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How Safe is the Environmental Electromagnetic Radiation?

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Abstract

The natural electromagnetic environment originates from the Earth (terrestrial sources) and from space (extraterrestrial sources). Compared with man-made fields, natural fields are extremely small, especially at the radiofrequency band. Electric and magnetic fields exist wherever electricity is generated, transmitted or distributed from power stations or used in electrical appliances. Since the use of electricity is an integral part of modern lifestyle, these fields are ubiquitous in the environment. The situation became 'heavier' with the impressive evolution of the mobile phone and telecommunication technology.

The incident fields interact or couple with the human body and induce electric and magnetic fields and currents within the body tissues. Oscillating charges may be induced on the surface of the exposed body and these induce currents inside the body. A different interaction mechanism exists for the electric- and magnetic-field components. Dosimetry describes the relationship between the external fields and the induced electric field and current density in the body and the outcome serves as the basis on which authorities recommend limits for human exposure.

The locally induced electric field and current density are of particular interest because they relate to the stimulation of excitable tissue such as nerve and muscle. The distribution of induced currents across the various organs and tissues is determined by the conductivity of those tissues. Many mechanisms, mainly when concerning thermal effects, become detectable only at fields above certain strength. Nevertheless, the lack of identified admissible mechanisms does not rule out the possibility of adverse health effects even at very low field levels, provided basic scientific principles are adhered to.

Introduction

Humans are being constantly exposed to environmental electromagnetic radiation (EMR). However, a substantial increase in exposure to non-ionising radiation and especially to low frequency EMR, started in the early 20th century with the generation of artificial electromagnetic fields. The increase continued through development of power stations, radios, radars, televisions, computers, mobile phones, microwave ovens and numerous devices used in medicine, industry and home. These technological advances have aroused concerns about the potential health risks associated with unprecedented levels of EMR exposure [1-9].

Non-ionising electromagnetic radiation comprises photons that do not have sufficient energy to break chemical bonds or ionize biological molecules [10]. The energy of a photon of an electromagnetic wave is given by $E = hf$, where h is Planck's constant, thus the energy of a photon in the Radio frequency energy varies from approximately 4.1×10^{-6}eV at 1 GHz to 1.2×10^{-3}eV at 300 GHz. This is thus far less than the minimum amount of energy needed to ionise organic materials or metals, which is approximately 5 - 10 eV. However, low frequency EMR energy is absorbed by living tissue and the amount and the nature of this absorption are determined by the frequency and type of incident radiation and the type of tissue that absorbs it. Exposure to multiple sources of non-ionising radiation (Table 1), including residential exposure to high-voltage power lines, transformers, and domestic electrical installations, varies in duration and depends on the distance from the source. EMR may be grouped as follows: static fields (0 Hz), extremely low frequency (ELF) EMR (1 - 300 Hz), intermediate frequency (IF) EMR (300 Hz - 100 kHz), radio-frequency (RF) EMR (100 kHz - 300 GHz) and THz EMR (0.3 - 20 THz). The frequency range known as low-frequency EMR (LF-EMR) includes ultra-low frequency (ULF) fields (0.0001 - 10 Hz), ELF and bands of IF EMR. Environmental exposure is usually due to LF and especially ELF EMR. This type of exposure is continuous and takes place especially among populations of the industrialised world. Exposures to ELF electric and magnetic fields emanating from generation, transmission and uses of electricity, constitute a ubiquitous part of modern life [8,11].

The External and the Induced Electric Fields

To achieve adequate estimations of energy absorption from tissue when exposed to non-ionising EMR, accurate electric and magnetic field measurements inside the body are necessary. Electric field is usually measured by suitable sensors such as small dipoles. Computational methods are also employed. These rely on detailed anatomical information and magnetic-electric properties of different tissues for each frequency band [12]. Measurements in phantoms are also reported where the electric field at various points is usually measured via a robotically positioned probe, small enough to minimise changes in the fields produced by its presence [12]. On the other hand, magnetic field is usually measured with small loop antennas. Nevertheless, in simple cases, internal exposure estimations may rely on measurement of the field out-

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Frequency	Type of radiation	Sources
0 Hz–300 kHz	Low frequency to extremely low frequency (LF–ELF) electromagnetic radiation	Electrical fields of devices, conventional electrical network, video monitors, sections of AM radio
3 kHz–300 MHz	Radio frequencies (RF)	Sections of AM radio, FM radio, medical short-wave, nuclear magnetic resonance (NMR)
300 MHz–300 GHz	Microwave (MW)	Domestic microwave devices, mobile telephones, microwave for medical physical therapy, radar and other microwave communications
$3 *10^{11} – 3*10^{14}$ Hz	Infrared (IR)	Solar light, heat and laser therapy devices
$10^{14} – 10^{15}$ Hz	Visible light	Solar light, phototherapy, laser
$10^{15} – 10^{17}$ Hz	Ultraviolet (UV)	Solar light, fluorescent tubes, food/air sterilization, radiotherapy, etc.

