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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.

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TABLE I
REFERENCE TABLE OF WHOLE-BODY NORMALIZED SPECIFIC ABSORPTION RATES (NSARs) FOR THE THREE SUBJECTS

Frequency (MHz)	Subject*	NSAR ($mW\ kg^{-1}/mW \cdot cm^{-2}$) (mean ± SE (N)) Free Space EKH	Free Space EHK	Grounded EKH	Grounded EHK
40.68	I	177 ± 5 (10)	135 ± 5 (8)	558 ± 9 (8)	505 ± 8 (8)
	L	163 ± 2 (8)	134 ± 4 (8)	585 ± 12 (8)	585 ± 5 (8)
23.25	I	34 ± 3 (12)	27 ± 3 (12)	375 ± 5 (8)	342 ± 7 (8)
	L	28 ± 2 (12)	21 ± 2 (12)	358 ± 11 (8)	335 ± 6 (8)
	M	32 ± 2 (13)	16 ± 1 (13)	350 ± 4 (9)	285 ± 9 (9)
13.56	L	-	-	116 ± 8 (8)	115 ± 9 (8)
10.0	L	-	-	67 ± 5 (12)	58 ± 5 (20)
	M	-	-	57 ± 5 (10)	55 ± 7 (12)
	Block model†	-	-	-	12.7
	Cylinder model†	-	-	16.0	16.0
7.0	L	-	-	36 ± 2 (8)	-

* Subject:	I	L	M
Mass (kg).	79	71	71
Height (cm)	177	172	171

† Standard models [2, Table 2].

All experiments were performed with the body in an E orientation (electric field parallel to the body length) and the subject's feet closest to, or touching, the ground plane. Both of the two possible orientations with respect to the magnetic field were employed: the *EKH* orientation, in which the magnetic field was perpendicular to the chest; and the *EHK* orientation, in which the magnetic field was in the shoulder-to-shoulder direction. In general, the results differed little between the two possible E orientations.

Most of the RF absorption rates are displayed in a comparative way, i.e., as a ratio to a reference absorption rate for the same subject. The reference value is either the free-space or grounded rate. Table I gives the reference figures for each combination of subject and frequency that was used. Only three subjects were employed in the study because other volunteers were not available for reasonable periods of time and the results for the three subjects were always found to be quite similar.

The five frequencies used for the experiments are also given in Table I. Frequencies of 13.56 and 40.68 MHz were employed because they are both ISM frequencies, at which human occupational exposures often occur. The highest usable frequency below all the interacting-resonance frequencies of the cell is 23.25 MHz. The use of 10 MHz made a direct comparison possible between our measurements and the two relevant published theories; the cylinder theory of Iskander *et al.* [5] and the block model calculation of Hagmann and Gandhi [6], [7]. Finally, 7 MHz is the lowest frequency for which reasonably accurate results are possible.

Since it was impractical to achieve a uniform-thickness air gap between the subject's feet and the ground plane, that ideal condition was simulated by using spacers of low-dielectric-constant materials. Two materials were used (both of dielectric constant 1.03): expanded polystyrene, and a hydrocarbon resin foam (ECCOFOAM PP-2 from Emerson and Cuming, Canton, MA).

In the first RF absorption study, 40.68 MHz was found to be at or near the grounded resonance. All frequencies below 25 MHz were clearly in a different, below-resonance, region. This distinction is also supported by the present results.

TABLE II
THE REDUCTION IN ABSORPTION RATE CAUSED BY SEPARATING THE FEET (IN THE SHOULDER-TO-SHOULDER DIRECTION) ON THE GROUND PLANE. RESULTS FOR SUBJECT L.

Frequency (MHz)	Orientation	NSAR (percent of zero-separation NSAR) Separation (cm) 0	15	30	60	90	Significant Differences*
40.68	EKH	100	99	94	85	74	± 4
	EHK	100	100	97	87	77	± 4
23.25	EKH	100	97	91	85	67	± 5
	EHK	100	97	92	86	71	± 5
13.56	EKH	100	99	94	91	82	± 7
	EHK	100	97	90	87	72	± 7
	Average of 6.	100	98	93	87	74	

*Estimated statistically significant differences at the 95 percent confidence limits.

