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Effects of Electromagnetic Fields On Living Organisms

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Summary

Preliminaries

1. Electric field $\underline{E}$ and flux density $\underline{D}$
2. Thermodynamics and energy
3. Dosimetry and SAR
4. Thermal considerations
5. Nervous system and blood-brain barrier
6. Influence of parameters of microwave exposure
7. Non-thermal, micro-thermal, and isothermal effects

Preliminaries

- ***frequency*** number or repetitions per second
  hertz Hz, kilohertz kHz, megahertz MHz, gigahertz GHz, (terahertz THz)

- ***wavelength*** x frequency = ***constant***
  wavelength in metre, smaller if frequency is high

- ***constant*** speed of phase ***in the medium considered***
  in **vacuum** : *speed of light* = 300.000 km/s

wavelength in vacuum	6.000 km	at 50 Hz
	3 m	at 100 MHz
	33.3 cm	at 900 MHz
	3 cm	at 10 GHz
	3 mm	at 100 GHz

wavelength smaller in human body (factor 1/9 at 900 MHz)

- ***microwaves (MW)*** frequency range

frequency	100 MHz to 300 GHz	(up to 1 THz)
wavelength	3 m to 1 mm ***in vacuum***	(down to 0.3 mm)

wavelength at MW is of the same order of magnitude as objects currently used

metre, decimetre, centimetre, millimetre

hence : specific biological effects ?

1. Electric field vector $\underline{E}$ and flux density vector $\underline{D}$

- ***electric field vector $\underline{E}$*** (V/m)

  defined : ratio of force exerted onto electric charge q

  by charge Δq in the limit case that Δq tends to zero $\underline{E} = q / 4\pi\varepsilon_o r^2 \underline{a}_r$

- ***polarization vector $\underline{P}$*** *electric dipole moment per unit volume* (C/m^2)

  when a material is submitted to an applied electric field, it becomes polarized :

  electric dipoles created or transformed into material : ***dielectric properties***

- ***displacement flux density*** or ***electric flux density vector $\underline{D}$*** (C/m^2)

  $\underline{D} = \varepsilon_o \underline{E} + \underline{P}$ valid for all materials, including biological, even when :

- $\underline{P}$ has not the same direction as $\underline{E}$: *anisotropic material*
- $\underline{P}$ is delayed with respect to $\underline{E}$: *lossy material*
- $\underline{P}$ is not proportional to $\underline{E}$: *nonlinear material*