High frequency ultraviolet (UV) is considered as ionizing radiation

Table 1: Frequencies and sources of non-ionizing radiation

Band name	Active sources	Range (MHz)
FM	VHF broadcast radio	88–108
TV 3	Digital audio broadcasting	174–223
Tetrapol	Terrestrial trunked radio	380–400
TV 4&5	UHF broadcast television	470–830
GSM[a] Tx[b]	GSM mobile phones (900 MHz)	880–915
GSM Rx[c]	GSM base stations (900 MHz)	925–960
DCS[d] Tx	DCS mobile phones (1800 MHz)	1710–1785
DCS Rx	DCS base stations (1800 MHz)	1805–1880
DECT[e]	Digital enhanced cordless telephony	1880–1900
UMTS[f] Tx	3 G mobile phones	1920–1980
UMTS Rx	3 G base stations	2110–2170
WiFi	Wireless networks and microwave ovens	2400–2500

[a] Global System for Mobile Communications
[b] Transmitted radio signal from the point of view of a mobile phone
[c] Received radio signal from the point of view of a mobile phone
[d] Digital Communication System
[e] Digital Enhanced Cordless Telephone
[f] Universal Mobile Telecommunication System

Table 2: Personal exposure meter frequency bands (EME SPY 120, Satimo, France)

side the body accompanied by reasonable approximations [3,12-16].

The strength of the electric or magnetic field can be indicated by its peak value, although it is often denoted by the root mean square (rms) value. The power density represents the intensity of the electromagnetic field and is determined by the amount of electromagnetic energy passing through a point per unit area perpendicular to the direction of propagation [3]. The power density of an electromagnetic wave is equal to the product of the electric and magnetic field intensities, although this is not true in near-field regions, i.e. when the distance from the source is comparable to the wavelength. In general, the fields can be divided into two components: radiative and reactive [3]. The radiative component is that part of the field which propagates energy away from the source, while the reactive component can be thought of as relating to energy stored in the region around the source. The reactive component dominates close to the source and the stored energy can be absorbed by people standing in the near-field region. In the near-field region, the electric and magnetic fields are decoupled and not uniform, wave impedance varies from point to point, power is transferred back and forth between the antenna and the surrounding object, and the energy distribution is a function of both the incident angle and distance from the antenna [17]. Because the electric and magnetic fields are decoupled in the near field, the induced field can be estimated by combining the independent strengths of the electric and magnetic fields, i.e. the electric and the magnetically induced electric fields inside the body [17]. Any measurement in the near-field region is particularly difficult since, even the introduction of a small probe, can substantially alter the field. The boundary radius depends on wavelength. Distances of about one-sixth of a wavelength from the source, define approximately the reactive near-field boundary. The frequency range of 3 kHz to 300 GHz corresponds to the wavelength range of 100 km to 1 mm [3,7,12,18,19]. It is important to note that power density quantity is not appropriate for low frequency calculations, as the magnetic-electric coupling is not strong enough.

Static electric and magnetic fields arise from both natural and man-made sources, whereas electric and magnetic fields in the extremely low-frequency (ELF) range (3-300 Hz) are mostly associated with man-made sources. These are numerous and include electric power systems, electric and electronic appliances and industrial devices. Environmental levels of ELF fields are very low. Exposure levels for the general population are typically between 5-50 Vm^{-1} for electric fields and 0.01 - 0.2 μT for magnetic fields. Considerably higher exposure occurs for short durations and in some occupational settings [20,21]. Observational studies have shown that movement in strong static magnetic fields may cause subjective symptoms like vertigo or nausea. These are more likely to occur at magnetic field strengths above 2 T [4]. It should be noted that the earth's magnetic field (25-65 μT, from equator to poles) is a static field to which everyone is exposed.

Besides LF-EMR, individuals are increasingly exposed to RF EMR from television (TV) towers, radio stations, mobile phone/Wi-Fi systems and personal computers. In contrast to ionising radiation, where natural sources contribute the largest proportion to population exposure, man-made non-ionising sources tend to dominate human exposure. In all cases, exposure depends not only on the strength of the field, but also on the distance from the source and, in the case of directional antennas, on the proximity to the main beam. The field strength often decreases rapidly with distance [13-16,22-24]. There exist several possible sources of RF fields to which people may be exposed. Within the frequency band from 3 kHz to 300 GHz the sources include those used for telecommunications and security. Communications equipment cover most of the frequency range with TV and radio transmission frequencies from about 200 kHz to 900 MHz. Personal telecommunication devices operate over the range of frequencies from 100 MHz to 5 GHz. RF EMR is emitted by numerous sources operating at different frequency bands (Table 2). These sources can be subdivided in two broad categories: (a) ambient sources, such as broadcast transmitters (radio, TV), or mobile phone base stations and (b) personal sources, such as mobile phones, in-house bases for cordless phones (DECT – Digital enhanced cordless telephony), microwave ovens, wireless networks.

Antennas generate electromagnetic fields across the spectrum. At very low frequencies the structures are massive with support towers as high as 200-250 m and the fields may be extensive over the site area. Electric field strengths of several hundred Vm^{-1} and magnetic field strengths (H) in the range 2 - 15 Am^{-1} (52 Am^{-1} close to low frequency towers) may be encountered. The currents induced in the human body (Figure 1) flow to ground through the feet and can reach a theoretical maximum of 10 - 12 mA per Vm^{-1} at the resonance frequency of around 35 MHz for an electrically grounded adult (the current is reduced to half of these values when the adult is wearing shoes) [3]. Nevertheless, the average magnetic flux density (in μT) is, generally, considered to be below maximum exposure limits established by different organisations [3,18].