Before the feet were separated from the ground plane, the effect of separating the two feet on the ground plane was tested. The results, in Table II, are clearly independent of frequency and of which E orientation (*EKH* or *EHK*) is employed. A small gap between the feet has only a slight effect. A larger separation significantly reduces the absorption rate compared to the rate with the feet together. This effect may be partly due to the reduction in effective height of the subject as the feet are spread far apart. In the case of subject L, used for Table II, his effective height is reduced by 10 cm from its normal value of 173 cm when his feet are 90 cm apart.

III. RESULTS FOR SMALL SEPARATIONS FROM THE GROUND PLANE

A. Effect of an Air Gap

The effect of an air gap on the normalized specific absorption rate (NSAR) is shown in Fig. 1 for three subjects exposed at the same frequency. Fig. 2 shows the same plot for one subject in both E orientations and at three different frequencies. It can be seen that the air-gap effect depends only slightly on the subject and choice of E orientation. Results for the two below-resonance frequencies are very similar to each other, but strikingly different from the results for the near-resonance frequency, 40.68 MHz. It can be seen in the two figures that, for below-resonance frequencies, the absorption rate is reduced to half the grounded value by an air gap of only three to six mm. At the near-resonance frequency, on the other hand, an air gap of 50 to 80 mm (based on Fig. 2 and other data) is necessary to produce the same effect.

B. Comparison of Air-Gap Results with Existing Theories

The two relevant existing theories are the approximate cylinder calculation of Iskander *et al.* [5] and the block model calculation of Hagmann and Gandhi [6], [7]. Since the latter theory was only calculated for the *EHK* orientation at 10 MHz, the comparison between theory and experiment was done for those conditions. The results are presented in Fig. 3. The theories are normalized to NSAR(0) for each theory, and not to the measured NSAR(0). This is important to note because the two measured NSAR values

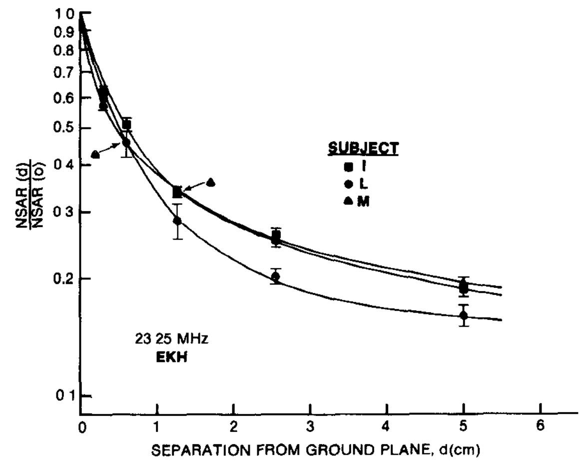

Fig. 1. The reduction in whole-body absorption rate caused by a small air gap between a subject's feet and the ground plane. NSAR is the Normalized Specific Absorption Rate ($\mathrm{mW \cdot kg^{-1} / mW \cdot cm^{-2}}$). The reference values, NSAR(0), are given in Table I. The arrows for two of the triangular data points indicate that they lie on top of the other point as shown.

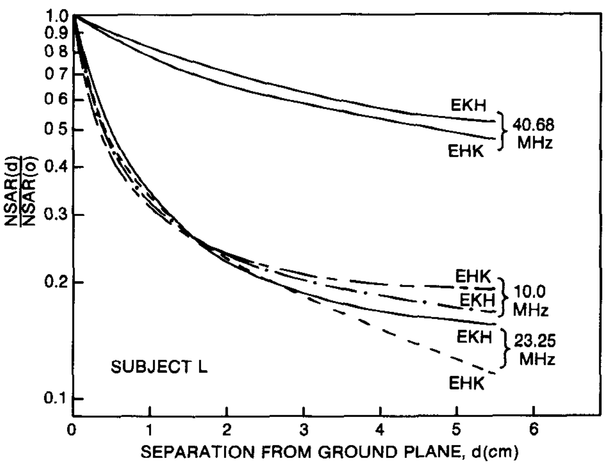

Fig. 2. The dependence of the air-gap separation effect on frequency and body orientation. The individual data points are not shown because there would be too much overlap between them.

