to be measured.

The most practical level at which to measure the impedance of surface electrodes seems to be in the 1 to 100 millivolt range. The practicality of this voltage range is implied in part from the voltage level of biological processes. For example certain biopotentials have the following magnitudes (Ref. 4):

(a) Resting potential of cardiac muscle, 80 mv.

(b) Resting potential of skeletal muscle, 70 mv.

(c) Osmotic neuron potential, 70 mv.

(d) Nerves can be stimulated by impulses above 800 mv.

(e) Electrocardiogram voltages are less than 50 mv.

When electrodes are attached to the skin and voltage is applied across them, the voltage must be kept well below 1 volt in order to assure that no neurons or muscle fibers will be triggered. While no experimental data has been taken or found confirming or denying the possibility, it may be that due to the "all or none" law of these tissues (Ref. 4), a fired neuron or muscle fiber has a different impedance from an unfired one. In order to keep this variation to a minimum, the voltage level impressed across the electrodes should be either below 500 mv, in which case no fibers would be stimulated, or above 2.5 volts in which case all would be stimulated.

It would be impractical for the applied voltage to be above 2.5 volts, as this level would cause danger and discomfort to the subject. Impedances measured in this higher voltage range may not be of much value since they might be quite different from impedances for the voltage levels at which biological measurements are usually made.

The low voltage level at which impedance measurements should be made presents a problem. Some preliminary measurements made under unshielded conditions have shown that electrical interference in the University laboratories and buildings is in the 3 to 200 millivolt range (as measured across the terminals of the attached electrodes). The electrical interference would in all probability be larger in close proximity to high current electrical equipment such as found in industrial or aircraft environments.

The frequency characteristics of the noise is wide band with components ranging up to several mega-Hertz. The predominant frequency of the noise is 60 Hz.

In order to reduce the electrical noise to an acceptable level, a screen room was constructed, and the screen shielding was connected to a common but floating electrical equipment ground. The subject was placed inside the shielded enclosure; all of the measuring equipment was located outside the enclosure; and electrical connections were made by means of shielded leads. Under these conditions, the electrical noise was reduced to the microvolt level (approximately 19 microvolts as measured across the electrode terminals). The residual noise was traced to transistors of the amplifier which was used in the measurements. No change was made in the amplifier design since the residual noise level was considered to be perfectly acceptable for the purposes of the measurements.

It may be expected that such complete shielding will alter the impedance measurements by increasing the apparent electrode capacitance. However, by compensating the amplifier for the effect of the shielded leads, and by the appropriate positioning of leads and the subject within the screened enclosure, the stray capacitance effects were reduced to a negligible level for frequencies in the d.c. to 10,000 Hz range.

VII. MEASUREMENT OF ELECTRODE CHARACTERISTICS

After preparing the skin as described in Section III, Beckman surface electrodes (Beckman Biopotential Skin Electrodes, No. 350040, for use with EKG) were applied to a subject's forearm at a separation of 10 centimeters with the Beckman electrode paste. In order to determine the electrical characteristics, the series combination of the electrodes and a 50,000 ohm resistor was driven by an audio frequency oscillator and precision attenuator (Wavetek Model 110 Oscillator), and the electrode voltage was compared with that across the series combination as a function of the oscillator frequency. The electrode voltage was measured with a transistorized amplifier (Philbrick Model P65A) and a calibrated oscilloscope.

Data for six subjects, which were obtained at several intervals of time after application of the electrodes, are presented in Tables I, II, and III. The tables give the ratio of the electrode voltage, E_o, to the voltage applied across the series combination of resistor and electrodes, E_i, as a function of frequency. The ratios have been expressed in decibels and increased by the amplifier gain, G, (46 db). The data were obtained at an electrode voltage, E_o, of 10 millivolts. (Increasing the electrode voltage to 50 millivolts, or reducing the electrode separation to 5 cm, was found to have only a small effect upon the data.) The geometrical averages or mean values of the data are also tabulated.