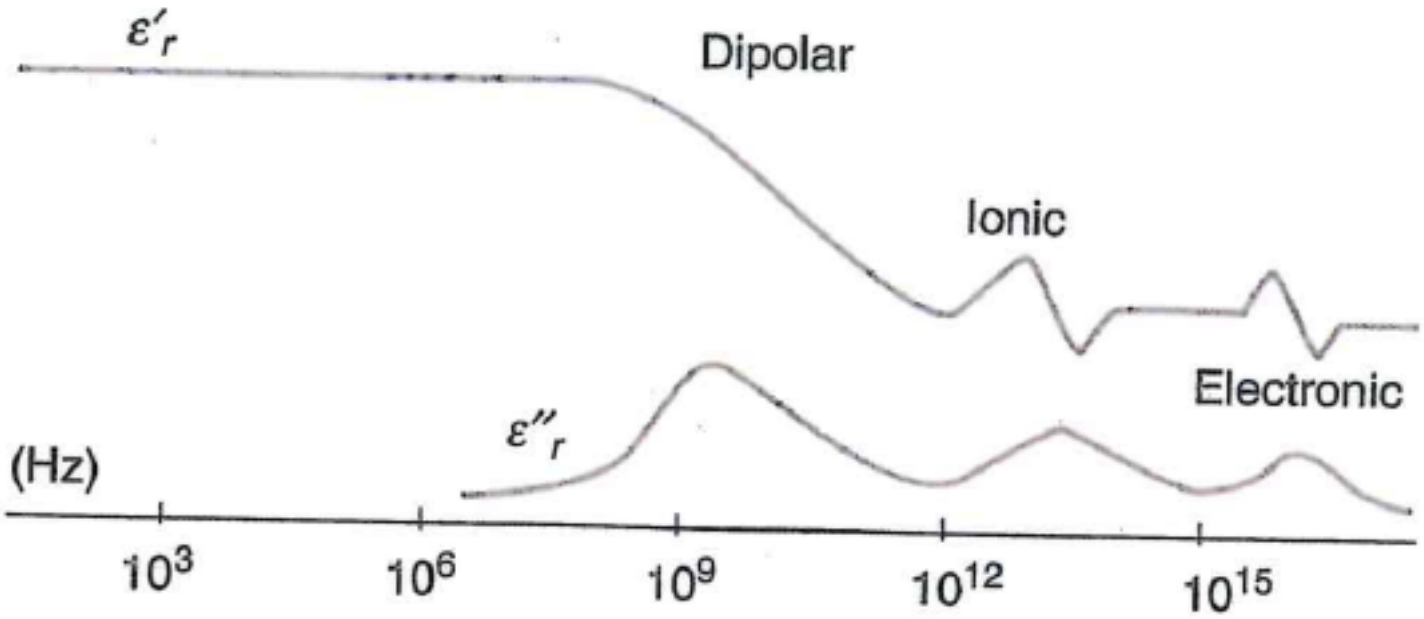
- ***dielectric polarization***

  rather complicated phenomenon

  may be due to a variety of mechanisms

1. Electric field vector *E* and flux density vector *D*

typical variation of real and imaginary parts of relative permittivity as a function of frequency



1. Electric field vector *E* and flux density vector *D*

- ***only the internal field*** in a material can influence the material !
  MW absorbed power converted into heat
  main absorbent **water**

- ***skin effect*** well known in engineering

- wave penetration: limited by ***skin effect***
  effect characterized by ***skin depth*** δ
  at 3 depths δ : power density = 1% of value on skin
  internal organs « shielded » by external layer (less in children !)

typical skin depths in human tissue

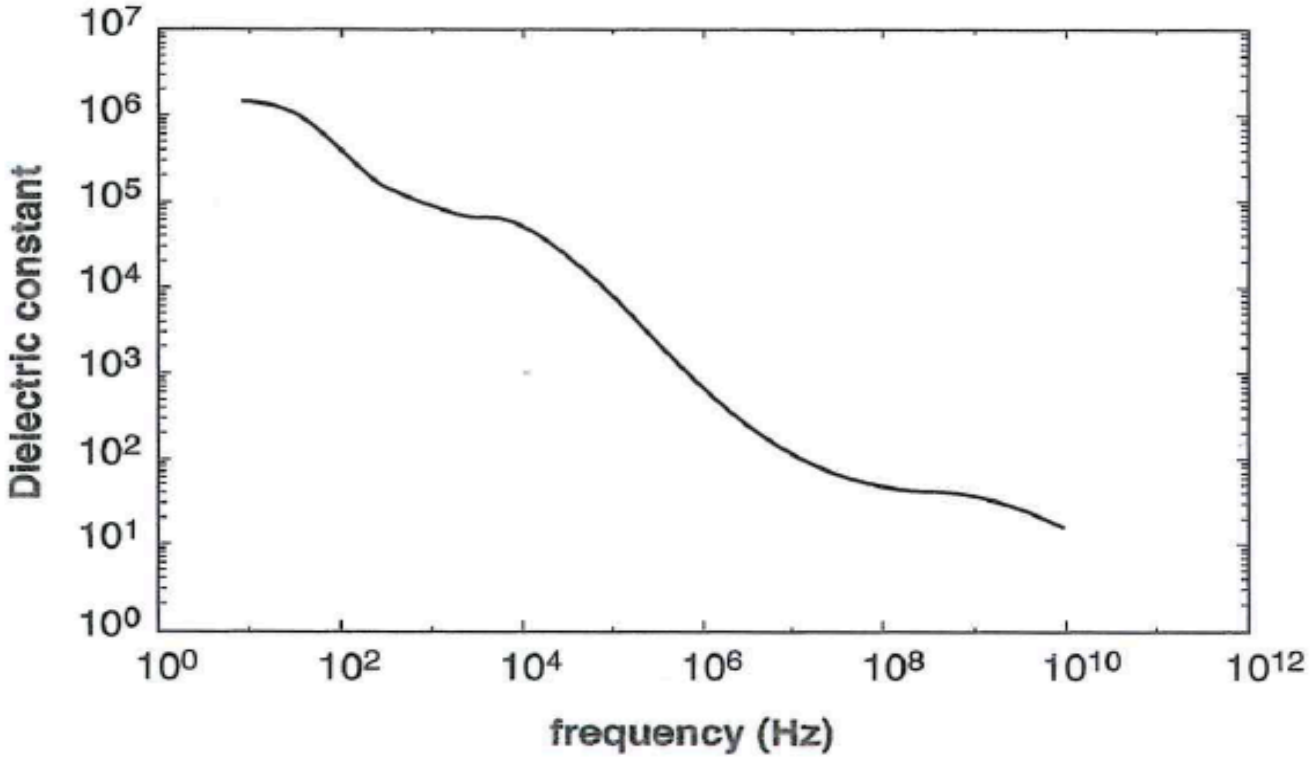
	Radio FM	Transmitter TV	Telephony Mobile	Telephony Mobile
frequency (MHz)	100	450	900	1800
skin depth (cm)	3	1.5	1	0.7
1% depth (cm)	**9**	**4.5**	**3**	**2**

