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UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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FOURTH ICTP-URSI-ITU(BDT) COLLEGE ON RADIOPROPAGATION:
Propagation, Informatics and Radiocommunication System Planning

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Miramare - Trieste, Italy

Biological Effects of Electromagnetic Fields

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1. Introduction
2. Emission and coupling parameters
3. Dielectric behaviour of biological materials
4. Dosimetry
5. Biological effects
6. Protection standards

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INTRODUCTION

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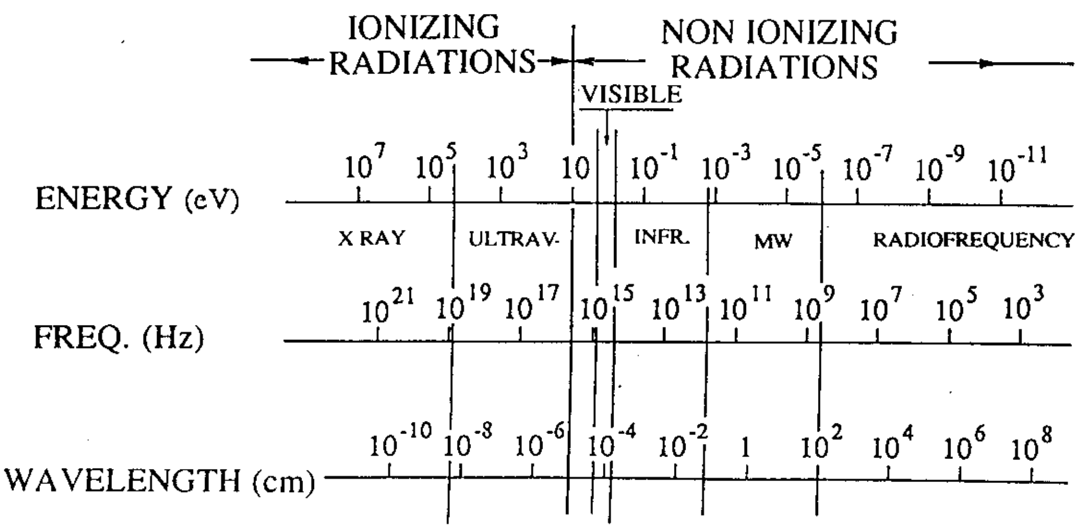
EM SPECTRUM CHARACTERISTICS



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TYPICAL APPLICATIONS

FREQUENCY	TYPICAL APPLICATIONS	WORKERS	GENERAL PUBLIC
50 Hz	power line carrier radionavigation radiolocation		rural people
< 3 MHz	AM broadcast amateur industrial RF heating	car, ship, air industry	all

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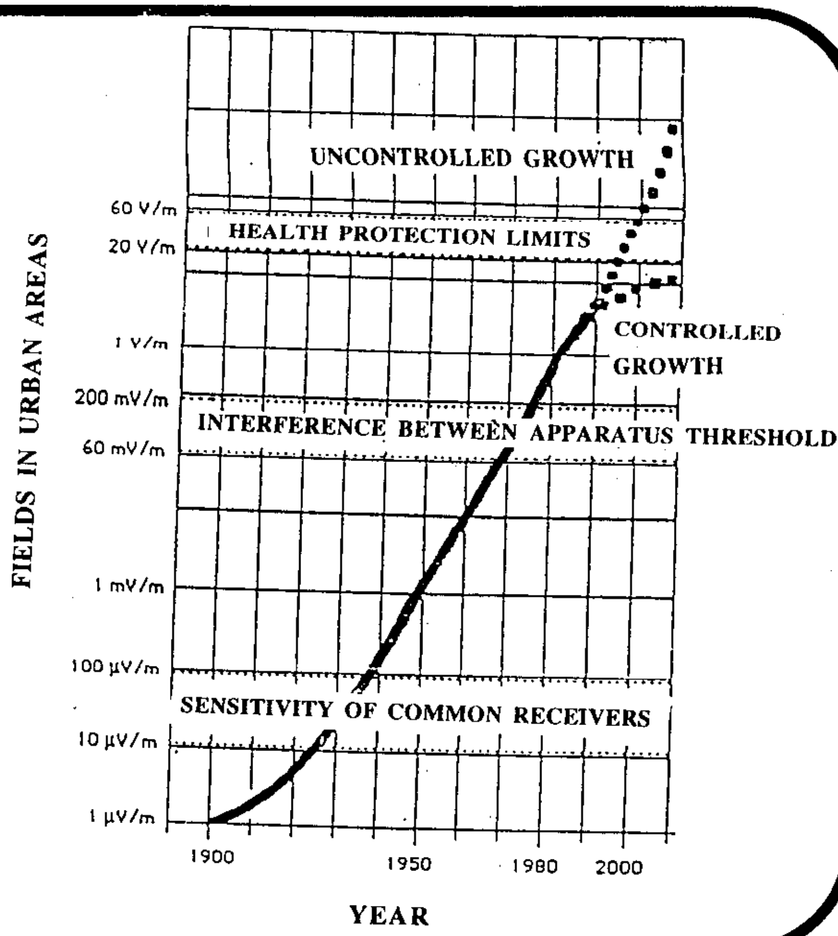
TYPICAL APPLICATIONS