In Table IV the geometric mean values of the electrode voltage ratios are tabulated. For the values given in parenthesis, a reference of zero decibels was chosen to correspond to the initial, low-frequency, limiting value of the voltage ratio. The mean values, for data obtained at 0 and 3 hours, are shown as curves in Figure 2. It may be noted that the

Table I. Electrode Voltage Ratio $\frac{E_o}{E_i}$ G, in Decibels

0 Hours

Subject	1	2	3	4	5	6	Mean
Frequency in Hz							
1	42.7						
5	42.7	44.8	44.1	38.4	39.2	44.8	42.3
10	42.5	44.8	44.1	38.4	39.2	44.8	42.3
20	42.5	44.8	44.0	38.4	39.0	44.8	42.25
40	42.4	44.8	43.7	38.1	38.8	44.3	42.01
80	41.9	44.3	43.4	37.8	38.3	43.8	41.59
160	41.3	43.7	42.9	36.9	37.5	43.0	40.89
320	40.2	42.3	42.0	35.6	36.0	41.6	39.62
640	38.2	39.7	40.4	33.6	33.6	39.2	37.45
1.28 K	34.0	34.7	37.5	30.7	29.8	35.3	33.67
2.56 K	29.0	29.7	33.3	27.1	23.2	30.7	28.71
5.12 K		24.6	28.3	22.9	20.0	25.3	24.22
10.24 K		18.9	22.6	16.9	14.0	19.7	18.42
20.48 K		14.0	17.6	12.1	8.0	14.8	13.3

0.5 Hours

1							
5	41.3	44.5		38.2		42.8	41.7
10	41.0	44.5		38.2		42.8	41.63
20	41.0	44.5		38.1		42.5	41.53
40	41.0	44.5		37.8		42.3	41.40
80	40.5	43.8		37.5		41.7	40.88
160	40.0	43.2		36.7		40.9	40.20
320	38.9	41.9		35.3		39.7	38.73
640	36.8	39.5		33.3		37.4	36.75
1.28 K	32.7	34.7		30.7		34.0	32.85
2.56 K	28.0	30.4		26.9		29.6	28.73
5.12 K		25.4		22.3		24.9	24.2
10.24 K		20.0		16.3		19.3	18.53
20.48 K		14.3		11.6		14.5	13.47

Table II. Electrode Voltage Ratio $\frac{E_o}{E_i}$ G, in Decibels

Subject	1	2	3	4	5	6	Mean
				1 Hour			
Frequency in Hz							
1							
5	43.2	44.5	43.4	38.0	37.6	41.8	41.42
10	43.2	44.5	43.4	38.0	37.6	41.8	41.42
20	43.2	44.5	43.3	37.7	37.2	41.6	41.25
40	43.2	44.5	43.1	37.5	37.0	41.4	41.12
80	41.4	43.8	42.8	37.2	36.7	40.9	40.47
160	40.7	43.2	42.2	36.4	35.6	40.2	39.72
320	39.3	41.9	41.4	35.1	34.0	38.9	38.43
640	34.8	39.5	39.7	32.9	31.5	36.9	35.88
1.28 K	28.0	34.7	36.7	30.1	28.0	33.7	31.87
2.56 K		30.4	32.4	26.0	23.2	29.3	28.26
5.12 K		25.4	28.0	21.6	18.5	24.7	23.64
10.24 K		20.0	21.9	16.0	14.0	18.9	18.16
20.48 K		14.3	16.9	11.6	8.00	14.0	12.93
				2 Hours			
1							
5		42.3	43.0	37.7		40.4	40.85
10		42.3	43.0	37.7		40.4	40.85
20		42.3	42.8	37.5		40.3	40.73
40		42.3	42.6	37.3		40.1	40.58
80		41.7	42.4	36.8		39.8	40.18
160		41.0	41.8	36.0		39.2	39.50
320		39.7	40.8	34.7		37.8	38.25
640		37.4	39.2	32.3		35.8	36.18
1.28 K		38.1	36.3	29.3		32.5	32.80
2.56 K		28.7	32.3	25.0		28.3	28.58
5.12 K		24.4	27.4	20.5		23.5	23.95
10.24 K		19.6	21.9	15.6		18.1	18.80
20.48 K		13.7	16.9	10.9		13.3	13.70

