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Environmental Health Criteria 137

ELECTROMAGNETIC FIELDS (300 Hz to 300 GHz)

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NOTE TO READERS OF THE CRITERIA MONOGRAPHS

Every effort has been made to present information in the criteria monographs as accurately as possible without unduly delaying their publication. In the interest of all users of the environmental health criteria monographs, readers are kindly requested to communicate any errors that may have occurred to the Director of the International Programme on Chemical Safety, World Health Organization, Geneva, Switzerland, in order that they may be included in corrigenda, which will appear in subsequent volumes.

DEDICATION

This monograph is dedicated to:

Professor Przemyslaw A. Czerski, a charter member of International Non-ionizing Radiation Committee, who died on 15 April 1990 in Silver Spring, MD (USA). He was a pioneer investigator into the effects of non-ionizing radiation on biosystems and the assessment of the potential hazards associated with such exposure. As a fervent promoter of international cooperation, Professor Czerski played an active part in the establishment of the International Non-Ionizing Radiation Committee and in the development of its activities. His broad scientific knowledge and his tireless energy made him a major contributor to the present publication.

PREFACE

The International Radiation Protection Association (IRPA) initiated activities concerned with non-ionizing radiation by forming a Working Group on Non-Ionizing Radiation in 1974. This Working Group later became the International Non-Ionizing Radiation Committee (IRPA/INIRC), at the IRPA meeting held in Paris in 1977. The IRPA/INIRC reviews the scientific literature on non-ionizing radiation and makes assessments of the health risks of human exposure to such radiation. On the basis of Environmental Health Criteria monographs, developed in conjunction with the World Health Organization, Division of Environmental Health, the IRPA/INIRC recommends guidelines on exposure limits, drafts codes of safe practice, and works in conjunction with other international organizations to promote safety and standardization in the non-ionizing radiation field.

A WHO/IRPA Task Group to review the final draft of the Environmental Health Criteria on Electromagnetic Fields (300 Hz-300 GHz) met at the WHO Collaborating Centre for NIR in Ottawa, Canada, from 22 to 26 October 1990. Dr A.J. Liston, Assistant Deputy Minister, Health Protection Branch, opened the meeting on behalf of the Minister for Health and Welfare Canada. Mr J.R. Hickman, Director General, Environmental Health Directorate, welcomed the participants. The support of Health and Welfare Canada and the local organization by the Environmental Health Directorate are gratefully acknowledged.

The first draft of this publication was compiled by Professor J. Bernhardt, Professor P. Czerski, Professor M. Grandolfo, Dr A. McKinlay, Dr M. Repacholi, Dr R. Saunders, Professor J. Stolwijk, and Dr M. Stuchly. An editorial group comprising Professor J. Bernhardt, Professor P. Czerski, Professor M. Grandolfo, Mr C. Hicks, Dr A. McKinlay, Dr R. Saunders, Mr D. Sliney, Professor J. Stolwijk, and Dr M. Swicord met at the US Army Environmental Hygiene Agency, Edgewood, MD, in February 1990 to revise the draft. A second editorial group comprising Professor J. Bernhardt, Mme A. Duchêne, Dr A. McKinlay (Chairman), Professor B. Knave, Dr R. Saunders, and Dr M. Stuchly met at the National Radiological Protection Board, Didcot, United Kingdom, in May 1990 to collate and incorporate the comments received by IPCS Focal

Points, IRPA Associate Societies, and individual experts. Dr M. Repacholi was responsible for the scientific editing of the text and Mrs M.O. Head of Oxford for the language editing.

This publication comprises a review of the data on the effects of electromagnetic field exposure on biological systems pertinent to the evaluation of human health risks. The purpose of the document is to provide an overview of the known biological effects of electromagnetic fields in the frequency range 300 Hz to 300 GHz, to identify gaps in this knowledge so that direction for further research can be given, and to provide information for health authorities, regulatory, and similar agencies on the possible effects of electromagnetic field exposure on human health, so that guidance can be given on the assessment of risks from occupational and general population exposure.

Most radiofrequency (RF) field standards are based on the premise that there exists a threshold specific absorption rate (SAR) of RF energy (for frequencies above about 1 MHz) of 1-4 W/kg, above which there is increasing likelihood of adverse health effects. Below about 1 MHz, standards are based on induced currents in the body, causing shocks and burns. The purpose of updating the original Environmental Health Criteria monograph on radio frequency (WHO, 1981) is not only to provide a description of more completely developed RF dosimetry in humans, but to critically review more recent scientific literature, to determine if the threshold SAR on which standards are based is still valid. With the frequency range covered by the document extended down to 300 Hz, more emphasis is placed on induced currents and other possible mechanisms of interaction.

In conducting the literature review, earlier reports are not necessarily included, since these were reviewed in UNEP/WHO/IRPA (1981). Every effort has been made to distinguish clearly between biological effects that have been established and those that have been reported as preliminary or isolated results, or as hypotheses proposed to explain observed results. The conclusions of this document are based on peer reviewed and established knowledge of interactions of electromagnetic fields with biological systems.

Subjects reviewed include: the physical characteristics of electromagnetic fields; measurement techniques; applications of electromagnetic fields and sources of exposure; mechanisms of interaction; biological effects; and guidance on the development of protective measures, such as regulations or safe-use guidelines.

Health agencies and regulatory authorities are encouraged to set up and develop programmes that ensure that the maximum benefit occurs with the lowest exposure. It is hoped that this criteria document will provide useful information for the development of national protection measures against electromagnetic fields, as well as serving as a reliable basis for such reports as environmental impact statements necessary for proposed electromagnetic field emission facilities.

The WHO Regional Office for Europe has published a second edition of the book entitled *Nonionizing radiation protection*, which includes a chapter on radiofrequency radiation (Suess & Benwell-Morison, 1989).

1. SUMMARY AND RECOMMENDATIONS FOR FURTHER STUDIES

1.1 Summary

1.1.1 Physical characteristics in relation to biological effects

This monograph is concerned with the health effects of electromagnetic fields in the frequency range of 300 Hz-300 GHz, which includes the radiofrequency (RF) range (100 kHz-300 GHz) covered in the earlier publication (WHO, 1981). For simplicity, RF is the term used in this document for electromagnetic fields of frequency 300 Hz-300 GHz. Within these frequencies are microwaves, having frequencies of between 300 MHz and 300 GHz.

Exposure levels in the microwave range are usually described in terms of "power density" and are normally reported in watt per square metre (W/m^2), or milliwatt or microwatts per square metre (mW/m^2, $\mu W/m^2$). However, close to RF sources with longer wavelengths, the values of both the electric (V/m) and magnetic (A/m) field strengths are necessary to describe the field.

Exposure conditions can be altered considerably by the presence of objects, the degree of perturbation depending on their size, shape, orientation in the field, and electrical properties. Very complex field distributions can occur, both inside and outside biological systems exposed to electromagnetic fields. Refraction within these systems can focus the transmitted energy resulting in markedly non-uniform fields and energy deposition. Different energy absorption rates can result in thermal gradients causing biological effects that may be generated locally, difficult to anticipate, and perhaps unique. The geometry and electrical properties of biological systems will also be determining factors in the magnitude and distribution of induced currents at frequencies below the microwave range.

