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INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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H4.SMR/841-11

FOURTH ICTP-URSI-ITU(BDT) COLLEGE ON RADIOPROPAGATION:
Propagation, Informatics and Radiocommunication System Planning

30 January - 3 March 1995

Miramare - Trieste, Italy

Biological Effects of Electromagnetic Fields

Part II

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LA SAPIENZA

BIOLOGICAL EFFECTS

ICTP Trieste 1995

LA SAPIENZA

BASIC PHYSICAL LAWS OF THE ELECTROMAGNETIC INTERACTIONS

1) Relaxation processes at microscopic level

2) Constitutive relations at macroscopic level

3) rate of energy absorption per unit mass (SAR)

DOSIMETRY AND THERMAL EFFECTS

- Cooperative
- Non linear
- Resonant processes at
- cell
- cell membrane
- nucleous levels

NONTHERMAL (WEAK FIELD) EFFECTS

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BASIC PHYSICAL LAWS OF THE INTERACTION

a) INTERACTION WITH ELECTRIC CHARGES (Ions)

b) INTERACTION WITH DIPOLES (Atoms, Molecules)

c) RESONANT INTERACTIONS

BASIC PHYSICAL LAWS OF THE INTERACTION

a) INTERACTION WITH MONOPOLES (IONS)

$\mathbf{F} = q\,\mathbf{E}$ [ELECTRIC FORCE]

$\mathbf{F} = q\,(\mathbf{v} \times \mathbf{B})$ [MAGNETIC FORCE]

b) INTERACTION WITH DIPOLES (MOLECULES)

$\mathbf{T} = \mathbf{m}_e \times \mathbf{E}$ [ELECTRIC COUPLE]

$\mathbf{T} = \mathbf{m}_m \times \mathbf{B}$ [MAGNETIC COUPLE]

$\mathbf{F} = \nabla\,(\mathbf{m}_e \times \mathbf{E})_{\theta=cost}$ [DIELECTROPHORETIC FORCE]

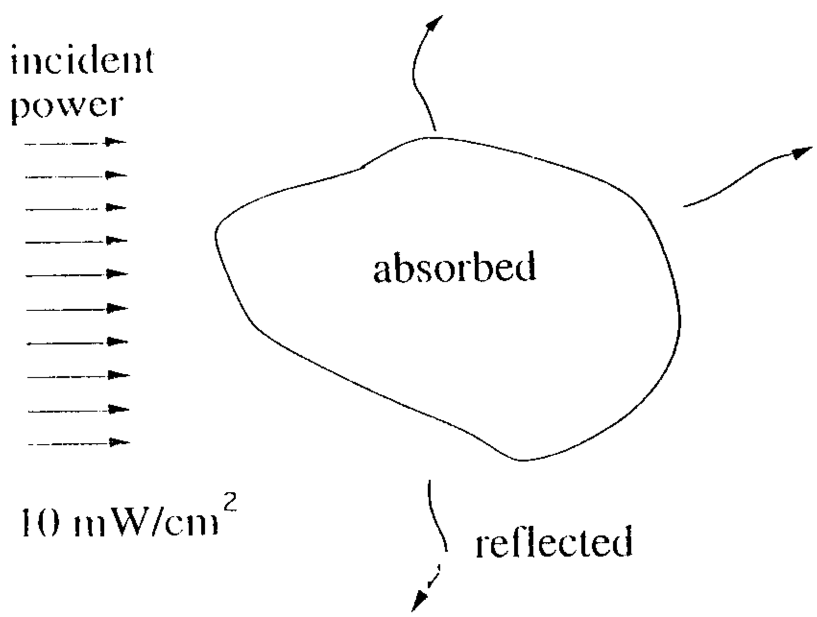
BASIC PHYSICAL LAWS OF THE INTERACTION

c) RESONANT INTERACTIONS

$$m \frac{d^2x}{dt^2} + \beta \frac{dx}{dt} + k\,x = q\,E_x$$ [VIBRATIONAL RESONANCES]

$$I \frac{d^2\theta}{dt^2}\,\mathbf{i}_0 + F \frac{d\theta}{dt}\,\mathbf{i}_0 + \mathbf{m}_e \times \mathbf{E} = 0$$ [ROTATIONAL RESONANCES]

