BIOLOGICAL AND HEALTH RELEVANT EFFECTS FROM EXPOSURE TO HIGH-FREQUENCY EMF

Michael Kundi

Institute of Environmental Health, Medical University of Vienna, Vienna, Austria

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Abstract: Electromagnetic fields are a constant companion of modern civilisation. It is undeniable that modern life is unthinkable without its ubiquitous presence. However, it is the responsibility of science to implement these technical achievements in such a way as to minimise adverse effects to humans and the environment. Concerning potential biological and health effects of high-frequency electromagnetic fields there exists a scientific controversy lasting for almost 50 years. There is agreement that immediate, acute reactions from increased temperatures due to absorption of electromagnetic energy exist and that adverse outcomes or even death may occur as a consequence of these thermal effects. However, there is disagreement about the existence of non-thermal or athermal effects and the role for human health of low-level exposures that do not result in a relevant temperature increase.

Epidemiological studies (especially about brain tumours and leukaemia) point to a moderately increased risk in subjects exposed to diverse types of high-frequency electromagnetic fields. Particularly prolonged exposure to mobile telephones seems to be associated with an elevated risk to develop brain tumours and maybe other malignancies localised in the head.

Animal experiments provide at most limited support to the assumption of a carcinogenic potential of high-frequency electromagnetic fields. However, most studies have severe methodological limitations and cannot contribute to risk assessment.

Biološke in zdravstvene posledice zaradi izpostavitve visokofrekvenčnim elektromagnetnim poljem

Kjučne besede: visokofrekvenčna elektromagnetna polja, vpliv EMF na zdravje, zaščita pred EMF, atermični vplivi EMF

Izvleček: Elektromagnetna polja so stalen spremljevalec moderne civilizacije. Ne moremo zanikati, da si modernega življenja ne znamo več predstavljati brez njihove prisotnosti. Odgovornost znanosti je, da vpelje tehnološke dosežke na ta način, da zmanjša njihove škodljive vplive na ljudi in okolje. Glede možnega vpliva visokofrekvenčnih elektromagnetnih polj na biološke sisteme in zdravje v znanstvenih krogih v zadnjih petdesetih letih vladajo nasprotujoča si mnenja. Obstaja strinjanje, da je možna takojšnja, akutna reakcija na povečanje temperature zaradi absorpcije elektromagnetne energije, ki lahko povzroči škodljive posledice ali celo smrt. Obstaja pa dvom, da nizkoenergijska sevanja, ki ne povzročajo povišanja temperature prizadenejo človekovo zdravje, oz. da taka sevanja sploh lahko imajo atermične efekte.

Epidemiološke študije (še posebej o možganskih tumorjih in levkemiji) kažejo na nekoliko povečan rizik pri osebah, ki so bile izpostavljene različnim visokofrekvenčnim elektromagnetnim poljem. Še posebej daljša izpostavljenost mobilnim telefonom kaže na povečan rizik razvoja možganskih tumorjev in mogoče še kakšnih drugih malignih tvorb v glavi.

Tudi poskusi na živalih nam podajajo omejene dokaze, ki bi podprli predpostavko o potencialni karcinogenosti visokofrekvenčnih elektromagnetnih polj. Večini študij lahko očitamo resne metodološke omejitve in le redke bistveno prispevajo k oceni rizika.

1. Introduction

Nothing is more central to modern technologies than electromagnetic fields (EMF). Since the middle of the 19th century electricity gradually replaced the steam engine and already a few years after Heinrich Hertz's experiments in the 1880ies demonstrating that EMF have exactly the properties predicted by Maxwell's equations (that unified the theories of electricity, magnetism and optics) radio broadcasting stations started to transmit regular programs all over the world. Military purposes accelerated the development of powerful and efficient radar technologies as well as applications of radio frequency (RF) fields during world war II. Miniaturisation of electric circuits made necessary by space flights led to the digital revolution we do experience in our days. Introduction of computer technology into telecommunication began to fundamentally change our habits in the 1990ies due to the introduction of digital cellular telephones. This process turned a whole branch of industry upside down, and rapidly changed a system (the analogue wired telephony) that remained almost unchanged for about 100 years.

All these new applications supplied us not only with a lot of new tools but changed also our environment. While the steam and smoke of the early days of industrialisation could be seen and smelt, and in some areas like the German Ruhrgebiet or the Manchester area hid the sun like a big cloud, emissions from these new facilities, like broadcasting towers, radar stations and high-voltage lines, can neither be seen nor smelt and therefore were more or less neglected. Only few critical comments concerning potential adverse health effects of EMFs can be found before the early 1950ies.

