

Health implications of exposure to radiofrequency/microwave energies

S M MICHAELSON

From the Department of Radiation Biology and Biophysics, University of Rochester, School of Medicine and Dentistry, Rochester, New York 14642

ABSTRACT The rapid development of and the increase in the number and variety of devices that emit microwave/radiofrequency (MW/RF) energies has resulted in a growing interest regarding the potential effects on health of these energies. The frequency ranges considered in this review are: 300 kHz to 300 MHz (radiofrequency) and 300 MHz to 300 GHz (microwaves). Investigations have shown that exposure to certain power densities for several minutes or hours can result in pathophysiological manifestations in laboratory animals. Such effects may or may not be characterised by a measurable rise in temperature, which is a function of thermal regulatory processes and active adaptation by the animal. The end result is either a reversible or irreversible change, depending on the irradiation conditions and the physiological state of the animal. At lower power densities, evidence of pathological changes or physiological alteration is non-existent or equivocal. Much discussion, nevertheless, has taken place on the relative importance of thermal or non-thermal effects of radiofrequency and microwave radiation. Several retrospective studies have been done on human populations exposed or believed to have been exposed to MW/RF energies. Those performed in the US have not shown any relationship of altered morbidity or mortality to MW/RF exposure. Reactions referable to the central nervous system and cardiovascular effects from exposure of man to microwave energy have been reported mostly in Eastern European publications. Individuals suffering from various ailments or psychological factors may exhibit the same dysfunctions of the central nervous and cardiovascular systems as those reported to result from exposure to MW/RF; thus it is extremely difficult, if not impossible, to rule out other factors in attempting to relate MW/RF exposure to clinical conditions. There is a need to set limits on the amount of exposure to MW/RF energies that individuals can accept with safety. Operative protection standards have apparently provided adequate safety to workers and the general population to permit the use of MW/RF energies without harm or detriment.

The elucidation of the biological effects of exposure to microwave or radiofrequency (MW/RF) energies requires a careful review and critical analysis of available publications. This entails differentiating established effects and mechanisms from speculative and unsubstantiated reports. Although most of the experimental data support the concept that the effects of microwave exposure are primarily, if not only, a response to heating or altered thermal gradients in the body, there are large areas of confusion, uncertainty, and misinformation.

The organs and organ systems affected by exposure to microwave (300 MHz-300 GHz) or radiofrequency

(300 kHz-300 MHz) energies are susceptible in terms of functional disturbance or structural alterations, or both. Some reactions to MW/RF exposure may lead to measurable biological effects that remain within the range of normal (physiological) compensation and are not necessarily hazardous or improve the efficiency of certain physiological processes and can thus be used for therapeutic purposes. Some reactions, on the other hand, may lead to effects that may be potential or actual hazards to health.

The non-uniform, largely unpredictable distribution of energy absorption may give rise to increases in temperature and rates of heating that could result in unique biological effects. Nevertheless, it is important to recognise that the mammalian body normally

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is not a uniform incubator at 37°C but does contain significant temperature gradients in deep body organs that may act as functional stimuli to alter normal function, both in the heated organ and in other organs or organ systems. Thus indirect effects can be elicited in organs far removed from the site of the primary interaction.

Most of the MW/RF responses are explained by thermal energy conversion, almost exclusively as enthalpic energy phenomena.

Specific organ tissue systems may "function" at a significantly different rate if local thermal gradients are altered. Relatively large changes in circulation are provoked by quite small deviations from neutral temperature.¹ Body content of heat is equilibrated by approach to equality of two overall processes, gain and loss.

Absorption of MW/RF energy leads to increased temperature when the rate of energy absorption exceeds the rate of energy dissipation. Whether the resultant increased temperature is diffuse or confined to specific anatomical sites, depends on:

(a) the electromagnetic field characteristics and distributions within the body, and

(b) the passive and active thermoregulatory mechanisms available to the organism, such as heat radiation, conduction, convection, and evaporative cooling. The efficacy of heat convection between a body and its immediate environment is influenced by the environmental conditions.

Experimental observations

Cellular effects—chromosomes—genetic effects

Some investigators have reported chromosome changes in various plant and animal cells and tissue cultures.^{2,3} These studies have been criticised because the systems were subjected to a thermal stress; the chosen parameters of the applied field caused biologically significant field induced force effects in in-vitro experiments, and many of these experiments have not yet been independently replicated. There is no conclusive evidence for microwave-induced genetic effects.⁴

Growth and development

A few reports suggest that particular combinations of MW/RF wavelength, duration of exposure, and power density produce effects on embryological development and postnatal growth. In almost all instances, however, the reported effects may be ascribed to the excessively increased temperature caused by the exposure.⁵

The gonads

The effect of microwaves on the testes has been

studied fairly extensively. Although reports indicate that high power density exposure can affect the testes,⁶ this can be related to the heating of the organs. The sensitivity of the testes to heat is well known.

Neuroendocrine effects

Some investigators believe that endocrine changes result from hypothalamic-hypophysial stimulation due to thermal interactions at the hypothalamic or adjacent levels of organisation, the hypophysis itself, or the particular endocrine gland or end-organ under study.⁷⁻¹³ According to other investigators, the observed changes are interpreted as resulting from direct microwave interactions with the central nervous system.¹⁴⁻¹⁷ In either case one should not consider neuroendocrine perturbations as necessarily harmful because the function of the neuroendocrine system is to maintain homeostasis, and hormone levels will fluctuate to maintain organ stability.¹¹

Before 1970, the investigation of the effects of microwaves on endocrine balance consisted primarily of retrospective studies of exposed microwave workers. In these studies various clinical parameters were analysed to assess thyroid integrity (thyroid gland size, radioactive iodide uptake, metabolic rate, and plasma protein bound iodide-PBI). The results, however, were not consistent, and diagnostic techniques are questionable.