When electromagnetic fields pass from one medium to another, they can be reflected, refracted, transmitted, or absorbed, depending on the conductivity of the exposed object and the frequency of the field. Absorbed RF energy can be converted to other forms of energy and cause interference with the functioning of the living system. Most of this energy is converted into heat. However, not all electromagnetic field effects can be explained in terms of the biophysical mechanisms of energy absorption and conversion to heat. At frequencies below about 100 kHz, it has been demonstrated that induced electric fields can stimulate nervous tissue. At the microscopic level, other interactions leading to perturbations in complex macromolecular biological systems (cell membranes, subcellular structures) have been postulated.

1.1.2 Sources and exposure

1.1.2.1 Community

In comprehensive community surveys of background levels of electromagnetic fields in the USA, a median exposure of the order of 50 $\mu W/m^2$ was found. Very high frequency broadcasts were identified as the main contributors to ambient electromagnetic fields. No more than 1% of the population was exposed to ambient power densities in excess of 10 mW/m^2. Exposure in the immediate vicinity (at a distance of the order of one half wavelength of the incident fields) of transmitting facilities, can be higher, and can be enhanced by nearby conducting objects. Such conditions should be evaluated for each specific situation.

1.1.2.2 Home

RF sources in the home include microwave ovens, induction heating stoves, burglar alarms, video display units (VDUs), and television receivers. Leakage from microwave ovens can be up to 1.5 W/m^2 at 0.3 m and 0.15 W/m^2 at a distance of 1 metre. Exposure to radiation from domestic appliances is best limited by design and by monitoring at the point of manufacture.

1.1.2.3 Workplace

Dielectric heaters for wood fabrication and the sealing of plastics, induction heaters for the heating of metals, and video display units, are widely used in a variety of occupational settings. VDUs create electric and magnetic fields at frequencies in the 15-35 kHz range and frequencies modulated in the ELF range. Personnel working on, or near, broadcasting towers or antennas can be exposed to substantial fields of up to 1 kV/m and 5 A/m, respectively. Workers near radar installations can be exposed to substantial peak power densities, if they are in the RF beam a few metres from radar antennas (up to tens of MW/m^2). Usually, the average power density in the vicinity of air traffic control radars, for example, is of the order of 0.03-0.8 W/m^2.

In the occupational environment, the protection of workers is best assured by referring to the emission specifications for individual items of equipment, and, where necessary, by monitoring and surveillance using appropriate instrumentation.

A special case of exposure occurs in the medical environment with the use of diathermy treatments for pain and inflammation in body tissues. Diathermy operators are likely to be exposed occupationally to stray radiation at relatively high levels, which can be reduced by appropriate shielding or machine design. Field strengths of 300 V/m and 1 A/m at 10 cm from the applicators have been measured. Similarly, surgeons using electrosurgical devices operating at frequencies near 27 MHz may be exposed to levels above recommended limits. These field strengths decline very rapidly with increasing distance from the applicators.

Most magnetic resonance imaging (MRI) systems use static magnetic fields with flux densities of up to 2 T, low-frequency gradient fields up to 20 T/s, and RF fields in the 1-100 MHz frequency range. Although power deposition in the patient can be substantial, staff exposures are much lower and are determined by equipment characteristics.

1.1.3 Biological effects

Electromagnetic fields in the frequency range of 300 Hz-300 GHz interact with human and other animal systems through direct and indirect pathways. Indirect interactions are important at frequencies below 100 MHz, but are specific to particular situations. When metallic objects (such as automobiles, fences) in an electromagnetic field have electrical charges induced in them, they can be discharged when a body comes into contact with the charged object. Such discharges can cause local current densities capable of shock and burns.

A major interaction mechanism is through the currents induced in tissues, so effects are dependent on frequency, wave shape, and intensity. For frequencies below approximately 100 kHz, the interactions with nervous system tissue are of interest, because of their increased sensitivity to induced currents. Above 100 kHz, the nervous tissue becomes less sensitive to direct stimulation by electromagnetic fields and the thermalization of energy becomes the major mechanism of interaction.

There is evidence from a number of studies that weak-field interactions also exist. Different mechanisms for such interactions have been postulated, but the precise mechanism(s) has not been elucidated. These weak-field interactions result from exposure to RF fields, amplitude modulated at lower frequencies.

1.1.4 Laboratory studies

Many of the biological effects of acute exposure to electromagnetic fields are consistent with responses to induced heating, resulting either in rises in tissue or body temperature of about 1 °C or more, or in responses to minimizing the total heat load. Most responses have been reported at specific absorption rates (SARs) above about 1-2 W/kg in different animal species exposed under various environmental conditions. The animal (particularly primate) data indicate the types of responses that are likely to occur in humans subjected to a sufficient heat load. However, direct quantitative extrapolation to humans is difficult, given species differences in responses in general, and in thermoregulatory ability, in particular.

The most sensitive animal responses to heat loads are thermoregulatory adjustments, such as reduced metabolic heat production and vasodilation, with thresholds ranging between about 0.5-5 W/kg, depending on environmental conditions. However, these reactions form part of the natural repertoire of thermoregulatory responses that serve to maintain normal body temperatures.

Transient effects seen in exposed animals, which are consistent with responses to increases in body temperature of 1 °C or more (and/or SARs in excess of about 2 W/kg in primates and rats), include reduced performance of learned tasks and increased plasma corticosteroid levels. Other heat-related effects include temporary haematopoietic and immune responses, possibly due to elevated corticosteroid levels. The most consistent effects observed are reduced levels of circulating lymphocytes, increased levels of neutrophils, and altered natural killer cell and macrophage function. An increase in the primary antibody response of B-lymphocytes has also been reported. Cardiovascular changes consistent with increased heat load, such as an increased heart rate and cardiac output, have been observed, together with a reduction in the effect of drugs, such as barbiturates, the action of which can be altered by circulatory changes.

Most animal data indicate that implantation and the development of the embryo and fetus are unlikely to be affected by exposures that increase maternal body temperature by less than 1 °C. Above these temperatures, adverse effects, such as growth retardation and post-natal changes in behaviour, may occur, with more severe effects occurring at higher maternal temperatures.

Most animal data suggest that low RF exposures that do not raise body temperatures above the normal physiological range are not mutagenic: Such exposures will not result in somatic mutation or hereditary effects. There is much less information describing the effects of long-term, low-level exposures. However, so far, it does not appear that any long-term effects result from exposures below thermally significant levels. The animal data indicate that male fertility is unlikely to be affected by long-term exposure to levels insufficient to raise the temperature of the body and testes.

Cataracts were not induced in rabbits exposed at 100 W/m^2 for 6 months, or in primates exposed at 1.5 kW/m^2 for over 3 months.

A study of 100 rats, exposed for most of their lifetime to about 0.4 W/kg, did not show any increased incidence of non-neoplastic lesions or total neoplasias compared with control animals; longevity was similar in both groups. There were differences in the overall incidence of primary malignancies, but these could not necessarily be attributed to the irradiation.

The possibility that exposure to RF fields might influence the process of carcinogenesis is of particular concern. So far, there is no definite evidence that irradiation does have an effect, but there is clearly a need for further studies to be carried out. Many experimental data indicate that RF fields are not mutagenic, and so they are unlikely to act as initiators of carcinogenesis; in the few studies carried out, the search has mainly been for evidence of an enhancement of the effect of a known carcinogen. Long-term exposure of mice at 2-8 W/kg resulted in an increase in the progression of spontaneous mammary tumours, and of skin tumours in animals treated dermally with a chemical carcinogen.

In vitro studies have revealed enhanced cell transformation rates after RF exposure at 4.4 W/kg (alone or combined with X-radiation) followed by treatment with a chemical promoter. The latter data have not always been consistent between studies. It is clear, however, that studies relevant to carcinogenesis need replicating and extending further.

