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Human Whole-Body Radiofrequency Absorption Studies Using a TEM-Cell Exposure System

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***Abstract*—A system has been constructed for measuring radiofrequency absorption in the human body resulting from exposure to high-frequency (HF) electromagnetic radiation. The exposure chamber is a 6.1×7.3×13.0-m rectangular-coaxial transverse-electromagnetic (TEM) cell. The absorbed power, determined from signal-averaged measurements of incident, reflected, and transmitted power, is measured to a precision of 0.06 percent of incident power (0.003 dB in insertion loss). A detailed analysis of systematic errors in the method has shown that a directional-coupler directivity approaching 50 dB is necessary for high accuracy in absorbed-power measurements and that any dielectric-loading effect of the subject on the cell absorption is undetectable. The total systematic error in determining absorption rate per unit exposure rate is about ±35 percent of the measurement. Operating frequencies are currently limited to the 3 to 20-MHz range due to the occurrence of the first cell resonance, associated with the TE_{01} mode, at 20.7 MHz. The first set of human whole-body absorption results is presented for three subjects exposed in free space to 11 μW/cm² at 18.5 MHz in six different body orientations with respect to the TEM wave. The measured absorption rates for the two principal *E* orientations are larger than the published predictions by a factor of 2 to 3.**

Manuscript received March 23, 1982; revised June 30, 1982. This work is also issued as DREO Report 865.

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I. INTRODUCTION

WHILE permissible human exposure levels for radiofrequency radiation (RFR) (10 kHz–300 GHz) are currently under active discussion, much information is lacking. For example, the absorption of RFR by humans has been studied only indirectly by calculating or measuring the heating patterns for various models. The calculations—too numerous to be individually referenced—have recently been reviewed by Durney [1]. Measurements of absorption in full-sized models have been performed by Olsen [2] at 1.3 GHz and by Allen *et al.* [3] from 10 to 50 MHz (a prolate spheroid in one orientation only). Guy *et al.* [4], [5] and Gandhi *et al.*, (e.g., [6]) have determined heating patterns in scale-model prolate spheroids and human figurines thermographically. Iskander *et al.* [7] have determined whole-body heating rates in scale-model prolate spheroids thermometrically. Human volunteers have only been used to date to a limited extent as transmitting [8] and receiving [9] radiofrequency monopole antennas, and in studies of microwave reflection-diffraction patterns (e.g., [10]). There are no reports of human whole-body absorption measurements from 10 kHz to 300 GHz.

One particular frequency range of concern is the HF band, 3–30 MHz, where people are often occupationally exposed to relatively high electric and magnetic field strengths near industrial heating sources [11]–[13] and from high-power shortwave communications systems [14].

This paper describes a system constructed for the measurement of whole-body absorption in human volunteers at frequencies from 3 to 20 MHz, carefully evaluates the systematic errors of the method, and gives the first set of human whole-body absorption results.

The method used, reported briefly in [15], [16], follows closely the technique of Allen *et al.* [3] for determining radiofrequency absorption in rhesus monkeys and ellipsoidal models of monkeys from 10 to 50 MHz. Free-space, grounded, and near-field exposures in all body orientations with respect to the propagating TEM mode can be simulated with this system.

Human volunteers were exposed to 11 μW/cm^2 for up to one hour per day, and never absorbed more than 1 W. The experimental protocol was approved by the Human Experimentation Committees of both organizations involved (DREO and NRC).

The body orientations of the subjects with respect to the TEM wave will be denoted by the usual ellipsoid-equivalent notation [17, table I]: the "***ABC***" orientation is where the field vector $\boldsymbol{A}$ ($\boldsymbol{A} = \boldsymbol{E}$ or $\boldsymbol{K}$ or $\boldsymbol{H}$) is aligned with the body length, $\boldsymbol{B}$ with the side-to-side direction, and $\boldsymbol{C}$ with the front-to-back direction. In this system, six principal body orientations are possible: ***EKH***, ***EHK***, ***KEH***, ***KHE***, ***HEK***, and ***HKE***. The ***EKH*** and ***EHK*** orientations will often be referred to together as the $\boldsymbol{E}$ orientations, and similarly for the $\boldsymbol{K}$ and $\boldsymbol{H}$ orientations.

II. The Exposure Chamber

The exposure chamber used (a modification of the original design [18]) is shown in Fig. 1. It consists of a large (6.1×7.3×13.0-m) low-loss "rectangular-coaxial" TEM-mode transmission line sharply tapered at each end to form a cell. This "TEM-cell" type of exposure chamber was chosen because the TEM-mode pattern simulates the desired plane-wave exposure pattern, and because the closed sides of the transmission line ensure that none of the radiation entering the cell is lost in spurious absorption due to fringing fields.