THERMAL EFFECTS



EXAMPLE

Area of the human body: 1.8 m^2

Absorbed power ≅ 0.5 incident power (at MW frequencies)

Energy absorbed in 24 hours for exposure to 10 mW/cm^2

100 x 1.8 x 0.5 x 24 = 2160 W h= 1860 Cal

For a body exposed to 10 mW/cm^2

after about 1/2 h the body temperature

increases of 1°C

BIO- HEAT EQUATION

$$\frac{dT}{dt} = \frac{(SAR + W_M - W_C - W_B)}{c}$$

T = temperature (°C)

SAR = specific absorption rate (W/kg)

W_M = metabolic heating rate (W/kg)

W_C = heat loss due to thermal conduction (W/kg)

W_B = power dissipated by blood flow (W/kg)

c = specific heat (Joule/ kg°C)

IN VIVO EXPERIMENT

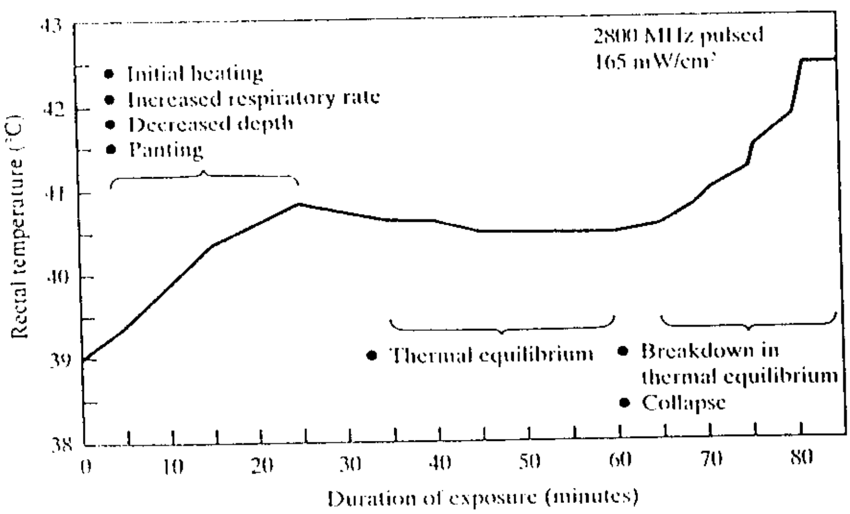
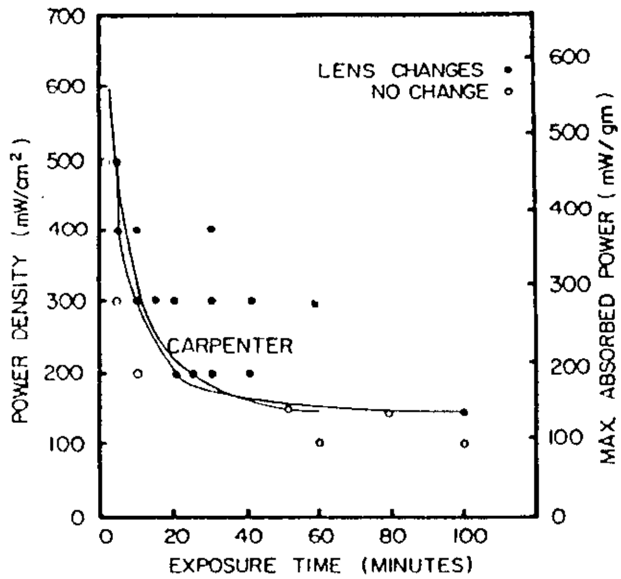


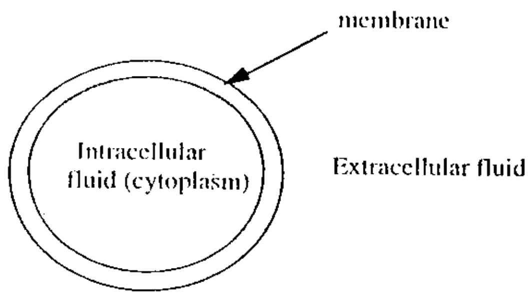
FIGURE 15.3. The triphasic response of the rectal temperature of dogs exposed to 2800 MHz pulsed microwaves at 165 mW/cm². Initial heating is followed by a period of thermal equilibrium and finally, if the exposure is continued, by thermoregulatory collapse.