Immunology

Microwaves have been reported to induce an increase in the frequency of complement receptor-bearing lymphoid spleen cells in mice.¹⁸ MW/RF-induced hyperthermia in mice has been associated with transient lymphopenia with a relative increase in splenic T and B lymphocytes,¹⁹ and decreased in-vivo local delayed hypersensitivity. The influence of increased temperature on immune responses is well known.²⁰

Effects on the nervous system

Transient functional changes referable to the central nervous system (CNS) have been reported after "low-level" (< 10 mW/cm²) microwave exposure of small laboratory animals. Although some reports describe the thermal nature of MW/RF energy absorption, others implicate non-thermal or "specific" effects at the molecular and cellular level. It should be noted, however, that specific—that is, non-thermal—MW/RF effects have not been experimentally verified. The first reports of the effect of microwave energy on conditional response activity in experimental animals was made by investigators in the USSR.²¹ In subsequent years the study of "non-thermal" effects of microwaves gradually

occupied the central role in electrophysiological studies in the Soviet Union.

The blood brain barrier

In the past few years considerable interest has been engendered by a report of a transient alteration in the permeability of small inert polar molecules across the blood brain barrier of rats exposed to microwaves.²² Attempts to duplicate these findings have yielded equivocal results unless the brain is subjected to a large increase in temperature.^{23 24}

Behavioural effects

Studies have been conducted on the effects of MW/RF on the performance of trained tasks by rats and rhesus and squirrel monkeys. Many of these studies indicate that exposure to MW/RF energies can be related to suppressed performance of a trained task, and that a power density/dose rate and duration threshold for achieving the suppression exists.

In this context it is important to realise that behaviour among animals reflects adaptive brain-behaviour patterns and behavioural thermoregulation expresses an attempt to maintain a nearly constant internal thermal environment. Changes in body temperature bring about not only autonomic drives but also behavioural drives²⁵; thus microwaves can influence behavioural thermoregulation.^{26 27}

Haematopoietic effects

Although several investigators state that the blood and blood-forming system are not affected by acute or chronic microwave exposure,²⁸⁻³⁰ effects on haematopoiesis have been reported.³¹⁻³⁵ The degree of haematopoietic change is dependent on the field intensity, duration of exposure, and induced hyperthermia. In evaluating reports of haematological changes one must be aware of the relative distribution of blood cells in the population and the susceptibility to thermal influences. Early and sustained leucocytosis in animals exposed to thermogenic levels of microwaves may be related to stimulation of the haematopoietic system, leucocytic mobilisation, or recirculation of sequestered cells.

Ocular effects

During the past 25 years, numerous investigations in animals and several surveys among human populations have been devoted to assessing the relationship between exposure to microwaves and the subsequent development of cataracts. It is significant that of the many experiments on rabbits by several investigators using various techniques, power density above 100 mW/cm² for one hour or longer appears to be the time-power threshold for cataractogenesis in the tested frequency range of 200 MHz to 10 000 MHz.^{36 37} In other species of animals such as dogs and non-human primates, the threshold for experimental microwave-induced cataractogenesis appears to be higher. All of the reported effects of microwave exposure on the lens can be explained on the basis of thermal injury.

That cataract can be produced in rabbits by exposure to microwaves is well established. Extrapolating results from animal studies to man is difficult, because the conditions, durations, and intensities of exposure are usually quite different.

Several cases of alleged cataract formation in people exposed to microwaves have been reported, but the precise details of exposure are generally impossible to determine. It is also difficult to relate cause and effect, because lens imperfections do occur in otherwise healthy individuals, especially with increasing age. Numerous drugs, industrial chemicals, and certain metabolic diseases are associated with cataracts.

Cutaneous perception

Perception of microwave energy is a function of

Table 2 Threshold for pain sensation as a function of exposure duration (3000 MHz, 9.5 cm² area)*

Power density (W/cm ²)	Exposure time (s)
3.1	20
2.5	30
1.8	60
1.0	120
0.83	> 180

*From Cook.⁴⁰

Table 1 Stimulus intensity and temperature increase to produce a threshold warmth sensation*

Exposure time (s)	3000 MHz		10 000 MHz		Far infrared	
	Power density (mW/cm ²)	Power density (mW/cm ²)	Increase in skin temp (°C)	Power density (mW/cm ²)	Increase in skin temp (°C)	
1	58.6	21.0	0.025	4.2-8.4	0.035	
2	46.0	16.7	0.040	4.2	0.025	
4	33.5	12.6	0.060	4.2	—	

*37 cm² forehead surface area—data from Hendler.^{38 39}

cutaneous thermal sensation (table 1) or pain (table 2). Several studies suggest that a threshold sensation is obtained when the temperature of the warmth receptors in the skin is increased by a certain amount (ΔT).³⁸⁻⁴⁰

Extrapolation from animal experiments to man

In any review of biological experiments one has to be aware of the importance of the experimental design and the interpretation of the results. Even in experiments that appear to be impeccably planned it is easy to come to incorrect conclusions.

To extrapolate observations in animals to predict results that might be obtained during human exposures, both physiological and physical scaling must be used.⁴¹⁻⁴³ Experiments with small animals, such as mice and rats, to evaluate the potential effects of a stressor, such as an electromagnetic field, must be carefully designed and performed. Some observations may result from an unrelated stressor inadvertently introduced into the experimental design rather than the stressor intended to be studied. The fact that a living organism responds to many stimuli is a part of the process of living; such responses are examples of biological "effects." Since biological organisms do have adaptive, compensatory ability and tolerance to change, these effects may be well within the capability of the organism to maintain a normal equilibrium or condition of homeostasis. If, on the other hand, an effect should compromise the individual's ability to function properly or overcomes the recovery capability of the individual, then the effect may be considered a "hazard." In any discussion of the potential for biological effects from exposure to MW/RF energies we must first determine whether any effect can be shown; and then determine whether such an observed effect is hazardous.

If a specified electromagnetic environment should produce a characterisable biological reaction, the effect must be evaluated as to its potential hazard to man. Since initial experiments are usually performed on animal models, extrapolation from the experimental animal to man is necessary.