A substantial body of data exists describing biological responses to amplitude-modulated RF or microwave fields at SARs too low to involve any response to heating. In some studies, effects have been reported after exposure at SARs of less than 0.01 W/kg, occurring within modulation frequency "windows" (usually between 1-100 Hz) and sometimes within power density "windows"; similar results have been reported at frequencies within the voice frequency (VF) range (300 Hz-3 kHz). Changes have been reported in: the electro-encephalograms of cats and rabbits; calcium ion mobility in brain tissue *in vitro*, and *in vivo*; lymphocyte cytotoxicity *in vitro*; and activity of an enzyme involved in cell growth and division. Some of these responses have been difficult to confirm, and their physiological consequences are not clear. However, any toxicological investigations should be based on tests carried out at appropriate levels of exposure. It is important that these studies be confirmed and that the health implications, if any, for exposed people, are determined. Of particular importance would be studies that link extremely low frequency, amplitude-modulated, RF or microwave interactions at the cell surface with changes in DNA synthesis or transcription. It is worth noting that this interaction implies a "demodulation" of the RF signal at the cell membrane.

1.1.5 Human studies

There are relatively few studies that address directly the effects of acute or long-term exposures of humans to RF fields. In studies in the laboratory, cutaneous perception of fields in the 2-10 GHz range has been reported. Thresholds for just noticeable warming have been reported at power densities of 270 W/m^2 - 2000 W/m^2, depending on the area irradiated (13-100 cm^2) and the duration of exposure (1-180 s). When human volunteers are exposed to SARs of 4 W/kg for 15-20 minutes their average body temperature rises by 0.2-0.5 °C, which is quite acceptable in healthy people. The impact that this added thermal load would have on thermoregulatory impaired individuals in environments that minimize the perspiration-based cooling mechanisms is not known.

The few epidemiological studies that have been carried out on populations exposed to RF fields have failed to produce significant associations between such exposures and outcomes of shortened life span, or excesses in particular causes of death, except for an increased incidence of death from cancer, where chemical exposure may have been a confounder. In some studies, there was no increase in the incidence of premature deliveries or congenital malformations, while other studies produced indications that there was an association between the level of exposure and adverse pregnancy outcome. Such studies tend to suffer from poor exposure assessment and poor ascertainment and determination of other risk factors.

1.1.6 Health hazard assessment

The following categories of health hazard have been identified in an overall assessment of the health hazards associated with RF exposures.

1.1.6.1 Thermal effects

The deposition of RF energy in the human body tends to increase the body temperature. During exercise, the metabolic heat production can reach levels of 3-5 W/kg. In normal thermal environments, an SAR of 1-4 W/kg for 30 minutes produces average body temperature increases of less than 1 °C for healthy adults. Thus, an occupational RF guideline of 0.4 W/kg SAR leaves a margin of protection against complications due to thermally unfavourable environmental conditions. For the general population, which includes sensitive subpopulations, such as infants and the elderly, an SAR of 0.08 W/kg would provide an adequate further margin of safety against adverse thermal effects from RF fields.

1.1.6.2 *Pulsed fields*

It has been shown, under a number of conditions, that the thresholds for biological effects at frequencies above several hundred MHz are decreased when the energy is delivered in short (1-10 μs) pulses. For example, auditory effects occur when pulses of less than 30 μs duration deliver more than 400 mJ/m^2 per pulse. A safe limit for such pulses cannot be identified on the basis of available evidence.

1.1.6.3 *Amplitude-modulated RF fields*

The effects described for this type of field at the cellular, tissue, and organ levels cannot be related to adverse health effects. No dose-effect relationships can be formulated that demonstrate threshold levels; thus, the available information cannot lead to specific recommendations.

1.1.6.4 *RF field effects on tumour induction and promotion*

It is not possible, from the reports of the effects of RF exposure in certain cell lines, on cell transformation, enzyme activity, and tumour incidence and progression in animals, to conclude that RF exposure has any effect on the incidence of cancer in humans, or, that specific recommendations are necessary to limit such fields to reduce cancer risks.

1.1.6.5 *RF-induced current densities*

In the frequency range of 300 Hz-100 kHz, the induction of fields and current densities in excitable tissues is the most important mechanism for hazard assessment. The thresholds for the stimulation of nerve and muscle tissue are strongly dependent on frequency, ranging from 0.1-1 A/m^2 at 300 Hz to about 10-100 A/m^2 at 100 kHz. However, with regard to other effects, reported to occur below these thresholds, there is not sufficient information available to make specific recommendations.

1.1.6.6 *RF contact shocks and burns*

Conducting objects in an RF field can become electrically charged. When a person touches a charged object or approaches it closely, a substantial current can flow between the object and the person. Depending on the frequency, the electric field strength, the size and the shape of the object,and the cross-sectional area of contact, the resulting current can cause shock through stimulation of peripheral nerves. If the current is strong enough, burns can result. Protective measures include the elimination or enclosure of conductive objects in strong RF fields, or the limiting of physical access.

1.1.7 Exposure standards

1.1.7.1 Basic exposure limits

To protect workers and the general population from the possible health effects of exposure to electromagnetic fields, basic exposure limits have been determined on the basis of knowledge of biological effects. Different scientific bases were used to develop the limits for frequencies above and below about 1 MHz. Above 1 MHz, biological effects on animals were studied to determine the lowest value of the whole body average SAR that caused detrimental health effects in animals. This value was found to be in the 3-4 W/kg range.

The vast majority of results pertained to exposures in the low GHz region. Thus, to determine the effects at lower frequencies requires an assumption concerning the frequency dependence of the biological response. Since the observed bioeffects in the 1-4 W/kg range are believed to be thermal, the SAR threshold was assumed to be independent of frequency. It was considered that exposure of humans to 4 W/kg for 30 minutes would result in a body temperature rise of less than 1 °C. This body temperature rise is considered acceptable.

A safety factor of 10 is introduced, in order to allow for unfavourable, thermal, environmental, and possible long-term effects, and other variables, thus arriving at a basic limit of 0.4 W/kg. An additional safety factor should be introduced for the general population, which includes persons with different sensitivities to RF exposure. A basic limit of 0.08 W/kg, corresponding to a further safety factor of 5, is generally recommended for the public at large.

Derived limits of exposure are given in Tables 34 and 35 of this publication.

The limitations for the whole body average SAR are not sufficiently restrictive, since the distribution of the absorbed energy in the human body can be very inhomogeneous and dependent on the RF exposure conditions. In partial body exposure situations, depending on frequency, the absorbed energy can be concentrated in a limited amount of tissue, even though the whole body average SAR is restricted to less than 0.4 W/kg. Therefore, additional basic limits of 2 W/100 g are recommended in any other part of the body, in order to avoid excessive local temperature elevations. The eye may need special consideration.

At frequencies below about 1 MHz, exposure limits are selected that will prevent stimulation of nerve and muscle cells. Basic exposure limits refer to current densities induced within body tissues. Exposure limits should have a sufficiently large safety factor to restrict the current density to 10 mA/m^2 at 300 Hz. This is the same order of magnitude as natural body currents. Above 300 Hz, the current density necessary for excitation of nervous tissue increases with frequency, until a frequency is reached at which thermal effects dominate. For frequencies around 2-3 MHz, the basic limit for current density is equivalent to the limit for the peak SAR of 1 W/100g. Since SAR or induced current density values cannot be measured easily in practical exposure situations, exposure limits in terms of conveniently measurable quantities must be derived from basic limits. These "derived limits" indicate the acceptable limits in terms of the measured and/or calculated field parameters that allow compliance with the basic limits.