During world war II some physicians noted health relevant reactions in radar personnel and therefore safety limits were introduced in some countries for military (and also in some occupational) areas. In 1953 a report of McLaughin /1/ about a cluster of leukaemia cases accusing radar exposure as a potential cause was answered with disbelief by the scientific community. Also research from Boysen /2/ in rabbits demonstrating haemorrhage and tissue necrosis in almost all organs from exposure to a 300 MHz RF field was answered with scepticism by the scientific community, although the microwave oven was already invented and tissue heating from high frequency exposures should have been expected.

In 1957 a case of death from an unknown amount of microwave energy had a great media coverage and led, in the Western World, to the onset of serious research and raising of research funds. In a sense this sad event can be said to be the starting point of the EMF controversy as well as of co-ordinated research. Barron and Baraff /3/, physicians at Lockheed Aircraft Corporation, published a study initiated by these startling findings in the influential Journal of the American Medical Association in 1958 comparing radar personnel with unexposed controls concerning differential blood count and other parameters. Authors concluded that there is no reason for concern as long as the precautionary measures (defining an area that exceeds a power density of 131 W/m^2 that should not be accessed) are observed. However, taking a closer look at their data a significant difference in monocytes and eosinophils between workers exposed for four years or longer and controls can be detected. This effect was obscured by combining the data from the whole workforce, the majority of which was employed for one or two years only. Already this first human study revealed a rather superficial consideration of facts in some parts of the scientific literature.

2. Effects of high frequency EMF

During the 1960s and 1970s the pioneering work of several groups of researchers clarified some of the basic problems of the interaction between high-frequency EMF and biological tissues. The strong frequency dependency of the interaction reflected by different relaxation modes was one of the key findings, although the microscopic reasons for the macroscopic differences in dielectric constants or conductivity spanning several orders of magnitude for the frequency range between several hundred Hz and several GHz are less well understood. Schwan /4/ concluded in 1978: "Among the established effects in biological systems the most important is heat development but direct field interaction with membranes, biopolymers, and biological fluids are all possible". Despite these various possibilities the focus was on the most simple and prominent effect: elevated temperatures from absorption of electromagnetic energy. Subsequently the concept of specific energy absorption formed the basis for exposure standards in most western countries. A different approach was followed in the former Soviet Union, China, and many other eastern countries: they started from observations in humans and studied biological reaction in animals and isolated tissues without basing their research on a thermal effects concept but were interested in health relevant effects in a broader sense. Furthermore, completely different models of the interaction of EMFs with biological molecules and tissues were developed that were recognised only recently by western scientists (e.g. resonance phenomena in the presence of the earth magnetic field and weak alternating magnetic fields).

Only for power-frequency fields there was some public awareness, especially concerning high-voltage lines. High-frequency fields were almost completely neglected by the media until the advent of modern telecommunication that was accompanied by the installation of thousands of mobile-phone base-stations in the midst of densely populated areas. The controversy about potential adverse health effects from exposure to high-frequency EMF, that was more or less confined to the scientific community, extended to the political and economical sphere which made the task to come to a balanced conclusion not easier. Furthermore, preventive concepts that were developed in the past 50 years and guided decisions about exposure standards for environmental and occupational pollutants were not or not fully adopted for EMFs.

2.1 Dosimetry

The guidelines /5/ of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) date back to the deliberations of the subcommittee of the Institute of Electrical and Electronics Engineers (IEEE) that prepared the exposure standard for the American National Standards Institute and is known as the IEEE standard C95.1 /6/. Although ICNIRP deviated in several points from the IEEE standard, the basic concept of issuing a single basic restriction that is formulated in terms of the specific energy absorption rate (SAR) for the total range of high-frequencies up to about 10 GHz and deriving at reference levels by using the relationship between frequency of the incident field and SAR, has been adopted.

SAR is defined as the time derivative of specific energy absorption (SA). SA is defined as the quotient of the incremental energy absorbed by, or dissipated in, an incremental mass. SAR is proportional to the square of the internal electrical field strengths and also proportional to the temperature increase in the exposed organism or tissue. The SAR concept is characterised by the view that SAR is the fundamental dosimetric parameter in the frequency range from 10 MHz to about 10 GHz from which exposure limits can be derived, as expressed by ICNIRP /5/: "...these guidelines are based on short-term, immediate health effects such as ... elevated temperatures resulting from absorption of energy during exposure to EMF." (p.496). The great strength of this concept is its independence from characteristics of the incident field. However, it is a macroscopic concept and introduces a gross simplification, maybe an oversimplification, even if only energy deposition is concerned.