To review rationally the publications and assess the implications of the reported results of exposure to microwaves, it is essential to consider fundamental principles and concepts related to biomedical research in the laboratory and extrapolation to man. Experimental animal models are extensively used to study physical factors in the environment to assure human health and safety. The best we can do experimentally is to create an arbitrary set of conditions which we consider to be as relevant as possible for the purpose of the study. Many factors such as

methods of animal care, the role of seasonal and circadian rhythms, temperature, and humidity, as well as psychosocial interactions must be considered in the experimental design and the analysis of the results. Reliability of laboratory studies depends on the following:

- (1) selection of the animal model with consideration of its cognitive limits,
- (2) methods applied for the investigation of biological processes in animals,
- (3) extrapolation of data from animals to man.

Obviously, direct extrapolation from animal experiments to man cannot be performed a priori. This is due not only to their physiological differences but also the physical dimensions and shape.

To extrapolate observations in animals to predict results that might be obtained during human exposures, some method of scaling must be used. The best method available at present, albeit fraught with oversimplifications, is frequency scaling. In this context, by approximating the bodies of animals and man as prolate spheroids, an attempt has been made to ascertain what is the maximum absorption of lower frequency energy required for larger animals if the total absorbed dose rate (at the same plane wave exposure field intensity) is to be the same as that obtained at a higher frequency for a smaller animal.⁴⁴

Where absorbed energy in a test animal is used to approximate the pattern that may exist in man under certain conditions of exposure, the intrinsic physical and physiological dissimilarities among species further confounds the problem of extrapolating from animals to man. In addition to the obvious external geometric differences, the differences in internal vascular anatomy and mechanisms of heat dissipation between fur-bearing animals and man suggest the limitations in such frequency scaling.

The need for proper dosimetry in experimental procedures and the importance of realistic scaling factors required for extrapolation of data obtained with small laboratory animals to man are clear. Detailed discussions that serve as bases for scaling have been presented by several authors.⁴⁴⁻⁴⁷ Maximum absorption during whole-body irradiation of small animals apparently occurs at frequencies between about 0.5 and 3 GHz, and for man at around 60-100 MHz with a peak at about 80 MHz. At frequencies below 30 MHz, absorption rate drops off rapidly and is also much less at frequencies above 500 MHz.

An effort is being made to standardise dosimetric measures of MW/RF exposure by using a quantity called the specific absorption rate (SAR)—the time rate at which radiofrequency electromagnetic energy is imparted to an element of mass of a biological body.⁴⁸ The SAR depends on a finite period

Table 3 Ratio of specific absorption rate to basal metabolic rate for an average man exposed to far-field incident power densities of 1 mW/sq cm and 5 mW/sq cm*

Frequency (MHz)	Av SAR/BMR (%)	
	1 mW/sq cm	5 mW/sq cm
10	0.13	0.65
20	0.60	3.00
50	5.80	29.00
60	10.00	50.00
80	16.00	80.00
100	12.00	60.00
200	5.20	26.00
500	3.70	18.50
1000	2.90	14.50
2000	2.50	12.50
5000	2.50	12.50
10000	2.50	12.50
20000	2.50	12.50

*Based on Stuchly.⁴⁹

of exposure to yield the amount of energy absorbed by a given mass of material, which is termed specific absorption (SA)—that is, joules per kilogram (J/kg). The SAR is the time rate at which radio-frequency electromagnetic energy is imparted to a component or mass of a biological body. Thus the SAR is applicable to any tissue or organ of interest or is expressed as a whole-body average and specified in SI units of watts per kilogram ($W\ kg^{-1}$).

Durney *et al*⁴⁴ have calculated the SAR as a function of frequency for different sizes of laboratory animals and for man. This concept is useful in allowing limited extrapolation from one species to another, but it should be used cautiously in view of its limitations as already noted. Because of the different properties of various tissues, energy deposition may be much more uneven in animals than the models predict.

Whole-body absorption rates approach maximal values when the long axis of a body is parallel to the E-field vector and is four-tenths the wavelength of the incident field. At 2450 MHz, ($\lambda = 12.5\ cm$) for example, standard man (long axis 175 cm) will

absorb about half of the incident energy. If the human whole-body SAR is divided by the basal metabolic rate for man, a ratio is obtained that provides a measure of the thermal load incurred due to a known incident power density.⁴⁹ Table 3 illustrates the variation of this ratio with frequency at two incident power densities. In the region of human whole-body resonance (60-80 MHz) this ratio reaches a maximum value (about 0.16 for an incident far-field power density of 1 mW/cm²). The ratio drops off rapidly on either side of this peak, and at 10 MHz and below the ratio would be less than 0.001.⁵⁰

At frequencies that result in maximal absorption, which defines whole-body resonance, the electrical cross section of an exposed body increases in area. This increase occurs at a frequency near 70 MHz for standard man and results, as shown in table 4, in an approximate eightfold increase in absorption relative to that in a 2450-MHz field.

Survey of human exposures

Epidemiological studies

There have been only a few epidemiological studies of MW/RF exposure and these have generally been limited in scope.⁵¹⁻⁵² Individuals exposed while assigned to the military services or occupationally exposed in industrial settings have been the principal groups studied. A few other populations living or working near generating sources or exposed to medical diathermy have been or are being investigated.⁵¹⁻⁵⁴ Information about health status has come from medical records, questionnaires, physical and laboratory examination, and vital statistics. Sources of exposure data include personnel records, questionnaires, environmental measurements, equipment emission measurements, and (assumed adherence to) established exposure limits. Although there have been advances in measurement, accurate estimates of dose present formidable problems in most epidemiological studies.⁵¹⁻⁵²

Table 4 Specific absorption rate (SAR) for animals and for man (W/kg for 1 mW/cm² incident PD)

Species	Max absorption (MHz)	Frequency (MHz)						
		20-30	70	300	1000	2450	3000	10 000
Mouse	2000	8×10^{-4} (0.05)*	0.008 (0.04)	0.06 (1.50)	0.4 (13)	1.00 (36)	0.965 (36.60)	0.322 (12.40)
Rat	600	1.8×10^{-3} (0.12)	0.0125 (0.06)	0.3 (7.50)	0.6 (20)	0.23 (8)	0.26 (9.60)	0.25 (9.60)
Rabbit	320	0.015 (1.00)	0.050 (0.22)	0.80 (20)	0.250 (8.30)	0.15 (5.40)	0.08 (2.96)	0.07 (2.69)
Rhesus	300	1.7×10^{-3} (0.01)	0.0125 (0.06)	0.195 (5.00)	0.10 (3.33)	0.07 (2.50)	0.065 (2.41)	0.060 (2.30)
Dog	200	1.5×10^{-3} (0.10)	0.010 (0.04)	0.100 (2.50)	0.050 (1.67)	0.040 (1.40)	0.037 (1.40)	0.030 (1.15)
Human (1 Y)	150	0.004	0.040	0.15	0.065	0.055	0.050	0.042
Man (Av)	70	0.015	0.225	0.04	0.03	0.028	0.027	0.026

*SAR relative to average man.