1.1.7.2 Occupational exposure limits

The occupationally-exposed populations consist of adults exposed under controlled conditions, who are aware of the occupational risks. Because of the wide frequency range addressed in this publication, a single limit number for occupational exposure is not possible. Recommended derived occupational limits in the frequency range 100 kHz to 300 GHz are provided in Table 34. A conservative approach is recommended for pulsed fields where electric and magnetic field strengths are limited to 32 times the values given in Table 34, as averaged over the pulse width, and the power density is limited to a value of 1000 times the corresponding value in Table 34, as averaged over the pulse width.

1.1.7.3 Exposure limits for the general population

The general population includes persons of different age groups, different states of health, and pregnant women. The possibility that the developing fetus could be particularly susceptible to exposure to RF deserves special consideration.

Exposure limits for the general population should be lower than those for occupational exposure. For example, recommended derived limits in the frequency range of 100 kHz-300 GHz are provided in Table 35, which are generally a factor of 5 lower than the occupational limits.

1.1.7.4 Implementation of standards

The implementation of RF field occupational and public health protection standards necessitates the allocation of responsibility for measurements of field intensity and interpretation of results, and the establishment of detailed field protection safety codes and guides for safe use, which indicate, where appropriate, ways and means of reducing exposure.

1.1.8 Protective measures

Protective measures include workplace surveillance (exposure surveys), engineering controls, administrative controls, personal protection, and medical surveillance. Where surveys of RF fields indicate levels of exposure in the workplace in excess of limits recommended for the general population, workplace surveillance should be conducted. Where surveys of RF fields in the workplace indicate levels of exposure in excess of recommended limits, action should be taken to protect workers. In the first instance, engineering controls should be applied, where possible, to reduce emissions to acceptable levels. Such controls include good safety design and, where necessary, the use of interlocks or similar protection devices.

Administrative controls, such as limitation of access and the use of audible and visible warnings, should be used in conjunction with engineering controls. The use of personal protection (protective clothing), though useful under certain circumstances, should be regarded as a last resort to ensure the safety of the worker. Wherever possible, priority should be given to engineering and administrative controls. Where workers could be expected to incur exposures in excess of the limits applicable to the general population, consideration should be given to providing appropriate medical surveillance.

Prevention of health hazards related to RF fields also necessitates the establishment and implementation of rules to ensure: (*a*) the prevention of interference with safety and medical electronic equipment and devices (including cardiac pacemakers); (*b*) the prevention of detonation of electroexplosive devices (detonators); and (*c*) the prevention of fires and explosions due to the ignition of flammable material from sparks caused by induced fields.

1.2 Recommendations for further studies

1.2.1 Introduction

There are concerns about the possible effects of RF fields in the areas of promotion and progression of cancer, of reproductive failures, such as spontaneous abortions and congenital malformations, and of effects on central nervous system function. Knowledge in all these areas is inadequate to determine whether such effects exist, and therefore, there is no rational basis for recommendations to protect the general population from possible adverse effects.

Future research efforts in the areas of weak-interaction mechanisms on the one hand, and studies of effects on carcinogenesis and reproduction in animals and humans on the other hand, should be coordinated to a high degree. This coordination can be brought about by focusing funding on research proposals of a multidisciplinary and multi-institutional nature. Studies on RF field effects could well be coordinated with similar programmes addressing ELF (50/60 Hz) field effects. A high priority should be placed on research that emphasizes causal relationships and dose-effect thresholds and coefficients.

The following is a list of priority areas identified by the Task Group as needing further study.

1.2.2 Pulsed fields

There is a major deficiency in the understanding of the effects of pulsed fields in which very high peak power densities occur, separated by periods of zero power. Only a few isolated reports of pulsed field effects are available and it is not possible to identify either the frequency or the peak power domain of importance. Data to assess human health hazard in terms of pulse peak power, repetition frequency, pulse length, and the frequency of the RF in the pulse, are urgently needed in view of the widening application of systems employing high power pulses, (mostly radar), and involving both occupational and general population exposures.

1.2.3 Cancer, reproduction, and nervous system studies

There is increasing concern about the possibility that RF exposure may play a role in the causation or promotion of cancer, specifically of the blood forming organs or in the CNS. Similar uncertainties surround possible effects on reproduction, such as increased rates of spontaneous abortion and of congenital malformations.

Effects of RF exposure on CNS function, with resulting changes in cognitive function, are also surrounded by uncertainties. In view of the potential importance of these interactions and the disruptive effects of the uncertainty on society, a high priority should be placed on research in this area. It is important that research efforts be coordinated to clarify rather than increase the level of uncertainty. Research on possible mechanisms, such as weak-field interactions, should be closely coordinated with appropriately designed animal toxicology studies and with human epidemiology.

1.2.4 Weak-field interactions

Very few people are exposed to thermally significant levels of RF; the vast majority of exposures occur at levels at which weak-field interactions would be the only possible source of any adverse health response. A substantial amount of experimental evidence implicates responses to amplitude-modulated RF fields, which show frequency and amplitude windows; some responses are dependent on co-exposure to physical and chemical agents. Establishing the significance of effects for human health and their dose-response relationships is of paramount importance. Studies are necessary that identify biophysical mechanisms of interaction and that extend the animal and human studies, in order to identify health risks.

1.2.5 Epidemiology

Epidemiological studies on the association between cancer and adverse reproductive outcomes and RF fields are made difficult by a number of factors:

- Most members of any population are exposed to levels of RF that are orders of magnitude below thermally significant levels.
- It is very difficult to establish RF exposure in individuals over a meaningful period of time.
- Control of major confounders is very difficult.

Some, but not all, of the sources of difficulties can be overcome by a suitably designed and implemented case-control study. Such studies are in progress and being planned to study childhood cancer and any effects of ELF fields. It is important that such studies evaluate any exposures to RF radiation.

2. PHYSICAL CHARACTERISTICS

2.1 Introduction

The study of the biological effects of electromagnetic fields is multidisciplinary; it draws from physics, engineering, mathematics, biology, chemistry, medicine, and environmental health. For this reason, background information has been included in this publication that may appear elementary to some readers, but is essential for those from a different discipline. Much of the confusion and the controversies that exist in the field today arise from individuals of one discipline not fully appreciating the basic facts or theories of another.

In this section, the aim is to summarize briefly the basic physical characteristics of electric, magnetic, and electromagnetic fields in the frequency range 300 Hz-300 GHz. The corresponding wavelengths extend from 1000 km to 1 mm. At low frequencies (below about 10 MHz) and for near-field conditions (see section 4), the electric (E) and magnetic (H) fields must be treated separately.

The quantum energies at these frequencies are extremely small and are not capable of altering the molecular structure or breaking any molecular bonds. The maximum quantum energy (at 300 GHz) is 1.2 millielectronvolts (meV), while disruption of the weakest hydrogen bond requires 80 meV; for comparison, the thermal motion energy at 30 °C is 26 meV.

Although there are other definitions of the radiofrequency (RF) spectrum, its use in this document covers 300 Hz-300 GHz. The region between 300 MHz and 300 GHz is called microwaves (MW).