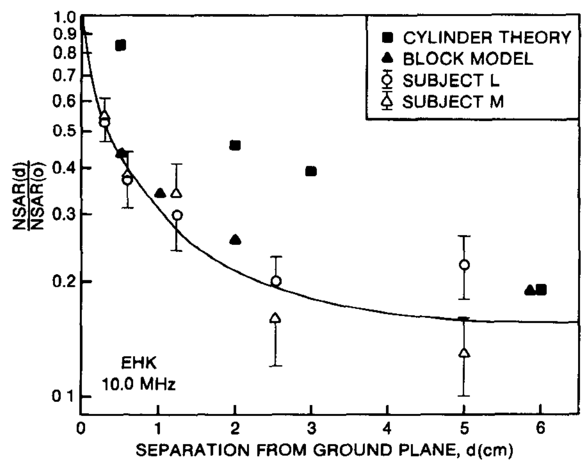

Fig. 3. Comparison of experimental and theoretical results for the *EHK* orientation at 10 MHz. A smooth curve has been drawn through the two sets of measurements.

are both approximately four times the two calculated values (see Table I). This discrepancy will be addressed in a later paper on improved models. Fig. 3 can be used, however, to compare the *relative* decrease in absorption as a function of separation distance from the ground plane. For separations up to three cm, the measurements agree with the block model and disagree with the cylinder model. At a separation of five or six cm, the two theories both agree reasonably well with the measurements.

At higher frequencies, quantitative predictions were only published for the cylinder theory. Since that model obviously does not distinguish between the *EKH* and *EHK* orientations, the comparison was made to the average of the measurements for the two *E* orientations. The results are presented in Fig. 4. The measured curve for 23.25 MHz is well below the cylinder theory, just as was found for the other below-resonance frequency (10 MHz). The measurements at 40.68 MHz are compared with the cylinder theory for the same frequency, and also for 47 MHz because the latter frequency is calculated to be at the grounded peak for the cylinder. The measurements are seen to be close to the 47-MHz curve for all separations measured. This agreement supports our contention that 40.68 MHz is actually very near the peak for grounded human subjects.

The block model only made a semiquantitative prediction for the resonant frequency [6, p. 25], one that is obviously wrong: "Several calculations made for the grounded resonant frequency of 47 MHz show a fall-off in magnitude of grounding effects with increasing distance from the ground plane, which is similar to the results at 10 MHz."

As far as the air-gap effect on the whole-body absorption rate is concerned, we conclude that the cylinder theory is more accurate for the near-resonant frequency, and the block model calculation is more accurate for the below-resonance frequencies.

Finally, the block model calculation made one more prediction that could be tested. That theory predicts [6, fig. 5] that the SAR in the heel is much larger than in the ball of the foot. This implies that most of the body's RF current is carried to ground through the heel and that contact with the ground plane is much more important for the heel than for the ball of the foot. The data of Table III prove that the opposite is the case. Most of the RF current through the foot goes through the toes and ball of the foot. This may be due to the larger contact area of that part of the foot, or due to the complex bone structure of the ankle and foot.