An early study on United States Navy personnel during world war II did not show any conditions that could be ascribed to radar exposure.⁵⁵ Ten years later a four-year surveillance of a relatively large group of radar workers in the US did not show any significant clinical or pathophysiological differences between the exposed and control groups.⁵⁶⁻⁵⁷ On the other hand, surveys of East European workers showed functional changes in the nervous and cardiovascular systems.⁵⁸⁻⁶⁰

In an extensive 12-year survey in Poland workers exposed to microwaves for various periods were examined for the incidence of functional disturbances and disorders considered as contraindications for occupational exposure to microwaves according to the criteria used in Poland.⁶¹⁻⁶³ The population worked in identical conditions except for the exposure levels, of which there were two subgroups. Workers in the first subgroup (507 individuals) were exposed to varying power densities between 0.2 and 6 mW/cm²; in the second subgroup power densities were below 0.2 mW/cm². No dependence of incidence of disorders, such as organic lesions of the nervous system, changes in translucency of the ocular lens, primary disorders of the blood system, neoplastic diseases, or endocrine disorders on exposure level, duration, or work history could be shown. The incidence of functional disturbances ("neurasthenic syndrome," gastrointestinal tract disturbances, cardiovascular disturbances with abnormal ECG) as reported in Soviet publications⁵⁸⁻⁶⁰ was found not to be related to the level or duration of occupational exposure. There were no instances of irreversible damage or disturbances caused by exposure to microwave energy.⁶¹

The Medical Follow-up Agency of the US National Academy of Sciences studied mortality and morbidity among 40 000 personnel of the United States Navy⁶⁴ potentially exposed to radar. There was no indication of any adverse effect due to exposure to microwaves. This study was preceded by a survey to investigate physiological and physical effects among United States Navy crewmen who could be exposed to 0.1-1 mW/cm² aboard an aircraft carrier.⁶⁵ No significant differences were found, with respect to task performance, psychological tests, or biological effects. Haematological findings were within the normal range.

A study of 4388 employees and 8283 dependents of the United States Embassy in Moscow, some of whom had possibly been exposed to 5-15 μ W/cm² of microwaves for variable periods (9-18 hours/day) up to eight months, showed no differences in health status as indicated by their mortality experience and various morbidity measures.⁶⁶⁻⁶⁷ Exhaustive comparative analyses were made of all symptoms,

conditions, diseases, and causes of death among employees and dependent groups of adults and children. No differences in health status by any measure could be attributed to microwave exposure.⁵²

This study was preceded by a cytogenetic evaluation for possible mutagenesis performed on 250 samples from 71 US State Department employees and family members before, during, and after exposure to microwaves at the American Embassy in Moscow.⁶⁷ No genetic or other adverse biologic effects among employees and dependants attributable to microwave exposure could be established.

A study was also conducted to determine the blood lymphocyte counts of adult employees and dependents at the American Embassy in Moscow.⁶⁷ About 350 adults who were employed at the embassy during the study period were examined; roughly 1000 foreign service personnel in the United States served as a comparison group. There was no correlation between the higher average lymphocyte count found in the Moscow population and microwave irradiation in the embassy. Altered lymphocyte count was believed to be of microbial origin.

Considerable publicity has recently been given to an alleged death from microwave exposure (Yannon)*. This case was a workmen's compensation award and not subjected to litigation. The individual was apparently suffering from Alzheimer's disease, which is not uncommon in the general population. Alzheimer's disease has been recognised since 1903 and is not related to MW/RF exposure, being first recognised before we had MW/RF emitting devices. At necropsy the diagnosis was bilateral lower-lobe bronchial pneumonia; the brain was not examined. The subject was never exposed to significant levels of microwaves, his activities required him only to work at the back of the transmitting system. He was never required to work in front of the "antenna dish," although even in front of the antenna dish, the power density would not have been greater than 1 mW/cm².

OCULAR EFFECTS

Numerous surveys of ocular effects of MW/RF energies in man have been made, especially in the United States.⁵¹⁻⁵² Most investigations have involved military personnel and civilian workers at military bases and in industrial settings. The principal factors of interest have been the significance of minor lens changes in the cataractogenic process and cataracts (opacities impairing vision). Several cases of cataract attributed to microwave exposure have been reported, but substantiation has not been established. There is no clinical or experimental evidence that

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ocular lens damage allegedly due to microwave exposure is morphologically different from lens abnormalities from other causes, including aging.

Lenticular defects too minor to affect visual acuity have been studied as possible early markers of microwave exposure or precursors of cataracts. The studies have been mainly prevalence surveys, although the time periods are often variable or not specified; re-examination data rarely permit estimates of incidence. Some generalisations, however, can be made about observations of lens changes in microwave workers and comparison groups.^{51 52}

(1) Lens imperfections occur normally and increase considerably with age among employed men studied. There is evidence that lens changes increase with age even during childhood.⁶⁸ By about age 50, lens defects have been reported in most comparison subjects, based on data from various studies.

(2) Although a few suggestive differences have been reported,⁶⁸⁻⁷⁰ there is no clear indication that minor lens defects are a marker for microwave exposure in terms of type or frequency of changes, exposure factors, or occupation.^{51 52} The reported earlier appearance of lens defects in microwave workers than in comparison groups is not convincing because there is considerable variation in the type, number, and size of defects recorded, in the scoring methods used by different observers, and in the numbers examined.

