"*Modulated RF energy: Mechanistic viewpoint on the health implications*"

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Modulated radio-wave sources

1. Cellular telephones, pagers
2. Commercial TV (VHF & UHF & digital)
3. Commercial radio (AM & FM)
4. Marine and aviation radio and radar
5. Satellite television / communications / global positioning (GPS)
6. Dispatch: fire, and police

Modulated radio-wave sources *(cont'd)*

7. Police radar
8. Amateur (ham) radio operators, international SW broadcasts
9. Cordless telephones, baby monitors, wireless toys
10. Computer monitors
11. Microwave ovens (leakage)
12. Microwave links for computers, television, and telephone

Modulated RF

Technology	Typical modulation	Ratio of BW to CW frequency	Ratio of peak-to-avg. amplitude	Example
AM broadcasting	Amplitude	Very small << 1	~2	AM radio, ~1 MHz
FM radio and television	Frequency	Very small << 1	~1	FM radio, ~100 MHz
Mobile communications	Pulse and frequency	Very small << 1	~10	TETRA, GSM, TDMA, CDMA, UMTS, ~400 to 2,000 MHz
Radar	Pulse	Small < 1	$\lesssim$100	Airport control radar ~4 GHz
Ultrawideband spread spectrum	Short pulse	Large ~1	$\lesssim$100	2-20 GHz military applications

Potential biological significance of RF modulation

- Changes in ratio of peak-to-average signal level
- Changes in frequency content of a signal
- Frequency of RF (carrier wave + modulation) approximately equal to carrier wave
- Modulation of power in RF signal covers frequency ~0 to 10 KHz

Types of Modulation Tested in Animal Tumorigenicity Assays

Modulation Tested (MHz Modulation)		Number of Studies	Effect on Tumor Incidence	
			Increase	No Increase
5500	UWB	1	0	1
435 to 2450	PW	3	1	2
860 to 9400	CW	10	2	8
915	AM	1	0	1
900	GSM	8	2	6
836 to 1500	TDMA	6	0	6
836 to 903	FM	3	0	3
845	CDMA	2	0	2
849	DAMPS	1	0	1
836	FDMA	1	0	1
1616	Iridium	1	0	1
Total # of Studies		**37**	**5**	**32**

(adapted from Elder, 2005)

Investigating modulated RF, key scientific components

Physics of RF / electric and magnetic fields

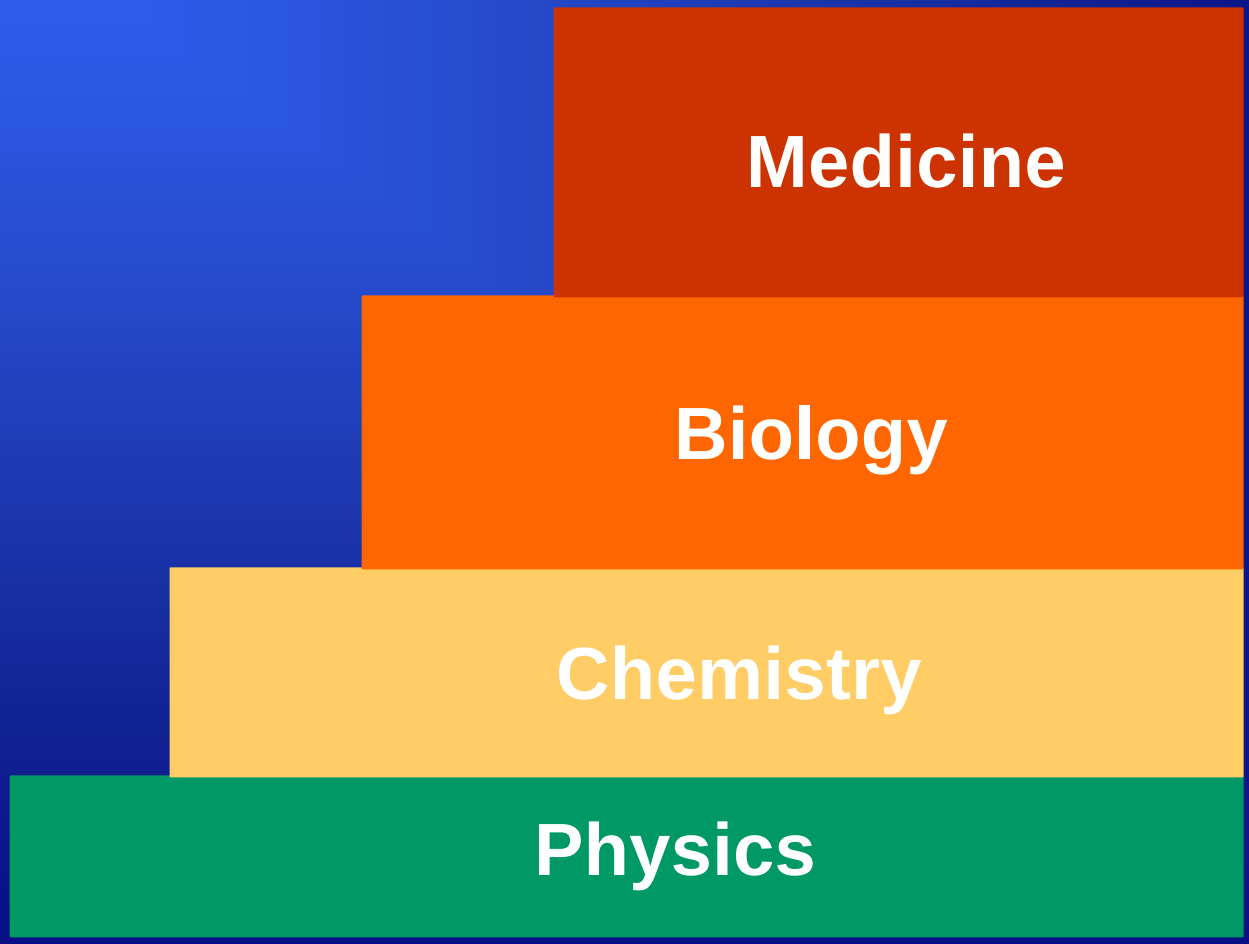
Dosimetry of RF / homogeneity of exposure

Cell biology / molecular biology / biochemistry

Animal toxicology / physiology / pathology

Epidemiology / statistics

Living organisms rely upon same laws that govern simple systems



Mechanistic thinking can provide insights on how modulated RF affects biology

- The principles of physics have been exhaustively validated
- Electromagnetic laws are accepted to be invariant in time and space
- Physics has been found valid in complex systems (chemistry, biology, technology, medicine, *etc*.)
- Simple conservation laws (energy, motion, charge, *etc*.) are universally applicable – biology is no exception

RF carrier waves are specified by wavelength and frequency

- frequency (n or *f*) = cycles per second, or Hz; *e.g.*, RF @ 1 GHz (1 billion cycles per second)
- period of oscillation (T) = 1 / *f*
  @ *f* = 1 GHz, T = 1 nanosecond = 1 ns
- frequency (*f*) ´ wavelength (?) = speed of light (*c*)
- wavelength (?) = distance between crests
  @ *f* = 1 GHz, ? = 30 cm (in air); ? ~ 10 cm (in tissue)
- speed of light (*c*) = 3 ´ 10^8 m/sec
- penetration depth of 1 GHz into tissue is ~ 3 cm

The electromagnetic spectrum: frequency *versus* photon energy

frequency (*f*) ´ wavelength (?) = speed of light (*c*)

Energy (*E*) = Planck's constant (*h*) ´ frequency (*f*)

Example, for 2 GHz (= 2 ´ 10^9/sec),

E = (4.1 ´ 10^{-15} eV-sec)(2 ´ 10^9/sec)

E = ~ 10^{-5} eV

"eV" = "electron volt" = is an energy unit for atoms and molecules

1 eV = 1.6 picoerg = singly charged particle accelerated through 1 V

The electromagnetic spectrum: wavelength, frequency, and energy

ELF	AM Radio	FM / TV	Microwaves, Radar	Radiant Heating, Infrared	Sun Lamps, Visible Light	Medical X-Rays	Gamma Rays from Radio-activity
3000 km 100 Hz 0.4 peV	3 km 100 kHz 0.4 neV	3 m 100 MHz 0.4 μeV	3 mm 100 GHz 0.0004 eV	30 μm 10^{13} Hz 0.04 eV	300 nm 10^{15} Hz 4 eV	3 Å 10^{18} Hz 4 keV	0.3 pm 10^{21} Hz 4 MeV

Power Lines

Cell Phones ~1 to 2 GHz

Human body heat

Vision

← ← ← Nonionizing ← | → Ionizing → → →

(induced currents; induced currents)

(photo – chemistry)

(molecular, DNA damage)

Typical photon energies for different types of “radiation”

Soft x-ray	10,000 eV	ionize molecules
Visible light	1.5 to 3.3 eV	bend molecules
Thermal energy of atoms and molecules	0.03 eV	dis-aggregate molecular clusters
Millimeter radar	0.0001 eV	vibrate molecules
2 GHz cellular phones	0.00001 eV	?

