matching Γ_{min}, and what vector direction to tune to decrease $|\Gamma_{min}|$ at the input.

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Dependence of Electromagnetic Energy Deposition Upon Angle of Incidence for an Inhomogeneous Block Model of Man Under Plane-Wave Irradiation

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***Abstract*—Whole-body and part-body energy deposition in a realistic inhomogeneous block model of man is presented as a function of angle of incidence for plane-wave irradiation for two cases: *E* arm-to-arm, with man in free space, *H* arm-to-arm, with man in free space, and also with man standing on a conducting plane. At the frequencies considered (27.12 and 77 MHz), the variation with angle is smooth and extrema occur at or near angles corresponding to the standard polarizations considered earlier by others. Part-body energy deposition and some of the fine structure in the angular dependence would not be seen with less realistic models of man.**

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I. INTRODUCTION

THE increasing exposure of man-to-radio frequency energy has necessitated obtaining dosimetric information for use in the evaluation of possible biological effects.

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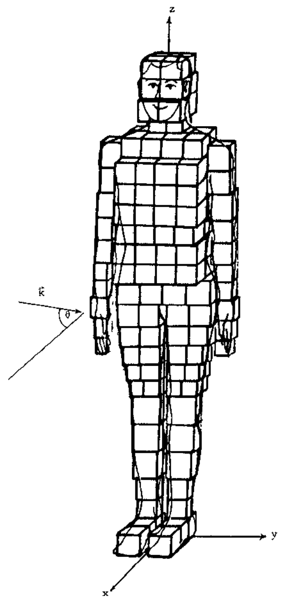

Fig. 1. Realistic inhomogeneous block model of man showing orientation of the propagation vector of the incident plane wave.

TABLE I
CORRESPONDENCE OF PRESENT SOLUTIONS WITH POLARIZATIONS USED WITH SIMPLER MODELS OF MAN

	Theta	Ellipsoid	Prolate Spheroid
$\vec{E}$ arm-to-arm	0°, 180°	HEK	H
	90°, 270°	KEH	K
$\vec{H}$ arm-to-arm	0°, 180°	EHK	E
	90°, 270°	KHE	K

Most of the numerical solutions obtained to date have been restricted to incident plane waves that have one of several standard orientations relative to the target model [1]. Real-life exposure to plane-wave irradiation is more likely to occur at intermediate orientations which have previously been given relatively little consideration in either theoretical [2] or experimental [3] work.

All of the calculations in the present paper have used a 180-cell block model of man which was designed using biometric and anatomical diagrams. Approximate allowance was made for dielectric inhomogeneities by using volume–weighted average values for the complex permittivity of the contents of each cubical cell. Frequencies chosen for the present calculations were 77 MHz, corresponding to whole-body resonance in free space, and 27.12 MHz which is used in many commercial applications for dielectric heating. Dielectric properties used for the cells were $38.8<\epsilon<149$ and 0.222 mho/m$<\sigma<$0.841 mho/m at 27.12 MHz, and $25.2<\epsilon<82.1$ and 0.286 mho/m$<\sigma<$ 0.997 mho/m at 77 MHz. More detail regarding the model and our procedures used for moment-method solutions with a pulse-function basis and delta-functions for testing have been presented earlier [4].

In the present paper we have generalized the orientation of the incident plane wave so that the direction of propagation defined by the vector $\boldsymbol{k}$, takes on possible angles within the plane of symmetry (x–z plane in Fig. 1). The angle between $\boldsymbol{k}$ and the horizontal is defined as θ in Fig. 1 and is used as the independent variable in the other figures of this paper. Two subcases are considered: $\boldsymbol{E}$ arm-to-arm ($\boldsymbol{E}$ horizontally oriented, i.e., $E \parallel \hat{y}$ and $\boldsymbol{H}$ in the x–z plane) and $\boldsymbol{H}$ arm-to-arm ($\boldsymbol{H}$ horizontally oriented, i.e., $\boldsymbol{H} \parallel \hat{y}$ and $\boldsymbol{E}$ in the x–z plane). Correspondence of the present solutions with polarizations used with ellipsoidal and prolate-spheroidal models of man is shown in Table I.