(3) Clinically significant lens changes, which would permit selection of individuals to be followed up, have not been identified.⁷¹

(4) There is no evidence from ophthalmological surveys to date that minor lens opacities are precursors of clinical cataracts^{51 52}; a case-control study of world war II and Korean war veterans was negative for cataract.⁷²

Neither definitions nor methods of detection of cataract are standardised.^{51 52} The common meaning of cataract, a lens opacity that interferes with visual acuity, is open to many interpretations as to degree and nature of the opacity and loss of visual acuity. Specific disorders, physical agents, and injuries are known to cause cataracts but many cataracts are loosely called "senile" when they occur after middle age. Alleged "microwave cataracts" are not distinguishable from other cataracts, in the opinion of most ophthalmologists.⁷³⁻⁷⁶

The most prominent characteristic of cataracts is their age distribution. Although estimates of frequency are not comparable because of differences in the population groups surveyed, as well as non-uniform methods of detection and definition, all point to low frequencies until about the fifth decade of life, when sharp increases occur. Although not

comparable with general population figures, recorded mean annual incidence rates are of the order of two per 100 000.^{51 52} In a preliminary national estimate by age of the total prevalence of cataracts in the civilian non-institutionalised population aged from 1 to 74 in the United States, one or more cataracts was found in 9% of the population.⁷⁷ For the various age groups under 45, the frequency of the condition increased gradually from 0.4% in those aged 1-5 years to 4% in those aged 35-44. The pronounced increase that occurs after age 45 reaches a maximum in the oldest group examined: of those aged 65-74 over half had cataracts. Cataract data for personnel on active duty in the armed services (who are mainly healthy, relatively young men) are available as incidence rates that show similar age dependence up to about age 55.⁷⁸ Parenthetically, in the United States as of August 1981 no alleged microwave-induced cataracts in man have been ruled in favour of the plaintiff in legal proceedings.

NERVOUS SYSTEM AND CARDIOVASCULAR EFFECTS

Clinical and laboratory studies of workers in the Soviet Union and other Eastern European countries employed in the operation, testing, maintenance, and manufacture of microwave-generating equipment are reported to have shown central nervous and cardiovascular reactions to MW/RF exposure.^{4 59 60} Functional disturbances of the central nervous system have been described as "radiowave sickness"—the neurasthenic or asthenic syndrome. The symptoms and signs include headache, fatigability, irritability, loss of appetite, sleepiness, sweating, thyroid gland enlargement, difficulties in concentration or memory, depression, and emotional instability. The clinical syndrome is generally reversible if exposure is discontinued.^{51 52}

Another frequently described manifestation is a set of labile functional cardiovascular changes including bradycardia (or occasional tachycardia), arterial hypertension (or hypotension), and changes in cardiac conduction. This form of neurocirculatory asthenia is also attributed to nervous system influence. Effects indicated by hypotonus, bradycardia, delayed auricular and ventricular conduction, decreased blood pressure, ECG alterations in workers in RF or microwave fields have been reported.^{58-60 79} The identification and assessment of these poorly defined, non-specific complaints, and symptom-complexes is extremely difficult.^{80 81} These changes, however, do not diminish the capacity to work and are reversible.⁸² No serious cardiovascular disturbances have been noted in man or animals as a result of microwave exposure.⁸³

GROWTH AND DEVELOPMENT

A case-control study of Down's syndrome in relation to exposure to ionising radiation yielded an unexpected finding regarding paternal exposure to radar.⁸⁴ Apparently, fathers of children with Down's syndrome gave more frequent histories of occupational exposure to radar during military service than did fathers of unaffected children, a difference that was of borderline statistical significance. Exposure during military service occurred before the birth of the affected child. After publication of the first report in 1965, expansion of the study group, follow-up of all fathers to obtain more detailed information about radar exposure, and a search of available military personnel records were all undertaken. The suggestive excess of radar exposure to fathers of babies with Down's syndrome was not confirmed on further study.⁸⁵

A report of congenital anomalies at a United States Army base⁸⁶ suggested that during the three-year period 1968-71 the communities surrounding the base had a reported number of cases of clubfoot among white babies that greatly exceeded the expected number (based on birth certificate notifications for the State). A more detailed investigation showed that in the six-county area surrounding the base, there was, during the same period, a considerably higher rate of anomalies (diagnosed within 24 hours after birth) among births to military personnel than in the State as a whole. This base was a training facility for fixed-wing and helicopter aircraft, situated within 35 miles (56 km) of dozens of radar stations. Analysis showed that apparently there were errors in the malformation data on the birth certificates and a probable over-reporting from the army base. Thus convincing evidence was lacking that radar exposure was related to congenital malformations.⁸⁷ The higher malformation rate across a group of counties of the State was presumably environmentally induced but no specific agent was suggested.^{51 52}

A few human data are available from studies in which radiofrequency heating of the pelvic region was used to treat gonorrhoea, pelvic inflammatory disease, endometriosis, carcinoma of the uterus, or pelvic peritonitis. In one report⁸⁸ the pelvic temperature in women was raised to 115°F (46°C). Although the author was concerned about possible harmful effects, he did not allude to specific complications. In another report four women were treated with microwave diathermy (2450-MHz, 100 W output) for chronic pelvic inflammatory disease before or during pregnancy.⁸⁹ Three women delivered normal infants; the fourth, who received eight treatments during the first 59 days of pregnancy, aborted on day 67 but delivered a normal baby after a subsequent pregnancy during which she again received micro-

wave treatment. The authors concluded that microwaves did not interfere with ovulation, conception, and pregnancy.

Microwave heating has been used to relieve the pain of uterine contractions during labour.^{90 91} The analgesic effect was found helpful in 2000 selected patients without obstetric pathology, and the babies were born healthy with good circulation. No evidence of injury was manifested in a one-year follow-up of the children; there was no evidence of mental retardation. Four cases of chromosomal anomalies in controls and two cases in the irradiated group were noted. It is important to note that the human fetus at parturition is almost fully developed, thus gross structural defects at this late stage of development would not be expected.