MICROWAVE CATARACTOGENESIS



Threshold for cataractogenesis in rabbits exposed to near-zone 2450 MHz radiation

CELLULAR MEMBRANE



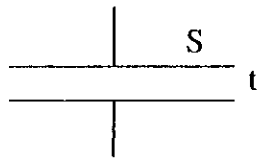
cell radius (r) = 25 - 250 μm

membrane thickness (t) = 2 - 20 nm (20 - 200 Å)

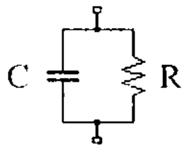
membrane constitution (phospholipids, H_2O, Na+, K^+, sugars)

EQUIVALENT CIRCUIT

Locally the membrane is like a parallel-plate capacitor



as a first approximation the membrane
has the following equivalent linear circuit



$$C = \varepsilon_0 \varepsilon_r \frac{S}{t}$$

$$R = \rho \frac{t}{S}$$

EXAMPLE

$\varepsilon_r = 2.5$ $\rho = 10^6\ \Omega \cdot m$ $(g = 10^{-6}\ S/m)$

$t = 10\ nm = 10^{-8}\ m$

$r = 150\ \mu m = 1.5 \cdot 10^{-4}\ m$

$S = 4\pi r^2 \cong 28 \cdot 10^{-8}\ m^2$

$C = 610\ pF$

$R = 35\ k\Omega$

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EXAMPLE

f(kHz)	$1/\omega C$ (kΩ)		
1	260	$R \ll 1/\omega C$	f < 1 kHz
10	26		
100	2.6	$R \gg 1/\omega C$	f > 100 kHz

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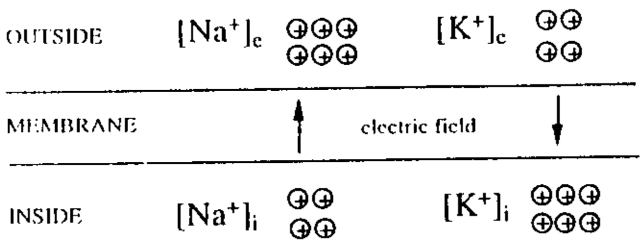
Usually the circuital parameters are expressed referring to an area of the membrane of 1-cm^2

$$\frac{C}{S}\left(\frac{\mu F}{cm^2}\right) \qquad R\,S\,(\Omega cm^2)$$

in the previous example:

$$\frac{C}{S} = 0.22\left(\frac{\mu F}{cm^2}\right) \qquad R\,S = 10^2\,(\Omega cm^2)$$

NERNST EQUATION



Different concentrations of various ions

EXPLANATION

Ions moves from the high concentration region to the low concentration region. An electric field, that contrasts with this flow, develops, and an equilibrium situation is reached.

NERNST EQUATION

The difference of potential at the ends of the membrane is evaluated with reference to the external potential

$$V_K = \frac{kT}{q} \log \frac{[K^+]_e}{[K^+]_i}$$

tipically for neurons $V_K \cong -70$ mV

$$V_{Na} = \frac{kT}{q} \log \frac{[Na^+]_e}{[Na^+]_i}$$

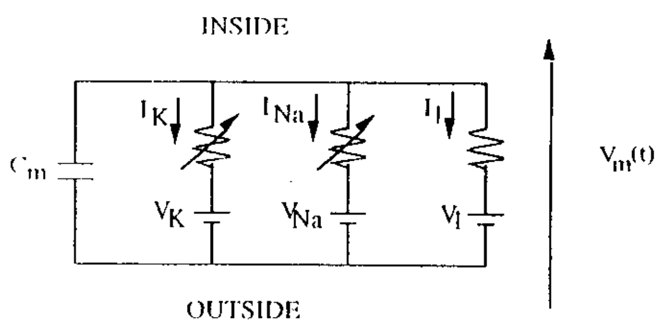
tipically for neurons $V_{Na} \cong 50$ mV

k = Boltzmann's constant

T = absolute temperature

q = ion charge

HODGKIN - HUXLEY MODEL



Convention: $V_m(t)$ inside relative to outside.