Due to the complex structure of biological tissues with grossly different dielectric properties an exact computation of SAR or SA is impossible. Therefore, for computational purposes as well as for the operationalisation of measurements simplifications are necessary. Usually measurements are conducted using phantoms filled with an electrolyte gel or liquid with defined dielectric properties. This procedure will result, at least for electrolytes which are deliberately chosen to give conservative estimates, in an upper limit for the SAR. However, this statement holds only for a big enough volume element and for exposures that are within one frequency range only (that is, not consisting of simultaneous exposure to several EMFs with strongly different frequencies). The multi-layer structure and specific form of tissues result in a considerable heterogeneity of absorption, which could not be completely accounted for by these measurements. It has to be borne in mind that as the field travels through tissues its wavelength and direction changes and the more so the higher the absorption. The depth of penetration into tissues is inversely related to the rate of absorption, thus tissues embedded into fat or bony structures will be exposed to higher internal field strengths as tissues that are surrounded by liquids. However, the measurement of the dielectric properties of tissues is very complicated and if done outside the living organism the rapid loss of extra- and intracellular fluid will result in a hardly quantifiable bias. The best currently available data concerning these properties can be found in Gabriel et al. /7,8/. However, recent measurements /9,10/ indicate that the values used so far may not be correct.

On the other hand computational methods like FDTD (finite difference time domain) could in principle be used to assess the distribution of energy absorption within the body. But also such methods have their limitations. Even if data from computerised tomography are utilised, the necessary simplifications that have to be applied in order to keep computational efforts within reasonable limits are apparent. Besides the mentioned fundamental limitations the measurement (and computational) errors have to be considered. At present it seems that even the best equipment results in a net coefficient of variation of not much less than 30%, a figure that seems untenable for regulatory purposes.

The main criticism however is related to the focus on the energetic aspect. The interaction of the electromagnetic field with the organism is restricted to the ensemble effect of the resulting increase of the kinetic and rotational energy of charged and polarized particles, which is reflected by a temperature increase. In the WHO Environmental Health Criteria from 1981 it is said about SAR that "it may not be the only factor, e.g. frequency and/or modulation of the radiation field may strongly affect biological effects. Consequently, the nature of the radiation fields should always be considered in addition to the SAR" (UNEP/WHO/IRPA /11/, p.45).

SAR is a rate. Hence the question arises about the role of duration of exposure. Using SAR as a basis for exposure limitations, implies that exposure duration plays no decisive role. While this is questionable for low intensities, it is surely wrong for high exposures. If the exposure exceeds the capacity of the organism to dissipate the heat induced by the absorption of electromagnetic energy, tissue damage and even death may occur. Thermal death could result from severe hemorrhage and tissue damage or from cardiac failure. Results from earlier studies /12-17/ on thermal death are summarized in fig 1. Data from four species indicate that time to thermal death is roughly inversely related to SAR. Hence thermal death occurs (over a wide frequency range) at a constant SA value. This value is approximately 95 kJ kg^{-1}. However, the data are compatible with an SAR asymptote of 2 to 5 W kg^{-1} (indicating that SAR values below this range would not result in thermal death even at indefinite exposure duration). This is in line with the observation that exposure at about 4 W kg^{-1} leads after a steep temperature increase to a steady state. However, it is not known how long this steady state can be maintained and whether the regulatory efforts of the organism results in any long term adverse effects.

Another point which is also of importance (and which led Italy not to adopt the SAR concept in its regulations) is the fact that while it is intrinsically an effect meter (that is a biophysiological response variable) it is practically impossible to demonstrate the compliance with any standard expressed in its terms in the exposed individual. In occupational medicine there are similar measures (biological tolerance limits), however, in these cases it could be shown for every exposed subject whether or not the limit has been exceeded.

It has been argued that SAR is important due to the possibility to compare exposures between species and frequencies. However, as has been stated in UNEP/WHO/IRPA / 11/: "...SAR alone cannot be used for the extrapolation of effects from one biological system to another, or for the extrapolation of biological effects from one frequency to another." (p.45). The problem here could be readily demonstrated by reference to the discussion concerning the applicability of results from animal experiments to human exposures. Should exposures be scaled to parallel relative absorption (for every pair of species A and B, e.g. mice and humans, there is a unique function S of frequency that results in equal relative absorption rates: SARr,A(f)=SARr,B(S(f)) in W kg-1 (W m-2)-1 for all frequencies f within a certain interval)? Using the same frequency for both species will generally result in completely different patterns of absorption within the organisms, using the scaled frequency will make the pattern more similar, however, the frequency 'seen' by the cells will be different. This issue cannot be resolved without a sound theory of the mechanisms underlying the effect in question. If only SAR counts then it is completely irrelevant which frequency is chosen for the experiments as long as the SAR is held constant within reasonable limits. If frequency counts then the SAR concept is invalid because SAR is a function of frequency. It should be noted that these arguments are, ceteris paribus, also applicable to local absorption rates.