There are reported case studies of increases in congenital abnormalities in women working in RF fields in Eastern Europe,⁹² but there are no unequivocal reports of microwave-induced human teratologies.

CANCER

Microwave-induced cancer has not been reported experimentally or suspected in medical surveillance examinations of microwave workers or Service personnel.^{51 52} Two cohort epidemiological studies^{64 66} that looked into the question systematically did not show an excess of any form of cancer to date that could be interpreted as microwave-related.^{51 52}

EASTERN EUROPEAN REPORTS

Nervous system perturbations and behavioural reactions in man after exposure to microwave energy have been reported mostly in Eastern European publications that describe subjective complaints consisting of fatigability, headache, sleepiness, irritability, loss of appetite, and memory difficulties.⁹²⁻⁹⁵ Psychic changes that include unstable mood, hypochondriasis, and anxiety have also been reported. Most of the subjective symptoms are reversible, and pathological damage to neural structures is insignificant.⁹⁶ Several reviewers^{36 37 51 52 97-101} have noted the difficulties in establishing the presence of and quantifying the frequency and severity of "subjective" complaints. Individuals suffering from a variety of chronic diseases may exhibit the same dysfunctions of the central nervous and cardiovascular systems as those reported to be a result of exposure to microwaves¹⁰¹; thus it is extremely difficult, if not impossible, to rule out other factors in attempting to relate microwave exposure to clinical conditions.

CRITIQUE OF EPIDEMIOLOGICAL STUDIES

An important concept of disease causation is that, in general, disease is not caused by a single factor or agent, but rather is influenced by multiple, interactive components including the subject and his environment. Health effects or manifestations of disease have a spectrum of intensity ranging from barely discernible and rapidly reversible symptomatic disorders, through an increasing gradient of severity to the point of irreversibility, and, finally, to disease states of such gravity as ultimately to cause death. For electromagnetic fields, in common with most other agents, biological or physical, the trivial end of this severity scale includes detectable physiological effects, which are well within the range of physiological adaptation and do not constitute disease in any meaningful sense.

The validity of application of the epidemiological method to the study of the health impact of an agent is largely determined by the ascertainability and definition of an effect. Perhaps the main limitation of epidemiological studies of MW/RF exposure is the lack of recognised pathophysiological manifestations at realistic levels of exposure as indicators for measuring the effects of the fields on man.

Eastern European reports describe such symptoms as listlessness, excitability, headache, drowsiness, fatigue, and cardiovascular deficits in individuals occupationally exposed to electromagnetic fields. These symptoms are also caused by many other occupational factors, so it is not possible to define a cause-effect relationship. Many other factors in the industrial setting or home environment as well as psychosocial interactions can cause similar symptoms. In addition to smoking and obesity, genetic factors, and emotional stress, psychological personality factors that determine an individual's reactivity to environmental conditions are proved risk factors in the development of cardiac ischaemia.¹⁰¹ Thus these factors are important in assessing the effects of environmental insults.

Reports of effects in man must be put in perspective. Epidemiological and incidence studies may suffer from inadequate design and examination as well as lack of data on actual power levels and duration of microwave exposure. It is essential that evaluation be made of the multiple environmental factors which may interact among themselves and with personal characteristics of the individual. There is always the danger that real factors may be overlooked leading to false association with factors of initial interest.

Analysis of occupational exposure to MW/RF energies is fraught with many difficulties. Of utmost importance is the assessment of the relationship between exposure levels and the health status of the

examined groups of workers. The problem of adequate control groups is controversial and hinges mostly on what one considers "adequate."

Quantification of occupational exposure is extremely difficult. This is particularly true when personnel move around in the course of their duties or are exposed to non-stationary fields, such as moving beams or antennae, as well as to near- and far-fields at random. The possible role of other environmental factors and of socioeconomic conditions must be taken into account. As often happens in such studies, it is difficult to show a causal relationship between a disease and the influence of environmental factors, at least in individual cases.⁶²

Protection guides and standards

EXPOSURE STANDARDS

The first standards for controlling exposure to MW/RF were introduced in the 1950s in both the USA and the USSR. The maximum permissible exposure levels proposed then have remained substantially unchanged; for continuous exposure these are respectively 10 mW/cm² and 10 μ W/cm². Most countries that developed national standards based them on either the United States¹⁰² or the Soviet¹⁰³ values. Subsequently, however, some countries have proposed standards intermediate between these extremes.

In the United States there are non-government organisations that develop recommended standards and safety criteria—for example, the American National Standards Institute (ANSI), a voluntary body with members from government, industry, various associations, and the academic community, develops consensus standards (guides) in various areas. ANSI issued a non-ionising radiation safety standard in 1966 with maximum permissible exposures of 10 mW/cm², as averaged over any six-minute period, for frequencies from 10 MHz to 100 GHz. This standard was reviewed and reissued with minor modifications in 1975. ANSI must review and withdraw, revise, or reissue ANSI standards every five years. New recommendations,¹⁰² based on frequency dependence and SARs state: for human exposure to electromagnetic energy of radiofrequencies from 300 kHz to 100 GHz, the radiofrequency protection guides, in terms of equivalent plane wave free space power density, and in terms of the mean squared electric (E^2) and magnetic (H^2) field strengths as a function of frequency, are shown in table 5.

These standards do not apply to practitioners of the healing arts. For near field exposure, the only applicable radiofrequency protection guides are the mean squared electric and magnetic field strengths

Table 5 *ANSI recommendations*

(1) Frequency (MHz)	(2) Power density (mW/cm ²)	(3) E ² (V ² /m ²)	(4) H ² (A ² /m ²)
0.3-3	100	400 000	2.5
3-30	900/f ²	4000 (900/f ²)	0.25 (900/f ²)
30-300	1.0	4000	0.025
300-1500	f/300	4000 (f/300)	0.025 (f/300)
1500-100 000	5	20 000	0.125

Note: f is the frequency, in megahertz (MHz).

given in columns 3 and 4. For convenience, these guides may be expressed in equivalent plane wave power density (column 2).

For both pulsed and non-pulsed fields, the power density, the mean squares of the field strengths, and the values of SAR or input power as applicable, are averaged over any 0.1-hour period and should not exceed the values given in the above table. Where whole-body exposure is concerned, the radiofrequency protection guide is believed to result in energy deposition averaged over the entire body for any 0.1-hour period of about 144 J/kg or less. This is equivalent to an SAR of about 0.40 W/kg or less, spatially and temporally averaged over the entire body mass. This recommendation will no doubt be adopted with only minor modifications, if any.

The ANSI standard applies to the total population. In other words, the standard applies to non-occupational as well as occupational exposures but is not intended to apply to the purposeful exposure of patients by or under the direction of practitioners of the healing arts. The US National Institute for Occupational Safety and Health (NIOSH) is developing a criteria document with recommended standards for occupational MW/RF exposures, which is, except for certain modifications, comparable to that recommended by ANSI. Britain has in the past followed the standards in the US. It is doubtful, however, that the British standard will be changed from the present 10 mW/cm² level.

In Canada (table 6) the maximum permissible occupational levels (MPLs) are 1 mW-h/cm² average energy flux for whole body exposure as averaged over one hour and a maximum exposure during any one minute of 25 mW/cm² in occupational settings. The MPLs would apply for the frequency range of 10 MHz-300 GHz. No distinction is made between CW and pulsed waveforms.¹⁰⁴⁻¹⁰⁶

Table 6 *Canadian standards*

Canada	Frequency	Power density	Limits		Comments*
			rms E strength	rms H strength	
Occupational	10 MHz-1 GHz	1 mW/cm ²	60 V/m	0.16 A/m	Averaged over 1 h
		25 mW/cm ²	300 V/m	0.8 A/m	Averaged over 1 min
	1 GHz-300 GHz	5 mW/cm ²	140 V/m	0.36 A/m	Averaged over 1 h
General public	10 MHz-300 GHz	25 mW/cm ²	300 V/m	0.8 A/m	Averaged over 1 min
		1 mW/cm ²	60 V/m	0.16 A/m	Averaged over 1 min

*Additional provisions for exposures shorter than 1 h and exposure of extremities.

The State Committee on Standards of the Council of Ministers of the USSR has promulgated "Occupational safety standards for electromagnetic fields of radiofrequency (GOST 12.1.006-76)," effective from 1 January 1977. It specifies (table 7) the maximum permissible magnitudes of voltage and current density of an EM field in the workplace. It does not apply to Ministry of Defence personnel. Maximum permissible RF fields in the workplace must not, during the course of the workday, exceed:

Table 7 *USSR standard*

Frequency range	P (mW/cm ²)	E (V/m)	H (A/m)
60 kHz-1.5 MHz			5
1.5 MHz-3.0 MHz		50	
3.0 MHz-30 MHz		20	
30 MHz-50 MHz		10	0.3
50 MHz-300 MHz		5	
	0.01	(entire workday)	
300 MHz-300 GHz	0.10	(2 h period during workday)	
	1.00	(20 min period during workday)	

Note 1: Also applies in environments with ambient temperatures above 28°C in the presence of x-ray radiation, or both, except, under the condition, that the maximum during a 20-minute period is restricted to 0.1 mW/cm².

Note 2: It appears that the workday level will be raised from 10 μW/cm² to 25 μW/cm² in January 1982 (USSR Committee on Science and Technology).

In 1972 and 1977 the Polish Council of Ministers and the Minister of Health and Social Welfare promulgated a change in the Polish Standard.^{61 107-109} For the general population the values of 10 and 100 microwatts/cm² were adopted for continuous and intermittent exposures respectively. These values were taken as the upper limits of a safe zone, in which occupation is unrestricted. Three other zones are also defined, based on power density. For stationary (continuous) fields, these are defined as follows:

(1) Safe zone—the mean power density cannot exceed 10 μW/cm², human exposure is unrestricted;

(2) Intermediate zone—minimal value 10 μW/cm² upper limit 200 μW/cm² occupational exposure is allowed during a whole working day (normally eight hours, but in principle can be extended to 10 hours);

(3) Hazardous zone—minimal value 200 μW/cm², upper limit 10 mW/cm² occupational exposure time per 24 hours is determined by the formula:

$$t = 32/p^2$$

where t = exposure time hrs,

p = mean power density in mW/cm^2 ;

(4) Dangerous zone—mean power density in excess of $100 \text{ W}/\text{m}^2$ ($10 \text{ mW}/\text{cm}^2$), human exposure is forbidden.

For exposures to non-stationary fields—that is, intermittent exposure the following values were adopted:

(1) Safe zone—mean power density does not exceed $1 \text{ W}/\text{m}^2$ ($100 \mu\text{W}/\text{cm}^2$).

(2) Intermediate zone—minimal value $100 \mu\text{W}/\text{cm}^2$, upper limit $1 \text{ mW}/\text{cm}^2$.

(3) Hazardous zone—the exposure time is determined by the formula

$$t = 800/p^2.$$

(4) Dangerous zone—mean power density in excess of $100 \text{ W}/\text{m}^2$ ($10 \text{ mW}/\text{cm}^2$), human exposure is forbidden.

The Swedish National Board for Industrial Safety promulgated a non-ionising radiofrequency standard (Worker Protection Authority Instruction No 111) effective 1 January 1977.¹¹⁰ This regulation applies to all work that may necessitate exposure to radiofrequencies between 10 MHz and 300 GHz. The instruction specifically excludes applications affecting the treatment of patients. Maximum permissible exposures (as averaged over a six minute period) are given in table 8.

Table 8 Swedish standard

Frequency range	Power density
10 MHz-300 MHz	$5 \text{ mW}/\text{cm}^2$
300 MHz-300 GHz	$1 \text{ mW}/\text{cm}^2$

According to the World Health Organisation and the International Radiation Protection Association the exposure range of 0.1 to 1 milliwatt per centimeter square has a high enough safety factor to permit continuous exposure over the whole frequency range.¹¹¹ Environmental exposure should be based on the ALARA principle—as low as reasonably achievable—with social and economic benefits considered.