CONNOR and STEVENS MODEL

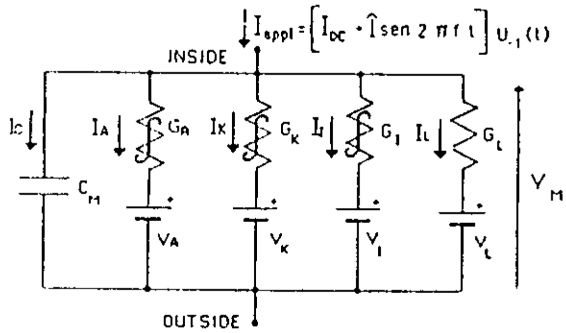


FIG 1. Circuital model of a neuronal cell membrane. Exciting current: I_{appl}. Membrane response: V_M. Parameters shown in the figure are discussed in (4). $U_{-1}(t)$ is the Heaviside function.

MEMBRANE RESPONSE SIMULATED

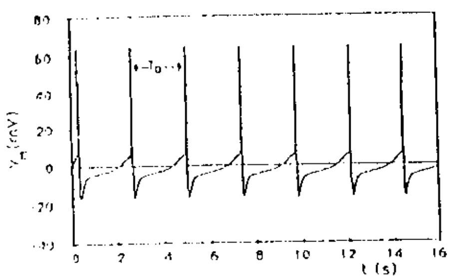


FIG 2a. Membrane response to a DC current I_{DC} = 0.5 nA. The current is applied at t=0. The interval T_0 between two APs can be controlled by varying I_{DC}.

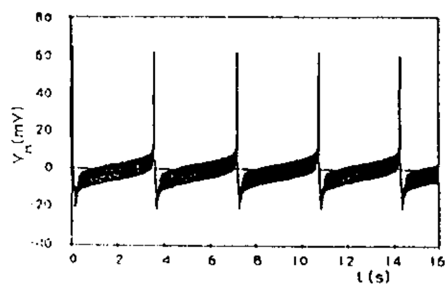


FIG 2b. The same as FIG 2a with the addition of the sinusoidal component of the applied current. $\hat{I}$ = 30 nA, f=70 Hz.

MEMBRANE RESPONSE EXPERIMENTS

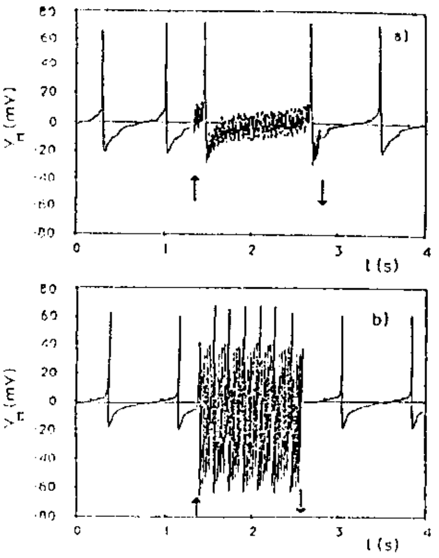
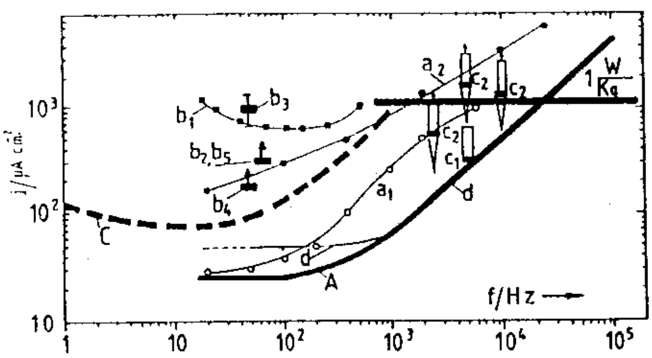


FIG 8. Recordings of the transmembrane voltage versus time for a pacemaker neuron stimulated by a sinusoidal current (f = 70 Hz): a) $\hat{I}$ = 2.5 nA; b) $\hat{I}$ = 15 nA
Stimulation timewidth indicated by arrows

STIMULATION OF SENSORY RECEPTORS



Threshold values of the electric current density for different biological effects.

- a_1, a_2: Stimulation of sensory receptors immediately underneath surface electrodes;
- b_1 - b_6: ventricular fibrillation thresholds for stimulation times of 1 second or longer (different authors, see text);
- C: threshold curve for extra-systole elicitation, stimulation 1 second or longer;
- c_1, c_2: extra-cellular stimulation thresholds of single cells,
- d: frequency dependence of stimulation thresholds for nerve/muscle systems;
- A: "envelope" threshold value curve for stimulating effects.