Table III. Electrode Voltage Ratio $\frac{E_o}{E_i}$ G, in Decibels

3 Hours

Subject	1	2	3	4	5	6	Mean
Frequency in Hz							
1							
5			43.1	37.6		39.7	40.13
10			43.1	37.6		39.7	40.13
20			42.9	37.4		39.5	39.93
40			42.6	37.2		39.2	39.67
80			42.3	36.5		38.7	39.17
160			41.7	35.5		37.9	38.67
320			40.7	34.1		36.6	37.13
640			39.0	31.8		34.3	35.03
1.28 K			36.1	29.5		31.3	32.30
2.56 K			32.0	24.7		26.9	27.87
5.12 K			27.0	20.0		22.5	23.18
10.24 K			21.6	15.4		17.2	18.07
20.48 K			16.9	10.4		12.7	13.33

4 Hours

	1	2	3	4	5	6	Mean
1							
5			42.8			39.9	41.35
10			42.8			39.9	41.35
20			42.6			39.8	41.20
40			42.4			39.5	40.95
80			42.1			38.9	40.50
160			41.4			37.8	39.60
320			40.4			36.5	38.45
640			38.7			34.3	36.50
1.28 K			35.7			30.9	33.30
2.56 K			31.6			26.9	29.25
5.12 K			26.6			22.3	24.45
10.24 K			21.3			17.2	19.25
20.48 K			16.4			12.8	14.60

Table IV. Mean Values of the Electrode Voltage Ratio $\frac{E_o}{E_i}$ G, in Decibels

Time / Frequency in Hz.	0 hr.	.5 hr.	1 hr.	2 hrs.	3 hrs.	4 hrs.
5	42.3 (0)	41.7 (-. 6)	41.42 (-.88)	40.85 (-1.45)	40.13 (-2.17)	41.35 (-.95)
10	42.3 (0)	41.63 (-.67)	41.42 (-.88)	40.85 (-1.45)	40.13 (-2.17)	41.35 (-.95)
20	42.25 (-.05)	41.53 (-.77)	41.25 (-1.05)	40.73 (-1.57)	39.93 (-2.37)	41.20 (1.1)
40	42.01 (-.29)	41.4 (-.9)	41.12 (-1.18)	40.58 (1.72)	39.67 (-2.63)	40.95 (-1.35)
80	41.59 (-.71)	40.88 (-1.42)	40.47 (-1.83)	40.18 (-2.12)	39.17 (-3.13)	40.50 (-1.8)
160	40.89 (-1.41)	40.20 (-2.1)	39.72 (-2.58)	39.50 (-2.8)	38.67 (-3.63)	39.60 (-2.7)
320	39.62 (-2.68)	38.73 (-3.57)	38.43 (-3.87)	38.25 (-4.05)	37.13 (-5.17)	38.45 (-3.85)
640	37.45 (-4.85)	36.75 (-5.55)	35.88 (-6.42)	36.18 (-6.12)	35.03 (-7.27)	36.50 (-5.8)
1.28 K	33.67 (-8.63)	32.85 (-9.45)	31.87 (-10.43)	32.80 (-9.5)	32.30 (-10.00)	33.3 (-9.0)
2.56 K	28.71 (-13.59)	28.73 (-13.57)	28.26 (-14.04)	28.58 (-13.72)	27.87 (-14.43)	29.25 (-13.05)
5.12 K	24.22 (-18.08)	24.2 (-18.5)	23.64 (-18.66)	23.95 (-18.35)	23.18 (-19.12)	24.45 (-17.85)
10.24 K	18.42 (-23.88)	18.53 (-23.77)	18.16 (-24.14)	18.80 (-23.5)	18.07 (-24.23)	19.25 (-23.05)
20.48 K	13.3 (-29.0)	13.47 (-28.83)	12.93 (-29.37)	13.70 (-28.60)	13.33 (-28.97)	14.60 (-27.7)