The British Radio Communications Agency (Ofcom: http://www.ofcom.org.uk/) performed ~~in~~during 2003 measurements in the UK that gave the following range and geometric mean (in parentheses) of power density values in μWm^{-2} from all signals: (a) indoor 2-1000 (75), (b) outdoor 50-1700 (240) and (c) all locations 3.5-1100 (110) [3,25]. Consequently, exposure to RF varies considerably across persons, space and time [26-30]. There are, therefore, significant challenges in assessing the sources of variation and related uncertainty, but also in identifying exposure relevant factors [31-40].

Issues Related to Interaction with Human Body

The signals generated by various sources may be different in type. The underlying waveform from a source is usually harmonic, the signal however may then be amplitude modulated (AM), frequency modulated (FM), pulse modulated (e.g. radar) or modulated in a more complex way (e.g. digital radio) [3,11,41]. Exposure to EMR sources is commonly described by electric and magnetic field strength, which is usually measured around the subject. Any biological effects would be the result of the exposure within the body, yet, this is difficult to be measured directly. In addition, the coupling mechanisms of the electric and magnetic incident field components are different. Hence, both must be determined separately to fully characterize human exposure.

In order to understand the effects of electric and magnetic fields on animals and humans, their electrical properties have to be considered. Static magnetic fields, which are not attenuated by the organism, can exert forces on moving charges, orient magnetic structures and affect the energy levels of some molecules. Static and ELF electric fields are greatly attenuated inside the body. The induced electric field increases with the frequency of the external field and the size of the object. A well-established effect of induced fields above a threshold level is the stimulation of excitable cells. Typical residential exposure results in very small induced electric fields, while some occupational exposure and exposure directly under very high-voltage power lines may result in electric fields of the order of 1 mVm^{-1} in some tissues. Non-perceptible contact currents under some conditions are calculated to produce electric fields exceeding 1 mVm^{-1} in the bone marrow of a child. Residential levels of ELF electric and magnetic fields produce much lower fields in tissues.

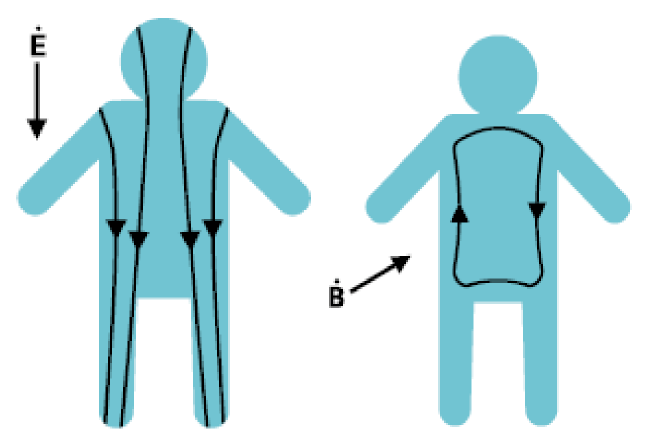

Figure 1. Induced currents to human body from (a) Electric (E) and (b) Magnetic (B) fields

In general, the interaction of RF magnetic fields with tissue would be expected to be much weaker than that of RF electric fields. Possible exceptions might be expected to include interaction with tissues like human brain, containing particles of magnetite. RF magnetic fields could interact either by ferromagnetic resonance or by mechanical activation of cellular ion channels. Positive findings are not yet confirmed. Sheppard et al. [42] have evaluated several potential mechanisms of interaction of RF radiation with biological systems and concluded that, other than heating and possible effects on reactions mediated by free radical pairs, RF field strengths in excess of system noise (collisions among various molecular oscillators generated largely by thermal agitation) could not alter physiological activities without also causing detectable tissue heating. The literature on non-thermal effects is inconsistent [1-3,12-16,24,31,43].

Low-frequency magnetic fields might produce biological effects if they induce ferromagnetic resonance in tissues that contain high concentrations of iron particles (magnetite) [44]. Free radicals, which are highly reactive molecules or ions with unpaired electrons, are formed when radical pairs dissociate. By altering the recombination of short-lived radical pairs, low-intensity magnetic fields may increase the concentration of free radicals [44,45]. The expected increase in radical concentration is 30% or less [46]. The extent to which this increase can produce oxidative stress-induced tissue damage (e.g. membrane-lipid peroxidation or DNA damage) is not known. Furthermore, radicals are also a part of normal cellular physiology, being involved in intracellular signal transduction [47]. Therefore, even small effects on radical concentration could potentially affect multiple biological functions.

In regard with the interaction mechanism, a number of hypotheses have also been stated: radical pair mechanisms, ion charge-to-mass resonance mechanisms, stochastic resonance, action on biogenic magnetite, etc. Theoretical and experimental evidence for the relevance of these mechanisms is being sought actively. There are well established in-vivo and in-vitro exposure systems that can provide electric fields of up to the order of 150 kVm^{-1} and ELF magnetic fields up to 2 mT. Magnetostatic fields up to 7.0 T can be produced in the laboratory.Analysing well conducted studies [8], no excess risk was seen for exposure to ELF magnetic fields below 0.4 μT and a twofold excess risk was seen for exposure above 0.4 μT [48]. Another pooled analysis used 0.3 μT as the highest cut-point [49]. A relative risk of 1.7 for exposure above 0.3 μT was reported. These studies were closely consistent. In contrast to these results for ELF magnetic fields, evidence that electric fields are associated with childhood leukaemia is inadequate for evaluation [8].