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PROTECTION STANDARDS

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BASIC DOSIMETRIC PARAMETERS

$f < 0.1$ MHz

Internal current density

ANSI limit $J < 35\, f_{MHz}$ mA/cm^2

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BASIC DOSIMETRIC PARAMETERS

$0.1 < f < 6000$ MHz

Whole body average SAR; local peak SAR

IEEE/ANSI LIMIT
CONTROLLED ENVIRONMENT

Whole body average SAR < 0.4 W/kg

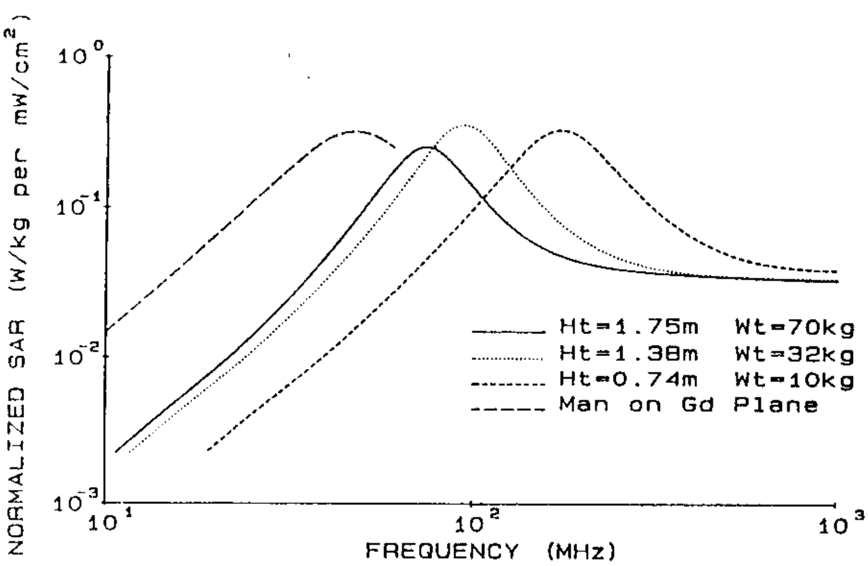
Local peak SAR < 8 W/kg
(averaged over any 1g of tissue)

IEEE/ANSI LIMIT
UNCONTROLLED ENVIRONMENT

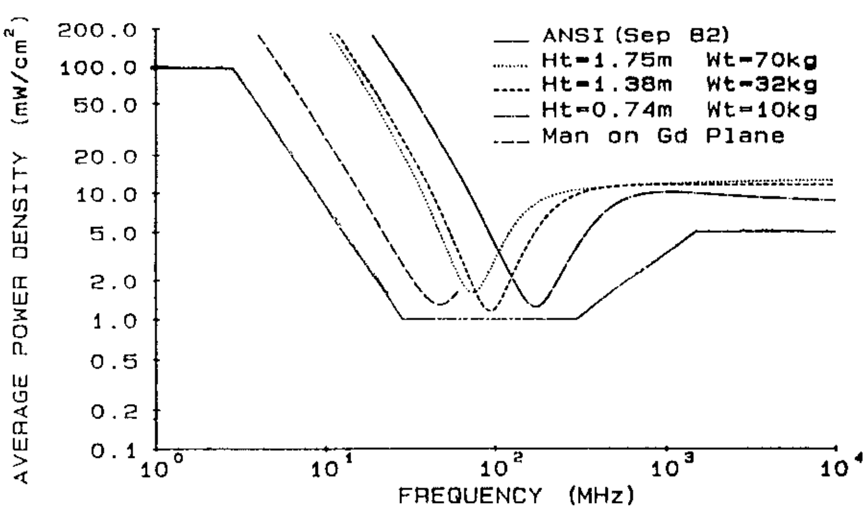
Whole body average SAR < 0.08 W/kg

Local peak SAR < 1.6 W/kg
(averaged over any 1g of tissue)

SAR FOR DIFFERENT SIZE HUMANS



POWER DENSITIES LIMIT SAR TO 0.4 W/kg



COMPARISON OF RFR SAFETY GUIDELINES