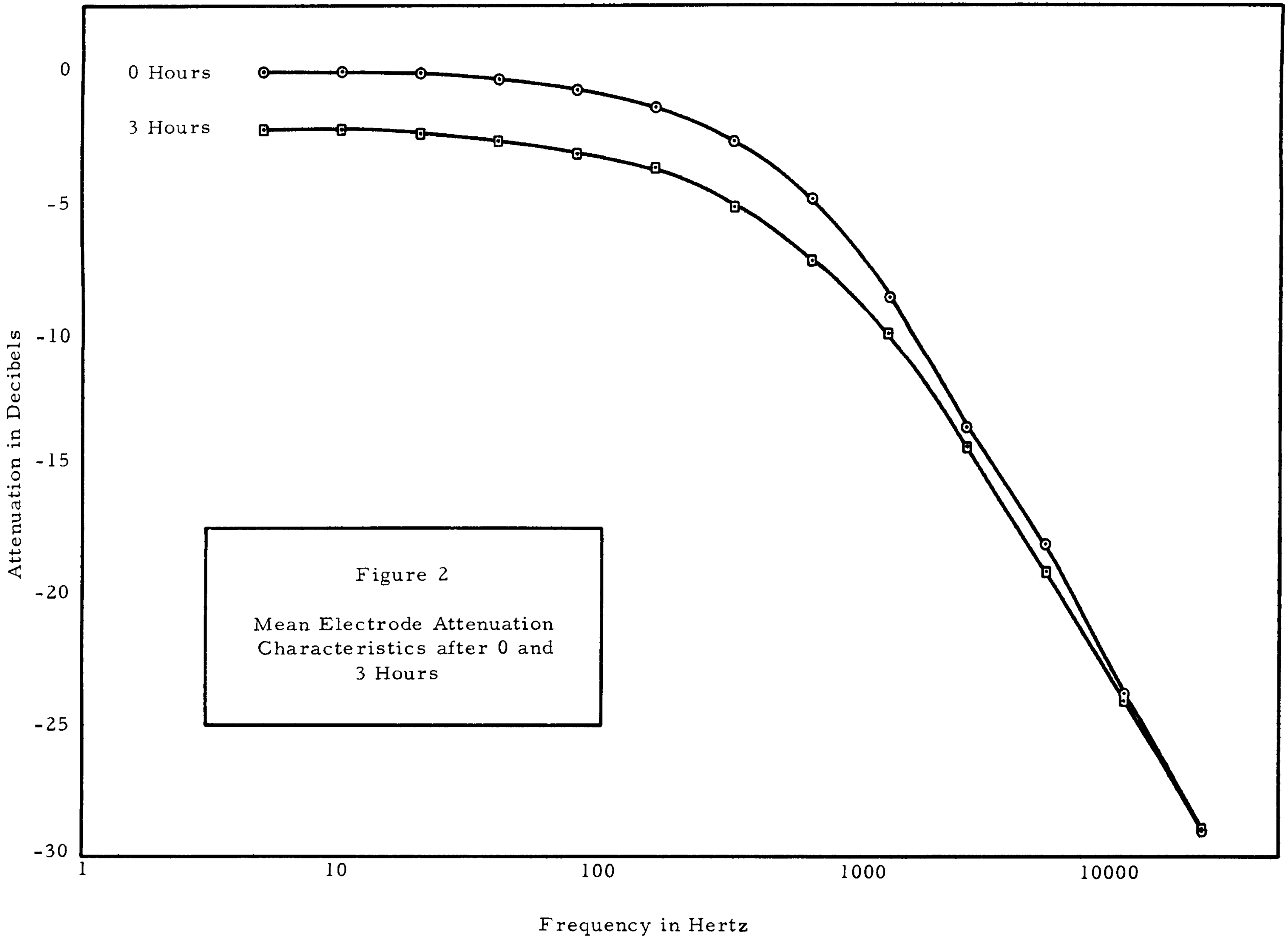

Figure 2

Mean Electrode Attenuation Characteristics after 0 and 3 Hours electrode impedance decreases with time after application of the electrodes.