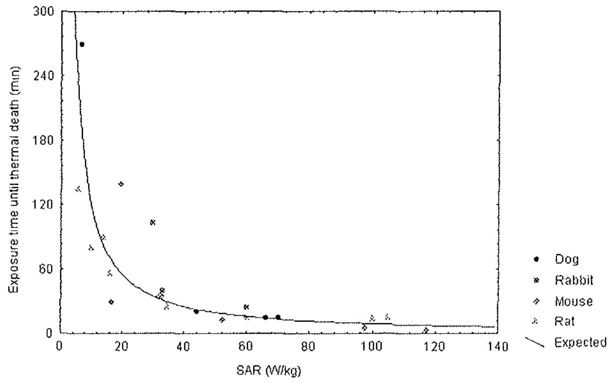

Figure 1: Relationship between SAR and time until thermal death for four species. Expected time to thermal death computed as inverse function of SAR

The strongest argument against the SAR concept might be formulated as follows: If there is a unique relationship between the incident electromagnetic field and SAR then SAR is superfluous and could readily be replaced by the far more precise measurement of external field strength. If there is no unique relationship then the properties of the relationship between body and field responsible for the lack of uniqueness will reduce the credibility of SAR estimates based on crude models as those generally applied. Hence the SAR concept is either easily dispensed of or inapplicable due to practical limitations.

2.2 Epidemiological Studies

Because most epidemiological studies relevant to public health are retrospective, exposure assessment is usually a weak point. Often exposure is categorised in classes (e.g. high, medium, low exposure) or is only dichotomised (exposed vs. non-exposed). The problem in the study of high-frequency EMFs, however, is additionally complicated by the fact, that it is not known which exposure parameters are associated with a possible outcome. Quantitative assessment of exposure is useless without this knowledge. It has frequently been stated (e.g. /18/) that epidemiological studies should give sufficiently comprehensive information about exposure to allow the determination of the relevant dosimetric parameters (that is of SAR in the case of high-frequency EMF). While a more detailed presentation of exposure characteristics should definitely be supported, it should be borne in mind that SAR cannot be considered an established dosimetric parameter for long-term and complex exposure conditions. In real life exposure conditions, the incident EMF, changes all the time in many aspects: in its intensity, direction, spectrum, wave form etc. There is no evidence that equal SAR from different combinations of exposure parameters results in equal long-term effects. Hence it is too early to condense exposure conditions into such a quantity. On several occasions ICNIRP pointed to the problem of exposure assessment without specifically justifying why results from studies that "...suffer from very poor assessment of exposure..." (p.504), that "...generally lack quantitative exposure assessment" (p.504) should be doubted. In fact, the same deficiencies are apparent in many studies on asbestos exposure, on formaldehyde, on passive smoking to name but a few with similar public awareness. All that is needed in epidemiological studies is a gradient of exposures. The steeper the gradient the higher the probability to detect an elevated risk if actually there is one. Furthermore, it should be stressed that in most cases exposure misclassification leads to a bias towards the null hypothesis of no association. Poor exposure assessment could therefore be an argument against studies reporting no effect. The evidence from studies reporting a significant risk, provided the study meets basic principles of scientific conduct, can only be dismissed by other evidence supporting the assumption that the deviation occurred by chance or by demonstrating empirically that the risk enhancement is due to the action of confounding factors. Only postulating such hypothetical factors does not conform to scientific reasoning.

Table 1 gives an overview of the results of epidemiological studies that investigated brain tumours as a major endpoint. Before 2000 studies were either dedicated to the analysis of occupational radio-frequency (RF) or microwave (MW) exposure or to exposures from emissions of radio or television towers. In the years thereafter studies focused on a potential brain tumour risk from exposures to mobile phones.

The major problem in these latter studies is the comparatively short period of time such devices are used on a greater scale. Brain tumours, like most other malignancies, need long times to develop, and decades of exposure may be necessary to consistently detect an increased risk. In the majority of investigations mobile phone use was short (less than two to three years) in most subjects included in the studies. It is of significance that in those few studies that approached meaningful latencies in a considerable proportion of study participants an increased risk was observed.

It has been argued that it is unlikely that microwave exposure from mobile telephone use induces brain tumours, rather a promotional effect may occur. Therefore, it was stated, also short and recent exposures may have an effect that could be detected in epidemiological studies. While it is in line with experimental research that microwaves at low intensities do not induce genetic alterations, a contribution of MW exposure during initiation phase is still possible. Furthermore, it is neglecting basic features of the process of carcinogenesis if it is assumed that recent exposures play a role in promotional processes. One has to differentiate between promotion of a precancerous cell clone and growth of an already established tumour. It is possible that factors that affect promotion do also have an impact on tumour growth, however, brain tumours of high malignancy have such a fast growth rate that it is impossible to detect an influence of any factor in an epidemiological investigation. Hence an influence on growth rate can only be detected for low grade slowly growing tumours. Therefore, the predominance of high-grade tumours in some of the investigations will reduce the determined risk.

If the predominant effect of exposure to MW is on growth rate the expected effect on estimates of incidence ratios will be small due to the short exposure duration. The shift in age-incidence function can only be a fraction of the exposure duration and hence is a function of the population gradient of the age-incidence relationship which is small for brain tumours. However, if an effect on promotion is assumed (with or without affecting the growth rate of an established lesion) and the exposure is early and long-term then the expected effect on incidence is high, higher even than for factors that induce genetic alterations.

Overall, from 18 studies on brain tumour risk and exposure to high-frequency EMFs 13 found elevated risks 6 of which were statistically significant. This is a clear indication of a possible association and warrants further study.

Except brain tumours malignancies of the haematopoietic and lymphatic tissues have been studied in several investigations. The focus on these types of malignancies is due to the pioneering research of Wertheimer and Leeper /40/ on a possible association between childhood cancer and low-frequency magnetic fields. Lymphatic and haematopoietic malignancies were predominantly studied in occupationally exposed subjects or people exposures to radio or TV towers.

Twelve of 16 studies reported increased risks at least for some subgroups, eight of which were statistically significant. For childhood leukaemia the most vulnerable period seems to be the foetal and perinatal period. Unfortunately no study has focused on the time point of exposure. Ecological studies are in general not easily assessed because of a number of potential biases that cannot always be avoid-

Table 1: Synopsis of studies assessing brain tumour risk of exposure to high-frequency EMF

Reference	Study type	No of cases	Exposure		Result
Thomas et al. [19]	CC	435	occupational RF	RR	1.6 [1.0-2.4]
Selvin et al. [20]	E	35	TV tower	RR	1.2 [0.7-1.9]
Tynes et al. [21]	pC	3	occupational RF	SIR	0.6 [0.1-1.8]
Armstrong et al. [22]	nCC	9	occupational PEMF	OR	1.9 [0.5-7.6]
Szmigielski [23]	rC	~47	military (pulsed) RF/MW	SIR	1.9 [1.1-3.5]
Beall et al. [24]	nCC	149	VDT development work	OR	1.3 [0.9-1.9]
Grayson [25]	nCC	230	military RF/MW	OR	1.4 [1.0-1.9]
Hocking et al. [26]	E	30	3 TV towers	$rR_{children}$	0.7 [0.3-2.1]
		600		rR_{adults}	0.8 [0.6-1.1]
Dolk et al. [27]	E	17	TV/FM radio tower	SIR	1.3 [0.8-2.3]
Lagorio et al. [28]	rC	1	dielectric heat sealers	SMR	10 [0.3-55.7]
Finkelstein [29]	rC	16	police radar (possible)	SMR	0.8 [0.5-1.4]
Morgan et al. [30]	rC	51	occupational RF	$rR_{high\ exp.}$	1.1 [0.3-2.7]
Hardell et al. [31-33]	CC	233	mobile telephones	OR	1.0 [0.7-1.4]
		13[a)]	ipsilateral use		2.6 [1.0-6.7]
Muscat et al. [34]	CC	469	mobile telephones	OR	0.9 [0.6-1.2]
Inskip et al. [35]	CC	782	mobile telephones	OR	1.0 [0.6-1.5]
Johansen et al. [36]	pC	154	mobile telephones	$SIR_{>2\ y}$	1.2 [0.6-1.6]
Auvinen et al. [37]	CC	398	mobile telephones	OR_{analog}	1.6 [1.1-2.3]
Hardell et al. [38-39]	CC	1429	mobile telephones	OR_{analog}	1.3 [1.0-1.6]
		93[a)]	ipsilateral use		1.8 [1.3-2.5]

[a)] number of cases of discordant pairs

CC...case-control, E...ecological, pC...population based cohort, nCC...nested case-control, rC...retrospective cohort, RR...relative risk, SIR,SMR...standardized incidence/mortality ratio, OR...odds ratio, rR...rate ratio ed. Nevertheless a moderately elevated risk for development of malignancies of the haematopoietic and lymphatic tissues can be inferred from the evidence compiled so far.

There is only weak support of the assumption of a carcinogenic potential of high-frequency EMFs from long-term animal experiments. There are about 25 studies that can be evaluated. Almost all of them have serious limitations that make an overall assessment impossible. Especially insufficient numbers of animals, an unsuitable choice of induction methods with a too steep decline of survival or too high rates of incidence may be responsible for the predominantly negative findings. None of the studies was conducted according to the recommendations of the US National Toxicological Program.

3. Conclusion

There is a decade long controversy about the existence of long-term low-level effects of high-frequency EMFs. According to the thermal effects principle no health relevant effect can occur without substantial increase of body or tissue temperature from absorption of electromagnetic energy. Therefore the specific energy absorption rate (SAR) is considered the basic dosimetric quantity that is also the focus of exposure guidelines for the protection of human health.

The critique against this concept can be summarised as follows:

- SAR is a macroscopic concept while effects may be due to microscopic interactions at the level of membranes or biomolecules
- SAR cannot account for the complex composition of tissues and gives at best an upper limit within rather big volume elements
- The problem of simultaneous exposure to fields of very different frequencies (e.g. short waves and microwaves) is unresolved with respect to SAR measurement
- SAR establishes an equivalence that has never been empirically demonstrated to be valid, to the contrary for high exposure it is surely invalid, whether it holds for low levels of exposure is unclear
- For thermal death there exists an inverse relationship between SAR and time to death, indicating that exposure duration plays a decisive role, hence SAR as a rate cannot be the basis for calculating exposure limits (if thermal effects are considered SA is definitely the better option!)
- Compliance with a limit value expressed in terms of SAR cannot be demonstrated in the exposed individual
- Measurement and calculation methods of SAR are complicated and result in a high coefficient of variation.

Table 2: Synopsis of studies assessing risk of exposure to high-frequency EMF with respect to haematopoietic and lymphatic neoplasms

Reference	Study type	No of cases	Exposure		Result
Robinette et al. [41]	rC	49	military radar	SMRr	2.0 [0.9-4.5]
Milham [42]	rC	89	amateur radio	SMR	1.2 [1.0-1.5]
Muhm [43]	rC	2	electromagnetic pulse	SMR	3.3 [0.4-12.0]
Selvin et al. [20]	E	51	TV tower	RR	1.0 [0.7-1.4]
Tynes et al. [21]	pC	9	occupational RF	SIR	2.9 [1.3-5.4]
Armstrong et al. [22]	nCC	807	occupational PEMF	OR	1.0 [0.5-1.9]
Szmigielski [23]	rC	~155	military (pulsed) RF/MW	SIR	6.3 [3.1-14.3]
Mascarinec et al. [44]	E	12	military radio tower	SIR	2.1 [1.1-3.7]
Hocking et al. [26]	E	59	3 TV towers	$rR_{children}$	2.3 [1.4-4.0]
		847		rR_{adults}	1.2 [1.0-1.4]
Dolk et al. [27]	E	45	TV/FM radio tower	$SIR_{0\text{-}2km}$	1.2 [0.9-1.6]
		51		$SIR_{1\text{-}5km}$	1.4 [1.1-1.9]
		935		$SIR_{0\text{-}10km}$	1.0 [1.0-1.1]
Dolk et al. [45]	E	759	20 TV/FM radio towers	$SIR_{1\text{-}5km}$	1.1 [1.0-1.2]
Lagorio et al. [28]	rC	1	dielectric heat sealers	SMR	5.0 [0.1-27.9]
Finkelstein [29]	rC	20	police radar (possible)	SMR	0.7 [0.4-1.0]
Morgan et al. [30]	rC	203	occupational RF	$rR_{high\ exp.}$	0.7 [0.3-1.5]
Johansen et al. [36]	pC	84	mobile telephones	$SIR_{>2\ y}$	1.5 [0.5-3.2]
Michelozzi et al. [46]	E	40	radio station	SMR_{adults}	1.8 [0.3-5.5]
		8		$SIR_{children}$	2.2 [1.0-4.1]

E...ecological, pC...population based cohort, nCC...nested case-control, rC...retrospective cohort, RR...relative risk, SIR,SMR...standardized incidence/mortality ratio, SMRr...ratio of SMR, OR...odds ratio, rR...rate ratio

Evidence from epidemiological investigations, most of which have focused on brain tumours or leukaemia, points to a moderate risk associated with occupational or environmental exposure to high-frequency EMFs. Mobile phone use, in particular, may be associated with a slight increase of the risk to develop brain tumours or other malignancies localised in the head. Support of these epidemiological findings from animal experiments is weak, which may be due to the non-existence of a risk or to methodological limitations apparent in most of these studies.

4. References

/1/ J.R. McLaughin, *A Survey of Possible Health Hazards from Exposure to Microwave Radiation*. Hughes Aircraft Corporation, Culver City, 1953

/2/ J.E. Boysen, Hyperthermic and pathologic effects of electromagnetic radiation (350 Mc), *A.M.A. Arch Indust Hyg.* 7, 1953, 516-525.

/3/ C.I. Barron, and A.A. Baraff, Medical considerations of exposure to microwaves (radar). *J.A.M.A.* 168, 1958, 1194-1999.

/4/ H.P. Schwan, Classical theory of microwave interaction with biological systems, In L.S. Taylor, and Y. Cheung (eds.) *Proceedings of a Workshop on the Physical Basis of Electromagnetic Interactions with Biological Systems*, US DHEW document No. HEW-FDA 78-8055.

/5/ International Commission on Non-Ionizing Radiation Protection (ICNIRP), Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). *Health Phys.* 74. 1998, 494-522.

/6/ Institute of Electrical and Electronics Engineers (IEEE), *IEEE standard for safety levels with respect to human exposure to radio frequency electromagnetic fields, 3 kHz to 300 GHz*. IEEE Std C95.1, 1999 Edition.