The cell dimensions in the vertical plane transverse to the long axis were chosen based on four design criteria: a) A spacing of twice a body length (3.66 m) between the vertical septum (center conductor) and cell wall was chosen to minimize possible dielectric-loading and field-enhancement effects when the subject is in an $\boldsymbol{E}$ orientation (i.e., body length perpendicular to the septum); b) A septum vertical dimension of about twice a body length is desirable to provide a fairly uniform field pattern when the subject is in an $\boldsymbol{H}$ orientation (i.e., body length vertical); c) The two outside dimensions of the cell should be as small as possible, and approximately equal, to keep the cutoff frequencies for each of the first two higher order modes (TE_{01} and TE_{10}) as high as possible; d) A cell characteristic impedance (Z_o) as high as practicable should be used to give maximum absorption detectability (ratio of E^2 to incident power) consistent with reasonable field uniformity.

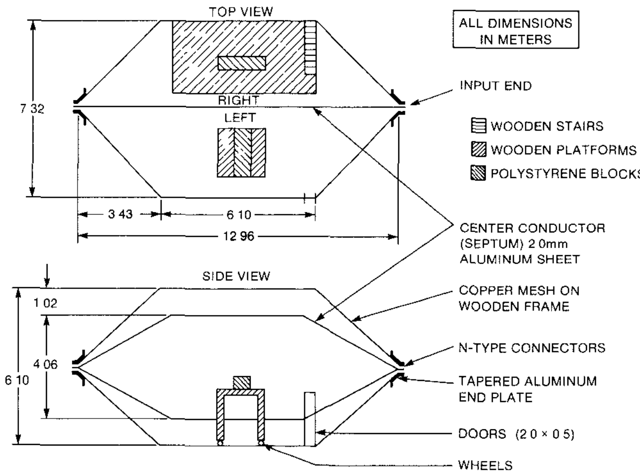

Fig. 1. Detailed drawing of the TEM-cell exposure chamber.

Z_o can be calculated from the cell dimensions using several different techniques which Weil [19] has shown to give excellent agreement. Using the calculation of Cruzan and Garver [20], found most convenient for our case, a value of 70.9±0.5 Ω was determined for Z_o. Using a time-domain reflectometer (Tektronix model 7S12), the characteristic impedance of the cell was found to be within 2 Ω of 70 Ω along its entire length, including the tapered regions.

The 70-Ω cell is used with a 73-Ω load consisting of a series combination of a 50-Ω directional coupler (for transmitted power) and a 75-Ω termination. The small mismatch between load and cell produced a slight standing-wave pattern inside the cell with a VWSR < 1.10.

At the input end, the 70-Ω cell is deliberately not matched to the 50-Ω power-feed transmission line. This causes the transmitted wave in the cell to be 17 percent higher in voltage than the wave incident on the cell, producing a 36 percent higher squared $\boldsymbol{E}$-field in the cell for a given incident power (design criteria d)). The mismatch is shown in Section VIII to not reduce measurement accuracy.

The septum is held firmly in place by braided nylon ropes spaced 0.6 m apart. The two small 2.0×0.5-m doors make contact with copper sheet door stops via spring-metal finger strips. The subject is exposed on top of either of the two wooden platforms; standing for the ***H*** orientations and lying down on a block of RF-transparent polystyrene foam for the ***E*** and ***K*** orientations. Both platforms are of dry wood construction and neither the wood nor the metal nails had appreciable RF absorption, nor did they alter field patterns significantly (more than 5 percent) except within 10 to 20 cm of the platform. The larger platform on the right is used for most measurements as it allows the subject to easily assume many different positions in the field pattern.

III. Field-Strength Measurements

The electric field-strength is measured using probes constructed following Greene's NBS design [21] and built in our shops. The RF field is measured with either of two brass dipole antennas (10 or 20 cm in length). The rectified RF voltage is filtered and then transmitted to an electrometer (Keithley model 610C) outside the cell by a high-resistance (60-kΩ/m carbon-impregnated teflon [22]) two-conductor transmission line. The dipole probes were calibrated in our TEM cell and intercompared with two other laboratories (Instruments for Industry and USAF-SAM [23]). The total error in the absolute electric field-strength measurements is estimated to be ± 8 percent, while the relative error in comparing any two readings at the same frequency is ± 1 percent.