1. Electric field vector *E* and flux density vector *D*

- more significant biological effects at *MW* than at *LF* and *ELF* ?

not necessarily true :

dielectric constant 10 000 times larger at *ELF* than at microwaves



Dielectric constant of living material (muscle) as a function of frequency

2. Thermodynamics and energy

EM properties are not the only way to characterize materials

- ***classical theory of thermodynamics***
  deals with time-averaged properties of systems
  with large number of particles
  avoids description of individual motions of the particles
- definition of ***entropy*** $S = dQ / T$
  Q is the heat and T is temperature in kelvin
- ***second law of thermodynamics*** $dS \geq 0$
  equality : reversible processes – inequality : irreversible processes
- thermodynamics handles four parameters :
  volume, pressure, ***temperature***, entropy
- considers interaction of the system with its environment
  dealing with only three types of systems
  - *isolated* system : no exchange at all with environment
  - *closed* system : can exchange energy with environment
  - *open* system : can exchange both energy and mass with environment

2. Thermodynamics and energy

- a ***simple medium*** – lossless dielectric – exhibits ***no dispersion***
  its electrical characteristics do not vary with frequency
  exact thermodynamic significance for EM energy :
  difference of internal energy per unit volume with and without the field

- not true anymore when ***variation with frequency*** : ***dispersion***
  EM energy cannot be rationally defined as thermodynamic quantity
  dispersion implies energy dissipation : **absorption**

3. Dosimetry and SAR

- ***below 100 kHz*** : ***current density*** is most often used

- ***MW exposure levels*** usually described in ***power density*** (W/m^2)
  main dosimetric measure : ***specific absorption rate*** (SAR) (W/kg)
  watts of absorbed power per kilo of absorbing material

- using only SAR does not help considering ***nonthermal*** effects as possible

- SAR : time derivative of incremental energy *dW* absorbed/dissipated
  in incremental mass *dm* contained in volume element *dV* of density ρ

$$SAR = (d/dt)(dW/dm) = (d/dt)\,[dW / \rho(dV)]$$

4. Thermal considerations

- ***thermal measurements***
  - *calorimetric* methods : in vitro
  - *thermometric* methods : special non-perturbing thermometers
  - *thermographic* methods : specific cameras
    (we measured ΔT on human face due to use of GSM)

- ***rate of temperature change*** in subcutaneous tissue

$$\Delta T/\Delta t = (SAR + P_m - P_c - P_b) / C$$

ΔT temperature increase
Δt exposure duration
P_m metabolic heating rate
P_c rate of heat loss per unit volume due to thermal conduction
P_b rate of heat loss per unit volume due to blood flow
C specific heat

4. Thermal considerations

- a number of ***specific thermals effects*** have been observed
  they depend on the spatial distribution of the SAR
- ***behaviour*** is the most sensitive measure of effects
- ***pulsed fields*** produce effect at power level smaller than continuous waves

some results

- SAR 1 W/kg produces 1°C increase in human body (thermoregulation)
- ocular damage (cataracts) observed at 100 mW/cm^2 above 1 GHz
- corneal damage observed on monkeys at 2.6 W/kg at 2.45 GHz
- same damage at 0.26-0.5 W/kg after pre-treatment phenythiazines/miotics
- retinal damage on monkeys at 4 W/kg at 1.25-2.345 GHz pulsed fields
- malformations above 15 W/kg, with more than 5°C increase

4. Thermal considerations

measurements on ***behaviour-cognitive functions*** on exposed rats

- 45 min., 2.45 GHz, power density 1mW/cm^2, avge whole-body SAR 0.6 W/kg
  show ***retarded learning*** while performing to obtain food rewards
  this deficit can be reversed by treatment before exposure

  (Lai et al., 1989)

- 21 months, 2 h/day, 970 MHz CW and 970 GHz pulsed, 9.7 GHz CW
  level of WHO limit for human adapted for rat (length)
  after 15 months of exposure : ***loss of memory***
  exposed rats do not recognize a known object after 15 minutes
  (confirmation of previous studies)

  (Adang et al., 2008)

- same study, ***after 21 months***
  increase in monocytes percentage in peripheral blood circulation
  mortality in exposed groups reaches almost twice value in sham group
  accelerated aging ?