/7/ S. Gabriel, R.W. Lau, C. Gabriel, The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz to 20 GHz. *Phys Med Biol.* 41, 1996, 2251-2269.

/8/ S. Gabriel, R.W. Lau, C. Gabriel, The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues. *Phys Med Biol.* 41, 1996, 2271-2293.

/9/ G. Schmid, G. Neubauer, P.R. Mazal, Dielectric properties of human brain tissue measured less than 10 h postmortem at frequencies from 800 to 2450 MHz. *Bioelectromagnetics* 24, 2003, 423-430.

/10/ G. Schmid, G. Neubauer, U.M. Illievich, F. Alesch, Dielectric properties of porcine brain tissue in the transition from life to death at frequencies from 800 to 1900 MHz. *Bioelectromagnetics* 24. 2003, 413-422.

/11/ United Nations Environment Programme/World Health Organization/International Radiation Protection Association (UNEP/WHO/IRPA). *Radiofrequency and Microwaves.* World Health Organization, Geneva, Environmental Health Criteria 16, 1981.

/12/ T.S. Ely, D.E. Goldman, Y.Z. Hearon, R.B. Williams, and H.M. Carpenter, *Heating Characteristics of Laboratory Animals Exposed to Ten Centimeter Microwaves.* Naval Medical Research Institute, Bethesda, Rep. NM 001.256).

/13/ T.S. Ely, and D.E. Goldman, Heat exchange characteristics of animals exposed to 10 centimeter microwave. *IRE Trans Med Electron*, 4, 1956, 38-49.

/14/ C. Addington, F. Fisher, R. Neubauer, C. Osborne, Y. Sarkees, and G. Swartz, Thermal effects of 200 megacycles (cw) irradiation as related to shape, location and orientation in the field. In *Proceedings of the 2nd Tri-Service Conference on the Biological Effects of Microwave Energy,* ASTIA Document No. AD 131477, 1958.

/15/ W.B. Deichmann, Biological effects of microwave radiation of 24 000 megacycles. *Arch Toxicol*, 22, 1966, 24-35.

/16/ Z.V. Gordon, Problems of industrial hygiene and the biological effects of electromagnetic superhigh frequency fields, Medicina, Moscow, 1966 /English translation in NASA Rep. TT-F-633, 1976/

/17/ S.M. Michaelson, J.W. Howland, and W.B. Deichman, Response of the dog to 24,000 and 1285 MHz microwave exposure. *Ind Med,* 40, 1971, 18-23.

/18/ J.H. Bernhardt, ICNIRP initiatives. *Radiat Prot Dosimetry,* 83, 1-2, 1999, 5-7.

/19/ T.L. Thomas, P.D. Stolley, A. Sternhagen, E.T.H. Fontham, M.L. Bleeker, P.A. Stewart, and R.N. Hoover, Brain tumour mortality risk among men with electrical and electronic jobs: a case-control study. *J. Nat. Cancer Inst*, 79, 1987, 233-238.

/20/ S. Selvin, J. Schulman, and D.W. Merrill, Distance and risk measures for the analysis of spatial data: a study of childhood cancers. *Soc. Sci. Med,* 34, 1992, 769-777.

/21/ T. Tynes, A. Andersen, and F. Langmark, Incidence of cancer in Norwegian workers potentially exposed to electromagnetic fields. *Am. J. Epidemiol,* 136, 1992, 81-88.

/22/ B. Armstrong, G. Theriault, P. Guenel, J. Deadman, M. Goldberg, and P. Heroux, Association between exposure to pulsed electromagnetic fields and cancer in electrical utility workers in Quebec, Canada, and France. *Am. J. Epidemiol,* 140, 1994, 805-820.

/23/ S. Szmigielski, Cancer morbidity in subjects occupationally exposed to high frequency (radiofrequency and microwave) electromagnetic radiation. *Sci. Total Environ,* 180, 1996, 9-17.

/24/ C. Beall, E. Delzell, P. Cole, and I. Brill, Brain tumors among electronic industry workers. *Epidemiology,* 7, 1996,125-130.

/25/ J.K. Grayson, Radiation exposure, socioeconomic status, and brain tumor risk in the US Air Force: a nested case-control study. *Am. J. Epidemiol,* 143, 1996, 480-486.

/26/ B. Hocking, I.R. Gordon, M.L. Grain, and G.E. Hatfield, Cancer incidence and mortality and proximity to TV towers. *Med. J. Aust,* 165, 1996, 601-605.

/27/ H. Dolk, G. Shaddick, P. Walls, C. Grundy, B. Thakrar, I. Kleinschmidt, and P. Elliott, Cancer incidence near radio and television transmitters in Great Britain, Part I. Sutton Coldfield Transmitter. *Am. J. Epidemiol,* 145, 1997, 1-9.