2.2 Electric field

Electric charges exert forces on each other. It is convenient to introduce the concept of an electric field to describe this interaction. Thus, a system of electric charges produces an electric field at all points in space and any other charge placed in the field will experience a force because of its presence. The electric field is denoted by **E** and is a vector quantity, which means that it has both a magnitude and a direction. The force, **F**, exerted on a point (infinitely small) body containing a net positive charge q placed in an electric field **E** is given by:

$$\mathbf{F} = q\mathbf{E} \qquad \text{(Equation 2.1)}$$

Various units of the electric field strength are in use; the SI unit is newton per coulomb (N/C). It is frequently easier and more useful to measure the electric potential, V, rather than the force and charge. This is because the potential is much less dependent on the physical geometry of a given system (e.g., location and sizes of conductors).

The potential difference V between two points in an electric field E is defined by $V = W/q$, where W is the work done by the field in moving a charge q between the two points. The work done is $W = Fd$, where d is the separation between the two points; or using equation 2-1, $W = qEd$. From $V = W/q$, it follows that:

$$E = V/d \qquad \text{(Equation 2.2)}$$

In practice, the unit of volt per metre (V/m) is used for the electric field strength.

Electric fields exert forces on charged particles. In an electrically conductive material, such as living tissue, these forces will set charges into motion to cause an electric current to flow. This current is frequently specified by the current density, **J**, the magnitude of which is equal to the current flowing through a unit surface perpendicular to its direction. The SI unit of current density is ampere per square metre (A/m^2). **J** is directly proportional to **E** in a wide variety of materials. Thus:

$$\mathbf{J} = \sigma\mathbf{E} \qquad \text{(Equation 2.3)}$$

where the constant of proportionality σ is called the electrical conductivity of the medium. The unit of σ is siemens per metre (S/m).

2.3 Magnetic field

The fundamental vector quantities describing a magnetic field are the magnetic field strength **H** and the magnetic flux density **B** (also called the magnetic induction).

Magnetic fields, like electric fields, are produced by electric charges, but only when these charges are in motion. Magnetic fields exert forces on other charges but, again, only on charges that are in motion.

The magnitude of the force F acting on an electric charge q moving with a velocity **v** in the direction perpendicular to a magnetic field of flux density **B** is given by:

$$F = qvB \qquad \text{(Equation 2.4)}$$

where the direction of **F** is perpendicular to both those of **v** and **B**. If, instead, the direction of **v** were parallel to **B**, then **F** would be zero. This illustrates an important characteristic of a magnetic field: it does no physical work, because the force, called the Lorentz force, generated by its interaction with a moving charge is always perpendicular to the direction of motion. The basic unit of the magnetic flux density can be deduced from Equation 2.4 to be newton second per coulomb metre [N s/C m]. According to the International System of Units (SI), this unit is called the tesla (T). In the literature, both mks and cgs units are also used to express flux density values. The conversion between the gauss (G), the cgs unit of flux density, and the tesla is $1\ T = 10^4\ G$.

The magnetic field strength **H** is the force with which the field acts on an element of current situated at a particular point. The value of **H** is measured in ampere per metre (A/m).

The magnetic flux density **B**, rather than the magnetic field strength, **H** (where $B = \mu H$), is used to describe the magnetic field generated by currents that flow in conductors. The value of μ (the magnetic permeability) is determined by the properties of the medium.

For most biological materials, the permeability μ is equal to μ_0, the value of permeability of free space (air) (1.257×10^{-6} H/m). Thus, for biological materials, the values of **B** and **H** are related by the constant μ_0.

2.4 Waves and radiation

Maxwell's equations form the theoretical foundation for all classical electromagnetic field theory. These equations are very powerful, but for complex systems, such as biological bodies, they are difficult to solve.

One class of their solutions results in wave descriptions of the electric and magnetic fields. When the source charges or currents oscillate and the frequency of oscillation is high enough, the **E** and **H** fields produced by these sources will radiate from them. A convenient and commonly used description of this radiation is wave propagation.

The basic ideas of wave propagation are illustrated in Fig. 1. The distance from one ascending, or descending, node to the next is defined as the wavelength, and is usually denoted by λ.

The wavelength and the frequency (the number of waves that pass a given point in unit time), denoted by f, are related and determine the characteristics of electromagnetic radiation. Frequency is the more fundamental quantity and for a given frequency, the wavelength depends on the velocity of propagation and, therefore, on the properties of the medium through which the radiation passes.

The wavelength normally quoted is that in a vacuum or in air, the difference being insignificant. However, the wavelength can change significantly when the wave passes through other media. The linking parameter with frequency is the speed of light as expressed in Equation 2.5 ($v = 3 \times 10^8$ m/s in air):

$$\lambda = v/f \qquad \text{(Equation 2.5)}$$

When RF traverses biological material, its speed is reduced and its wavelength becomes shorter than in air.

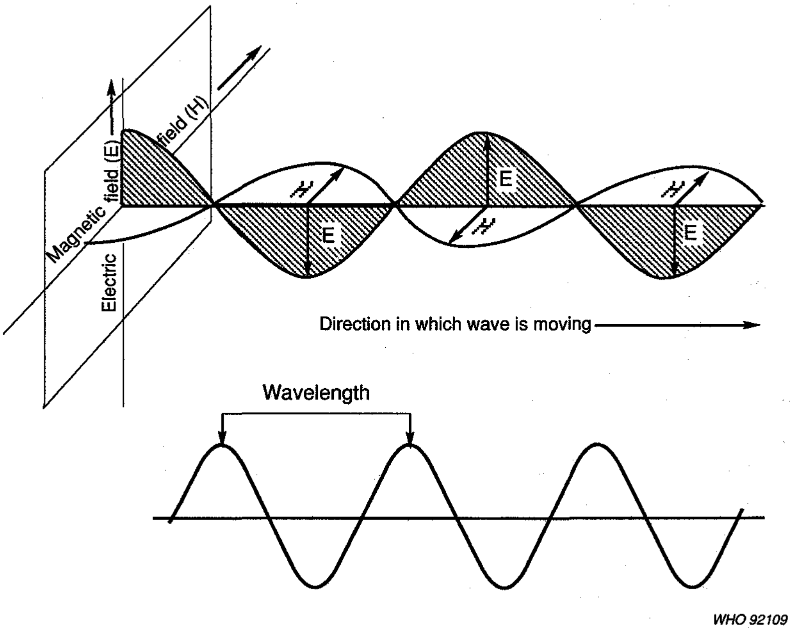

Fig. 1. An electromagnetic monochromatic wave. Electromagnetic waves consist of electrical and magnetic forces that move in consistent wave-like patterns at right angles to each other for far-field propagation, but at varying angles in the near-field.

Two idealizations of wave propagation are commonly used: spherical waves and plane waves (Stuchly, 1983; Grandolfo & Vecchia, 1988). A spherical wave is a good approximation to some electromagnetic waves that occur. Their wavefronts have spherical surfaces and each crest and trough has a spherical surface. On every spherical surface, the **E** and **H** fields are constant. The wavefronts propagate radially outwards from the source and **E** and **H** are both tangential to the spherical surfaces.

A plane wave is another model that approximately represents some electromagnetic waves. Plane waves have characteristics similar to spherical waves because, at points far from the source, the curvature of the spherical wavefronts is so small that they appear to be almost planar.

The defining characteristics of a plane wave are:

(*a*) **E**, **H**, and the direction of propagation are all mutually perpendicular.

(*b*) The quotient **E/H** is constant and is called the wave impedance. For free space E/H = 377 Ω. For other media and for sinusoidal steady-state fields, the wave impedance includes losses in the medium in which the wave is travelling.