Magnetic field strengths are measured using a 10-cm-diameter brass circular loop antenna also designed by Greene [21], and calibrated using a standard procedure [22]. The ***E***-field pickup of the small loop antenna was shown to be less than ± 2 percent. The total error in absolute magnetic field-strength readings is estimated at ± 10 percent, while the relative error in comparing any two readings at the same frequency is ± 3 percent.

IV. Exposure-Field Patterns

The fundamental propagating mode, transmitted at all frequencies, is a TEM mode which approximates a free-space plane wave. The TEM-mode field pattern in the transverse plane has been calculated by solving the corresponding electrostatic problem using an over-relaxation calculation like Metcalf's [24]. Silvester [25] has discussed the method in detail and given useful plotting suggestions. The results are shown in Fig. 2.

In addition to the TEM mode, there are two undesirable types of field pattern which may exist in the cell. The first kind are the higher order TE_{mn} and TM_{mn} modes which may propagate above their individual cutoff frequencies. The second undesirable type consists of standing-wave field patterns which only occur over a narrow frequency range surrounding a resonant frequency. Each resonance is associated with one of the higher order modes [26].

The first resonance, related to the TE_{01} mode, was found at 20.70 MHz by vertical and transverse ***E***-field measurements in the cell. The presence of one person in the cell lowers the first resonant frequency by up to 0.1 MHz. The operating frequencies used for the first absorption studies range from 3.5 MHz, where the absorption for a grounded

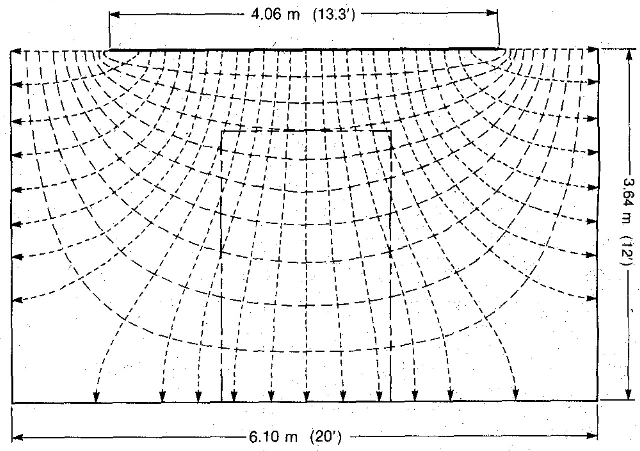

Fig. 2. The results of an electrostatic calculation of the field pattern of our TEM cell in a transverse plane. Only half the cell is shown. Legend: —— inner and outer conductors; ----- electric field lines; — — — electrostatic equipotential lines (pattern similar to the RF ***H***-field lines); —·-·— outlines the cell volume occupied by subjects in the free-space and grounded conditions.

TABLE I
THE MEASURED EXPOSURE-FIELD PATTERN AT 18.5 MHz IN THE ABSENCE OF THE SUBJECT. ELECTRIC FIELD TRANSVERSE FROM SEPTUM TO WALL. MAGNETIC FIELD VERTICAL. INCIDENT POWER IS 9.52 W.

Position	Electric field E_t		Magnetic Field H_v	Power density $P_d = E_t \cdot H_v$	Wave impedance $Z_w = E_t/H_v$
Center of subject		6.52 V/m (± 8%)	16.9 mA/m (± 10%)	11.0 µW/cm² (± 18%)	386 Ω (± 18%)
Offset from the above by 0.91 m (3') towards the:	Calc.* (± 2)	(± 1)	Deviation from the above (%) (± 3)	(± 4)	(± 4)
Septum	29	31	27	67	3
Wall	-20	-21	-21	-38	- 1
Generator	0	- 1	1	0	- 2
Load	0	- 1	4	3	- 5
Ceiling	- 5	- 9	- 6	-14	- 3
Floor	- 5	- 2	- 4	- 6	3

*From the relaxation calculation (see Text).

subject in the ***E*** orientation is barely detectable, to 18.5 MHz, which is chosen to be well below the first resonant frequency.

Table I gives the measured field pattern used for human subjects at 18.50 MHz. The calculated TEM-mode pattern is seen to be in excellent agreement with the measured variations of the transverse electric field, except in the vertical direction, where the perturbing effect of the large wooden platform is present. The vertical asymmetry is not present on the other side of the septum. The effective exposure field for a subject in the ***E*** orientation is calculated as the average of the "center", "septum", and "wall" figures, giving a double weight to the center figure to correctly account for the distribution of the fields over the length of the body. Similarly, the appropriate weighted averages are calculated for the effective exposure fields in the ***K*** and ***H*** orientations. Field patterns for the other operating frequencies below the first resonance are very similar to that given in Table I.