C. Effect of Dielectric Spacers

For small separations from the ground plane, the soles of the subject's feet may be considered to form a parallel-plate capacitor with the ground plane. The equivalent circuit representing the exposure situation then consists of a resistive human body separated from its image in the ground plane by a capacitive impedance. Iskander *et al.* [5] used this approach in calculating the RF absorption rate of a cylinder. To test the capacitance idea, the functional

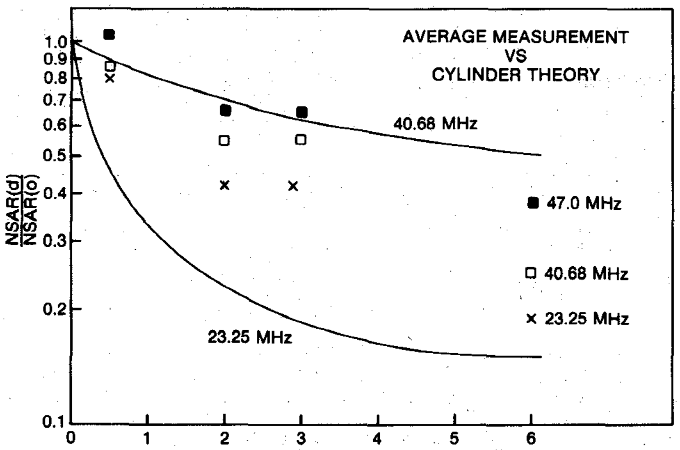

Fig. 4. Comparison of the measured separation effect with the predictions of the cylinder theory. Each curve is the average of the measurements for subjects *I* and *L* in both the *EKH* and the *EHK* orientations. The twelve points are the predictions of the cylinder theory for the three frequencies as marked, and for separations up to six centimeters.

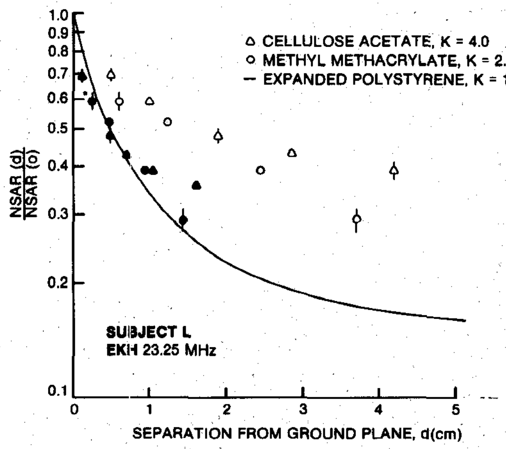

Fig. 5. The near-ground separation effect with plastic spacers between the subject's feet and the ground plane. The open points are the actual absorption measurements for the given material and separation. The solid points are the open points replotted for an effective separation equal to the actual separation divided by the dielectric constant. The * near the solid circle indicates that a solid triangle lies on top of it. Error bars (±1 SEM) are shown only where they are larger than the size of the point.

TABLE III
THE EFFECT OF PARTIAL FOOT CONTACT WITH THE GROUND PLANE. SUBJECT *L* WAS EXPOSED GROUNDED IN AN *EKH* ORIENTATION AT 23.25 MHz.

Separation from Ground (cm)		$\frac{\text{NSAR (separation)}}{\text{NSAR (none)}}$ $\left(\frac{\text{mean} \pm \text{SE}(5)}{\text{mean}}\right)$
Heel	Ball and Toe	
0	0	1.00 ± 0.02
2.5	0	0.95 ± 0.02
0	2.5	0.40 ± 0.03
2.5	2.5	0.25 ± 0.01

dependence of the absorption rate on capacitance is not needed. It is only necessary to utilize the fact that the capacitance of a parallel-plate capacitor is proportional to the ratio of the material dielectric constant to the separation between the plates. Thus, the capacitance idea is confirmed if the absorption rate depends only on the ratio of the two quantities.

This idea was tested using different numbers of plastic sheets between the subject's feet and the ground plane. In each test, the plastic sheets extended beyond the edge of the feet by a distance at least as large as the total thickness of the sheets. The two plastics that were used, and their dielectric constants (measured in our lab), were: methyl methacrylate (or lucite, $K = 2.6$) and cellulose acetate ($K = 4.0$).

The results of these experiments are shown in Fig. 5. It can be seen that most of the data points, after scaling for the effect of the dielectric constant, lie on or close to the curve for $K = 1.0$. The last point for cellulose acetate, at a reduced separation of 1.6 cm, is likely off the curve because the actual separation of 6.4 cm is comparable to the width of the feet; this violates the assumptions underlying the parallel-plate capacitor model. Overall, the data of Fig. 5 adequately confirm the capacitance concept. That idea will now be applied, in a qualitative way, to the practical case of the effect of footwear.

D. Effect of Footwear

The effect of different footwear on the nearly grounded absorption rates was first tested at 23.25 MHz. The data are presented in Table IV.

The results for socks alone are interesting for two reasons. First, even thin nylon socks, only 0.65 mm thick, reduce the absorption rate by a measurable amount, to 87 percent of the grounded rate. Secondly, the results for both the nylon socks and the wool socks (1.7 mm thick) are the same as the results for an air gap of exactly the same thickness. This is a rather indirect way of proving the well-known fact that the bulk of the volume of a sock consists of air pockets, not material.

The use of shoes as well as socks further reduces the absorption rate (Table IV). It is not possible to compare the data with shoes and socks to the capacitor model because: the heel is usually further from the ground plane than the ball of the foot; the socks and shoes form a dual-layer capacitor; and the dielectric constant of the leather soles (which could not be measured easily) depends strongly on its moisture content. For the experiments using both shoes and socks, the absorption rate compared to no footwear was found to vary from 54±1 percent (for nylon socks and dress shoes with leather soles) to 32±1 percent (for wool socks and rubber-soled athletic shoes).

The same two combinations of shoes and socks, which represent the maximum range of the results for 23.25 MHz, were used to study the effect of footwear as a function of frequency. Those measurements are presented in Fig. 6. Results are very similar at all the below-resonance frequencies. At 40.68 MHz, however, footwear produces a much smaller reduction in absorption; this is consistent with the data of Fig. 2 for the effect of an air gap.

TABLE IV
THE EFFECT OF FOOTWEAR ON THE GROUNDED ABSORPTION RATE. SUBJECT L WAS EXPOSED GROUNDED IN AN EKH ORIENTATION AT 23.25 MHz.

Footwear: Socks	Footwear: Shoes Type	Footwear: Shoes Sole		$\left(\frac{\text{NSAR(footwear)}}{\text{NSAR (none)}}\right)$ $\left(\frac{\text{mean} \pm \text{SE (6)}}{\text{mean}}\right)$
none	none			1.00 ± 0.03
nylon	none			0.87 ± 0.04
nylon	dress	thin leather	*	0.54 ± 0.01
nylon	dress	thick leather		0.54 ± 0.05
nylon	casual	rubber		0.40 ± 0.01
wool	none			0.70 ± 0.02
wool	work boot	thick leather		0.36 ± 0.02
wool	athletic	rubber	*	0.32 ± 0.01

* Used for tests at other frequencies.

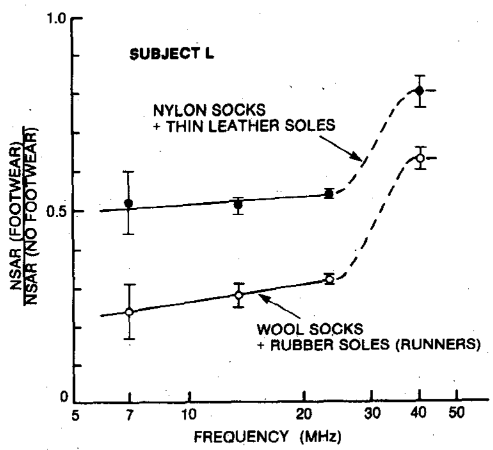

Fig. 6. The frequency dependence of the reduction in absorption rate caused by different combinations of footwear. The measurement frequencies are 7.0, 13.56, 23.25, and 40.68 MHz.

In occupational exposure situations, where the grounding effect may occur, it is recommended that footwear always be worn. This will provide some radiation protection at all frequencies: a reduction in the RF absorption rate of 15 to 35 percent near resonance; and of 45 to 75 percent at below-resonance frequencies. For the commonly used ISM frequency of 27.12 MHz, the reduction is estimated from Fig. 6 to be between 40 and 60 percent. A second radiation protection alternative is the employment of a thick rug, rubber mat, plastic sheet, or any other insulating material over the ground plane.

IV. RESULTS FOR LARGE SEPARATIONS FROM THE GROUND PLANE

A. Below-Resonance Extrapolation to Free Space

The rate of change of the absorption rate with separation from the ground plane is seen in Fig. 1 to diminish considerably for separations greater than about 2 cm. It is obvious that the graphical analysis of Fig. 1 is poorly suited to extending the measurements to the free space situation, which is simulated in our TEM cell by a separation of 90 cm from the ground plane. A much more suitable plotting scheme, illustrated in Fig. 7, was found. Absorption rates are plotted as a function of the inverse

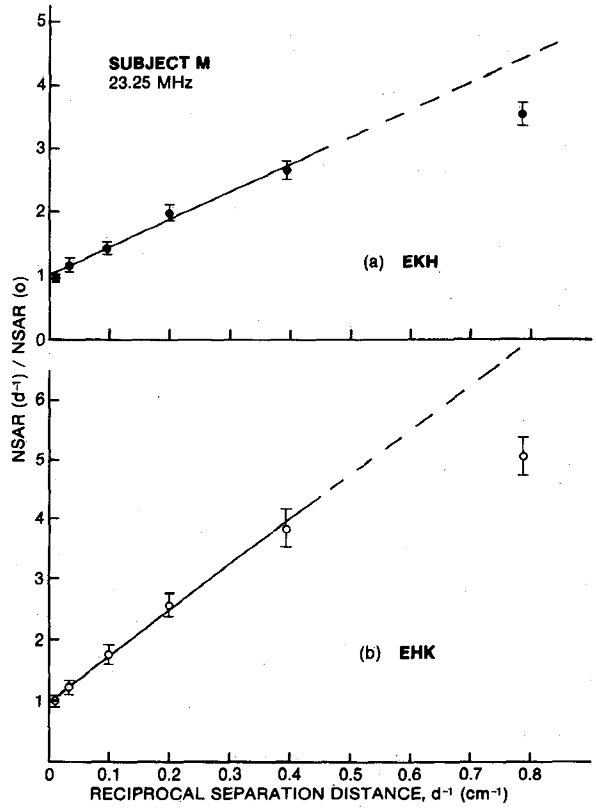

Fig. 7. The approach of the below-resonance absorption rates to the ideal free-space limit ($d^{-1} = 0$). The solid line is the regression line fit to the first five data points. It is extended by a dashed line for comparison to the point at $d^{-1} = 0.8$ cm^{-1}.

separation distance d^{-1}. Two advantages of this method are that the extrapolation curves are linear (at below resonance frequencies) and that the absorption rate for the ideal free-space condition ($d = \infty$) is simply the intercept of the regression line with the ordinate scale.

The data of Fig. 7, for subject L, overlap the data of Fig. 1 for the same subject. The three points on the right-hand side of Fig. 7(a) are the same as the three points on the right-hand side of Fig. 1. It is seen in Fig. 7 that the linear extrapolation to free space is valid for $d^{-1} \leqslant 0.5$ cm^{-1} or $d \geqslant 2$ cm. Graphs similar to Fig. 7 were also plotted for the other two subjects at the same frequency. All the lines fit reasonably well ($R^2 > 0.9$ for all six lines). The regression-line slopes and intercepts for the three subjects in both E orientations are compared in Table V. Slopes range from 2.8 ± 0.5 to 7.4 ± 0.3 cm. Additionally, the slope is not consistently larger for either of the two E orientations. The reason for these variations is not known.