(*c*) Both **E** and **H** vary as 1/r, where r is the distance from the source.

In RF plane wave propagation (far-field), the power crossing a unit area normal to the direction of wave propagation is usually designated by the symbol S. When the electric and magnetic field strengths are expressed in V/m and A/m, respectively, S represents their product, which yields VA/m^2, i.e., W/m^2 (watts per square metre).

In free space, electromagnetic waves spread uniformly in all directions from a theoretical point (isotropic) source. As the distance from the point source increases, the area of the wavefront surface increases as a square of the distance, so that the source power is spread over a larger area.

As power density S corresponds also to the quotient of the total radiated power and the spherical surface area enclosing the source, it is inversely proportional to the square of the distance from the source, and can be expressed as:

$$S = P/4\pi r^2 \qquad \text{(Equation 2.6)}$$

where P is the total radiated power and r is the distance from the source.

In the case of plane waves, frequently called far-field conditions, the power density can be derived from $E^2/377$ or from 377 H^2 (see Table 1). Therefore, in many practical applications only the E field or the H field needs to be measured when the point of measurement is at least one wavelength from the source. In this case, measurement of E makes possible the determination of H and vice-versa.

Table 1. Comparison of power densities in the more commonly used units for free-space, far-field conditions (Note: values have been rounded to one or two significant figures, based on the relationships above)

W/m^2	mW/cm^2	$\mu W/cm^2$	V/m	A/m
10^{-2}	10^{-3}	1	2	$5\ 10^{-3}$
10^{-1}	10^{-2}	10	6	$1.5\ 10^{-2}$
1	10^{-1}	10^2	20	$5\ 10^{-2}$
10	1	10^3	60	$1.5\ 10^{-1}$
10^2	10	10^4	$2\ 10^2$	$5\ 10^{-1}$
10^3	10^2	10^5	$6\ 10^2$	1.5
10^4	10^3	10^6	$2\ 10^3$	5

The region close to a source is called the near-field. In the near-field, the **E** and **H** fields are not necessarily perpendicular; in fact, they are not always conveniently characterized by waves. They are often nonpropagating in nature and are sometimes referred to as fringing fields, reactive near-fields, or evanescent modes. Near-fields often vary rapidly with distance; the inverse square law of the dependence with distance does not apply, and the impedance (E/H) may differ from 377 Ω. Objects located near sources may strongly affect the nature of the fields. For example, placing a probe near a source to measure the fields may change the characteristics of the fields considerably (Dumansky et al., 1986).

When RF fields are incident on a conductive object, RF currents are induced in the object. These currents produce surface fields that are highly localized to the object and are often referred to as RF hot spots. RF hot spots are better characterized as electric and magnetic fields rather than radiation, since, for many conditions, the fields leading to the hot spot never propagate away from the object. At higher frequencies, the electric and magnetic fields maintain an approximately constant relationship in propagating waves. In general, the lower the frequency, the less coupled the fields become. This is particularly so when the wavelength is very large with respect to the physical size of the source. In practice, the fields of concern from a hazard perspective will be near-fields at frequencies below about 1 MHz.

3. NATURAL BACKGROUND AND HUMAN-MADE FIELDS

3.1 General

In the last few decades, the use of devices that emit electromagnetic fields has increased considerably. This proliferation has been accompanied by an increased concern about possible health effects of exposure to these fields (Grandolfo et al., 1983; Repacholi, 1988; Shandala & Zvinyatskovski, 1988, Franceschetti et al., 1989). As a result, throughout the world, many organizations, both governmental and nongovernmental, have established safety standards or guidelines for exposure (see section 10).

Electromagnetic devices already in use and the continuous addition of new sources result in the expansion to new frequencies in the spectrum and the increasing presence of RF fields. Comprehensive data on existing emission systems, and evaluation of present levels of exposure, are essential for the assessment of potential radiation hazards (Repacholi, 1983a; Shandala et al., 1983; Savin, 1986; Stuchly & Mild, 1987).

In this section, sources of electromagnetic fields, both natural and human-made, in the 300 Hz-300 GHz frequency range are surveyed. The human-made electromagnetic environment consists of fields that are produced either intentionally or as by-products of the use of other devices.

Human-made sources in the spectrum considered here, however, produce local field levels many orders of magnitude above the natural background. Therefore, for the practical purposes of hazard assessment, the electromagnetic fields on the earth's surface arise from human-made sources. According to the treaty of the International Telecommunications Union (ITU, 1981), the electromagnetic spectrum up to 3 THz is subdivided into 12 frequency bands. These bands are designated by numbers as shown in Table 2; only the bands referred to in this publication are given.

3.2 Natural background

The natural electromagnetic environment originates from processes such as discharges in the earth's atmosphere (terrestrial sources) or in the sun and deep space (extra-terrestrial sources).

Table 2. Frequency bands of the electromagnetic spectrum in the frequency range 300 Hz-300 GHz [a]

Band number	Frequency range subdivision	Metric	Description and symbol
3	0.3 to 3 kHz	-	voice frequency [VF]
4	3 to 30 kHz	myriametric	very low frequency [VLF]
5	30 to 300 kHz	kilometric	low frequency [LF]
6	0.3 to 3 MHz	hectometric	medium frequency [MF]
7	3 to 30 MHz	decametric	high frequency [HF]
8	30 to 300 MHz	metric	very high frequency [VHF]
9	0.3 to 3 GHz	decimetric	ultra high frequency [UHF]
10	3 to 30 GHz	centimetric	super high frequency [SHF]
11	30 to 300 GHz	millimetric	extremely high frequency [EHF]

[a] From: ITU (1981).

3.2.1 *Atmospheric fields*

Atmospheric fields of frequencies of less than 30 MHz originate predominantly from thunderstorms. Their strengths and range of frequencies vary widely with geographical location, time of day, and season. Some of these variations are systematic and some are random. Overall, atmospheric fields have an emission spectrum with the largest amplitude components having frequencies of between 2 and 30 kHz. Generally, the atmospheric field level decreases with increasing frequency. The geographical dependence is such that the highest levels are observed in equatorial areas and the lowest in polar areas.

3.2.2 *Terrestrial emissions*

The earth emits electromagnetic radiation (black-body radiation), as do all media, at a temperature T that is different from that at absolute zero. In the RF range, the black-body radiation follows the Rayleigh-Jeans law and the thermal noise from the earth (T about 300 K) is 0.003 W/m^2 (0.3 $\mu W/cm^2$), when integrated up to 300 GHz (Repacholi 1983).

The human body also emits electromagnetic fields at frequencies of up to 300 GHz at a power density of approximately 0.003 W/m^2. For a total body surface area of about 1.8 m^2, the total radiated power is approximately 0.0054 W.

3.2.3 *Extraterrestrial fields*

The atmosphere, ionosphere, and magnetosphere of the earth shield it from extra-terrestrial sources of nonionizing electromagnetic energy. Electromagnetic waves that are able to penetrate this shield are limited to two frequency windows, one optical and the other encompassing radiowaves of frequencies from about 10 MHz to 37.5 GHz. The short-wave boundary of the RF-window is due to energy absorption by molecules contained in the atmosphere (primarily O_2 and H_2O), whereas the long-wave boundary is related to the shielding action of the ionosphere.

RF radiation of cosmic origin observed with earth satellites ranges in magnitude from 1.8×10^{-20} $W/m^2/Hz$ at 200 kHz to 8×10^{-20} $W/m^2/Hz$ at 10 MHz (Struzak, 1982).