Source strengths

Cellular telephone handset	~ ½ Watt
Single light bulb (visible and infrared waves)	100 Watts
Single ham-radio antenna	1,000 Watts
Array of cellular phone base-station antennas	1,200 Watts
Typical AM radio station transmitter	50,000 Watts
Typical FM radio station transmitter	100,000 Watts
Typical UHF TV transmitter	1,000,000 Watts

Measuring incident energy per unit area

"milliwatts per square centimeter" **mW/cm^2**

sunlight at noon is about:

$140\ mW / cm^2$

microwave oven leakage standard (in-home use):

$5\ mW / cm^2$

cell telephone (2 GHz) whole-body public guideline is:

$1\ mW / cm^2$

Thermodynamic facts about organisms at 310 K

- Peak electromagnetic emissions (Wien's Law) are at a wavelength of ~10 µm
- Black-body radiation at 310 K is ~2 mW / cm² (Stefan's Law)
- In body fluids, molecules move at 1000 m / sec, undergo about 10^{12} collisions per second, and have a Brownian displacement in one second of about 15 µm

Electromagnetic energy exposure, mW / cm^2

Noonday sunlight at the earth's surface		140
Heat loss from 37°C body (radiation)		2
3 feet from a 100-watt light bulb		1
RF guidelines, for 850 MHz	Occupational	3
	Public	½
RF guidelines, for 1900 MHz	Occupational	5
	Public	1

Dose of energy absorbed

SAR = specific absorption rate

= energy absorbed per unit time per unit mass

= Watts / kilogram (W / kg)

= $s \, |E|^2 / \rho_m$

SAR limits are the basis for exposure limits

- Limits on the whole-body energy absorbed

  0.4 W/kg occupational

  0.08 W/kg general public

- Limits on local RF energy absorbed (over 10 g tissue)

  2.0 W/kg general public

- How much heat delivery is 0.4 W/kg?

  0.4 W / kg will melt an ice cube (0˚C) to water (0˚C) in 10 days

Energy gains and losses for the human body

Human metabolic energy (basal, total body heat) output:	~150 Watts
Heavy exercise:	~1,000 Watts
Solar energy absorbed, while sunbathing at noontime:	~200 Watts
Whole-body, absorbed RF, public guideline:	5.6 Watts

Both modulated and unmodulated RF consist of E and B fields

electric (E) fields ➡ force on electric charges

magnetic (B) fields ➡ force on moving charges

“and nothing else”

All sources of E and B are summed together as“vectors”

- Electric charges respond to the vector sum E-field and/or B-field (internal, external, all frequencies combined).
- The charges / currents “know nothing” about the separate sources of the fields

E and B affect all matter in a defined fashion

E-field is force per unit charge →

"newtons / coulomb"
"volts / meter"

B-field is force per unit current and acts on moving charges →

"newton per amp-meter"
"tesla"

Actions on fixed or free charges

RF fields applied to tissue will cause force on

- free charges -- current may flow,
- fixed charges -- dipoles may twist,
- confined charges -- polarization, induced dipole
- confined charge rearrangement -- quadrupole

These established RF interactions may (to some degree)

- lead to temperature changes
- re-orient proteins
- distort proteins
- cause membrane breakdown

Can pushing and pulling on electric charges affect biology?

POSSIBLY YES,

+ Charged ions, molecules, structures are present
+ At molecular level, interactions are electrical in nature
+ Electrical phenomena are integral to normal body function

BUT PERHAPS NOT,

- Can the forces caused by RF be “heard” in the “noise” of existing activities and E-fields in living cells?
- Because RF fields average to zero, can “effect” accumulate?
- How do RF “effects” link to malfunction and disease?

A useful unit of force on the scale of cells and molecules: ➔ "piconewton"

- The force of one pound (weight)
  - » 4½ newtons (N)
- One cm^3 of water weighs » 0.01 N
- 1 piconewton (pN) = 10^{-12} N
- Effect of gravity on a human cell » 5 pN (weight in air)

Biological force generator, or force transducer	Measured force
hair cell activation in inner ear	1 pN
single kinesin molecule	3 pN
single actin molecule	4 pN
mechano-receptive ion channel	12 pN
(10+)molecule in membrane V_m	16 pN
stretch DNA molecule 10%	20 pN
receptor-to-ligand forces	90 pN
DNA strand-to-strand binding	70 pN
stall force of flagellar motor	100 pN

What force can E-fields from RF exert on charged biological molecules?

- Use ICNIRP guideline for maximum allowable SAR for head and neck (2 W/kg); the associated electric field strength in tissue is about 45 V/m at 1 GHz
- Then, (using Coulomb's Law) the force on a cell-membrane protein with 100 unbalanced charges is ~ 0.001 pN
- Moreover, higher order effects (dipole, quadrupole, induced dipole) will result in <u>less</u> overall force.

Spectrum of RF signals vs. time course of signal power

Problem: biological systems have slow response times (milliseconds or longer)

Low-frequency modulation of the RF signal might be extracted if a mechanism demodulated the RF field.

Biologists, physiologists, and anatomists have been unable to identify a demodulator.

The Paradox

- A repeatable, explicit, and predictive mechanism capable of producing biologically significant responses (modulation dependent or not) from low-level RF fields has not been found
- Yet, numerous biological effects have been reported from RF fields, some apparently related to modulation
- Continue to examine experimental protocols and underlying biophysics, and seek evidence of replication.