FREQUENCY	TYPICAL APPLICATIONS	WORKERS	GENERAL PUBLIC
3 - 300 MHz	AM, FM broadcast, VHF - TV, citizens band, amateur industrial RF equipment medical applications	chemistry and machinery industry medical and paramedical	all patients
300-3000 MHz (0.3 - 3 GHz) MICROWAVES	mobile communications short range broadcast UHF-TV, citizens band microwave ovens industrial heating medical applications	food industry MW industry medical and paramedical	mobile phone users housewifes,
3 - 300 GHz MICROWAVES	satellite communications radar	military researcher	rural people

FIELDS IN URBAN AREAS



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EMISSION AND COUPLING PARAMETERS

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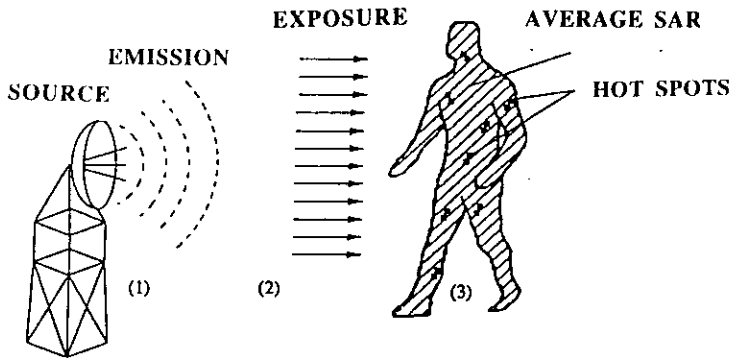
BASIC DEFINITIONS

EMISSION (from a source)

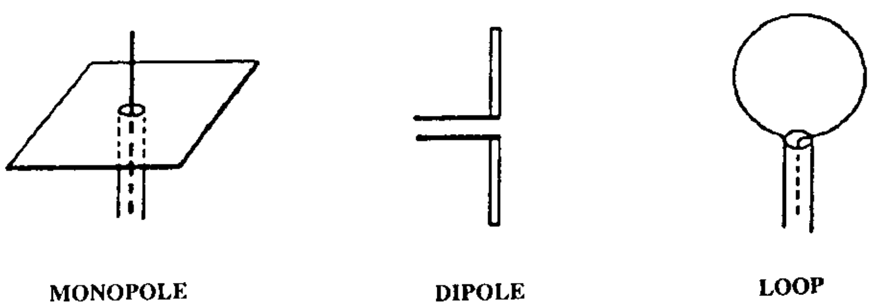
EXPOSURE (of a subject)

ABSORPTION (in the subject)

PICTURE OF THE SITUATION



EM SOURCES



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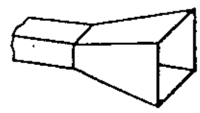
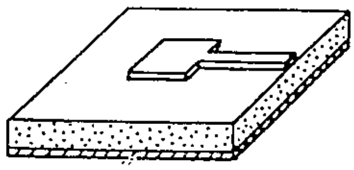
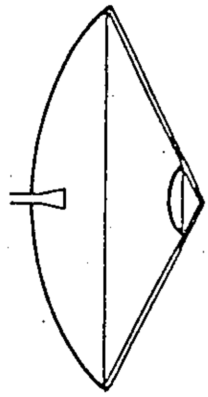
EM SOURCES



HORN



MICROSTRIP PATCH ANTENNA



REFLECTOR

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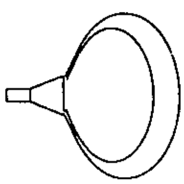
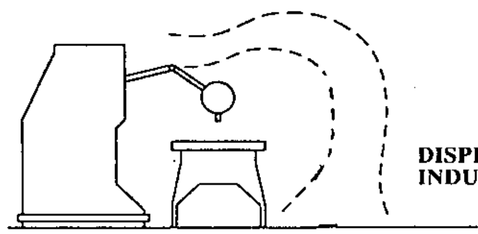
KINDS OF EMISSIONS



FOCUSED EMISSION



DISPERSION FROM
INDUSTRIAL EQUIPMENT

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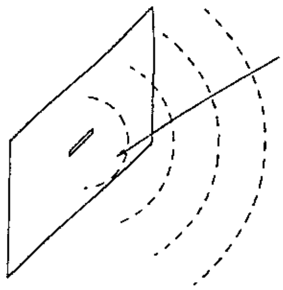
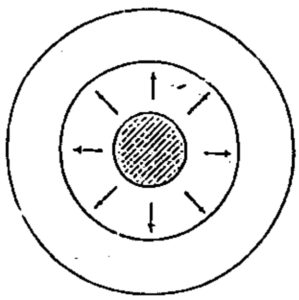
KINDS OF EMISSIONS



EMISSION FROM AN APERTURE



OMNIDIRETIONAL EMISSION

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EXPOSURE OF THE SUBJECT

The exposure is evaluated

in the body-absent situation

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CONSTITUTIVE RELATION

$$\mathbf{D} = \varepsilon_0 \, \varepsilon^* \, \mathbf{E}$$

TOTAL CURRENT

$$\mathbf{J} = g \, \mathbf{E} + j\omega \, \mathbf{D} = \left(g + j\omega\varepsilon_0\varepsilon^*\right) \mathbf{E}$$

$$\mathbf{J} = \left[g + j\,\omega\varepsilon_0 \left(\varepsilon' - j\varepsilon''\right)\right] \mathbf{E} =$$
$$= \left(g + \omega\varepsilon_0 \, \varepsilon''\right) \mathbf{E} + j\,\omega\varepsilon_0 \, \varepsilon' \, \mathbf{E}$$

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RMS VALUE FOR A VECTOR QUANTITY

$$\mathbf{A} = a_x \, \mathbf{x}_0 + a_y \, \mathbf{y}_0 + a_z \, \mathbf{z}_0$$

$$a_{x\,eff} = \sqrt{\frac{1}{T}\int_0^T a_x^2 \, dt}$$

$$a_{y\,eff} = \sqrt{\frac{1}{T}\int_0^T a_y^2 \, dt}$$

$$a_{z\,eff} = \sqrt{\frac{1}{T}\int_0^T a_z^2 \, dt}$$

RMS VALUE FOR A VECTOR QUANTITY

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$$A_{eff} = \sqrt{\frac{1}{T}\int_0^T \mathbf{A} \cdot \mathbf{A}\, dt} = \sqrt{\frac{1}{T}\int_0^T \left(a_x^2 + a_y^2 + a_z^2\right) dt} =$$

$$= \sqrt{a_{x\ eff}^2 + a_{y\ eff}^2 + a_{z\ eff}^2}$$

EXPOSURE PARAMETERS

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E_{rms} (V/m) rms value of the time harmonic EM field of period T

$$E_{rms}^2 = \frac{1}{T}\int_0^T |\mathcal{E}(t)|^2 dt$$

H_{rms} (A/m) rms value of the time harmonic EM field of period T

$$H_{rms}^2 = \frac{1}{T}\int_0^T |\mathcal{H}(t)|^2 dt$$

EXPOSURE PARAMETERS

S (W/m²) Time average Power density

$$S = \frac{1}{T}\int_0^T S(t)dt$$

For a TEM plane wave

$$S = H_{rms} \cdot E_{rms} = E_{rms}^2 / 377 = H_{rms}^2 \cdot 377$$

EXPOSURE CONDITIONS

Reactive field

radiative field

Near-field

Far-field $\left\langle \begin{array}{l} r \geq \lambda \\ r \geq \frac{D^2}{\lambda} \end{array} \right.$

ABSORPTION PARAMETERS

SAR (W/Kg) Specific absorption Rate

Absorbed power, per unit of mass

FULL BODY AVERAGE SAR (W/Kg)

Total Absorbed power divided by the total mass of the body

LOCAL SAR (W/Kg)

Absorbed power in an infinitesimal volume at a point in the body divided by the mass of the infinitesimal volume

SAR EVALUATION

$$SAR = \frac{\omega \varepsilon_0 \varepsilon'' E_{in}^2}{\rho} = \frac{4.186\ \rho\ c\Delta T}{\Delta t}\ (W/kg)$$

E_{in} = magnitude of the internal field (V/m)RMS

ρ = mass density (kg/m^3)

ε_0 = free space permittivity (F/m)

ε'' = imaginary part of the relative complex permittivity

c = specific heat (cal/Kg °C)

ΔT = temperature variation (°C)

Δt = exposure time (s)

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INDUCED CURRENT DENSITY

$$J_{in} = \sqrt{g^2 + (\omega\varepsilon_0\varepsilon')^2}\,E_{in}$$

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FOOT CURRENT

Total current crossing the feet toward the ground

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DIELECTRIC BEHAVIOUR OF BIOLOGICAL MATERIALS

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DIELECTRIC POLARIZATION

$$P = P_1 + P_2$$

P = dielectric polarization

P_1 = atomic and electronic displacement

P_2 = dipolar reorientation

DEBYE THEORY

$$\mathbf{P}_1 = \varepsilon_0 \chi_1 \mathbf{E}$$

$$\frac{d\mathbf{P}_2}{dt} = \frac{1}{\tau}\left(\varepsilon_0 \chi_2 \mathbf{E} - \mathbf{P}_2\right)$$

DEBYE THEORY

For a time harmonic field

$$\mathcal{E}(t) = \mathrm{Real}\left(\mathbf{E}\, e^{j\omega t}\right)$$

$$\mathbf{P} = \mathbf{P}_1 + \mathbf{P}_2 = \varepsilon_0 \left(\chi_1 + \frac{\chi_2}{1 + j\omega\tau}\right) \mathbf{E}$$

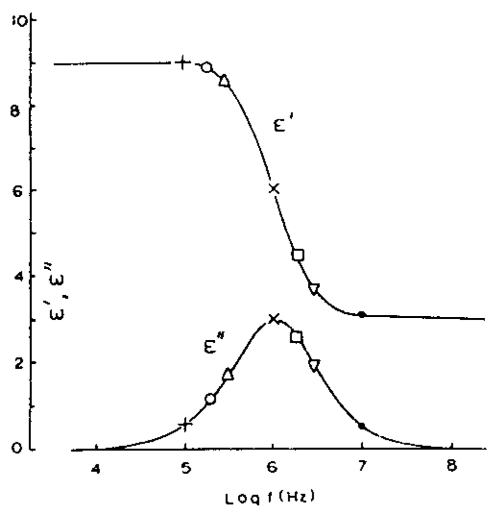
COMPLEX PERMITTIVITY

$$\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P} = \varepsilon_0 \varepsilon^* \mathbf{E}$$

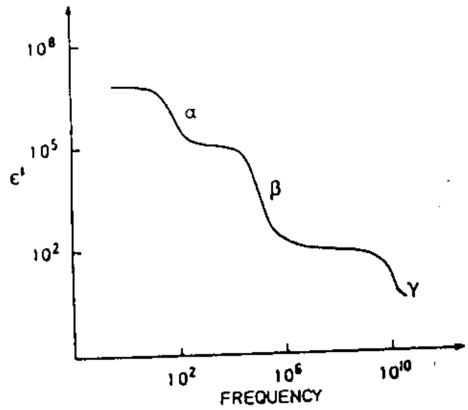
$$\varepsilon^* = \varepsilon' - j\varepsilon''$$

$$\varepsilon' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + (\omega\tau)^2} \qquad \varepsilon'' = \frac{(\varepsilon_s - \varepsilon_\infty)\,\omega\tau}{1 + (\omega\tau)^2}$$

DEBYE-TYPE RELAXATION PROCESS



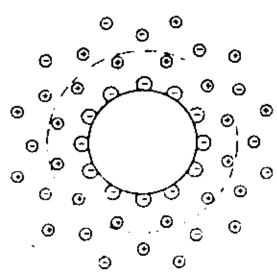
TYPICAL TISSUE



α - RELAXATION

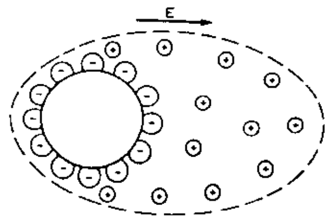
Counter-ions diffusion polarization

Is associated with the electrical double layer surrounding cells



α - RELAXATION

Polarization results from the net displacement
of counterions as a result of the influence
of an external electric field



α - RELAXATION

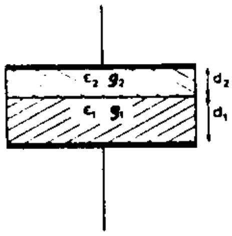
the relative permittivity may reach values greater

than 10^4 at frequencies below 1 kHz.

β - RELAXATION

Interfacial polarization (Maxwell-Wagner effect)

Is associated with the charging of the interfaces within the material



β - RELAXATION

with $g_2 \approx 0$

$$C_1 = A\varepsilon_0 \frac{\left(\varepsilon_1 - j\,\frac{g_1}{\omega\varepsilon_0}\right)}{d_1}$$

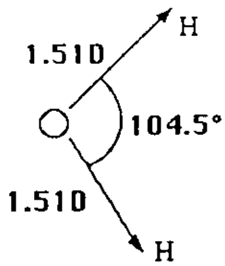
$$C_2 = \frac{A\varepsilon_0\varepsilon_2}{d_2}$$

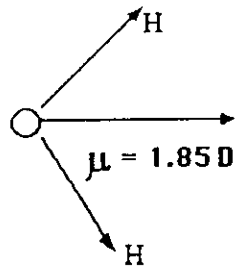
$$C = \frac{C_1\,C_2}{C_1 + C_2} = \frac{A\varepsilon_0\varepsilon_2\left(\varepsilon_1 - j\frac{g_1}{\omega\varepsilon_0}\right)}{d_2\left(\varepsilon_1 - j\frac{g_1}{\omega\varepsilon_0}\right) + d_1\varepsilon_2}$$

$$\varepsilon_s = \varepsilon_2\,\frac{d}{d_2} \qquad \varepsilon_\infty = \frac{\varepsilon_1\varepsilon_2 d}{d_2\varepsilon_1 + d_1\varepsilon_2}$$

γ - RELAXATION

Dipolar polarization of free water
is associated with the partial orientation
of permanent dipoles





γ - RELAXATION

Considering an ensemble of indipendent dipoles with moment μ, the externally imposed Electric field will exert a torque of magnitude $\mu E \sin\theta$, where θ is the angle between the dipole and the field.

At equilibrium

$$\langle \cos\theta \rangle \approx \frac{\mu E}{3KT} \qquad P \approx \frac{N \mu^2 E}{3KT}$$

γ - RELAXATION

After application of the E-field, the ensemble of dipoles approach equilibrium after a time

$$\tau \approx \frac{4 \pi \eta a^3}{K T} \qquad \text{(Stokes law)}$$

a = radius of the dipole

η = viscosity of the medium

γ - RELAXATION

For pure water

$$\tau \approx 8 \text{ ps}$$

corresponding to a relaxation frequency of

$$f_r = \frac{1}{2 \pi \tau} \approx 20 \text{ GHz} \qquad \text{(at 25 °C)}$$

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DOSIMETRY

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DOSIMETRY

f < 30 MHz

- Analytical techniques
- Empirical formulation
- Numerical techniques

30 MHz < f < 300 MHz

- Numerical techniques

f > 300 MHz

- Analytical techniques

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f < 30 MHz

Wavelength of the incident radiation large compared to the size of the body

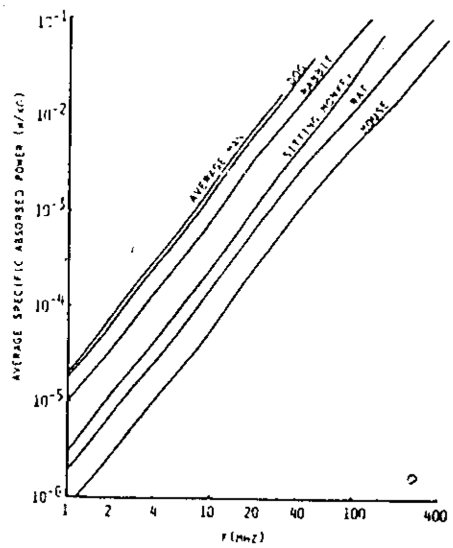
ANALYTICAL TECHNIQUES

quasi-static solution of Maxwell's equations

spheroidal and ellipsoidal models of man

useful information about the average SAR

AVERAGE SAR



The average SAR increases proportionally to the square of the frequency

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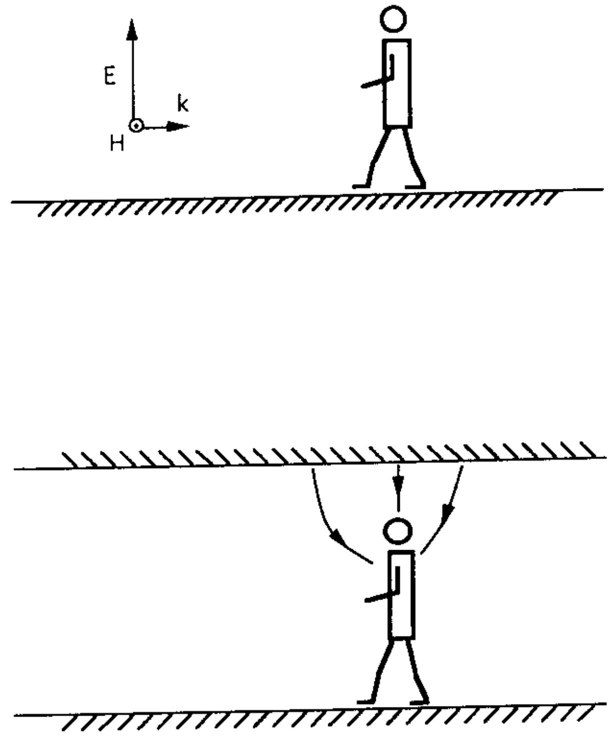
EMPIRICAL FORMULATION



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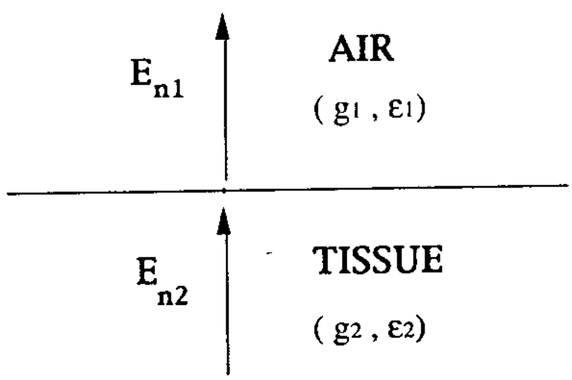
PLANAR SIMULATION



$$E_{n2} = \frac{g_1 + j\omega\varepsilon_1}{g_2 + j\omega\varepsilon_2} E_{n1}$$

$f = 50$ Hz

1 = Air $g_1 = 10^{-13}$(S/m) $\varepsilon_0\varepsilon_1 = 10^{-11}$ (F/m)

2 = Tissue $g_2 = 10^{-1}$(S/m) $\varepsilon_0\varepsilon_2 = 10^{-5}$ (F/m)

$$E_{n2} = \frac{j\omega\varepsilon_1}{g_2} E_{n1}$$

$$\frac{E_{n2}}{E_{n1}} = \frac{E_{IN}}{E_{OUT}} \cong 4 \cdot 10^{-8}$$

EMPIRICAL FORMULA

$$|J_{IN}| = \omega\varepsilon_0 E_{OUT} = 0.108\ h_m^2 \frac{f_{MHz}}{A_{eq}}$$

$$SAR = \frac{J_{IN}^2}{g\ \rho}$$

h_m = human height

A_{eq} = Equivalent area of the cross section of the body

ρ (kg/m3) is the density of the considered tissue

g (S/m) is the conductivity of the considered tissue

SAR AVERAGE

$$SAR_{av} = \frac{\text{Total power absorbed}}{\text{Weight}} =$$

$$= \frac{(0.108\ h_m^2 f_{MHz}\ E_{OUT})^2\ h_m}{70\ g\ A} \cdot 10^{-2} \qquad \frac{W}{kg}$$

f = 20 MHz; A = 400 cm^2; h_m = 1.75 m

g = 0.5 S/m ; E_{OUT} = 61.4 V/m

SAR_{AV} = 0.21 W/kg

SAR PEAK

$$SAR_{peak} = \frac{(0.108\ h_m^2\ f_{MHz}\ E_{OUT})^2}{g\ \rho\ A_{eq}^2(0)} \cdot 10^2 \quad \frac{W}{kg}$$

$A_{eq}(0)$ = Equivalent area of the ankle

Under plane wave exposure the SAR_{peak} is ever located in the ankles

FOOT CURRENT

The current flowing through the feet into a conductive ground

$$\frac{I_f}{E_{inc}} = 0.108\ h_m^2\ f_{MHz} \qquad \frac{mA}{V/m}$$

30 < f <300 MHz

Body resonance region

NUMERICAL TECHNIQUES

FDTD METHOD

MOMENT METHOD

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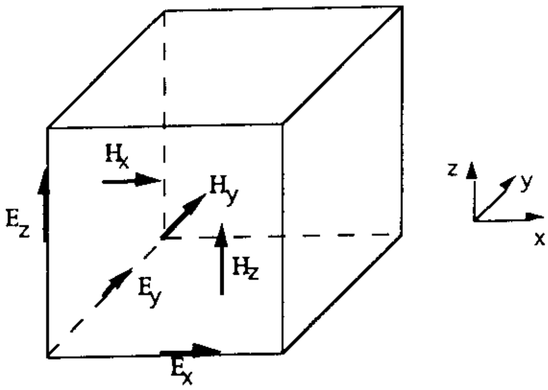
FDTD METHOD



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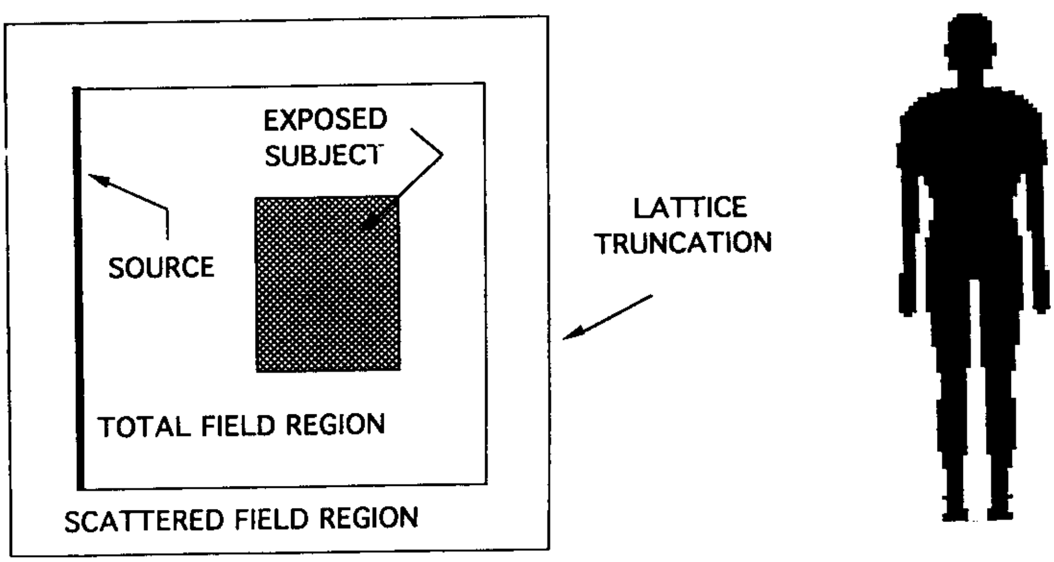
FDTD / CONSIDERED GEOMETRY



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BASIC ABSORPTION PARAMETERS

$$SAR(i,j,k) = \frac{g\left[\left(\widehat{E}_x^2 + \widehat{E}_y^2 + \widehat{E}_z^2\right)\right]}{2\,\rho}$$

$$\hat{I}(h) = \sum_{i,j} \delta^2\, \widehat{E}_z(i,j,h) \sqrt{g^2 + [2\,\pi\, f\, \varepsilon_0\, \varepsilon_r]^2}$$

$$I(h,\ n) = \sum_{i,j} \delta^2\, [E_z(i,j,h,n)\, s + \varepsilon_0\, \varepsilon_r \frac{E_z(i,j,h,n) - E_z(i,j,h,n-1)}{\delta t}\,]$$

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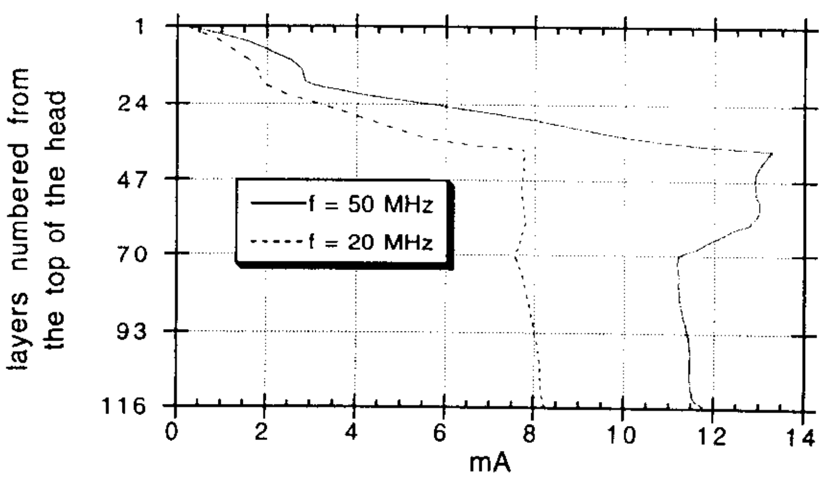
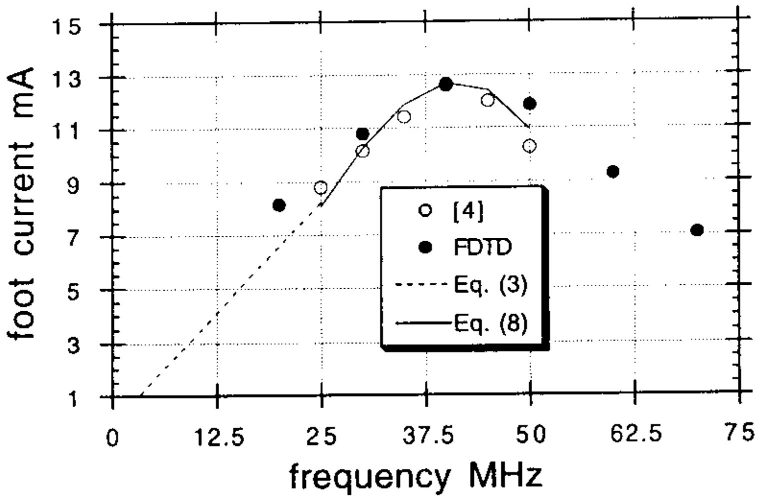
INDUCED CURRENT DISTRIBUTION

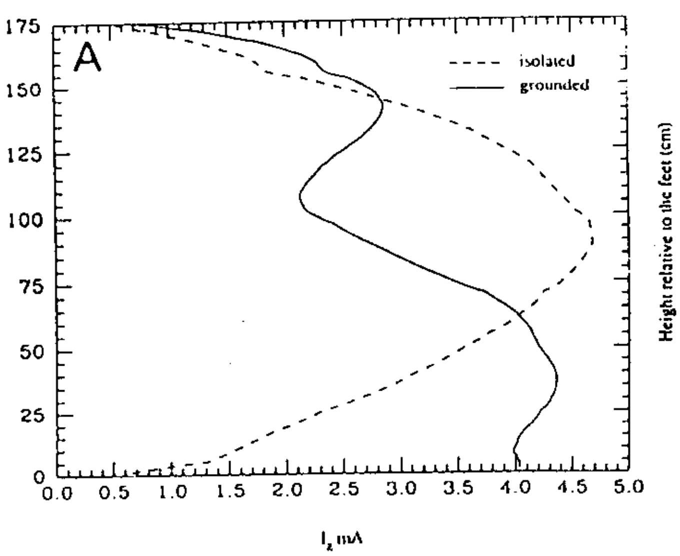


FOOT CURRENT



CURRENT DISTRIBUTION

(f = 100 MHz)



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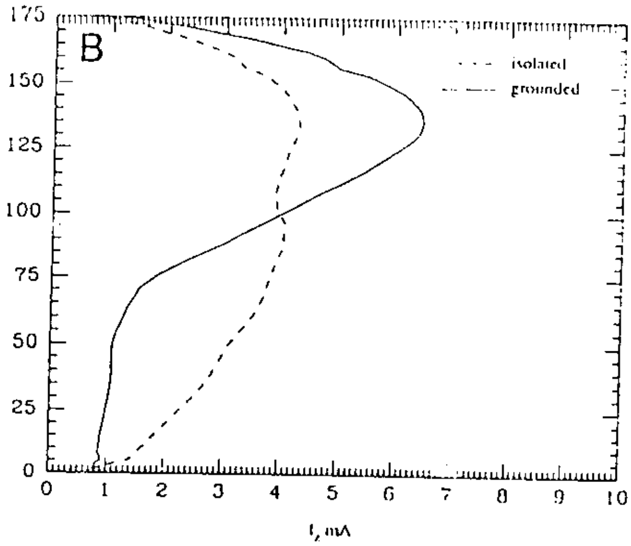
CURRENT DISTRIBUTION

(f = 160 MHz)



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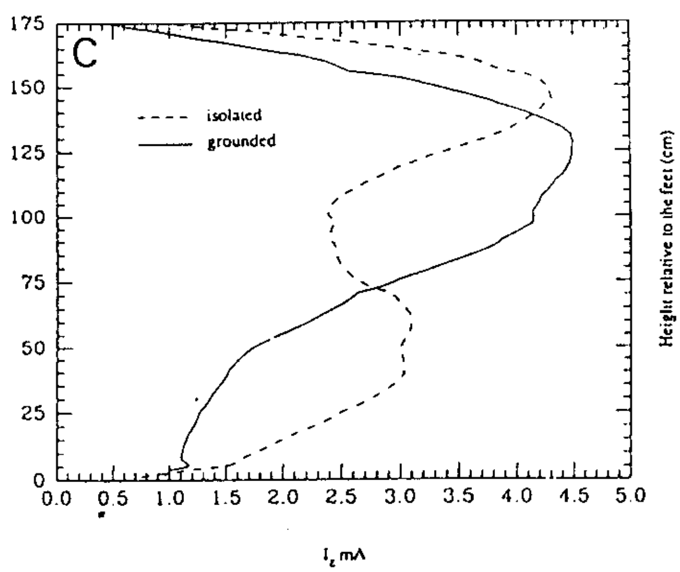
CURRENT DISTRIBUTION

(f = 200 MHz)



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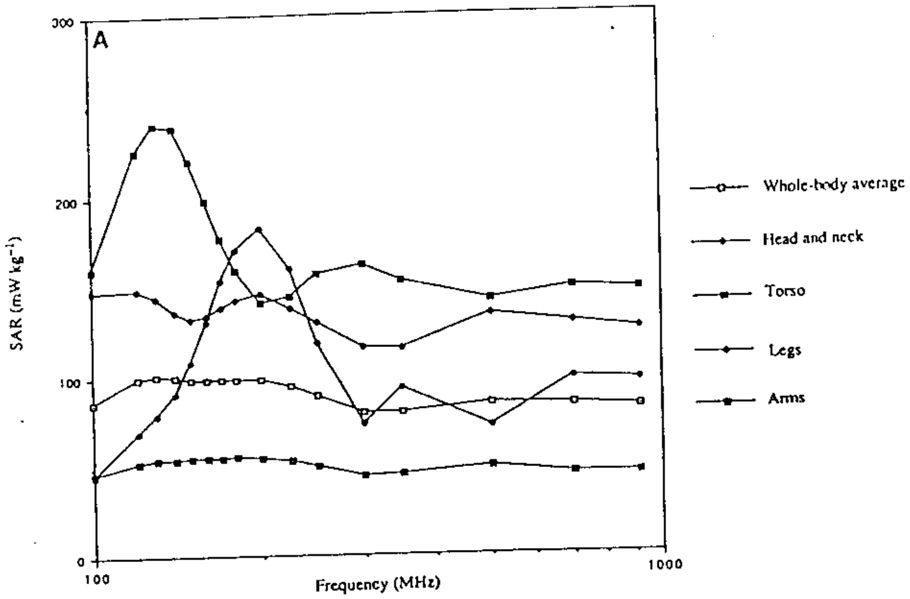
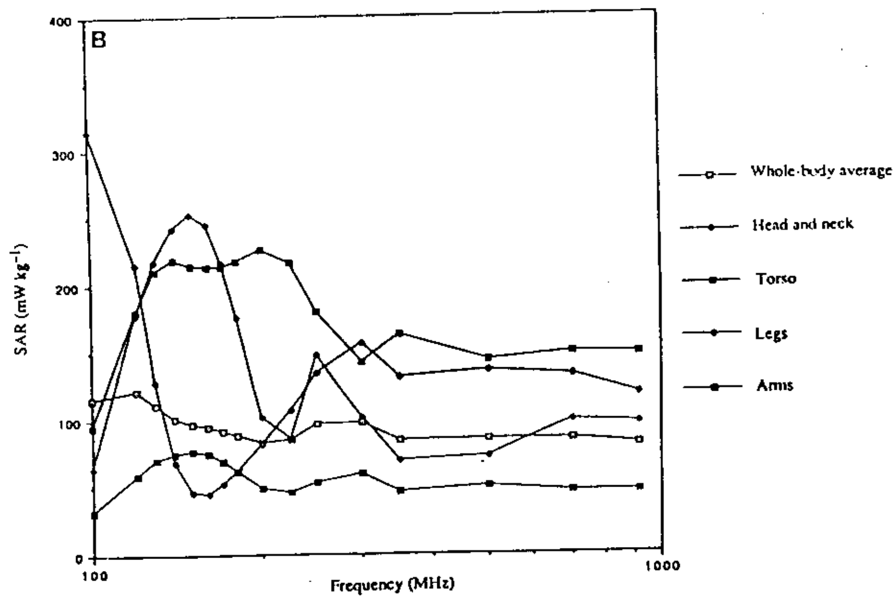
PART-BODY AVERAGE SAR

ISOLATED



PART-BODY AVERAGE SAR

GROUNDED



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f > 300 MHz

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ANALYTICAL TECHNIQUES

Analytical solution of Maxwell's equations
for cylindrical models

This solution appear to be a good
approximation beyond 400 MHz

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AVERAGE SAR

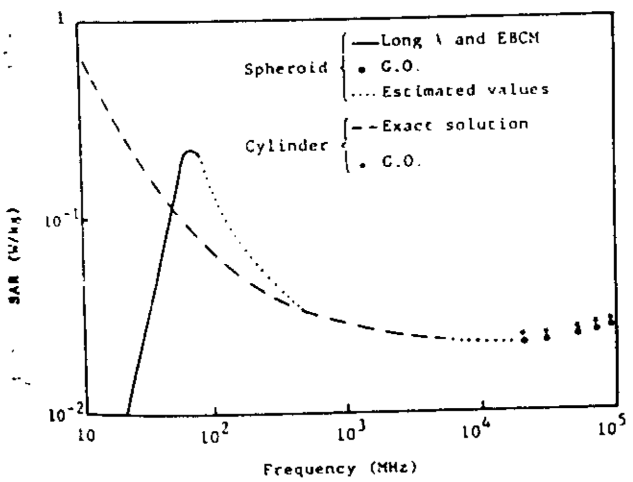

Fig. 4. Average SAR in 70-kg prolate spheroidal and cylindrical models of man (electric polarization). The radius of the cylinder is 11.28 cm, the length is 1.75 m, and the spheroid has the same height as the cylinder; the power density of incident radiation is 1 mW cm⁻². G.O. = geometrical-optics solution; EBCM = extended-boundary-condition method.

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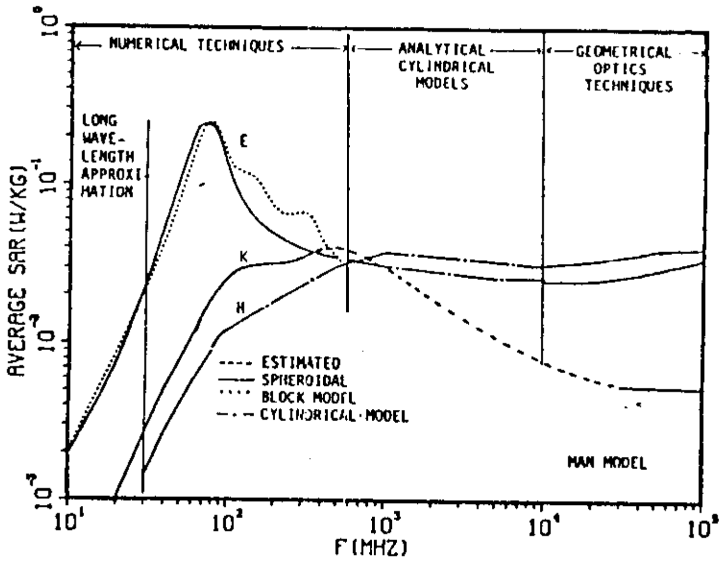
AVERAGE SAR



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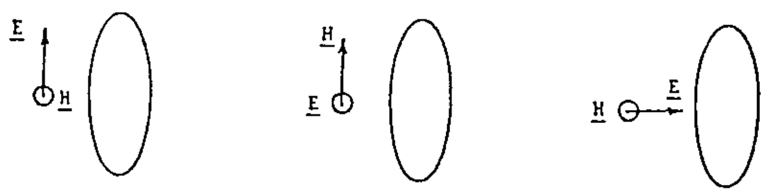
TYPES OF INCIDENCE



E Polarization	H Polarization	K Polarization
E_e strong	E_e weak	E_e weak
E_h strong	E_h weak	E_h strong

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NEAR FIELD EXPOSURE

CELLULAR PHONES