There are three main types of solar emission. The first is the so-called background, which is the constant component of the emission observed during periods of low solar activity. The second is the component that displays long-term changes, associated with variations in the number of sunspots. Its main contribution is in the frequency range from 500 MHz to 10 GHz. The third type of emission arises from isolated radio flares or radio emission bursts. The intensity of such emission can exceed the average intensity of the quiet radiation by a factor of one thousand or more; its duration varies from seconds to hours.

Natural sources of lesser intensity also exist and include the moon, Jupiter, Cassiopeia-A, the universal thermal background radiation at 3 K, hydrogen emissions from ionized clouds, line emissions from neutral hydrogen, the OH radical and, most recently observed, from ammonia.

3.3 Human-made sources

3.3.1 General

Radio and television transmitters are examples of human-made RF sources that intentionally produce electromagnetic emissions for telecommunication purposes. At frequencies of 3 kHz-3 MHz, normal service coverage is provided by ground-wave propagation. At VLF, propagation over distances of thousands of km is possible using this method. At LF and MF, during night-time, reflections from the ionosphere make propagation up to 2000 km possible with little attenuation. At HF, other propagation modes are also possible. At frequencies of 30 MHz-30 GHz, service coverage is provided by line-of-sight (short paths), diffraction (intermediate paths), or by forward scattering (long paths) propagation.

Broadcasting systems vary greatly in terms of their design. This diversity results in somewhat different approaches in evaluating human exposure and potential problems. The situations are significantly different for workers and for the general population. In the case of some workers, such as those maintaining equipment on broadcasting towers, there is a potential for exposure to strong RF fields. Workers may also be exposed to strong fields in the close vicinity of towers and particularly broadcasting antennas in the VLF, LF, and MF. In contrast, it is rare for the general population to be exposed to strong RF fields from broadcasting. However, there is simultaneous exposure to more than one source.

Some insight on the levels of exposure of the general population may be gained from data collected in the USA, indicating that, in large cities, the median exposure level is about 50 $\mu W/m^2$ (Tell & Mantiply, 1980). SAR values ranging from 0.05 to 0.3 $\mu W/kg$ are expected in the frequency range 170-800 MHz.

There are also human-made sources of electromagnetic fields used for non-communication purposes, in industry (I), science (S), and medicine (M). ISM applications are intended to transport and concentrate electromagnetic energy in a restricted working area to produce physical, chemical, and/or biological effects.

The frequency bands for ISM applications designated by the ITU are shown in Table 3. However, in individual countries, different and/or additional frequencies may be designated for use by ISM equipment (ITU, 1981; Metaxas & Meredith, 1983).

Table 3. Centre frequencies and frequency bands agreed internationally and assigned for ISM applications [a]

Centre frequency	Frequency bands	Area permitted
70 kHz	60-80 kHz	USSR
6.780 MHz 13.560 MHz	6.765-6.795 MHz 13.553-13.567 MHz	subject to agreement worldwide
27.120 MHz	26.957-27.283 MHz	worldwide
40.68 MHz	40.66-40.70 MHz	worldwide
42;49;56;61;66 MHz	~ 0.2%	United Kingdom
84;168 MHz 433.92 MHz	~ 0.005% 433.05-434.79 MHz	United Kingdom, Austria, Liechtenstein, The Netherlands, Portugal, Switzerland W. Germany Yugoslavia
896 MHz	886-906 MHz	United Kingdom
915 MHz	902-928 MHz	North and South America
2.375 GHz	2.325-2.425 GHz	Albania, Bulgaria, Czechoslovakia, Hungary, Romania, and USSR
2.45 GHz	2.4-2.5 GHz	worldwide, except where 2.375 GHz is used
3.39 GHz	3.37-3.41 GHz	The Netherlands
5.8 GHz 6.78 GHz	5.724-5.875 GHz 6.74-6.82 GHz	worldwide The Netherlands
24.125 GHz 40.68 GHz	24.0-24.05 GHz 40.43-40.92 GHz	worldwide United Kingdom
61.25 GHz 122.5 GHz 245 GHz	61.0-61.5 GHz 122-123 GHz 244-246 GHz	subject to agreement subject to agreement subject to agreement

[a] Adapted from: ITU (1981) and Metaxus & Meredith (1983).

Because of unavoidable imperfections in the construction, production, and use of ISM equipment, and of fundamental physical laws, there is always unintentional leakage of electromagnetic energy from such equipment. As a result, each ISM generator acts as an unintentional source producing signals capable of causing harmful effects, depending upon the amount of leakage.

To date, the total number of ISM installations in the world is estimated at 120 million (Struzak, 1985). The number of ISM generators constantly increases at a rate of about 3-7% per year. With such growth, the number of ISM generators expected by the year 2000 will be 2-4 times greater than it is now.

ISM equipment is usually designed at minimum cost, and, typically, is reduced to the essentials necessary for operation. Frequency stability and spectral purity of the power delivered to the work piece are not normally major objectives. In almost every case, the work piece is strongly coupled to the oscillator/amplifier, and since the electromagnetic characteristics of the material change during the work cycle, the magnitude, phase, and frequency of the radiation may be affected by these changes.

Electromagnetic energy leaks from ISM equipment mainly from the applicator and associated leads (e.g., RF heaters and sealers), the oscillator body/cabinet, and also from surrounding structures in which RF currents are induced. The amount of energy radiated from the applicator and associated leads depends on the particular arrangement of the devices and the work piece, which together act like an antenna the radiation efficiency of which is usually very low. However, the radiated power may be considerable if the nominal power is high.

Stray fields are also associated with currents flowing over the surface of the body/cabinet and over the surrounding structures. The equipment acts as a complex antenna system consisting of coupled radiating surface elements resonating at some unspecified frequencies. Often all the power and control wires are situated close to RF power circuits with no shielding. As a result, a considerable amount of RF energy may be fed into these leads and is conducted outwards at a distance and then reradiated.

Table 4. Typical applications of equipment generating electromagnetic fields in the range 300 Hz-300 GHz

Frequency	Wavelength	Typical applications
0.3-3 kHz	1000-100 km	Broadcast modulation, medical applications, electric furnaces, induction heating, hardening, soldering, melting, refining
3-30 kHz	100-10 km	Very long range communications, radio navigation, broadcast modulation, medical applications, induction heating, hardening, soldering, melting, refining, VDUs
30-300 kHz	10-1 km	Radionavigation, marine and aeronautical communications, long-range communications, radiolocation, VDUs, electro-erosion treatment, induction heating and melting of metals, power inverters
0.3-3 MHz	1 km-100 m	Communications, radionavigation, marine radiophone, amateur radio, industrial RF equipment, AM broadcasting, RF excited arc welders, sealing for packaging, production of semiconductor material, medical applications
3-30 MHz	100-10 m	Citizen band, amateur radio broadcasting, international communications, medical diathermy, magnetic resonance imaging, dielectric heating, wood drying and gluing, plasma heating
30-300 MHz	10-1 m	Police, fire, amateur FM, VHF-TV, diathermy, emergency medical radio, air traffic control, magnetic resonance imaging, dielectric heating, plastic welding, food processing, plasma heating, particle separation
0.3-3 GHz	100-10 cm	Microwave point to point, amateur, taxi, police, fire, radar, citizen band, radionavigation, UHF-TV, microwave ovens, medical diathermy, food processing, material manufacture, insecticide, plasma heating, particle acceleration
3-30 GHz	10-1 cm	Radar, satellite communications, amateur, fire, taxi, airborne weather radar, police, microwave relay, anti-intruder alarms, plasma heating, thermonuclear fusion experiments
30-300 GHz	10-1 mm	Radar, satellite communications, microwave relay, radionavigation, amateur radio

Typical uses of equipment generating electromagnetic fields in the frequency range 300 Hz-300 GHz are shown in Table 4.