II. RESULTS FOR *E* ARM-TO-ARM

The energy deposition in an inhomogeneous block model of man for incident plane waves having $\boldsymbol{E}$ arm-to-arm at 27.12 and 77 MHz is given in Figs. 2 and 3, respectively. At both frequencies the deposition is greatest in the arm and least in the head and neck. In these and all subsequent figures of this paper, markers are used for the computed values and the smooth curves were formed by splining

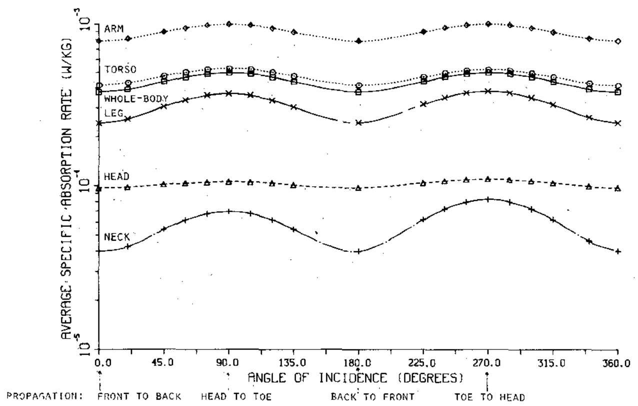

Fig. 2. Whole-body and part-body deposition for an inhomogeneous model of man in free space with an incident plane wave at 27.12 MHz with ***E*** arm-to-arm. Incident power density is 1 mW/cm^2.

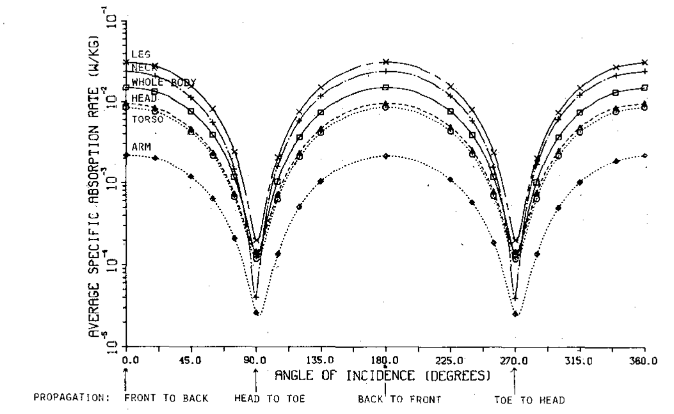

Fig. 4. Whole-body and part-body deposition for an inhomogeneous model of man in free space with an incident plane wave at 27.12 MHz with ***H*** arm-to-arm. Incident power density is 1 mW/cm^2.

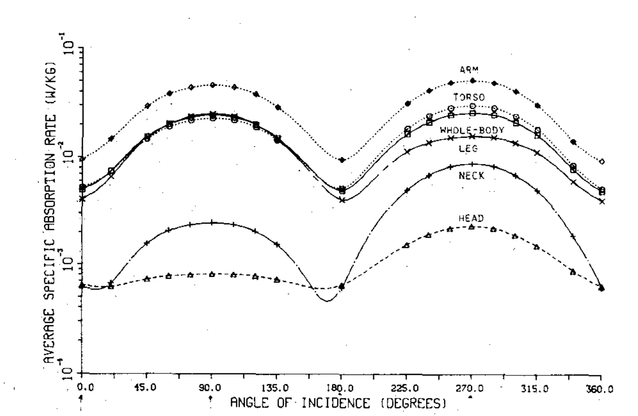

Fig. 3. Whole-body and part-body deposition for an inhomogeneous model of man in free space with an incident plane wave at 77 MHz with ***E*** arm-to-arm. Incident power density is 1 mW/cm^2.

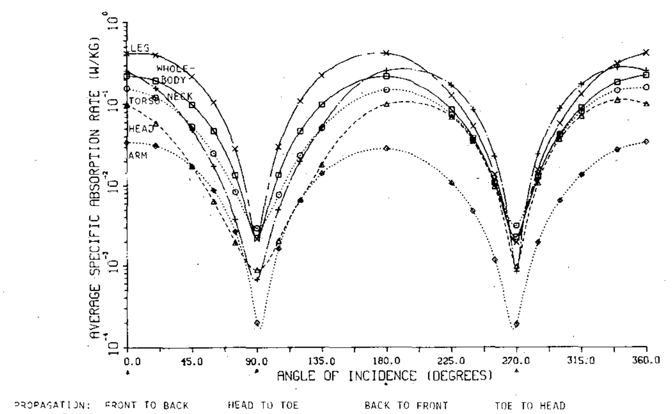

Fig. 5. Whole-body and part-body deposition for an inhomogeneous model of man in free space with an incident plane wave at 77 MHz with ***H*** arm-to-arm. Incident power density is 1 mW/cm^2.

those values. Experiments with biological-phantom figurines concur that for ***E*** arm-to-arm and $\theta = 90°$, the hottest region is in the arm [5].

The variation of whole-body and part-body energy deposition with angle is less at the lower frequency and significantly less than for ***H*** arm-to-arm. At 77 MHz there are significant differences in part-body energy deposition for ***k*** head-to-toe and toe-to-head, which polarizations would be indistinguishable with ellipsoidal and prolate-spheroidal models of man.

III. Results for *H* Arm-to-Arm

The energy deposition in a block model of man for incident plane waves having ***H*** arm-to-arm at 27.12 and 77 MHz is given in Figs. 4 and 5, respectively. At both frequencies the deposition in generally greatest in the leg and least in the arm. The distribution of deposition through the body has been shown to be in good agreement with experimental results for biological-phantom figurines for $\theta = 0°$ [4]. The variation of whole-body SAR with angle has been measured for ***H*** arm-to-arm with saline-filled figurines at 115 and 284 MHz [3]. A smooth variation was observed at the lower frequency which is similar to that shown in Fig. 5 for 77 MHz.

The most pronounced variation of part-body deposition with angle occurs for the neck. At 0° and 180° when the electric vector is vertical, the predominantly vertical current flow is constricted by the neck region, causing increased local heating. At 90° and 270° the current pattern is altered so that neck heating is not as significant.

The energy deposition for a block model of man standing on a ground plane at 27.12 and 77 MHz is given in Figs. 6 and 7, respectively. Image theory was used to allow for the effects of grounding [6]. At 27.12 MHz the deposition at 0° is markedly greater than for the same polarization in free space since the effective length of the target is doubled, thus bringing it closer to resonance. At both frequencies the deposition at 90° has little effect due to the presence of the ground plane. For these reasons the dependence of whole-body and part-body deposition upon angle in Fig. 6 are markedly greater than those in the other figures of this paper. The ratios of extrema in the curves of

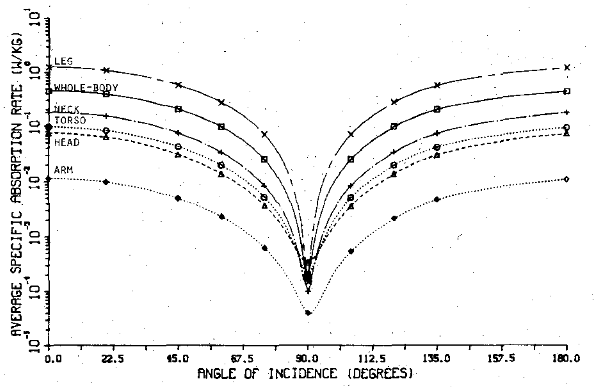

Fig. 6. Whole-body and part-body deposition for an inhomogeneous model of man under grounded conditions with an incident plane wave at 27.12 MHz with $\boldsymbol{H}$ arm-to-arm. Incident power density is 1 mW/cm^2.

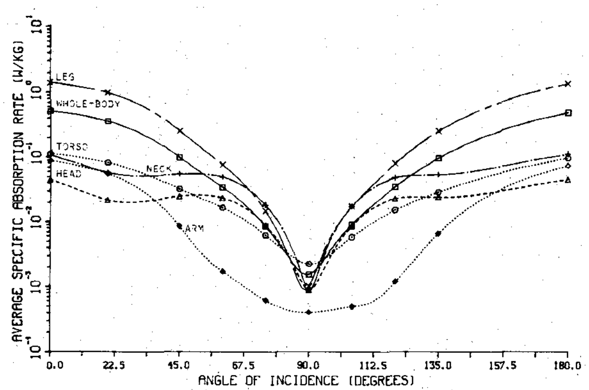

Fig. 7. Whole-body and part-body deposition for an inhomogeneous model of man under grounded conditions with an incident plane wave at 77 MHz with $\boldsymbol{H}$ arm-to-arm. Incident power density is 1 mW/cm^2.

Fig. 6 for the whole-body average and leg regions are approximately 2600 and 8700, respectively.

IV. Conclusions

In all figures presented in this paper, the extrema in whole-body and part-body energy deposition occur at or near values of θ which are integral multiples of 90° so that the standard polarizations used earlier by others correspond to the most interesting cases. In general, for the frequences considered in this paper, the energy deposition varies smoothly with angle between the extrema.

A comparison of the present solutions with those reported for the simpler models of man at the corresponding polarization [1] is made in Table II. Deposition in the simpler models is known to be strongly dependent on body mass, and most of the values for whole-body deposition of the more realistic block model fall between those for the ectomorphic (skinny) and endomorphic (fat) ellipsoidal and prolate-spheroidal models, although some are significantly different from the average-man ellipsoidal and prolate-spheroidal models, as may be seen in Table II.

TABLE II
Comparison of Present Solutions with Those for Simpler Models of Man

	Frequency	Theta	Whole-Body SAR (W/kg) for 1 mW/cm^2 Incident: Block Model	Average Man Ellipsoid	Average Man Prolate-Spheroid
$\vec{E}$ arm-to-arm	27.12 MHz	0°	0.000376	0.0010	0.0011
		90°	0.000495	0.0040	0.0021
		180°	0.000376	0.0010	0.0011
		270°	0.000496	0.0040	0.0021
	77 MHz	0°	0.00494		0.0083
		90°	0.0244		0.015
		180°	0.00496		0.0083
		270°	0.0258		0.015
$\vec{H}$ arm-to-arm	27.12 MHz	0°	0.0149	0.013	0.017
		90°	0.000134	0.0010	0.0021
		180°	0.0149	0.013	0.017
		270°	0.000135	0.0010	0.0021
	77 MHz	0°	0.221		0.24
		90°	0.00222		0.015
		180°	0.217		0.24
		270°	0.00227		0.015

If ellipsoidal or prolate-spheroidal models of man were used, only the portions from 0° to 90° would be unique in Figs. 2–6. Significant departure from such a symmetry at the higher frequency (77 MHz) shows the necessity of more detailed modeling. Part-body deposition also requires the more realistic block model of man.

The degree of variation of whole-body energy deposition with angle is markedly greater for $\boldsymbol{H}$ arm-to-arm than for $\boldsymbol{E}$ arm-to-arm and is further increased by the presence of a ground plane.

The results given here are applicable to an average sized man in free space or with grounding. Energy deposition would be different with other sizes or nonideal exposure conditions.

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