5. Nervous system and blood-brain barrier (BBB) 1/2

- ***experiments on rats***

  dose- and frequency-dependent changes observed on :

  nicotinamide adenine dinucleotide NADH

  adenosine triphosphate ATP

  creatine phosphate CP

  all three key compounds in brain energy metabolism

- ***experiments on rabbits***

  push-pull canula inserted in centre of pain reception in brain

  CW stimulation 2.45 GHz applied by coaxial cable in acupuncture point

  variation in *pain threshold* and *neurotransmitter release* : proportional

- ***blood-brain barrier***

  differential filter permitting selected biological substances passage

  from blood to brain

  advantage : protecting the physiochemical environment of brain

  disadvantage : disease-treating agents and drugs cannot penetrate brain

5. Nervous system and blood-brain barrier (BBB) 2/2

about ***30 investigations*** on animals ***reported in 2001***

(*Lin, 2001*)

those showing ***increased BBB permeability***
in ***equal number*** with ***those who do not***

- observed at ***SAR high, low, very low*** (0.016 W/kg ; GSM limit : 1.6 W/kg)
- ***both CW and pulsed microwaves*** can open up BBB for albumin passage
- specific results
  - exposed animals are at risk for opening BBB (odds ration 3.8 ; $P = 0.0004$)
  - response independent of pulse repetition rate
  - same response for CW compared with pulse modulated waves
  - response independent of SAR in interval $0.016 < SAR < 2.5$ W/kg
    it rises for SAR > 2.5 W/kg

6. Influence of parameters of microwave exposure 1/1

can be significant

- different ***durations*** of acute exposure lead to different biological effects
  different long-term effects may occur after repeated exposure
- ***waveform***
  pulsed- versus continuous-wave exposure
  plane- versus circularly-polarized wave exposure
- ***pattern of energy absorption*** in the body

can SAR be used as only determining factor in evaluating effects ?

- measurements on ***NADH, ATP,* and *CP*** : *MW* inhibition of mitochondrial electron transport chain function of ATP production ?
- *evoked body movements* associated with high-peak low-average power
  investigated on mice
  increase proportional with SA (dose) at whole-body constant SAR
  can be provoked by one single pulse
- influence of *below 300 Hz modulation components* in the MW signal
- non-linear effects : *frequency windows*, *power windows*

7. Nonthermal, microthermal, and isothermal effects 1/3

- ***soviet norms*** : 10 μW/cm^2 URSS to compare to 10 mW/cm^2 USA (***ratio 1 000!***)
  difference due to acceptance or rejection of possibility of nonthermal effects
  (Michelson and Dodge, 1971)

- *microwave syndrome*
  East European studies revealed variety of *asthenic problems*
  (headache, perspiration, emotional instability, irritability, tiredness, somnolence, sexual problems loss of memory, concentration, insomnia, …)
  exposure of US embassy in Berlin in the 60ies
  causal link difficult to establish, no control group
  multifactorial effect ?
  hypersensibility : 5% of population ?

- *MW as a trigger*
  biological resonances are properties of the *whole system*
  random energy supply to many modes may excite a single mode : strong!
  (Fröhlich, 1980)

7. Nonthermal, microthermal, and isothermal effects 2/3

- ***heartbeat stimulation*** and *MW* control effect on heart electrical activity
  hearts of chicken embryos have been isolated
  exposed to low MW power density because of skin effect
  pulse-modulated 2.45 GHz, 10 mW peak power, 10% duty cycle
  pulse interval decreases : heartbeat synchronizes and increases