The most significant difference between our exposure-field pattern and that of an ideal plane wave in free space is the nonuniformity of the fields in the direction of septum-to-wall. The field gradient results from the design constraints explained above. If the width of the septum were increased to 5.16 m to create a more uniform field pattern (and a 50-Ω cell), the relaxation calculation shows that the theoretical difference between the fields at the head and the foot would still be 41 percent in comparison to the 49 percent (29–(−20) percent) shown in Table I. Thus the design criterion c) in Section II, for an outer conductor with an approximately square cross-section, is incompatible with good field uniformity, regardless of the septum dimensions or cell characteristic impedance. While the field gradients make comparison between measurements and calculations assuming uniform fields less precise, they have the advantage of being more realistic as a model of human occupational exposure fields.

To make the copper-mesh cell wall into a more nearly ideal ground plane, a 1.2×4.5-m copper sheet has been soldered to the length of the wall. Grounded exposures in the $\boldsymbol{E}$ orientation are then simulated by placing the subject's feet in contact with the clean copper sheet.

V. The Power Absorption Measurement System

A. Introduction

The power absorbed by the empty TEM cell, A_c, is given by

$$A_c = (\text{net incident power}) - (\text{net transmitted power}) = (I - R) - (T - R') \quad (1)$$

where I and R are the incident and reflected power at the cell input, T is the power transmitted from the cell towards the load, and R' is the power reflected from the load back towards the cell. Since R' is proportional to T regardless of the presence or absence of the subject in the cell, R' is not measured separately. Thus

$$A_c = I - R - \alpha T \quad (2)$$

where α is a known constant for the load used.

When the subject enters the cell, I and R change because of the change in cell input impedance and T decreases, primarily due to the subject's absorption. The absorption of the cell with the subject inside, A_{c+s}, is also determined using (2). Finally, the subject's absorption, A_s is obtained by the subtraction

$$A_s = A_{c+s} - A_c \quad (3)$$

based on the assumption (proven below) that the cell's own absorption does not change when the subject enters.

For the typical case of a man exposed at 18.50 MHz in an $\boldsymbol{E}$ orientation in free space, the quantities take the values: $\alpha = 0.964$, $I = 9.540$ W, $R = 0.360$ W, $\alpha T = 8.960$ W, $A_c = 220$ mW, $A_{c+s} = 240$ mW, and $A_s = 20$ mW. Since A_s is one order of magnitude smaller than A_c and nearly three orders of magnitude smaller than I and T, the need for an exceptionally accurate, stable, and low-noise power-measurement system is apparent.

B. Description

The power-measurement system is shown in Fig. 3. It operates from 3 to 50 MHz with up to 100 W of power incident on the TEM cell. For normal operations using human volunteers an incident power of 9.5 W is used, producing an exposure power density of 11 μW/cm^2.

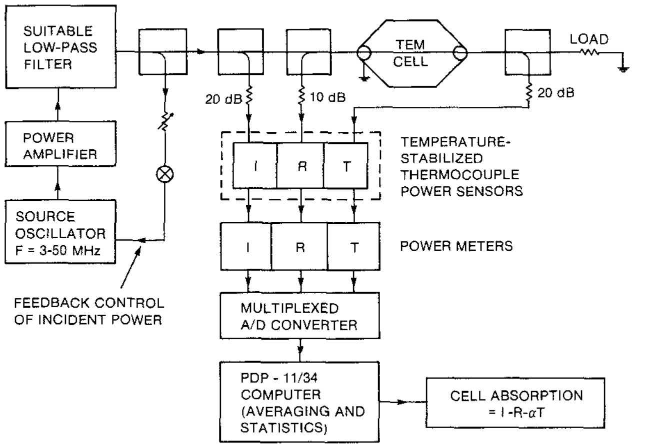

Fig. 3. The transmission-line measurement system for determining TEM-cell absorption from 3 to 50 MHz.

To eliminate problems in both power and field measurements caused by harmonics, a set of 200-W low-pass filters (K & L Microwave tubular type 5L) is used to reduce all harmonics to at least 50 dB below the fundamental.

A feedback loop is used to stabilize incident power. The three directional couplers used to measure I, R, and T (Wide-Band Engineering model A73-20PX) have 20 dB of coupling and 50 dB of directivity, shown below to be essential for accurate measurements.

The three thermocouple power sensors (Hewlett-Packard model 8482A) are mounted together in a (30.0±0.5)°C temperature-controlled box to reduce the change in sensitivity as room temperature varies (by as much as 5 C° in one day).

The analog recorder outputs from the three power meters are digitized by a multiplexed A/D converter (Digital Equipment model AD 11-K) and fed into a PDP 11-34 computer for analysis. A Fortran IV program measures and averages I, R, and T for one minute and calculates a mean value for A_c. Because of a slight amount of unavoidable drift in power meter readings, A_s was determined by measuring A_{c+s} for three minutes, preceeded and followed by a three-minute "baseline" measurement of A_c. A typical standard deviation for these three-minute measurements of A_s is about 6 mW or 0.06 percent of the incident power. Expressed as a change in insertion loss, this resolution is ±0.003 dB which is better than any commercial network analyser available for the 3 to 50 MHz range.

VI. Evaluation of Systematic Errors

Systematic errors in the method were carefully assessed because i) A_s is very small and is determined indirectly as a difference of differences, ii) preliminary human absorption results for the $\boldsymbol{E}$ orientations in free space were two to three times most predictions, and iii) such an analysis is not available in the open literature.

A. Absorbed-Power Errors

The determination of A_s is limited by five possible sources of systematic error (labeled i) to v) below). Errors i) and ii) are easily assessed; errors iii) and iv) have been analysed in detail by Crawford *et al.*, but only in an internal report [27]; and error v) is assessed for the first time using a new method.

i) The possible error in absolute RF power measurements is $< \pm 2$ percent of the readings, based on the equipment specifications and a calibration done for us by the Canadian standards laboratory.

ii) A second possible source of error in power measurements arises from the possibility of a nonlinear relationship between the three power-meter readings, due mainly to different zero or full-scale settings. Tests showed that significant errors could occur. However, when the zero and full scale (1.00-mW calibration signal) readings on each of the three power meters were digitized on each day of operation, the residual nonlinearity error was found to be less than ± 5 percent.

iii) The coupling constants of the three directional couplers used to measure I, R, and T have each been determined, relative to the others, to within ± 0.05 dB ($\pm$ 1 percent), but the question still arises as to whether or not this is precise enough. A linear error analysis of (2) and (3) leads one to the conclusion that an error of ± 1 percent in the transmitted coupling coefficient (relative to the incident) will cause a large error in the determination of A_c, but only a ± 1 percent error in the determination of A_s. For example, for a 183-cm long saline-filled tube ($\sigma = 0.95$ S/m, ID = 2.54 cm) and an incident power of 9.55 W at 18.50 MHz, it was found that $A_c = 236.3 \pm 0.9$ (SE, $N = 6$) mW and $A_s = 26.9 \pm 2.4$ mW. When the transmitted coupling coefficient was increased by 1.0 percent the results were $A_c = 142.5 \pm 1.3$ mW and $A_s = 26.8 \pm 2.8$ mW. The results illustrate the paradoxical conclusion that it is easier to determine accurately the power absorbed by the test object than that absorbed by the empty cell, even though the latter absorption is much larger. It is concluded that errors due to the coupling coefficients cannot contribute more than ± 3 percent to the total error in A_s.

iv) Crawford *et al.* [27] identified other coupler errors in the measurement of TEM-cell insertion loss. They concluded [27, p. 49] that the largest error in measuring A_s is due to the finite directivity of the incident and reflected directional couplers and to the main-line mismatch of the reflected coupler. The result of their calculation (their eq. (30) in my notation) is

$$\left|\begin{array}{l}\text{Relative}\\ \text{error in}\\ A_s\end{array}\right| \leqslant \frac{2I}{A_s}\left(|D_I| + |D_R| + |S_{22}|\right)\left|\Gamma_{c+s} - \Gamma_c\right| \qquad (4)$$

where I is the incident power, A_s the power absorbed by the subject, Γ_c the complex reflection coefficient of the empty cell input port, and Γ_{c+s} the same quantity with the subject present in the cell. The directional-coupler factors enter through the complex directivity parameters for the incident (D_I) and reflected (D_R) couplers and the S_{22} parameter for the reflected coupler. With a directivity of 50 dB, $|D_I| = |D_R| = 10^{-5/2} = 0.003$. Also, $|S_{22}| = 0.004$ since the main-line VSWR of the reflected coupler is 1.008. The analysis was applied to the absorption of subject F at 18.50 MHz. Γ_c and Γ_{c+s} were determined with an RF vector impedance meter (Hewlett-Packard model 4815A). The error limit in A_s, from (4), and the data of Table II, was found to be ± 8 percent (***EKH***) or ± 14 percent (***EHK***) in free space (and $< \pm 2$ percent grounded). If a directional coupler directivity of only 30 dB were used, the free-space error limits would have been ± 50 percent (***EKH***) or ± 89 percent (***EHK***)—unacceptably large.

TABLE II
DIELECTRIC LOADING TEST: COMPARISON OF SCATTERING AND ABSORPTION OF 18.5-MHZ RADIATION BY A METAL-COVERED MANIKIN AND HUMAN SUBJECT F.

Subject	Orientation	Scattering $\Delta\Gamma = \Gamma_{c+s} - \Gamma_c^{\dagger}$	Absorption rate* (mW) mean ± SE (N)
Manikin	EKH	(0 005, - 0.006)	0.8 ± 2 6 (10)
Human		(0.004, - 0 008)	21 5 ± 3 0 (8)
Manikin	EHK	(0.004, - 0.007)	-0.3 ± 2 7 (10)
Human		(0 004, - 0.007)	11.1 ± 5 3 (8)

$^{\dagger}\Gamma_c$ = complex reflection coefficient of TEM-cell input port = (0 198, 0 031)

*Incident power = 9.55 W

Data for the same subject in the ***K*** and ***H*** orientations at 18.5 MHz shows that both A_s and $|\Gamma_{c+s} - \Gamma_c|$ are barely detectable, being 1–2 mW and < 0.0005, respectively. From (4) the error for these orientations is no more than ± 10 percent.

v) Finally, the presence of the subject in the cell may alter the "empty-cell" absorption through altering the electric current patterns in the cell wall and wooden platform. In using (3) to determine A_s we are assuming that this dielectric-loading effect of the subject on the cell absorption is negligible.

This was tested experimentally by measuring the absorption of a full-sized commercial manikin covered with a layer of thick aluminum foil. The covered manikin is presumed to be nonabsorbing. Test results are given in Table II, where it is seen that the manikin's scattering of radiation, characterized by the change in Γ_c, is very similar to the human's. The manikin is seen to be causing no detectable change in cell absorption within the standard error of ± 2.7 mW. This puts an upper limit of ± 12 percent on the dielectric loading error of a human subject in the ***EKH*** orientation of 18.5 MHz.

B. Estimated Total Uncertainty

The estimated systematic errors are listed in Table III to compare their relative magnitudes and estimate the total uncertainty. The best estimate for the total is ± 35 percent. Since most of the systematic errors are constant, although unknown, the uncertainty in comparing any two measurements for the same orientation is closer to ± 10 percent. The only frequency-dependent systematic errors are iv) and v), which are both larger at lower frequencies due to the smaller value of A_s.

As a further test of the above error analysis, a direct comparison was made between the measured and calculated absorption rates for a set of thin saline-filled tubes, as shown in Table IV. By using five different combinations of tube diameter and saline conductivity a range of more than a factor of 10 was created in the specific absorption rates. The tubes were modeled as thin prolate spheroids by

TABLE III
SUMMARY OF ESTIMATED SYSTEMATIC ERRORS IN DOSIMETRY MEASUREMENTS FOR FREE-SPACE EXPOSURES (***EKH*** ORIENTATION) AT 18.5 MHz IN THE TEM CELL.

Source of error	Estimated value (%)
I. Absorbed power, A_s	
(i) absolute power	± 2
(ii) system linearity	± 5
(iii) coupler calibration	± 3
(iv) coupler directivity and mismatch error	± 8
(v) dielectric loading	± 12
II. Exposure fields	
electric (E_t)	± 8
magnetic (H_v)	± 10
III Total uncertainty in $A_s/(E_t H_v)$	
probable value (root-sum-of-squares)	± 20
maximum value (worst-case sum)	± 48
best estimate (average of probable and maximum)	± 35

TABLE IV
COMPARISON OF MEASURED AND CALCULATED RADIOFREQUENCY ABSORPTION RATES OF THIN SALINE-FILLED TUBES EXPOSED TO 18.5-MHz RADIATION.

Tube ID (in)	Tube wall (in)	σ (S/m)	Absorption rates: Calculated* (W/kg per mW/cm²)	Absorption rates: (Measured ± SE (6) / calculated)
1/2	1/16	0.95	3.33	1.35 ± 0 20
		2.9	7.68	0.98 ± 0.13
1	1/8	0.29	0.94	1.05 ± 0.25
		0.95	2.21	1.23 ± 0.10 1.15 ± 0.10
2	1/8	0.29	0.57	1.32 ± 0.20
			average ratio:	1.18

† E ∥ tube length, acrylic tubing, ℓ = 183 cm

* Calculation for a thin prolate spheroid using the long-wavelength dielectric-model calculation.

equating both the masses and the (a/b) ratios of the two objects. The prolate-spheroid absorption rates were then calculated with a Fortran IV program using the published formulas [17], and evaluating the elliptic integrals using Simpson's rule with 1000 steps. The program was validated by reproducing all the data of Figs. 2–5 of the original paper [17].