PRODUCT EMISSION STANDARD

The Radiation Control for Health and Safety Act of 1968 (PL 90-602), administered by the US Department of Health, Education and Welfare/Food and Drug Administration (Bureau of Radiological Health), provides authority for controlling radiation from electronic devices. One standard, the BRH microwave oven standard, effective October 1971, declares: Ovens may not emit (leak) more than $1 \text{ mW}/\text{cm}^2$ at time of manufacture and $5 \text{ mW}/\text{cm}^2$ subsequently, for the life of the product measured at a distance of 5 cm and under conditions specified in

the standard.¹¹²

The Canadian standard^{106 113} restricts the maximum leakage to $1 \text{ mW}/\text{cm}^2$ at 5 cm from the oven (consumer, commercial, and industrial). The US standard¹¹² specifies a maximum emission level at 5 cm of $1 \text{ mW}/\text{cm}^2$ before purchase and $5 \text{ mW}/\text{cm}^2$ thereafter, which is consistent with standards for the general population in the USSR and Poland.⁴ The standard applies to domestic and commercial ovens, but not to industrial equipment. A similar standard has been adopted in Japan and most of Western Europe.¹¹⁴ Computation of human exposure during typical operation of a microwave oven leaking up to $1 \text{ mW}/\text{cm}^2$ at a distance of 5 cm indicates that actual exposure of the body is 5-20 $\mu\text{W}/\text{cm}^2$. In the USSR an emission level of $10 \mu\text{W}/\text{cm}^2$ at a distance of 50 cm from the oven's surface has been adopted.

PROBLEMS AND RECOMMENDATIONS

Elucidation of the biological effects of microwave exposure requires a careful review and critical analysis of available publications. Such a review requires the differentiation of the established effects and mechanisms from speculative and unsubstantiated reports. Most of the experimental data support the concept that the effects of microwave exposure are primarily, if not only, a response to hyperthermia or altered thermal gradients in the body. There are, nevertheless, large areas of confusion, uncertainty, and actual misinformation.

There is a philosophical question about the definition of hazard. One objective definition of injury is an irreversible change in biological function as observed at the organ or system level. Thus it is possible to define a hazard as a probability of injury on a statistical basis. It is important to differentiate between the hazard levels at which injury may be sustained and effect per se or perception. All effects are not necessarily hazards. In fact, some effects may have beneficial applications under appropriately controlled conditions, diathermy and cancer therapy, for example. Microwave-induced changes must be understood sufficiently so that their clinical significance can be determined, their hazard potential assessed, and the appropriate benefit-risk analyses applied. It is important to determine whether an observed effect is irreparable, transient, or reversible, disappearing when the electromagnetic field is removed or after some interval of time. Of course, even reversible effects are unacceptable if they transiently impair the ability of the individual to function properly or to perform a required task.

A critical review of studies into the biological effects of microwaves indicates that many of the investigations suffer from inadequacies of either technical facilities and energy measurement skills or

insufficient control of the biological specimens and the criteria for biological change. More sophisticated conceptual approaches and more rigorous experimental design must be developed. There is a great need for systematic and quantitative comparative investigation of the biological effects, using well-controlled experiments. This should be done by using sound biomedical and biophysical approaches at the various levels of biological organisation from the subcellular to the whole animal on an integrated basis, with full recognition of the multiple associated and interdependent variables.

Proper investigation of the biological effects of MW/RF requires an understanding and appreciation of biophysical principles and "comparative biomedicine," such studies require interspecies "scaling," the selection of biomedical parameters that consider basic physiological functions and work capacity, identification of specific and non-specific reactions, and differentiation of adaptational or compensatory changes from pathological manifestations.

It is important that research be conducted in such a way that all aspects of the study are quantified, the type and magnitude of the effect, whether the effect is harmful, harmless, or merely an artifact, and how it relates to the results obtained by other investigators. For microwave bioeffects, body size of the experimental animal must be taken into account. Since body-absorption cross-sections and internal heating patterns can differ widely, an investigator may think he is observing a low-level or a "non-thermal" effect in an animal because the incident power is low, while in fact the animal may be exposed to as much absorbed power in a specific region of the body as another larger animal exposed to a much higher incident power density. The contrary can hold at low frequencies. In the performance of experimental studies on animals, interspecies scaling factors must, therefore, be used for extrapolation to man.

Well-designed and appropriately controlled epidemiological and clinical investigations of groups of workers and others exposed to microwaves should be fostered. Studies of workers and individuals exposed to MW/RF energies along with appropriate control groups should include a thorough analysis of the exposure environment, including co-factors as well as electromagnetic fields. There is always the danger that real factors may be overlooked, leading to false association with factors included in the study. Such interacting factors could be heat, cold, toxic agents, hypoxia, noise, other radiant energies such as x rays, chronic disease, and medication.

Because of the difficulties in extrapolating from animal experiments to man, epidemiological studies,

including appropriate clinical and laboratory examinations, are essential to improve our understanding of possible health hazards from exposure to MW/RF energies. As noted by Silverman,^{51 52} it is difficult to identify exposed populations, select suitable controls, and obtain exposure data. Some study groups already characterised can be improved by the acquisition of additional exposure data, some groups should be followed for longer periods, and some should be investigated for additional endpoints.

The reports from Eastern Europe of a wide variety of functional changes and possible nervous system effects have yet to be confirmed. In appropriate epidemiological studies, medical reports should be augmented to include an assessment of emotional and psychological status.

A careful search should be made for exposed groups not yet investigated or considered for study. In epidemiological studies, as in experimental or clinical work, there is rarely a single study, positive or negative, that can be accepted as definitive. Replication and validation are needed at all exposure levels.

Although there is no direct evidence that microwaves are carcinogenic, more intensive and extended morbidity monitoring to identify malignancies would be appropriate.^{51 52}

There is a need for scientific competence and integrity. It is important to maintain a proper perspective and assess realistically the biomedical effects of MW/RF exposure, so that the worker or general public will not be unduly exposed nor will research, development, and beneficial use of these energies be hampered or unnecessarily restricted.

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