3.3.2 Environment, home, and public premises

A comprehensive evaluation of general population exposure to RF has been performed by the USA Environmental Protection Agency (Tell& Mantiply, 1980). Broadcasting services, particularly those usingthe VHF and UHF bands, have been identified as the main sources of ambient RF fields (Karachev & Bitkin, 1985). Measurements performed in 15 large cities in the USA led to the conclusions that the median exposure level was 50 $\mu W/m^2$ and that approximately 1% of the population studied was potentially exposed to levels greater than 10 mW/m^2.

The presence of conducting objects can give rise to field strengths higher than those expected from theoretical considerations, since they act as diffracting elements for the electromagnetic fields. Consequently, the presence of such objects in the near-field zone of radio stations makes the area between the radiator and the object potentially more hazardous and indicates that problems of safety should be considered carefully (Bernardi et al., 1981).

Although measurements as well as theory indicate that there is no high-level exposure from broadcasting stations, the existence of limited areas of relatively high irradiation close to the sources should be checked (Dumansky et al., 1985a). Such situations can exist in proximity to very powerful, ground-level transmitters. In several cases, urban areas are served locally by low-power, in-town repeaters. These are placed, for convenience, on the top of tall buildings; unless properly designed, this creates the possibility of stray fields in a densely populated area directly below the RF source. A typical, high-power, MF transmitter can have a carrier power of 100 kW, plus up to 50 kW in the sidebands of the propagated field. This is an example of how high field strengths can occur in a space open to the public.

Although a broadcasting station's property is usually fenced to keep out unauthorized individuals, the fence may be close to the tower base and people may be able to get as close as a few tens of metres or less from the antenna. Because the wavelengths involved are so long, a near-field exposure situation may exist and a field strength considerably greater than the theoretical ground-wave field strength is to be expected (Bini et al., 1980).

Local MF transmitters find widespread use in cities, where they provide coverage on "blind spots" or other low-signal receiving areas. Powers range from 100 to 1000 W at the amplifier output and much less than that can be expected to be radiated into space. In a typical arrangement, the transmitting module is located at the top of a stucture. The radiating system is fed via a coaxial cable. It consists of a dipole over a ground plane or counterpoise laid directly on the roof. More than one transmitter can serve the same radiator. Currents can set up fields in a complicated pattern inside the building (Bini et al., 1980).

When RF fields are incident on conductive objects, RF currents are induced in the objects. Because of these currents, the objects become sources of additional fields that are highly localized and in some situations can constructively add to original fields.

Among the general population, the most popular application of microwave power is in the cooking of food. Power levels range from 300 W to 1 kW in consumer microwave models, at a frequency of 2.45 GHz. In a properly designed microwave oven, a very small fraction of this power escapes from the oven housing through various leakage paths. When leakage occurs, it is most frequently through the door seal. It may increase with use or mechanical abuse of the oven. Small amounts of leakage can also occur through the viewing screen (Osepchuk, 1979).

Personal exposure from microwave ovens is extremely small because of the rapid decrease of the power flux density with increasing distance from the oven. For worst case leakage from the microwave oven of 5 mW/cm^2, the power density at a distance of 0.3 m is less than 0.15 mW/cm^2 and, at 1 m it is about 10 μW/cm^2. Typical leakage values, therefore, imply exposure values well below the most conservative RF exposure standards in the world (Stuchly, 1977; Dumansky et al., 1980).

Recently, the induction heating stove, a new appliance for domestic use, has been introduced on the market. This appliance operates in the kilohertz range. Exposure levels at distances greater than 0.5 m are low compared with existing exposure limits, being less than 5 V/m and 0.5-10 A/m, respectively, at a distance of 0.3 m (Stuchly & Lecuyer, 1987).

Microwave anti-intrusion alarms are typical of low-power devices. These operate continuously to avoid thermal drift or switching problems, thus exposing people in the protected area. With a typical power of 10 mW, power densities of the order of 10 $\mu W/cm^2$ are measured at a distance of about 0.5 m. Population exposure to RF fields from commonly encountered sources, such as airport, marine, and police radar, is similarly very low (Stuchly, 1977; Dumansky et al., 1980, 1985b, 1988).

3.3.3 Workplace

Levels of occupational exposure vary considerably, and are strongly dependent upon the particular application. While most communication and radar workers are exposed to fields of only relatively low intensity, some can be exposed to high levels of RF. Workers climbing FM radio or TV broadcasting towers may be exposed to E fields up to 1 kV/m and H fields up to 5 A/m (Repacholi 1983a; Mild & Lovstrand, 1990).

Radar systems produce strong RF fields along the axis of the antenna. However, in most systems, average field strengths are reduced typically by a factor of 100-1000, because of antenna rotation and because the field is pulsed. With stationary antennas, which represent the worst case, peak power flux densities of 10 MW/m^2 may occur on the antenna axis up to a few metres away from the source.

In areas surrounding air traffic control radars (ATCRs), workers can be exposed to power flux densities of up to tens of W/m^2, but are normally exposed to fields in the range 0.03-0.8 W/m^2. In an exposure survey of civilian airport radar workers in Australia, it was found that, unless working on open waveguide slots, or within transmitter cabinets when high voltage arcing was occurring, personnel were, in general, not exposed to levels of radiation exceeding the specified limits in the Australian and IRPA radiofrequency exposure standards (Joyner & Bangay, 1986a).

Dielectric or RF heaters are widespread in many industries. RF energy produces heat directly within the processed material. This unique characteristic is commonly used for such purposes as sealing plastics or drying glue for joining wood. All RF heaters have a higher efficiency in comparison with conventional ovens. According to several surveys (Conover et al., 1980; Stuchly et al., 1980; Grandolfo et al., 1982; Bini et al., 1986; Joyner & Bangay, 1986b; Stuchly & Mild, 1987), the sealing or welding of polyvinyl chloride (PVC) is the most common use for RF dielectric heaters. Two pieces of plastic are compressed between electrodes and RF power is applied. The plastic material heats, partially fuses, and forms a bond. Plastic heaters frequently operate at the ISM frequency of 27.12 MHz. However, during the operating cycle, this value may vary by several megahertz. The RF output power ranges from fractions of a kilowatt to about 100 kW.

Since the exposure of heater sealer operators and other personnel working in the same area takes place in the near-field, both E and H field strengths must be measured to evaluate exposure levels. However, to demonstrate compliance with basic limits of RF exposure, the development of body current measurement techniques should prove to be useful (Allen et al., 1986). In the vicinity of RF sources, measurements of fields must be made with the operators absent from the positions that they normally occupy. The stray fields are localized in the immediate vicinity of the sealers, so that exposure of the body is highly inhomogeneous.

RF industrial heaters (plastic sealers and other devices) have been found to produce exposure fields exceeding the limits recommended in various countries and by the IRPA. Furthermore, direct current measurements have confirmed coupling of the RF energy from the device to its operator. Various methods have been developed to ameliorate the situation, such as shields, grounding strips, and others. Potential overexposure to RF radiation is probably one of the most common occurrences in the case of RF heaters, unless protective measures are employed.

Magnetic fields below a few tens of megahertz are used in industry for the induction heating of metals and semiconductors and in arc welding. