time, he also served as Consultant to the Department of Rehabilitation Medicine, working on problems associated with the effect of electromagnetic fields on living tissue. In 1966, he joined the faculty of the Department of Rehabilitation Medicine. Presently, he is a Professor in the Center for Bioengineering, has a joint appointment as Professor in Rehabilitation Medicine and adjunct Professor in Electrical Engineering. He is involved in teaching and research in the area of biological effects and medical applications of electromagnetic energy.

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Human Body Impedance for Electromagnetic Hazard Analysis in the VLF to MF Band

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***Abstract*—A knowledge of the average electrical impedance of the human body is essential for the analysis of electromagnetic hazards in the VLF to MF band. The purpose of our measurements was to determine the average body impedance of several human subjects as a function of frequency. Measurements were carried out with the subjects standing barefoot on a ground plane and touching various metal electrodes with the hand or index finger. The measured impedance includes the electrode polarization and skin impedances, spread impedance near the electrode, body impedance, stray capacitance between the body surface and ground, and inductance due to the body and grounding strap. These components are separated and simplified equivalent circuits are presented for body impedance of humans exposed to free-space electromagnetic waves as well as in contact with large ungrounded metallic objects therein.**

Manuscript received October 12, 1983; revised March 4, 1984. This work was supported by the USAF School of Aerospace Medicine, Brooks Air Force Base, TX, under Contract F33615-83-R-0613.

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I. INTRODUCTION

THE HAZARD to humans due to exposure to electromagnetic (EM) waves in the VLF to MF band (10 kHz–3 MHz) is of two kinds. The first is the energy absorption as a result of direct exposure to free-space EM fields. The second is the hazard due to current flow when a human makes contact with large ungrounded metallic objects, like cars, trucks, etc., which are exposed to EM fields. This latter effect is on account of an open-circuit RF voltage induced on these insulated objects which may result in high current densities passing through a human subject upon contact. A knowledge of the average electrical impedance of the human body is essential for the evaluation of currents flowing through the body. It is also necessary to know the electrode polarization and skin impedances, and the spreading impedance near the electrode as a function of frequency for the calculation of currents.

0018-9480/84/0800-0763$01.00

The electric hazard due to contact with metallic objects in the frequency range 50 Hz–200 kHz is well understood and there exists sufficient data on threshold currents for perception, let-go, and fibrillation [1].

The hazards to humans due to exposure to EM waves in the RF and microwave regions have been well studied and documented [2]. The American National Standards Institute has recently approved a new RF protection guide for whole-body exposure of human beings in the frequency range 300 kHz–100 GHz [3].

The knowledge of hazards in the VLF to MF band is relatively scanty, one of the reasons being the lack of reliable information on the variation of body impedance with frequency. In this paper, we present some initial data and propose a simplified equivalent circuit for the body impedance and electrode, skin and spreading impedances in the frequency range 10 kHz–10 MHz, based on measurements made on seven human subjects. This simple circuit will be useful in the estimation of hazards to humans exposed either directly to free-space EM fields or in contact with large ungrounded metallic objects therein.

II. Frequency Characteristics of Human Tissue Impedance in the VLF to MF Band

The electrical properties of living tissues show that each tissue has its own dielectric dispersion phenomenon, known as β-dispersion, at frequencies in the VLF to MF band. β dispersion is ascribed to the relaxation of the structural characteristics of the tissue cells. Measurements by various researchers have shown that the β-dispersion frequencies for the various cells in a tissue are distributed over a frequency band. The electrical characteristics of a tissue can therefore be represented by a multi-time-constant circuit as shown in Fig. 1(a). Here, R_e is the resistance measured at a low frequency like 10 kHz and represents the equivalent resistance of extracellular fluid. C_j and R_{ij} $(j=1,2,\cdots)$ are the membrane capacitance and intracellular fluid resistance, respectively, of the various tissues comprising the body. A simplified version of this complicated model is shown in Fig. 1(b). This simple equivalent circuit is considered to be an adequate approximation for the analysis of hazards to humans in the frequency range 10 kHz–10 MHz. Here, C_m and R_m are mainly due to the membrane capacitance and intracellular fluid resistance of muscle tissues, respectively, and represent the β-dispersion in the frequency range 10–500 kHz. C_b and R_b are mainly due to the membrane capacitance and intracellular fluid resistance of red blood cells, respectively, and represent the β-dispersion in the frequency range 500 kHz–10 MHz. C_t represents the capacitance of tissue and is an important factor contributing to the impedance only at frequencies above 10 MHz.

Although the circuit of Fig. 1(b) is valid for individual tissues, it is felt that it can also be applied to the whole body. The parameters R_m and C_m can be obtained from the measured values of parallel body resistance R_p as a function of frequency as follows.

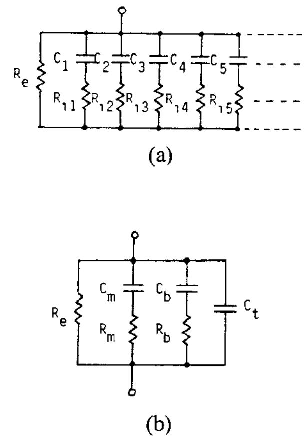


Fig. 1. Equivalent circuits of biological tissues in the frequency range between 10 kHz and 10 MHz. (a) Distributed time-constant circuit. (b) Simplified equivalent circuit.

In the frequency range 10–500 kHz, at 10 kHz, C_m represents an open circuit

$$R_p = R_e \tag{1}$$

which equals the measured parallel resistance at 10 kHz. At 500 kHz, C_m represents a short circuit

$$R_p = \frac{R_e R_m}{R_e + R_m} \tag{2}$$

which equals measured parallel resistance at 500 kHz. Therefore, R_m can be calculated from (2). The equivalent parallel body resistance R_p and capacitance C_p are represented by (3) and (4) in the frequency range 10–500 kHz

$$R_p = \frac{R_e(1+\omega^2 C_m^2 R_m^2)}{1+\omega^2 C_m^2 R_m (R_e + R_m)} \tag{3}$$

$$C_p = \frac{C_m}{1+\omega^2 C_m^2 R_m^2} + C_t. \tag{4}$$

Here, $\omega = 2\pi f$, f is the applied frequency. At the β-dispersion frequency ω_0

$$\omega_0 R_m C_m = 1 \tag{5}$$

$$R_p|_{\omega=\omega_0} = R_0 = \frac{2R_e R_m}{R_e + 2R_m}. \tag{6}$$

The frequency ω_0 corresponding to R_0 can be obtained by interpolation from the measured values of parallel resistance R_p versus frequency. Knowing ω_0, C_m can be obtained from (5). C_b and R_b can be similarly calculated.

Values of the parameters R_m, C_m, R_b, C_b, and R_e calculated from measured data on human subjects are given in Section V. Examples of R_p and C_p as a function of frequency obtained by measurement and those calculated using the simplified equivalent circuit of Fig. 1(b) are also presented.

The stray capacitance between the body and ground and the body inductance should also be taken into account above 10 MHz. Most of the stray capacitance is due to the lower body surface, such as the feet, and is about 55 pF for a standing adult human being. The capacitance and inductance due to the body and the inductance due to the grounding strap cause a series resonance of the equivalent circuit at a frequency of about 70 MHz.

III. Contact Impedance Between an Electrode and the Human Body

When a human touches a large ungrounded metal object (like a car, truck, etc.), the total impedance between the object and ground can be represented by a series combination of circuits equivalent to the electrode, skin and spread impedances, body impedance, and impedance between the feet and ground.

The ac electrode polarization impedance between a metal electrode and tissue is a complicated function of frequency, dependent on the temperature, electrode material, electrode surface treatment, and concentration of electrolytic solution in contact with the electrode [4]–[7]. It can be represented by the theoretical equivalent circuit shown in Fig. 2(a) [4], [7]. C_d is the double-layer capacitance between the electrode and electrolytic solution in the tissue. R_a is the activation polarization resistance. R_w and C_w constitute the diffusion polarization impedance called Warburg impedance, caused by the change of ionic concentration near the electrode due to electrochemical reactions. R_w and C_w are inversely proportional to $\sqrt{f}$, where f is the applied frequency. Z is the reaction impedance and Z_t is the impedance of tissue under the electrode.

The electrode polarization impedance is usually represented by the simplified series circuit shown in Fig. 2(b) [5], [6]. Here

$$R_{se} = K_1 f^m / A \tag{7}$$

$$X_{se} = \frac{1}{\omega C_{se}} = K_2 f^{m'} / A. \tag{8}$$

Here, K_1 and K_2 are constants depending on the electrode material and treatment of the electrode surface, applied voltage, concentration of electrolytic solution, and temperature where

A = contact area,
m, m' = constants,
= -0.5 for diffusion control,
= -1.0 for activation control.

The electrode polarization impedance is usually much less than the tissue impedance at frequencies greater than 10 kHz and hence can be neglected except for small contact areas.

The skin impedance depends on the skin surface condition, thickness of the stratum corneum, applied current density, and frequency. It is usually represented by a series combination of two parallel circuits shown in Fig. 2(c) [8]–[11]. R_C, C_C and R_G, C_G are the resistance and capacitance of the stratum corneum and granular layer, respectively. Typical values of R_C and C_C for normal skin covered with electrode paste are 10 $k\Omega \cdot cm^2$ and 0.01 $\mu F/cm^2$, respectively. Therefore, at frequencies greater than 10 kHz, the resistance of normal skin is much greater than the susceptance and hence can be neglected.

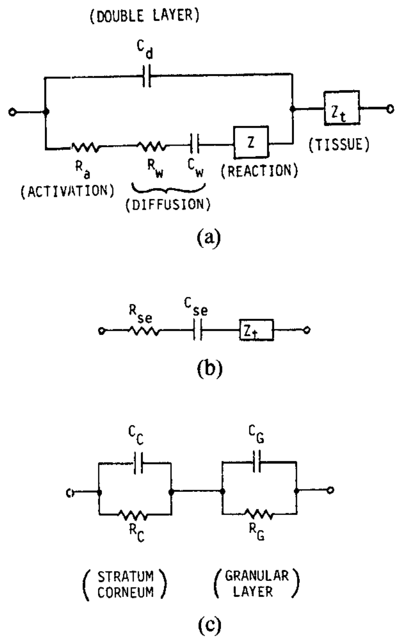


Fig. 2. Equivalent circuits for electrode polarization and skin impedances. (a) Theoretical equivalent circuit for electrode polarization impedance. (b) Series equivalent circuit for electrode polarization impedance. (c) Equivalent circuit of skin.

The applied current spreads near the electrode in the tissue under the skin. The spread impedance for a circular disk electrode of radius a can be calculated from (9)

$$Z_t = \frac{1}{4\sigma^* a} = \frac{\rho^*}{4a} = \frac{\rho^*}{4\sqrt{A/\pi}} \tag{9}$$

where σ^* and ρ^* are the complex conductivity and resistivity of the tissue under the stratum corneum, respectively. At 10 kHz

$$\sigma^* = 3 \times 10^{-3} \text{ S/cm}$$

and

$$Z_t = 80/a \ \Omega.$$

IV. Experimental Procedure

The contact impedances of one female and six male subjects were measured for various electrode contact areas. The ages of the subjects were between 23 and 52 years. The experimental arrangement is illustrated in Fig. 3. Impedances in the frequency range 0.5–500 kHz were measured with a Hewlett-Packard (HP) model 4800A Vector Impedance Meter and in the frequency range 0.5–50 MHz with an HP model 4815A RF Vector Impedance Meter. The electrodes used were a brass rod of 1.5-cm diameter and square copper plates of areas 1.5, 1.0, 0.5, and 0.27 cm^2. The subjects stood barefoot on a ground plane provided by a sheet of aluminum of dimensions 2.5×2.5 m or on a 4.5-cm-thick block of wood above this ground plane. Measurements were made with the subject's hand moistened with 0.9-percent physiological saline solution to en-

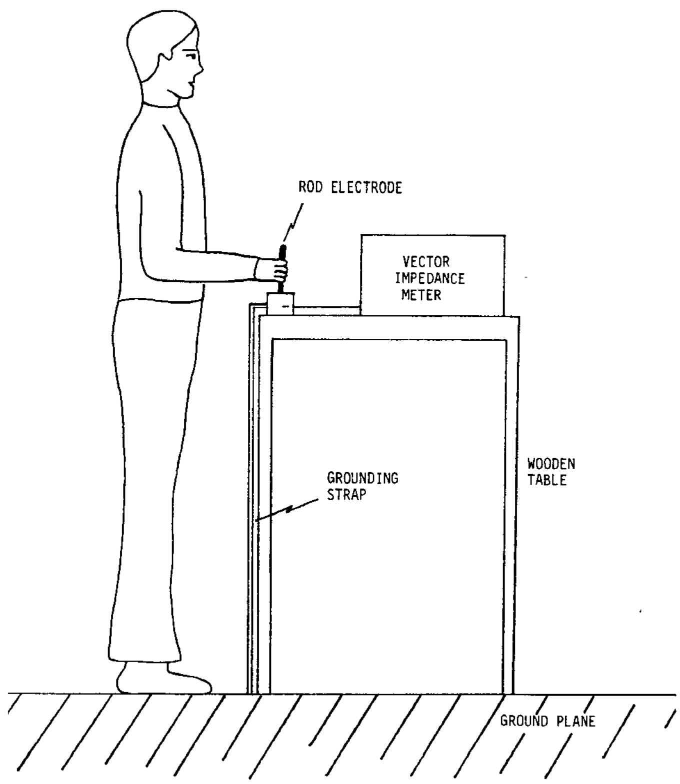


Fig. 3. Experimental arrangement for the measurement of human body impedance.

sure good conductive contact with the electrodes. The height and weight of each subject as well as the dimensions of the finger, arm, torso, and leg were measured.

The human body impedance can be expressed as the sum $Z_f + Z_a + Z_{to} + Z_L/2$, where $Z_f = F_f/\sigma_f$, $Z_a = F_a/\sigma_a$, $Z_{to} = F_{to}/\sigma_{to}$, and $Z_L = F_L/\sigma_L$ are the impedances equivalent to the finger, arm, torso, and leg, respectively. Here, F_f, F_a, F_{to}, and F_L are the shape factors and can be expressed as $l/\sqrt{A_1 A_2}$, where l, A_1, and A_2 are the length, smallest and largest cross-sectional areas, respectively, of the corresponding part of the body. σ_f, σ_a, σ_{to}, and σ_L are the corresponding tissue-averaged complex conductivities.

The electrode polarization impedance between two similar electrodes was measured in 0.9-percent saline solution using the HP 4800A vector impedance meter. The electrodes consisted of wires of stainless steel, copper, and brass of length 20 mm and diameters 0.48, 0.45, and 0.35 mm, respectively.

Skin impedances were measured by having the subjects hold the brass rod electrode in one of their hands and touching a test electrode with the index finger of the same hand. The impedance between the rod and test electrodes was measured using the HP 4800A vector impedance meter. The test electrodes were copper plates of surface areas 3.1, 7.1, 28, 60, 110, and 150 mm^2. The contact area of the rod electrode with the skin is much larger than the surface area of the test electrodes and hence the contact impedance between the rod electrode and skin can be neglected. Measurements were made with dry skin and skin moistened with 0.9-percent saline solution.

TABLE I
MEASURED VALUES OF THE VARIOUS PARAMETERS FOR ELECTRODE POLARIZATION IMPEDANCE $R_{se} - JX_{se}$

	copper	brass	stainless steel
m	-1.15	-1.06	-0.84
m'	-0.81	-0.85	-0.77
* K_1, Ω cm^2	5.6×10^3	7.9×10^3	16×10^3
* K_2, Ω cm^2	3.2×10^4	1.5×10^4	2.2×10^4

From (7) and (8), $R_{se} = K_1 f^m/A$ and $X_{se} = K_2 f^{m'}/A$.
*The values of K_1 and K_2 are given for f in kilohertz.

V. MEASURED RESULTS

The measured values of electrode polarization impedance were used to obtain the values of m, m', K_1, and K_2 in (7) and (8) and are tabulated in Table I. The values of m and m' compare well with published values for noble metals, platinum, and other electrodes [4], [12], [13]. These results show that the electrode polarization impedance is nearly inversely proportional to the frequency.

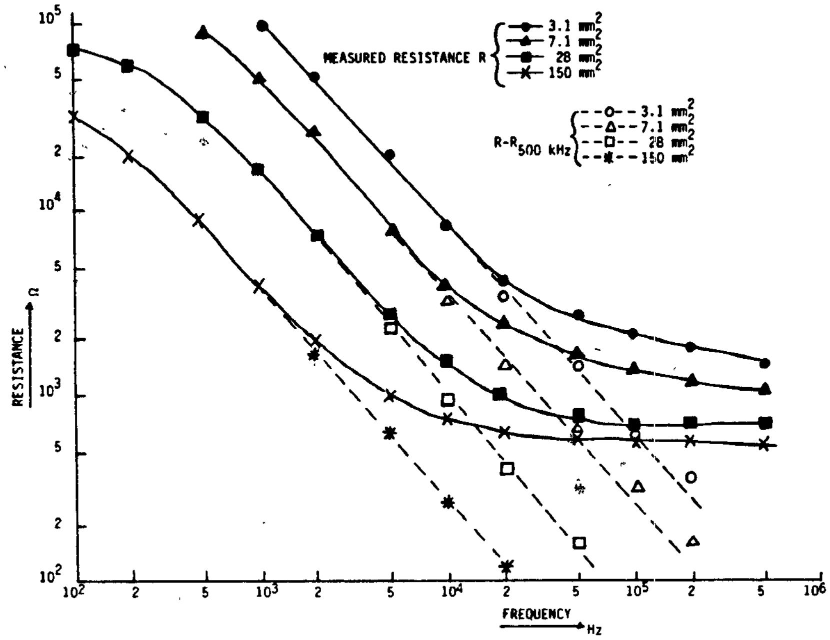
Some of the measured results of skin impedance for dry skin are shown in Fig. 4 (solid lines). The broken lines in Fig. 4(a) represent the difference between the measured resistance values and the value measured at 500 kHz and give the pure contact impedance constituted by the skin and electrode polarization impedances. The contact resistances and reactances are nearly inversely proportional to frequency above 1 kHz.

The relationship between the measured resistance and area of the electrodes is shown by the solid lines in Fig. 5. The broken lines represent the difference between the measured values for each electrode and that measured for the largest electrode. The resistances are inversely proportional to electrode area at low frequencies and to the square root of electrode area at high frequencies. This implies that the electrode polarization and skin impedances predominate at a low frequency, such as 1 kHz, and the spread impedance is predominant at a high frequency, such as 100 kHz. The electrode reactances are almost inversely proportional to the electrode area at all frequencies. It is concluded from these results that the contact impedance which includes skin and electrode polarization impedances can be represented by (7) and (8) with $K_1 = 3 \times 10^6$ Ω·cm^2 Hz and $K_2 = 1.5 \times 10^7$ Ω·cm^2 Hz. The equivalent capacitance is about 0.01 μF/cm^2 as can be seen from Fig. 4.

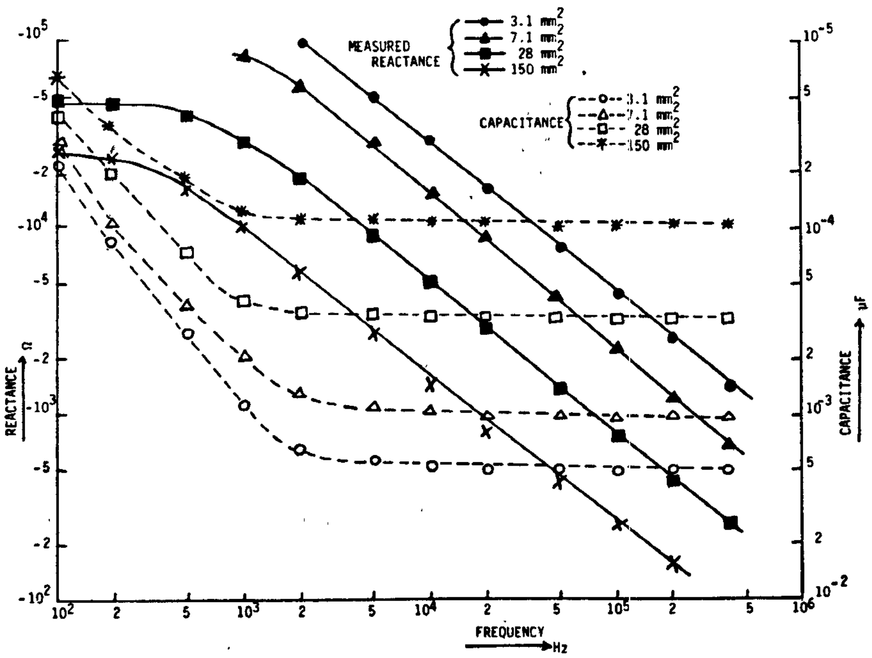
Similar results are obtained in the case of wet skin. The impedance of wet skin is dependent on the surface condition and time after moistening. K_1 for wet skin is much smaller than for dry skin. All other parameters are almost the same.

It is concluded that the contact impedance can be represented by a series combination of a resistance R_s and capacitance C_s at frequencies above 1 kHz, where R_s is inversely proportional to frequency and C_s is a constant.

Typical impedance data for one of the seven subjects as measured using the arrangement shown in Fig. 3 are il-



(a)



(b)

Fig. 4. Measured impedance for dry skin. (a) Resistance. (b) Reactance and capacitance.

lustrated in Fig. 6. Similar data were also obtained for the other six subjects. The solid lines represent the measured series resistances and reactances. The dotted lines represent the contact resistances and reactances which are inversely proportional to frequency. The broken lines are the difference of the solid and dotted lines and represent the body impedance between skin and ground.

The values of the parameters R_e, R_m, C_m, R_b, C_b, and the β-dispersion frequencies f_{om} and f_{ob} in the equivalent circuit of Fig. 1(b) are obtained from (1) to (6) using the measured impedance values and are tabulated in Table II. The values of parallel resistance and capacitance calculated from the equivalent circuit using these parameters agree quite well with the measured results. This is illustrated in Fig. 7, in which the measured parallel resistance and that calculated from the equivalent circuit are compared for four of the seven subjects.

The shape factors F and the heights and weights of the seven subjects are tabulated in Table III. Fig. 8 shows the relation between the measured parallel resistance and the shape factor $F = F_a + F_{to} + F_L/2$ at 10 kHz, 500 kHz, and 10 MHz, for the rod electrode. The measured resistances

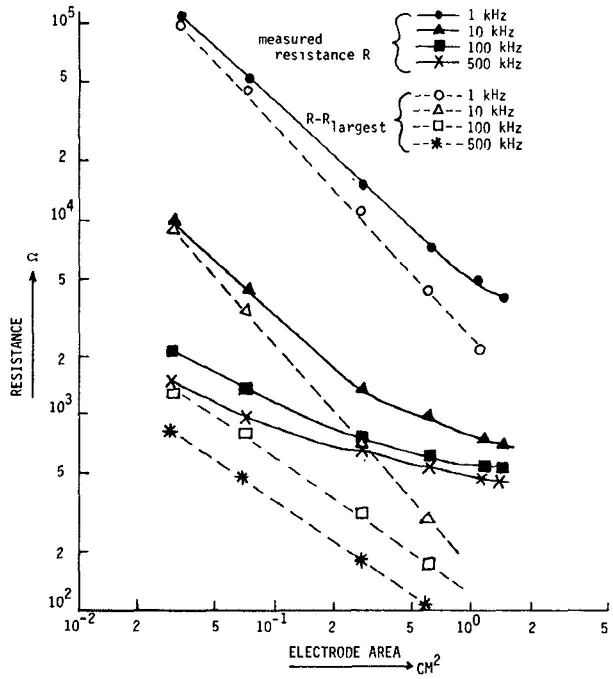
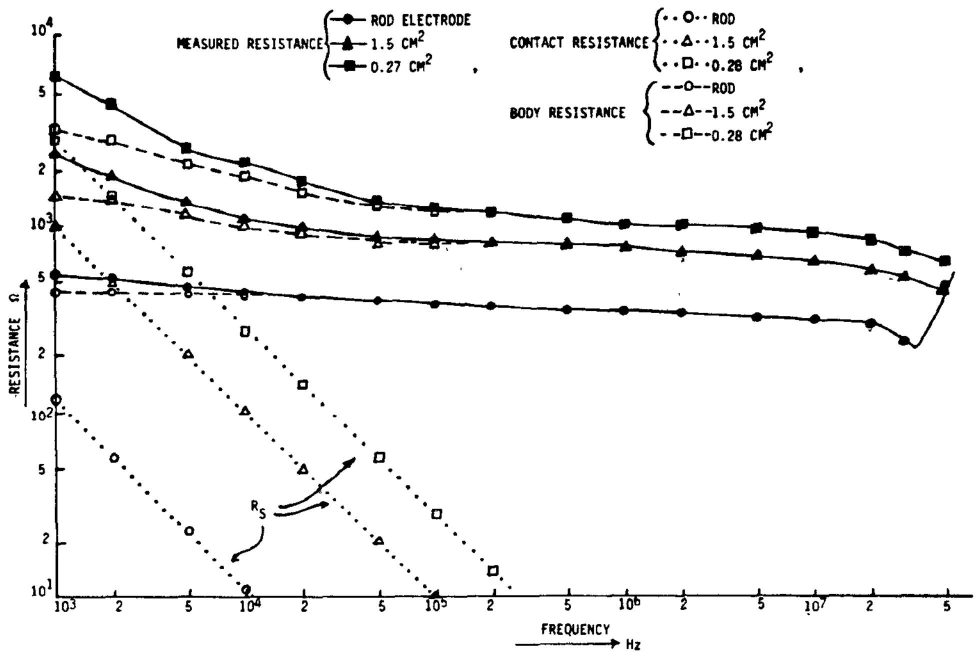
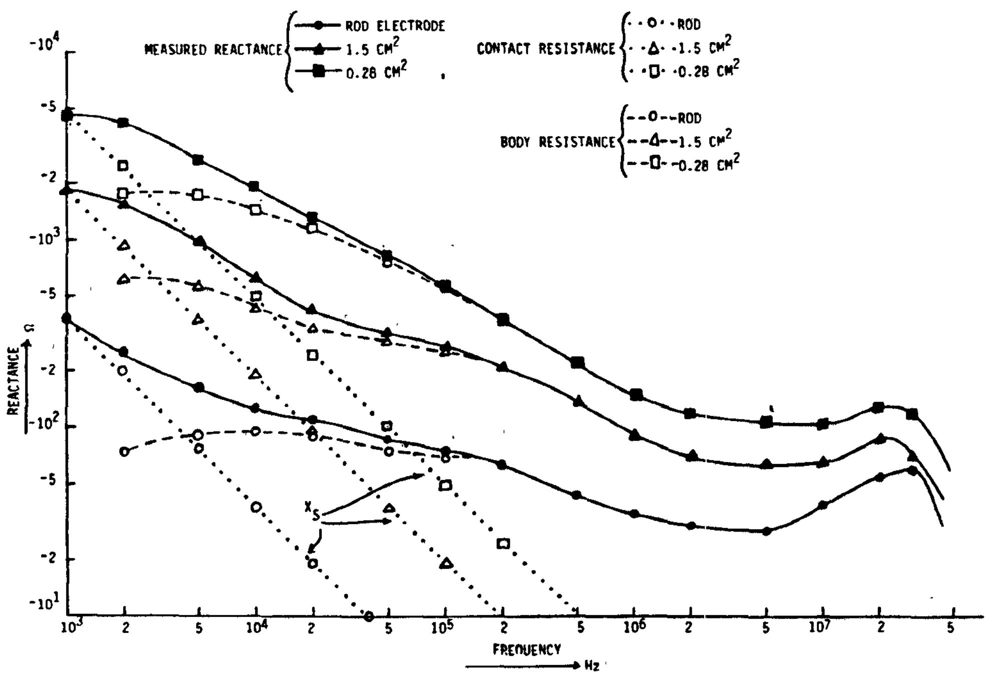


Fig. 5. Contact resistance versus electrode area.



(a)

Fig. 6. Measured impedance, contact impedance, and body impedance for various electrodes. (a) Resistance. (b) Reactance.



(b)

Fig. 6. (*Continued*)

TABLE II
VALUES OF THE VARIOUS COMPONENTS IN THE BODY IMPEDANCE EQUIVALENT CIRCUIT OF FIG. 1(b)

ELECTRODE	PARAMETERS / SUBJECT	R_e Ω	R_m Ω	R_e/R_m	C_m pF	f_{om} kHz	R_b Ω	R_e/R_b	C_b pF	f_{ob} MHz	C_t pF
ROD ELECTRODE	A	690	3,000	0.23	510	90	3,300	0.22	14	3.4	8.6
	B	640	2,200	0.30	950	78	3,100	0.21	15	3.4	7.8
	C	570	1,500	0.37	1,300	78	3,000	0.19	12	4.3	13.6
	D	560	1,600	0.35	1,600	65	1,900	0.30	22	3.8	11.3
	E	460	2,000	0.23	1,500	51	2,500	0.18	24	2.6	8.0
	F	450	1,200	0.37	1,700	77	1,700	0.27	29	3.3	11.7
	G	440	1,100	0.37	2,000	68	3,100	0.14	15	3.5	9.6
	AVERAGE	544	1,800	0.31	1,300	72	2,660	0.22	19	3.5	10.0
PLATE ELECTRODE 1.5 cm²	A	1,750	3,100	0.57	1,000	50	3,900	0.45	13	3.3	3.9
	B	1,500	3,000	0.50	900	57	3,400	0.44	14	3.3	5.4
	C	1,100	2,400	0.46	1,300	51	2,400	0.46	17	4.0	8.9
	D	1,450	3,500	0.41	1,000	44	4,000	0.36	13	3.2	3.8
	E	1,200	2,500	0.48	1,600	39	3,300	0.36	19	2.5	4.2
	F	930	1,700	0.54	1,100	83	2,200	0.43	22	3.3	3.8
	G	1,000	1,500	0.67	1,700	61	2,400	0.42	19	2.5	4.2
	AVERAGE	1,280	2,530	0.52	1,230	55	3,090	0.42	17	3.2	5.1
DIFFERENCE		736	730	1.01	5,000	45	430	1.7	160	1.7	10.0

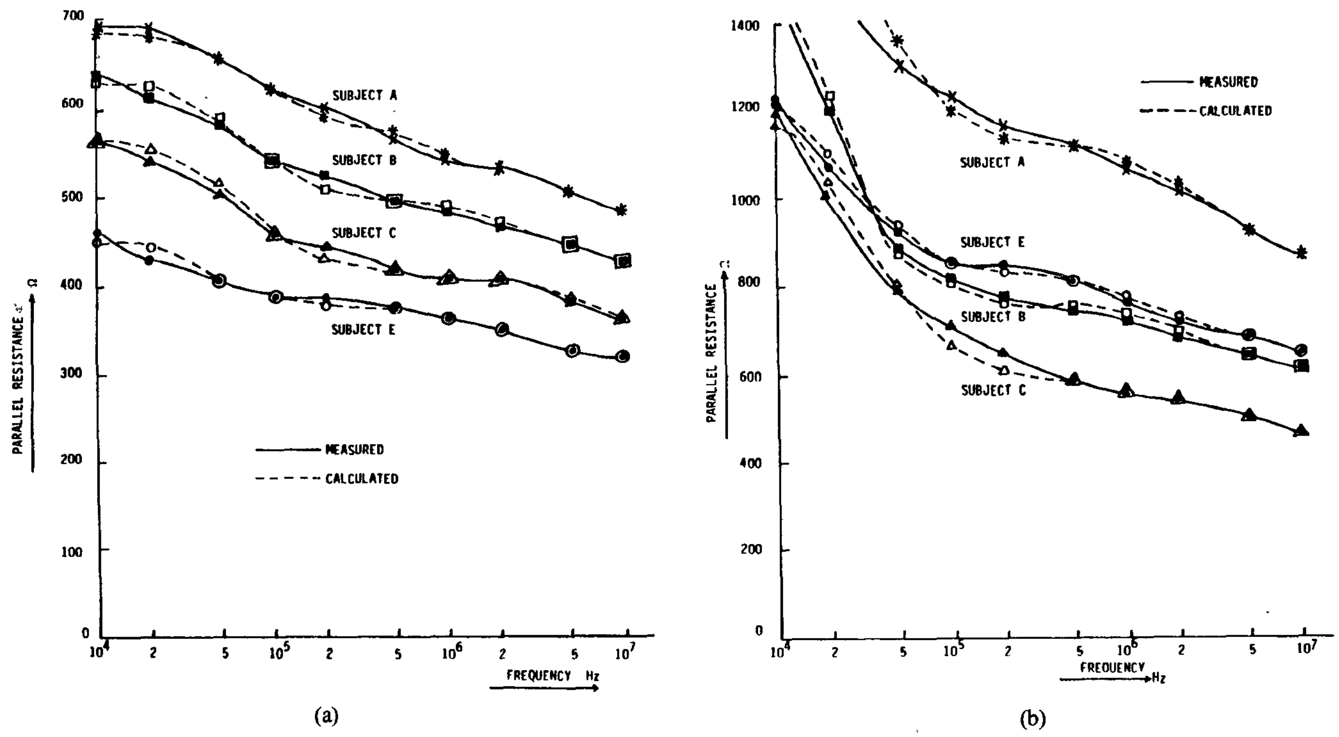


Fig. 7. Parallel resistance of the body impedance for the subjects A, B, C, and E in contact with various electrodes. (a) Rod electrode electrode of area 1.5 cm^2.

TABLE III
Shape Factors

SUBJECT	HEIGHT H cm	WEIGHT $\bar{W}$ kg	$H^2/\bar{W}$ cm^2/kg	SHAPE FACTOR cm^{-1} FINGER F_f	ARM F_a	TORSO F_{to}	LEG F_l	ROD ELECTRODE $F_r = F_a + F_{to} + F_l/2$	PLATE ELECTRODE $F_p = F_f + F_a + F_{to} + F_l/2$
A	170	54	540	3.33	1.61	0.13	0.98	2.23	5.56
B	163	58	455	2.32	1.49	0.11	0.88	2.04	4.36
C	176	80	386	2.27	1.39	0.09	0.72	1.84	4.11
D	182	75	441	2.94	1.45	0.10	0.76	1.93	4.87
E	175	75	408	2.63	1.12	0.10	0.82	1.63	4.26
F	170	76	380	1.96	1.01	0.09	0.66	1.43	3.39
G	168	70	403	2.44	1.07	0.12	0.90	1.64	4.08
AVERAGE	172	70	430	2.56	1.30	0.11	0.82	1.82	4.38

are nearly proportional to F which means that the average resistivities for the seven subjects are almost the same irrespective of the differences in shape. The average resistivities are 300 Ω·cm at 10 kHz, 230 Ω·cm at 500 kHz, and 200 Ω·cm at 10 MHz. Similar relationships were also obtained between the measured resistance at 10 kHz and shape factor for the plate electrodes of areas 1.5 and 0.28 cm^2.

VI. Discussion

When a human subject stands barefoot on the ground and touches a large ungrounded metallic object like a car, truck, etc., the impedance between the object and ground can be represented by the equivalent circuit shown in Fig. 9. Here, the sum of the electrode polarization and skin impedances is usually much smaller than the body impedance in the frequency range 10 kHz–10 MHz. It is also inversely related to the electrode area and can be represented by (7) and (8). The spread impedance R_t is inversely proportional to the square root of the electrode area as shown by (9).

The body impedance can be represented by Fig. 1(b), where the values of the various elements are given in Table II, and is proportional to the shape factor F. It is convenient to divide the body impedance into two parts, the

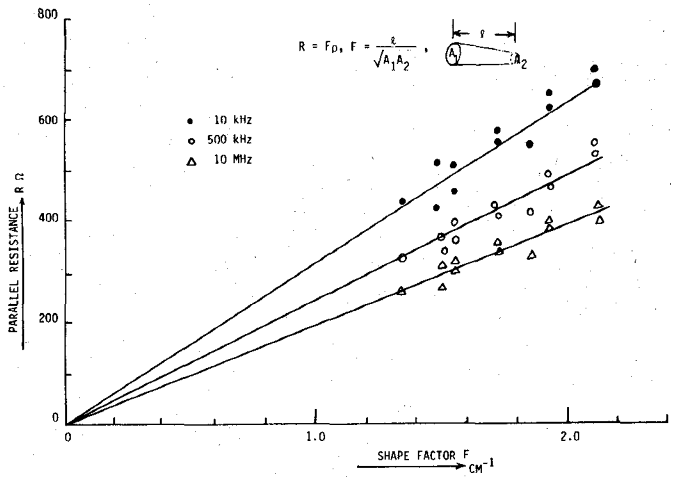


Fig. 8. The relations between the measured parallel resistance for the rod electrode at the frequencies of 10 kHz, 500 kHz, and 10 MHz and the shape factor.

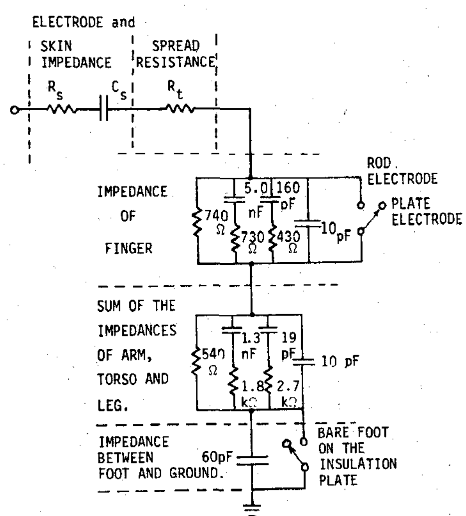


Fig. 9. Simplified equivalent circuit for contact body impedance in the frequency range 10 kHz to 10 MHz (average value for seven subjects). $R_s = 3\times10^6/(fA)$ Ω; $C_s = 0.01\ A$ μF; $R_t = 150/\sqrt{A}$ Ω; where f—frequency in hertz and A—electrode area in square centimeters.

impedance of the finger and the sum of the impedances of the arm, torso, and leg.

The equivalent circuit of Fig. 9 can be used for the estimation of contact body impedance under various conditions. R_s, C_s, and R_t can be calculated from the equations shown in Fig. 9, the contact area being known. The finger impedance must be shorted when the subject holds a rod electrode and the impedance between the feet and ground must be shorted when the subject stands barefoot on the ground.

The simplified circuit for body impedance shown in Fig. 1(b) can be used for the estimation of body current and SAR when a human is exposed to a free-space EM field. Measurements using many more subjects, both male and female, have to be made in order to obtain standard values of body impedance. This is part of an ongoing project in our laboratory.

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Effect of Separation From Ground on Human Whole-Body RF Absorption Rates

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***Abstract*—Whole-body absorption rates of human volunteers exposed in *E*-polarization are reported as a function of the separation between the subject's feet and the ground plane. Little difference is observed between the results for the *EKH* and *EHK* orientations. At frequencies below the grounded resonance (7 to 25 MHz), and air gap of 3 to 6 mm reduces the absorption rate to half the grounded rate. On the other hand, near the grounded resonance (at 40.68 MHz), an air gap of 50 to 80 mm is required for the same effect. Typical footwear provides some radiation protection by reducing the RF absorption rate by approximately 50 percent at below-resonance frequencies, or 20 percent at near-resonance frequencies. Experiments with different dielectric materials between the soles of the feet and the ground plane support the idea that those two surfaces effectively form a parallel-plate capacitor. The experimental results are compared to the predictions of the cylinder and block-model calculations.**

I. INTRODUCTION

CURRENT radiofrequency (RF) radiation safety standards (e.g., ANSI C95.1-1982) are based, to a significant extent, on presumed rates of human whole-body RF absorption. To date, whole-body absorption rates in actual human subjects have only been measured by our group. The experiments were performed using a TEM cell as the exposure system [1]. Initially, the effect of frequency and grounding on the *E*-polarization absorption rates was studied [2]. In that study, only the ideal free-space and grounded conditions were simulated. In the present work, the effect of different spacings from the ground plane on the *E*-polarization absorption rates is reported. The other two possible body orientations with respect to the wave, *K* and *H*, will be ignored since their absorption rates are much smaller than for the *E* orientation [1].

II. METHODS

All measurements were performed using the modified version of the TEM cell [3] in which all the TE resonances are suppressed. Tests showed that the modified cell could only be used reliably at frequencies below 25 MHz or from 40 to 42 MHz. Within the latter range, the ISM frequency of 40.68 MHz was selected as the measurement frequency. Absorbed-power measurements were performed with the RF system previously described and evaluated [1].

All volunteers were adult males in good health. Exposures were limited to one hour per day at a power density not exceeding 13 $\mu W \cdot cm^{-2}$ and no subject ever absorbed more than one W.

Manuscript received October 12, 1983; revised March 13, 1984. This work was issued as DREO Report No.: 899.

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