By prolonging the lifetime of free radicals, RF fields can increase the probability of free-radical-induced biological damage. To affect DNA recombination and thus the repair of damage caused by radicals, external magnetic fields must act for a time period longer than the one required for the dissociation of radical pairs(> 10^{-9} s). Hence, Adair [50] concludes that the effect of RF fields on free-radical concentrations would likely be limited to about 10 MHz or less. Resonance phenomena occur below 10 MHz, and may result in biological effects from low-level RF fields at about 1 MHz [51]. Georgiou [45] cited several studies that provide evidence for the induction of oxidative stress via the free-radical pair mechanism in biological systems exposed to RF radiation;

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some of the reported effects include increased production of reactive oxygen species, enhancement of oxidative stress-related metabolic processes, an increase in DNA single-strand breaks, increased lipid peroxidation, and alterations in the activities of enzymes associated with antioxidative defence. Furthermore, many of the changes observed in RF-exposed cells were prevented by (pre)treatment with antioxidants.

Since coupling with the human body also depends on the ratio of wavelength versus body size, the RF-EMF spectrum is often divided into at least three ranges, namely 30 kHz – 10 MHz (below body resonance); 10 MHz to 2 GHz (body resonance and partial body resonance); and 2 GHz to 300 GHz (surface-dominated absorption). At exposures below the body-resonance frequency (30 kHz – 10 MHz) the body can be described as a short poor conductor. The dominant exposures of concern are from near-field sources that generally have strong field gradients. Under these conditions, the energy is capacitively coupled in the case of a dominant electric-field source (dielectric heaters, diathermy applicators, etc.) or inductively coupled in the case of a dominant magnetic-field source (e.g. inductive cooking hobs, antitheft systems, wireless power transfer systems, MRI, etc) [9]. Strong induced currents are also caused by touching metallic objects such as fences or towers exposed to fields from transmitting antennas (contact currents). At exposures above the body-resonance frequency (2 GHz to 300 GHz) the body can be described as a dielectric object that is large with respect to the wavelength and the penetration depth. Therefore, the absorption is approximately proportional to the exposed surface area of the body [52,53]. In this case, the energy absorbed by whole body is proportional to the largest ratio between the exposed surface of the body and its weight [53]. At the resonance frequency range (10 MHz to 2 GHz), human body can be described as an elongated poor conductor. Therefore, it couples energy best if the electric field is polarized along the long body axis and when the electrical length of the body is resonant, i.e. human height is equal to approximately half a wavelength ($\lambda/2$) for an ungrounded body, or equal to one quarter of wavelength ($\lambda/4$) for a grounded body. This was investigated with ellipsoids and available human models [54-56]. The results of these modelling studies explain the main characteristics of far-field exposures of between 10 MHz and 2 GHz, i.e. a strong dependence on body size and posture, and on polarization.

Issues Related to Interactions inside the Human Body

Thermal effects

The aforementioned frequency bands are associated with the interaction of EMR with human body as a whole, however the absorption of energy depends also on local tissue composition and the RF energy is delivered through very short range mechanisms. More specifically, at frequencies below 100 kHz, the physical quantity associated with most biological effects is the electric field strength in tissue, which is related to the induced current density [12,25,43]. At higher frequencies, the most appropriate quantity to assess the exposure is the specific absorption rate (SAR) which is related to the second power of the electric field strength in tissue [3,21,57]. At 100 MHz bone and fat are poor conductors, while high water content tissues (muscle and skin) are better conductors, absorb RF energy stronger and the signal penetrates less. Nevertheless, as frequency increases above the resonance region (10 MHz to 2 GHz), energy absorption becomes confined to the surface layers of the body and absorption is limited just to the skin when frequency increases up to a few tens of GHz [1-6,9,12,31,43]. At mobile phone frequencies (1 - 2 GHz) most of the energy from the incident radiation will be absorbed in one side of the head within a few centimetres of the handset.

When a biological body (animal or human) or tissue is exposed to an RF-EMF, the RF energy is scattered and attenuated as it penetrates body tissues. Energy absorption is largely a function of the radiation frequency and the composition of the exposed tissue. Because of the high dielectric constant of water, the water content of the tissue determines to a large extent the penetration of a frequency-specified electromagnetic wave. The rate of energy absorbed by or deposited per unit mass per unit time is the specific absorption rate (SAR); this value is proportional to the root-mean-square (rms) of the induced electrical field strength $[E]^2$ and to the electrical conductivity (σ) of the tissue per tissue density (ρ). Thus SAR is given by the following equation:

$$\mathrm{SAR} = [E]^2 \bullet \sigma/\rho$$

The SAR expressed in units of watts per kilogram (or mW/g) can also is estimated from measurements of the rise in temperature caused by RF-energy absorption in tissue. To cause a biological response, the EMF must penetrate the exposed biological system and induce internal EMR. RF-energy absorption depends on incident field parameters (frequency, intensity, polarization), zone of exposure (near field or far field), characteristics of the exposed object (size, geometry, dielectric permittivity and electric conductivity) and absorption or scattering effects of objects near the exposed body [10].