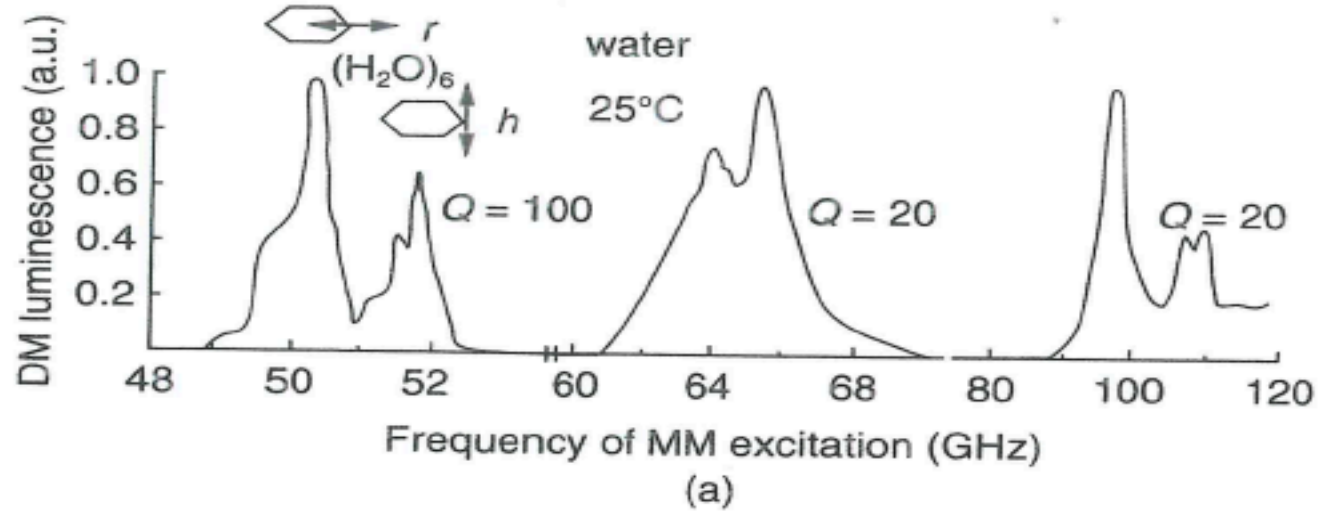
  (Tamburiello et al., 1991)

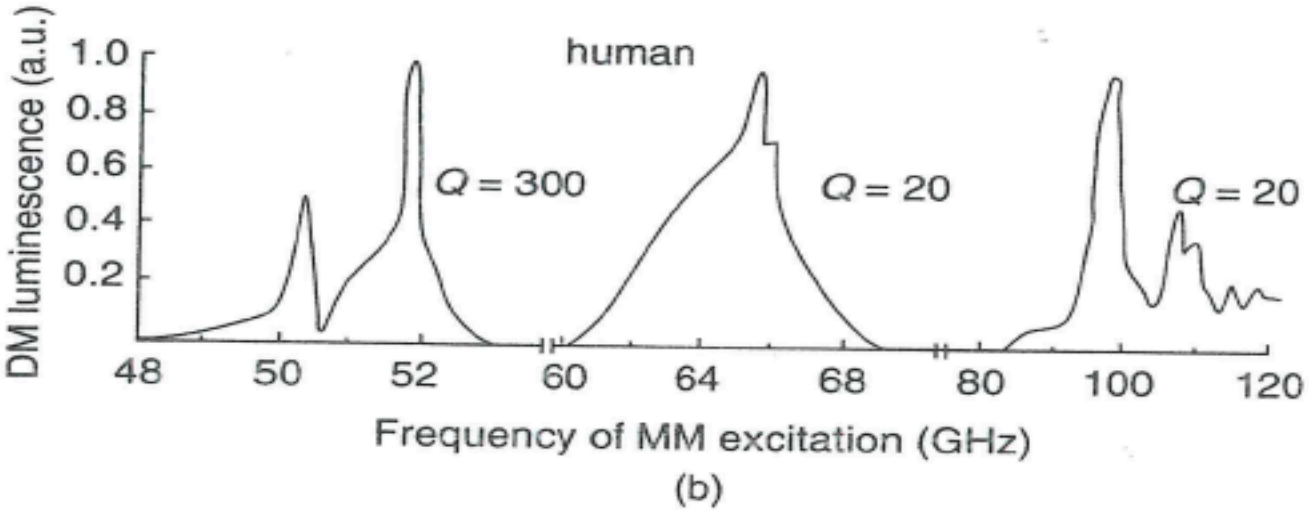
- ***luminescence*** requires thermodynamics for correct analysis
  conversion of heat into EM radiation (frequency down conversion)
  efficiency can be > 1 at expense of thermal energy of crystal lattice
  thermodynamic *closed systems* : can exchange energy with environment
- exposing *air-water* ***interface to millimeter (MM) waves*** : Saratov phenomenon
  - power density usually 1 $\mu W/cm^2$
  - *MM* wave excitation in sweeping mode
  - response of water in decimeter (*DM*) region observed at 0.4 and 1.0 GHz
  - *DM* radiation power low : 10^{-16} W

(Chukova, 2001)

7. Nonthermal, microthermal, and isothermal effects 3/3

- *various liquid media have been tested* (varied salinity, alcohol, glycerin, etc.)
  human tissue has also been tested





(Chukova, 2001)