It is seen in the table that the measured absorption rates exceed the calculated values by only 18 percent on average. This difference is well within the estimated uncertainty of ± 35 percent due to systematic errors and confirms the analysis.

VII. HUMAN WHOLE-BODY ABSORPTION MEASUREMENTS

Tests showed that the wearing of clothing (underwear, long pants, shirt, socks, shoes) or metal accessories (wrist watch, neck chain, glasses frame, belt buckle) caused no statistically detectable difference in human absorption rates.

The whole-body absorption rates of three male subjects at 18.5 MHz were measured for all six different ellipsoid-equivalent standard body orientations. The results are presented in Table V, where the dielectric-ellipsoid model [17] calculations are shown for comparison. That model is the only one which predicts absorption rates at this frequency for more than one of the six orientations. The only other published calculation giving usable predictions for 18.5 MHz is that of Hagmann *et al.* [29]. They predict the ***EHK*** orientation will absorb 7.0 mW/kg per mW/cm^2—not significantly different from the value of 6.56 for the dielectric-ellipsoid model.

TABLE V
NORMALIZED SPECIFIC ABSORPTION RATES, NSAR, (mW/kg *per* mW/cm^2) ($\pm$ SE ($N = 6–9$)) FOR THREE MALE SUBJECTS EXPOSED TO 18.50-MHz RADIATION IN FREE SPACE.

Body Orientation	Human Subjects: F	Human Subjects: I	Human Subjects: K	Ellipsoid Model†: Calculated NSAR	Ellipsoid Model†: (Human average / calculation)
EKH	22.3 ± 3 1	18.4 ± 3.7	26.8 ± 2.2	7.77	2.9
EHK	11.5 ± 5.5	12.3 ± 2.7	15.8 ± 1.9	6 56	2 0
KEH	3.5 ± 2.9	2.8 ± 0.9	3 7 ± 0 7	1.74	2 0
KHE	0.9 ± 1 5	-0.4 ± 1.6	2.3 ± 1 1	0.45	*
HEK	1 7 ± 1.4	0.0 ± 1.6	3 0 ± 1.0	0.44	*
HKE	0.3 ± 0.9	-0.7 ± 1.5	-1.7 ± 2 3	0.37	*
Height (cm)	175.3	178 2	179 5	175	
Mass (kg)	84 6	77.7	73.2	70	

† 70 kg, (b/c) = 2.0, (ε', σ(S/m)) = (90, 0 40) = 2/3 of the wet-tissue values (from [28], p. 22 and Fig. 3).

* Comparisons would be meaningless because |SE| ≐ mean.

The data of Table V are limited in scope due to the use of only one frequency and because the three available subjects were of similar build. The other limitation is that the free-space absorption rates for the ***KHE***, ***HEK***, and ***HKE*** orientations are barely detectable, so that comparison with calculations was not done. Nevertheless, it is noteworthy that the absorption in the ***E*** orientations are two to three times the predictions, and that, within the standard errors shown, the order of the measured free-space absorption rates for the six orientations is consistent with the order predicted by the standard dielectric-ellipsoid calculation. More detailed comparisons with theory will await more data as a function of frequency, grounding and body orientation.

VIII. DISCUSSION AND SUMMARY

A system for measuring radiofrequency absorption from 3 to 20 MHz in human volunteers has been described. The exposure chamber, a large TEM cell, allows the irradiation of subjects in any orientation with respect to the propagating TEM mode under simulated free-space or grounded conditions. The cell was designed with a characteristic impedance of 70 Ω, rather than 50 Ω, to increase the absorption detectability (ratio of E^2 to input power) by 36 percent while sacrificing only 8 percent in field uniformity. This design compromise could likely only be extended to a characteristic impedance of about 100 Ω, as field uniformity begins to decrease more rapidly than the gain in absorption detectability.