The most recognized effect of RF radiation in biological systems is tissue heating. The absorption of RF-EMF energy by biological systems generates an oscillating current that is transferred into molecular motion of charged particles and water molecules, which are strongly bipolar and are the major component of biological tissues. Polar molecules move to align themselves with EMF EMR to minimize the potential energy of the dipoles. Absorption and resonant oscillations in polar subgroups of macromolecules (e.g. proteins, DNA) are largely damped by collisions with surrounding water molecules. Damping or friction slows the motion of the oscillator. These collisions disperse the energy of the RF signal into random molecular motion. Tissue heating occurs because the rotational motion of molecular dipoles is hindered by the viscosity of water and interactions with other molecules, i.e. the rotational energy is transferred to the surrounding aqueous environment as heat [12].

As aforementioned, SAR quantifies the energy absorbed by a particular mass of tissue and depends on the density and the electrical conductivity of the tissue [3,21,57]. As SAR varies from point to point, it may be estimated by averaging over a small mass or over the whole body mass. The most commonly used methods for experimental measurement of SAR involve measurement of the internal electric field strength or the rate of temperature rise, both methods however, being very difficult in practice [3]. Thermal effects from RF electric fields occur because most biological tissues are electrically conducting.

Estimates of SAR in the head of individuals exposed to RF radiation during use of mobile phones that operate at a power output of 0.25 W indicate that the emitted energy would cause a rise in brain temperature of approximately 0.1°C [58,59]; therefore, it has been suggested that it is unlikely that effects in the brain would be caused by increases in temperature [60]. However, it is possible that temperature-sensitive molecular and physiological effects occur already with a temperature increase even less than 0.1°C, while temperature changes approaching 1°C are likely to affect several biological processes [61]. Low levels of exposure to RF radiation may result in small temperature changes that cause conformational changes in temperature-sensitive proteins and induce the expression of heat-shock proteins.

The International Commission on Non-Ionising Radiation Protection (ICNIRP) and the UK's National Radiological Protection Board (NRPB), together with the Health Protection Agency (HPA), the Institute of Electrical and Electronics Engineers (IEEE), the International Telecommunication Union Recommendation [62] and European Union (EU) committees, have reviewed many relevant studies and recommended guidelines on restrictions for exposure to EMR (see references below).

Recommended restrictions are based on biological data relating to thresholds for adverse direct and indirect effects of acute exposure. Direct effects are those resulting from the interactions of electromagnetic fields with the human body (basic restrictions). Indirect effects are those resulting from an interaction between electromagnetic fields, an external object and the human body (e.g. to avoid burns). As compliance with the basic restrictions cannot be easily determined, ICNIRP recommended reference levels as values of measurable field quantities [3,25]. Table 3 summarises the reference levels for electric field intensity (Vm^{-1}), magnetic flux density (μT) and power density (Wm^{-2}). Corresponding values for occupational exposure are about five times higher [3,12,25].

In Table 4, Reference Levels for exposure to Electric Field, Magnetic Field and Wave Power Density are shown for mobile phones, as well as Wi-Fi frequencies for general population and workers (in parenthesis), according to ICNIRP and NRPB guidance. The Greek Atomic Energy Agency, according to EU recommendations, made a series of electromagnetic field measurements in selected regions in Greece. Table 5 gives average and maximum values of Electric Field, Magnetic Field and Wave Power Density measured for mobile phones frequencies together with the Reference Levels estimated for the Greek environment. Depending on the particular environmental situation, two groups of Reference Levels are established in Greece: (a) 70 per cent of the proposed values for general purpose and (b) 60 per cent of the proposed values for regions with more sensitive population [63]. In Table 5 the 70 per cent Reference Levels are given.

Non-thermal effects

Non-thermal effects (or effects associated with a negligible increase in temperature) are defined as biological changes that occur with body temperature changes that are below 1 °C, below measurable heating, or in the range of thermal noise. Several arguments have been presented against the plausibility of a non-thermal mechanism by which RF radiation could affect physiological changes; these include the following: (a) damping effects of the water surrounding biological structures are too strong to allow resonances to exist at radiofrequencies [64]; (b) the relaxation time – the time for a molecule to return from an excited state to equilibrium – for excitations produced by RF fields (e.g. vibrations in molecules), is similar to the relaxation time for thermal noise, and shorter than the lifetime of the absorption and transfer of energy into resonant modes of oscillating elements in biological systems [50]; and (c) the perturbation of the biological structure induced by the applied field must be greater than the effects of random thermal motion and the effects of other dissipative forces, such as viscous damping by the surrounding medium [61]. Random thermal motion of charged components in biological systems (i.e. thermal noise) creates random fluctuating EMFs. Adair (2003) has concluded that it is unlikely that RF radiation with a power density of less than 10 $mWcm^{-2}$ (or 100 Wm^{-2}) could have a significant effect on biological processes by non-thermal mechanisms. Non-thermal effects could be associated with changes in protein conformation (different dipole moment and energy, transitions that would result in changes in protein folding), conformational changes in the ATPases associated with cell membrane ion channels (ion pumping across membranes produced by RF fields), heat shock proteins (an increase in unfolded protein produces an increase in aggregation), changes in binding ability of Ca^{2+} ions to cell receptor proteins.

Frequency range	E-field intensity (Vm^{-1})	B-field intensity (μT)	Wave Power Density (Wm^{-2})
0–1 Hz	–	4×10^4	–
1–8 Hz	10,000	$4 \times 10^4 / f^2$	–
8–25 Hz	10,000	5000 / f	–
0.025–0.8 kHz	250 / f	5/ f	–
0.8–3 kHz	250 / f	6.25	–
3–150 kHz	87	6.25	–
0.15–1 MHz	87	0.92 / f	–
1–10 MHz	$87 / f^{1/2}$	0.92 / f	–
10–400 MHz	28	0.09	2
400–2000 MHz	$1.375 \times f^{1/2}$	$0.0046 \times f^{1/2}$	f / 200
2–300 GHz	61	0.2	10

f: frequencies as indicated in the column of frequency range

Table 3: ICNIRP reference levels for general public exposure to time-varying electric and magnetic fields (rms values)

MHz	Electric Field (V/m)	Magnetic Field (A/m)	Wave Power Density (W/m^2)
900 (GSM)	41.25 (90)	0.11 (0.24)	4.5 (22.5)
1800 (DCS)	58.34 (127.3)	0.16 (0.34)	9 (45)
2100 (UMTS)	63.01 (137.5)	0.17 (0.37)	10.5 (52.5)
2400 (Wi-Fi)	67.36 (147)	0.18 (0.39)	12 (60)

Table 4: Reference Levels for exposure to Electric Field, Magnetic Field and Wave Power Density for mobile phones, as well as Wi-Fi frequencies for general population and workers (in parenthesis), according to ICNIRP and NRPB guidance

	Average values (all related frequencies)	Maximum values	Ref Levels GSM 900	Ref Levels DCS 1800	Ref Levels UMTS 2100
Electric Field (V/m)	0.25 – 5.0	20	34.5	48.8	51
Magnetic Field (A/m)	0.005 - 0.01	0.05	0.093	0.131	0.134
Wave Power Density (W/m^2)	0.0001 - 0.05	1	3.1	6.3	7

Table 5: Average and maximum values of Electric Field, Magnetic Field and Wave Power Density measured, together with the Reference Levels estimated for Greek environment, for mobile phones frequencies, according to the Greek Atomic Energy Agency

The association between childhood leukaemia and high levels of magnetic fields is unlikely to be due to chance, but it may be affected by bias. In particular, selection bias may account for part of the association. The overall evaluation of IARC 2002 was that *"There is limited evidence in humans for the carcinogenicity of extremely low-frequency magnetic fields in relation to childhood leukaemia. There is inadequate evidence in humans for the carcinogenicity of extremely low-frequency magnetic fields in relation to all other cancers. There is inadequate evidence in humans for the carcinogenicity of static electric or magnetic fields and extremely low-frequency electric fields. Extremely low-frequency magnetic fields are possibly carcinogenic to humans (Group 2B). Static electric and magnetic fields and extremely low-frequency electric fields are not classifiable as to their carcinogenicity to humans (Group 3)".*

Hardell et al. [65-77] have published a series of papers reporting findings regarding associations between use of mobile phones and brain tumours. All these epidemiological analysis studies have been of the case–control design, with cases identified from records of regional cancer registries in Sweden and controls identified from the Swedish population or the Swedish death registry. In the latest paper available, Hardell et al. [77] reported the findings of a pooled analysis of associations between mobile -and cordless- phone use and glioma. Cases were ascertained from January 1997 to December 2003 from population-based cancer registries in Uppsala-Orebro, Stockholm, Linköping and Göthenburg. Eligible cases were aged 20–80 years at diagnosis. Controls were matched to cases based on calendar year of diagnosis as well as age, sex and study region. Deceased controls for deceased cases were selected from the death registry. Questionnaire solicited information regarding demographic characteristics, occupational history, and other potential risk factors for cancer of the brain, and asked detailed questions on use of mobile phones and other wireless communication technologies, including year of first use, type of phone, average number of minutes of daily use, and side of head on which the phone had been used most frequently. A trained interviewer, using a structured protocol, carried out supplementary phone interviews to verify information provided in the questionnaire. Questionnaires were assigned an identification code such that the phone interviews and coding of data from questionnaires were blinded to case–control status.

Hardell's results were included in a highly-respected international program that evaluated the carcinogenicity of RF fields, especially cell phones [9]. The IARC Monographs programme started evaluating chemical agents risk but has expanded beyond chemicals to include complex mixtures, occupational exposures, physical and biological agents, lifestyle factors and other potentially carcinogenic exposures. IARC's Monograph *Non-ionising Radiation, Part II: Radiofrequency Electromagnetic Fields [includes mobile telephones]* conclusions are summarized in Lancet Oncology (2011) and state that *"There is limited evidence in humans for the carcinogenicity of radiofrequency radiation. Positive associations have been observed between exposure to radiofrequency radiation from wireless phones and glioma, and acoustic neuroma"*. The overall evaluation is that *"Radiofrequency electromagnetic fields are possibly carcinogenic to humans (Group 2B)"*.

In Table 6 Reference Levels established in selected countries are given, presenting the variability in interpreting the scientific data when applied [78].

Unavoidable Exposure

Since the introduction of mobile phones in the early 90s, there has been a constant and rapid increase in the number of base stations. Joseph et al. [35] compared the total RF-EMF exposure in five European countries and found that in outdoor urban environments mobile phone base stations are a major, if not the largest, source of environmental RF-EMF. There has been concern about potential health effects of the electromagnetic waves emitted by these base stations [7,79], which have led to studies assessing the relationship between RF-EMF and the health impact on the general population. To date, no consistent health effect has been found [3,12,39]. However, if there are health effects, they are likely to be small and subtle and, as such, large population samples and a reliable exposure assessment are needed to confirm or reject the hypothesis of a certain health effect, minimizing statistical uncertainties [3-5,80]. In general, in the last few years, several countries have published measurements [26,29-38,81-85]. In some of these studies, measurements were performed in different microenvironments such as offices or outdoor urban areas, to characterise typical exposure levels in these places (micro-environmental studies). Other studies were population surveys, where the personal exposure distribution in the population of interest was determined. The strategies for the recruitment of the study participants as well as the data analysis methods differed between them and therefore, a direct comparison of their results is difficult.

Despite the rapid growth of new technologies using RF EMR, information on the exposure of individual persons for these and older existing RF sources is scarce and even less is known about the relative importance of different sources. Existing RF sources are operated in different frequency bands and can be subdivided in two broad categories: (a) external sources, such as broadcast transmitters (radio, TV) or mobile phone base stations, and (b) internal sources, such as mobile phones, in-house bases for cordless phones (DECT), or microwave ovens. The relative contribution of these sources to exposure depends on individual home and workplace circumstances. For a given source, the actual exposure to RF depends on a number of factors. Regarding mobile phones, the characteristics of a certain phone (particularly type and location of the antenna), the way the phone is handled, the distance from the base station, the frequency of handovers and RF traffic conditions are of prime importance [1,31,81,86]. Similarly, RF fields from mobile phone base stations also exhibit a complex pattern, influenced by numerous factors, such as, the output power of the antenna, the direction of transmission, the attenuation due to obstacles or walls, and any existing scattering from buildings and trees [32-37,79]. There are, therefore, significant challenges in assessing the exposure of individuals in the general population to RF signals, including the number and range of sources involved and the effect of the environment on signal's strength, as people move around. In principle, two different types of RF-EMF exposure sources can be distinguished: (a) sources which are applied close to the human body usually causing high and periodic short-term exposure mainly to the head (e.g. mobile phones) and (b) environmental sources which, in general, cause lower but relatively continuous whole-body exposure (e.g. mobile phone base stations). While exposure from mobile phones can be assessed using self-reported mobile phone use or operator data [40], valid assessment of exposure to environmental fields is more challenging. Frei et al. [26] studied temporal and spatial variability's of personal exposure to radio frequency electromagnetic fields. They concluded that exposure to RF-EMF varied considerably between persons and locations but was fairly consistent within persons.

A study regarding indoor incident-field exposure from cellular base-station sites was conducted by Austrian Research Centers (ARCS) in the city of Salzburg, Austria. The values are between 0.1 and 1 Vm^{-1} for distances of up to several hundred metres. Values greater than 1 Vm^{-1} and up to 3.9 Vm^{-1} were measured for distances of less than 86 m. These data also underline that the distance to the base station site has a poor correlation for the incident exposure. Similar results were reported in a study that also included outdoor measurement points and addressed the time dependence, i.e. traffic dependence of the exposure from cellular base stations.In these cases, clearly lower exposure can be expected at night and at weekends [87]. In an attempt to measure typical exposure to RF radiation over a whole week, volunteers in a Swiss study were asked to wear an RF exposimeter and to complete an activity diary [27]. The main contributions to exposure were found to come from mobile-phone base stations (32.0%), mobile-phone hands sets (29.1%) and DECT phones (22.7%). Highest exposures were measured in the office environment. In most studies, the lowest exposures were in the house, with exposures of about 0.1 mWm^{-2}. In transport vehicles, the exposure was from mobile phones, whereas in offices and homes,

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	50 Hz (ELF)		900 MHz (GSM)			1800 MHz (GSM)			2100 MHz (UMTS)		
Country	electric field strength	magnetic flux density	electric field strength	magnetic flux density	equivalent plain wave power density	electric field strength	magnetic flux density	equivalent plain wave power density	electric field strength	magnetic flux density	equivalent plain wave power density
	(V/m)	(µT)	(V/m)	(µT)	(W/m^2)	(V/m)	(µT)	(W/m^2)	(V/m)	(µT)	(W/m^2)
Recommendation 1999/519/EC	5000	100	41	0.14	4.5	58	0.20	9	61	0.20	10
Austria	[5000]	[100]	[41]	[0.14]	[4.5]	[58]	[0.20]	[9]	[61]	[0.20]	[10]
Belgium (Flanders)		10	21			29			31		
Bulgaria	-	-			0.1			0.1			0.1
Cyprus	[5000]	[100]	41	0.14	4.5	58	0.20	9	61	0.20	10
Czech Republic	5000	100	41	0.14	4.5	58	0.20	9	61	0.20	10
Denmark	-	-									
France	5000	100	41	0.14	4.5	58	0.20	9	61	0.20	10
Greece	5000	100	32	0.11	2.7	45	0.15	5.4	47	0.16	6
Italy		3	6	0.02	0.1	6	0.02	0.1	6	0.02	0.1
Lithuania	500				0.1			0.1			0.1
Recommendation 1999/519/EC	5000	100	41	0.14	4.5	58	0.20	9	61	0.20	10
Luxembourg	5000	100	41	0.14	4.5	58	0.20	9	61	0.20	10
Poland	1000	75	7		0.1	7		0.1	7		0.1
Slovenia	500	10	13	0.04	0.45	18	0.06	0.9	19	0.06	1
Sweden	-	-	[41]	[0.14]	[4.5]	[58]	[0.20]	[9]	[61]	[0.20]	[10]
Australia	[5000]	[100]	41	0.14	4.5	58	0.20	9	61	0.20	10
Russia	500	10			0.1			0.1			0.1
Switzerland		1	4			6			6		
U.S.A.	-	-			6			10			10

Table 6. Recommended (Reference Levels) values established in selected countries (adopted from Stam R, 2011)

the sources were quite variable between countries. Mean values were highest in trains (1.16 mWm^{-2}), airports (0.74 mWm^{-2}) and tramways or buses (0.36 mWm^{-2}) and higher during daytime (0.16 mWm^{-2}) than night-time (0.08 mWm^{-2}).

A further study of a random sample of 200 subjects in France used a personal exposure meter to estimate the doses, time patterns and frequencies of RF exposures with measurements of electric-field strength in 12 different bands at regular intervals over 24 hours [29]. This allowed differentiation of different sources of RF radiation, including mobile-phone base stations. For each of GSM, DCS and UMTS, more than 96% of the measurements were below the detection limit and the median of the maximum levels for all three systems ranged between 0.05 and 0.07 Vm^{-1}.

Frei et al. [28] claim that "exposure to RF-EMF in everyday life is highly temporally and spatially variable due to various emitting sources like broadcast transmitters or wireless local area networks (W-LAN). The use of personal exposure meters (exposimeters) has been recommended in order to characterize personal exposure to RF-EMFs [80]. Several exposure assessment studies have been conducted so far using exposimeters [30,32,82-84], which allow capture of exposure from all relevant RF-EMF sources in the different environments where a study participant spends time [79,88]. They are suitable for measuring RF-EMF from environmental far-field sources like mobile phone base stations, but are less able to accurately measure exposure to personal mobile or cordless phones [86] because measurements during personal phone calls are dependent on the distance between the emitting device and the exposimeter. Joseph et al. reported their research [36] about in-situ electromagnetic radio frequency exposure to existing and emerging wireless technologies by using spectrum analyser measurements at 311 locations (68 indoor, 243 outdoor), subdivided into six different categories (rural, residential, urban, suburban, office and industrial), geographically spread across Belgium, The Netherlands and Sweden. The maximal total field value was measured in a residential environment and found to be equal to 3.9 Vm^{-1}, mainly due to the GSM900 signal. Exposure ratios for maximal electric field values, with respect to ICNIRP reference levels, ranged from 0.5% (Wi MAX – Worldwide Interoperability for Microwave Access) to 9.3% (GSM900) for the 311 measurement locations. The exposure ratios for total exposures varied from 3.1% for the rural environment to 9.4% for the residential environment. Exposures were log-normally distributed and were in general the lowest in rural environments and the highest in urban environments. The dominating outdoor source was GSM900 (95th percentile of 1.9 Vm^{-1}) while indoor DECT dominated (95th percentile 1.5 Vm^{-1}) if present. The average contribution to the total electric field was more than 60% for GSM. Except for the rural environment, average contributions of UMTS-HSPA (High Speed Packet Access) were more than 3%. The contributions of LTE (Long Term Evolution) and Wi MAX were on average less than 1%.

Conclusions

Tissue heating is the best-established mechanism for RF radiation-induced effects in biological systems. However, there are also numerous reports of specific biological effects from ELF and RF fields. Although it has been argued that RF radiation cannot induce physiological effects at exposure intensities that do not cause an increase in tissue temperature, it is likely that not all mechanisms of interaction between weak RF-EMF and biological structures have been discovered or fully characterised. Biological systems are complex and factors such as metabolic activity, growth phase, cell density and antioxidant level might alter the potential effects of RF and/or ELF radiation. Alternative mechanisms need to be considered and explored to explain consistently observed ELF and RF dependent changes in controlled studies of biological exposure. The debate on whether or not non-thermal biological effects occur as a result of exposures to low-intensity RF radiation continues and the difficulty to specify observed effects as non-thermal remains unsolved. Concerns are justifiable.

Exposure to non-ionising radiation leads to energy absorption from the human body in a similar way with that of energy absorption from ionizing radiation. Even though non-ionizing radiation does not seem to induce immediate negative biological effects (as is the case for ionizing radiation), there is increasing experimental evidence that it can also become dangerous cumulatively, after long periods of continuous exposure.

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