/28/ S. Lagorio, S. Rossi, P. Vecchia, M. De Santis, L. Bastianini, M. Fusilli, A. Ferrucci, E. Desideri, and P. Comba, Mortality of plastic-ware workers exposed to radiofrequencies. *Bioelectromagnetics*, 18, 1997, 418-421.

/29/ M.M. Finkelstein, Cancer incidence among Ontario police officers. *Am. J. Ind. Med,* 34, 1998, 157-162.

/30/ R.W. Morgan, M.A. Kelsh, K. Zhao, K.A. Exuzides, S. Heringer, and W. Negrete, Radiofrequency exposure and mortality from cancer of the brain and lymphatic/hematopoietic systems. *Epidemiology* 11, 2000,118-127.

/31/ L. Hardell, L. Näsman, A. Pĺhlson, and A. Hallquist, Use of cellular telephones and the risk for brain tumors: A case-control study. *Int. J. Oncol,* 15, 1999, 113-116.

/32/ L. Hardell, L. Näsman, A. Pĺhlson, and A. Hallquist, Case-control study on radiology work, medical x-ray investigations, and use of cellular telephones as risk factors for brain tumors. *MedGenMed* May 4. (http://www.medscape.com/Medscape/GeneralMedicine/journal2000/v02.n03/mgm0504.hard/mgm0)

/33/ L. Hardell, K. Hansson Mild, A. Pĺhlson, and A. Hallquist, Ionizing radiation, cellular telephones and the risk for brain tumours. *Eur. J. Cancer Prev,* 10, 2001, 523-529.

/34/ J.E. Muscat, M.G. Malkin, S. Thompson, R.E. Shore, S.D. Stellman, D. McRee, A.I. Neugut, and E.L. Wynder, Handheld cellular telephone use and risk of brain cancer. *J.Am.Med.Assoc,* 284, 2000, 3001-3007.

/35/ P.D. Inskip, R.E. Tarone, E.E. Hatch, T.C. Wilcosky, W.R. Shapiro, R.G. Selker, H.A. Fine, P.M. Black, J.S. Loeffler, and M.S. Linet, Cellular-telephone use and brain tumors. *New Engl. J. Med,* 344, 2001, 79-86.

/36/ C. Johansen, J.D. Boice, Jr., J.K. McLaughlin, and J.H. Olsen, Cellular telephones and cancer - a nationwide cohort study in Denmark. *J. Natl .Cancer Inst,* 93, 2001, 203-207.

/37/ A. Auvinen, M. Hietanen, R. Luukonen, and R.S. Koskela, Brain tumors and salivary gland cancers among cellular telephone users. *Epidemiology,* 13, 2002, 356-359.

/38/ L. Hardell, K. Hansson Mild, and M. Carlberg, Case-control study on the use of cellular and cordless phones and the risk for malignant brain tumours. *Int. J. Radiat. Biol,* 78, 2002, 931-936.

/39/ L. Hardell, A. Hallquist, K. Hansson Mild, M. Carlberg, A. Pǐhlson, and A. Lilja, Cellular and cordless telephones and the risk for brain tumours. *Eur. J. Cancer Prev,* 11, 2002, 377-386.

/40/ N. Wertheimer, and E. Leeper, Electrical wiring configuration and childhood cancer, *Am.J.Epidemiol,* 109, 1979, 273-284.

/41/ C.D. Robinette, C. Silverman, and S. Jablon, Effects upon health of occupational exposure to microwave radiation (radar). *Am.J.Epidemiol,* 112, 1980, 39-53.

/42/ S. Milham, Increased mortality in amateur radio operators due to lymphatic and hematopoietic malignancies. *Am.J.Epidemiol,* 127, 1988, 50-54.

/43/ J.M. Muhm, Mortality investigation of workers in an electromagnetic pulse test program. *J. Occup. Med,* 34, 1992, 287-292.

/44/ G. Maskarinec, J. Cooper, and L. Swygert, Investigation of increased incidence in childhood leukemia near radio towers in Hawaii: preliminary observations. *J. Environ. Pathol. Toxicol. Oncol,* 13, 1994, 33-37.

/45/ H. Dolk, P. Elliot, G. Shaddick, P. Walls, and B. Thakrar, Cancer incidence near radio and television transmitters in Great Britain, Part II. All high-power transmitters. *Am. J. Epidemiol,* 145, 1997, 10-17.

/46/ P. Michelozzi, A. Capon, U. Kirchmayer, F. Forastiere, A. Biggeri, A. Barca, and C.A. Perucci, Adult and childhood leukemia near a high-power radio station in Rome, Italy. *Am. J. Epidmiol,* 155, 2002, 1096-1103.

Michael Kundi
Institute of Environmental Health,
Medical University of Vienna
Kinderspitalgasse 15, 1095 Vienna, Austria

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