The mismatch between the 70-Ω cell and the 50-Ω transmission line might be thought to increase the coupler directivity error, since $\Gamma_c \neq 0$ and the term $|\Delta\Gamma| = |\Gamma_{c+s} - \Gamma_c|$ appears in the directivity error formula ((4)). While $|\Gamma_c|$ is 0.20 at 18.5 MHz, $|\Delta\Gamma|$ is only 0.01, which compares favorably with the values of $|\Delta\Gamma| = 0.01$ to 0.02 ([27], tables 2 and 3) for the nominal 50-Ω cell ($|\Gamma_c| = 0.02$ to 0.06) analyzed by Crawford *et al.*, and used to measure the absorption of twelve rhesus monkeys from 10.6 to 26.6

MHz. From these two examples, it can be seen that larger values of $|\Gamma_c|$ do not correlate with larger values of $|\Delta\Gamma|$; i.e. cell mismatch is not a primary cause of large directivity errors.

The measured field pattern agrees very well with the calculated TEM pattern and thus denies the possibility of a significant propagating higher order mode. The greatest deviation of the field pattern from the ideal plane wave is in the nonuniformity of the exposure; the ***E*** and ***H*** fields each change 50 percent over the length of a subject oriented parallel to the ***E*** field. Exposures for the ***H*** and ***K*** orientations are much more uniform. The field nonuniformity is not a major problem—except for those who do model calculations—because most human occupational exposures take place in very nonuniform fields.

The accurate measurement of the very low absorption rates (eg., 0.2 percent of incident power) requires the use of high-directivity directional couplers and signal averaging. Five sources of systematic errors in the method were carefully assessed. In particular, a new technique, using a metal manikin which scatters radiation like a human but is nonabsorbing, was used to show that any dielectric-loading effect of the subject on the cell's absorption is undetectable. The total systematic error has been carefully estimated to be ± 35 percent of the measurement; the error in comparing any two measurements is substantially less. The error analysis was confirmed by showing that a set of thin saline-filled cylinders, modeled as thin prolate spheroids, absorbed power at rates about 20 percent higher than the calculated rates, well within the estimated uncertainty of ± 35 percent. The error analysis should apply directly to other TEM-cell dosimetry studies such as the exposure of animals inside a 50-Ω TEM cell.

Human volunteers are exposed to 11 μW/cm^2, and never absorb more than 1 W (even in preliminary measurements of a subject grounded at 35 MHz). These exposures are considered very safe. The wearing of clothing and metal accessories by the subject caused no detectable change in absorption rate. The measured whole-body absorption rates for the two principal ***E*** orientations in free space were found to exceed the calculations by a factor of 2.0 (***EHK***) or 2.9 (***EKH***). A similar result was reported by Marshall *et al.* [30] who found that mice absorb twice as much as saline mice models which in turn absorb what the prolate spheroid calculation predicts.

These direct measurements of human whole-body absorption rates are the first reported at any frequency from ELF to millimeter-wave frequencies. They are currently being continued from 3 to 18.5 MHz, staying well below the first cell resonance at 20.7 MHz. A detailed analysis of resonances and propagating higher order modes in this cell has been completed [31]. It indicates that by operating between resonances, or using mode-suppression techniques, it will likely be possible to extend the usable frequency range of the TEM cell above the first resonance.

Acknowledgment

The author is grateful to his professional colleagues H. M. Assenheim, G. A. Grant, F. R. Hunt, and S. C. Kashyap for their earlier work on this project [15], [18]. The reliable technical work of G. W. Hartsgrove was invaluable [15]. The further technical assistance of J. Peeke, L. W. Hargrove, and D. S. Wood was also greatly appreciated. Finally, S. J. Allen of the USAF School of Aerospace Medicine has been very helpful with advice and assistance, especially regarding the probe calibration intercomparison [23]. The work presented in this paper was performed at the Division of Biological Sciences, National Research Council, Ottawa.

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An Accurate, Unified Solution to Various Fin-Line Structures, of Phase Constant, Characteristic Impedance, and Attenuation

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Abstract—**The analysis of several fin-line configurations (unilateral fin-line, bilateral fin-line, antipodal fin-line, and coupled fin-lines) has been completed accurately. In this unified method, propagation constant is achieved via the generalized spectral domain technique where the basis functions for the bounded and unbounded fields are chosen to be trigonometric functions and Legendre polynomials, respectively. The conduction loss and dielectric loss solution for the first time are found through a perturbation method. The conductor loss so derived is believed to be sufficiently accurate for practical purposes. Characteristic impedances of these transmission lines using tentative definitions have been presented. The CPU time on an IBM 360/65 for calculation of the mentioned parameters does not exceed five seconds if the fourth-order solution in the spectral analysis gives the required accuracy. The programs are also capable of detection of higher order modes.**

Manuscript received July 29, 1981; revised March 3, 1982.
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