B. Below-Resonance Size Effect

The farthest a subject can be from the ground plane in the TEM cell is 90 cm, when the subject is located halfway between septum and wall. The subject's length of about 180 cm half fills the distance from septum to wall. The question of whether or not these spacings adequately simulate the ideal free-space situation can be answered by comparing the intercepts of the regression lines ($d = \infty$) with the last data points ($d = 90$ cm). In every case, the

TABLE V
EXTRAPOLATION OF THE PARTLY GROUNDED ABSORPTION RATES TO FREE SPACE. THE DATA AT 23.25 MHz FIT THE REGRESSION EQUATION NSAR (d^{-1}) = NSAR(0)$[1 \pm B \cdot d^{-1}]$, WHERE d(cm) IS THE DISTANCE SEPARATING THE SUBJECT'S FEET FROM THE GROUND PLANE.
$0 \leqslant d^{-1} \leqslant 0.4\ \mathrm{cm}^{-1}$ $(d \geqslant 2.5$ cm).

Subject	B (cm) (mean ± SE)		Comparison of data point nearest free space to the extrapolated free space value. NSAR([90 cm]$^{-1}$)/NSAR(0)	
Orientation:	EKH	EHK	EKH	EHK
I	5.3 ± 0.4	2.8 ± 0.5	1.03	0.91
L	4.0 ± 0.4	5.1 ± 0.7	0.95	0.91
M	4.4 ± 0.3	7.4 ± 0.3	0.96	1.01
mean ± SE	4.8 ± 0.6		0.96 ± 0.02	

difference was less than 10 percent and not statistically significant. The average difference between the two values was 4 ± 2 percent. This result proves that, for below-resonance frequencies, a septum-to-wall separation of twice a body length provides an exposure situation which very closely simulates the ideal free-space situation.

C. Near-Resonance Extrapolation to Free Space

The linear extrapolation process which was found to work so well for below-resonance frequencies did not work for 40.68 MHz. The measurements for subject L, shown in Fig. 8, are clearly not on a straight line. Neither are similar plots for subject I. This difference in behavior at near-resonance frequencies is not surprising since it is also observed for small separations from the ground plane.

For the near-resonance frequency, a separation of 90 cm from the ground plane may not be considered equivalent to the ideal free-space condition. Based on the four available curves, it is estimated that NSAR([90 cm]$^{-1}$) is 10 ± 5 percent greater than the extrapolated intercept NSAR(0), and that this difference is real. Thus, all our simulated free-space absorption measurements at 40.68 MHz should be reduced by 10 ± 5 percent. This has the effect of reducing slightly the frequency exponent n (NSAR $\propto f^n$) for the free-space absorption curves from 18 to 41 MHz. The corrected mean exponent is 2.7 ± 0.2, in comparison to the value of 2.9 ± 0.2 originally reported by us [2, table 3].

D. Complete Absorption Curves

A complete set of absorption measurements for one subject in the EKH orientation is shown in Fig. 9. The data for the grounded condition and the smallest separation (0.6 cm) are fit by a single (weighted) regression line on the log-log scale. The data for the free-space condition are fit with two regression lines, as was previously found necessary [2]. Two lines were also found to give a better fit to the data for a separation of 5 cm.

In terms of both the positions of the curves and the number of required regression lines (one or two), it can be seen that the data for a 0.6-cm separation are similar to the grounded results, while the measurements for a separation of 5 cm are more like the free-space results. This supports our previous observation that a separation of about two cm

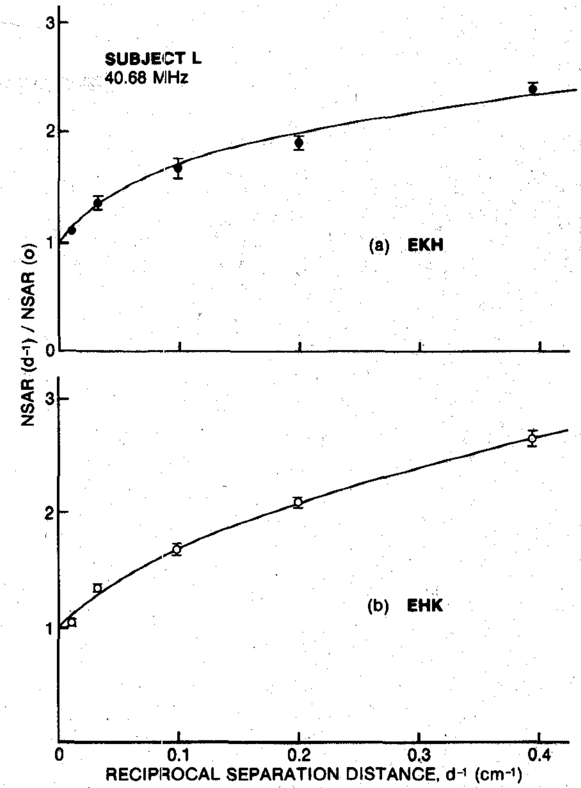

Fig. 8. The approach of the near-resonance absorption rates to the ideal free-space limit $(d^{-1} = 0)$. Smooth nonlinear curves have been drawn through the data points.

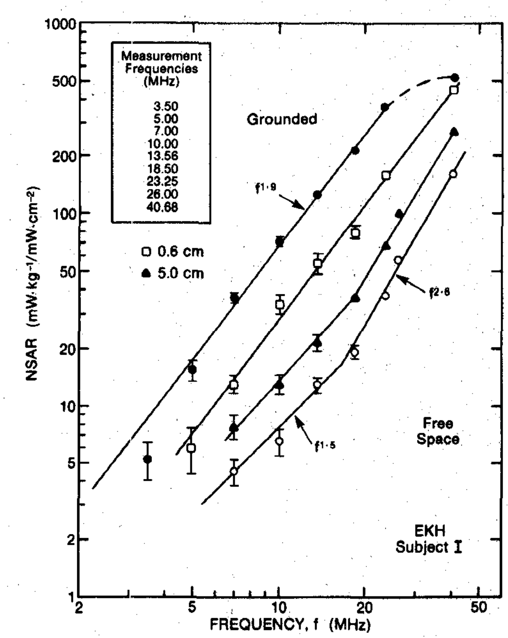

Fig. 9. A complete set of absorption curves for subject I in an EKH orientation.

is the dividing line between the nearly grounded and nearly free-space behaviors.

V. SUMMARY

The results of this study fall conveniently into four distinct categories, depending on whether the frequency is near the grounded resonance ($f \doteq 40$ MHz) or below it

($f \leqslant 25$ MHz) and whether or not the subject's feet are within two cm of the ground plane.

A. Frequencies Below Resonance

Near the ground plane, the decrease in NSAR with increasing separation is very rapid. The absorption is reduced to half the grounded value by a separation of only 3 to 6 mm. The results agree very well with the predictions of the block model for all separations out to 6 cm, while they only agree with the cylinder model at a separation of 5 or 6 cm.

The idea that the soles of the feet and the ground plane effectively form a parallel-plate capacitor was proved by measuring RF absorption rates with different thickness of three different materials between the two surfaces. Naturally, the capacitor model only works for separations from ground which are less than the width of the foot.

Ordinary footwear provides practical radiation protection by reducing the RF absorption rates, compared to grounded, by 45 to 75 percent, depending on the choice of footwear.

Finally, the absorption rates were found, when plotted against inverse separation distance, to extrapolate in a linear manner to the ideal free-space limit. The linear relationship permitted the inference that a separation of 90 cm, the maximum possible in our TEM cell, is a very good approximation to the free-space condition.

B. Frequencies Near Resonance

For near-resonance frequencies, the decrease in NSAR with separation from the ground plane is an order of magnitude slower than for the below-resonance frequencies. The curve agrees fairly well with the predictions of the cylinder model, but disagrees with the block model. Similarly, footwear provide much less RF radiation protection; the RF absorption rates compared to grounded are reduced by only 15 to 35 percent, depending on the choice of footwear.

Finally, the absorption rates could not be extrapolated to free space in a linear maner, and it appears that a separation of more than 90 cm is needed to properly simulate free space for frequencies near the grounded resonance.

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