An examination of Tables I, II, and III shows that individual sets of data differ from the mean values by as much as 5 db. These differences are attributed, in part, to variations in the degree of skin preparation.

At high frequencies, the curves of Figure 2 decrease at a rate of 4.5 to 5 db per octave. Thus, at frequencies above 1000 Hertz, the electrodes may not be accurately represented by a simple, parallel, resistance-capacitance, equivalent circuit which is characterized by a 6-db per octave, high-frequency, attenuation characteristic. In order to simulate the electrode attenuation characteristics over a wide frequency range (d.c. to 20,000 Hertz), the equivalent circuit shown in Figure 3 was selected.

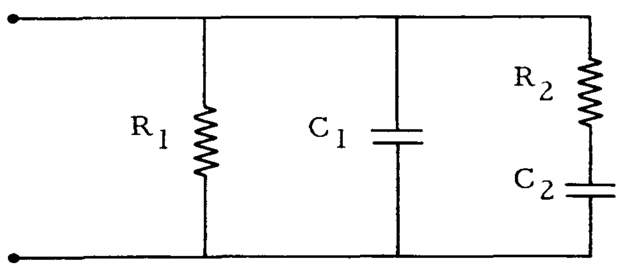

Figure 3. Electrical Equivalent Circuit for Surface Type Electrodes

The Bode diagram for the network of Figure 3 is characterized by three break points. By selecting the frequencies at which these break points occur, the attenuation characteristic of the network may be matched to that of the electrodes. Having specified the break-point frequencies, the values of the circuit elements in the network are easily determined.

The first break point is associated with the frequency at which the electrode-attenuation characteristic is 3 db below its low-frequency value. The two higher frequency break points are selected to produce a slope of 4.5 or 5 db per octave, in the attenuation characteristic, over the frequency range of 2 to 20 kilo-Hertz.

The arithmetic mean values, of data obtained one hour after application of the electrodes, were used to determine the parameters of an equivalent circuit. Approximate values of the circuit parameters were obtained by the method described above. These values were used as starting points in an iterative precedure using an IBM 1620 digital computer. The computer was used to compare the calculated network-attenuation characteristic with that of the electrodes. In the procedure, minimization of the mean-square error was used as a criterion to determine closeness of fit. After approximately 10 iterations, an acceptable set of values for the circuit elements were obtained. These values are as follows:

R_1 = 64,500 ohms $\qquad$ R_2 = 40,000 ohms

C_1 = 0.0075 μf $\qquad$ C_2 = 0.008 μf

In Figure 4, the attenuation characteristic for the equivalent

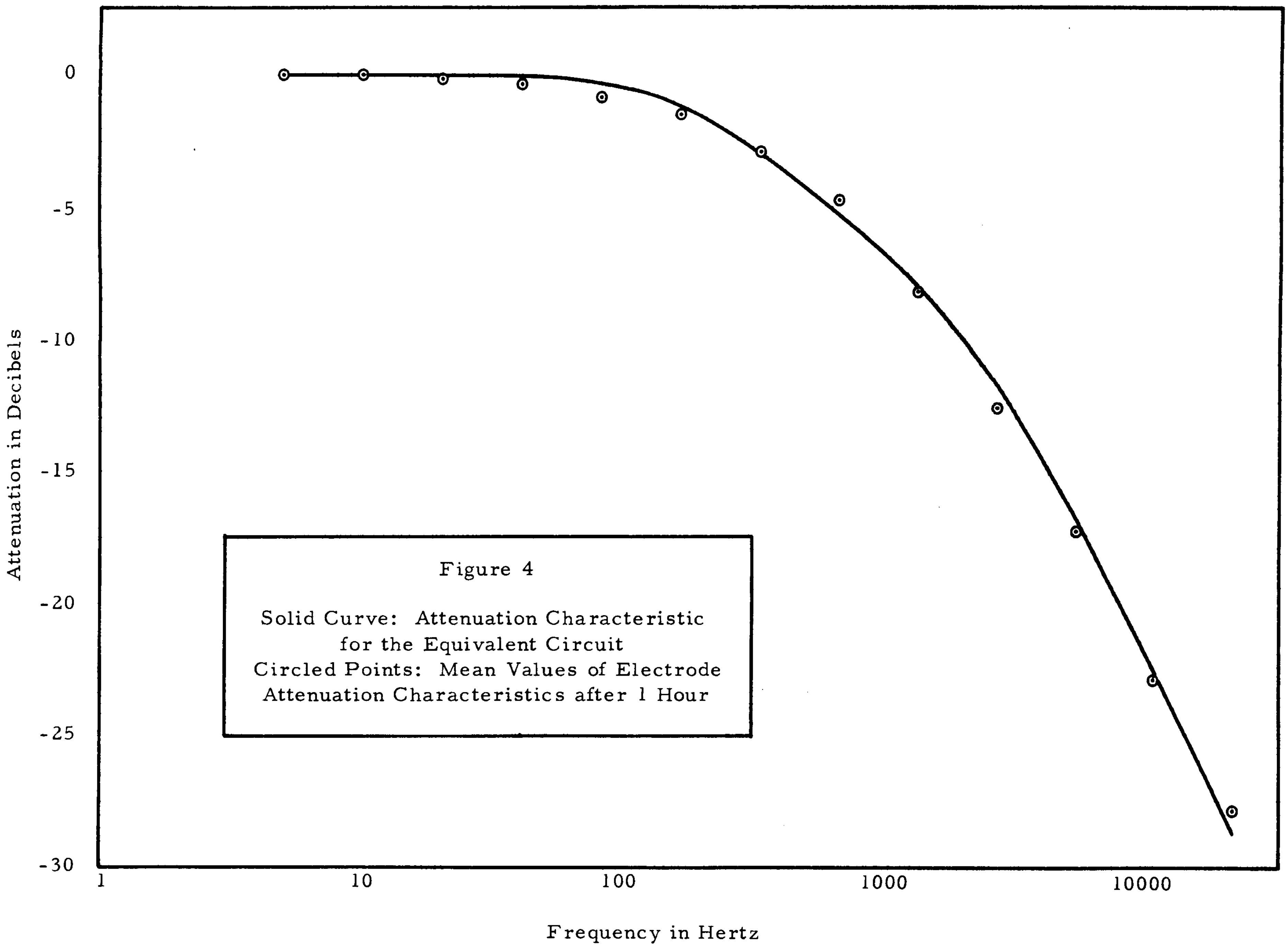

Figure 4

Solid Curve: Attenuation Characteristic for the Equivalent Circuit
Circled Points: Mean Values of Electrode Attenuation Characteristics after 1 Hour

circuit is shown as a curve. The arithmetic mean values, of data obtained one hour after application of the electrodes, are shown as circled points in the figure.

It is believed that an equivalent circuit of the type shown in Figure 3 can be used to represent surface electrodes under a wide variety of conditions. The values of the circuit elements will of course depend upon a number of factors such as the type of surface electrodes and their separation, the degree of skin preparation, the length of time that the electrodes have been attached, and etc.

In a continuing study, it is planned to further investigate the equivalent circuit with the motive of learning how it varies under different environmental and subject conditions and of accounting for the generation of the motion artifact.

BIBLIOGRAPHY

(1) Fatt, P., "An Analysis of the Transverse Electrical Impedance of Striated Muscle", Proc. of Royal Society of London (B), pp. 606-651.

(2) Roman, James, "High Impedance Electrode Techniques", unpublished paper, NASA, January 31, 1966.

(3) Bolie, V. W. and Bishop, L. G., "Theoretical Aspects of Metal Electrode Interfaces", unpublished paper, Autonetics, September 14, 1966.

(4) Guyton, Arthur C., "Functions of the Human Body", W. B. Saunders Co. (a book).

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13. ABSTRACT

The results of an experimental study, to determine and describe properties of the present surface electrodes which are used for monitoring physiological processes of human subjects in the dynamic environment, are presented. The electrical characteristics of electrodes were measured over a frequency range of 5 Hertz to 20,000 Hertz. An equivalent circuit which simulates the electrical characteristics of these electrodes has been obtained.

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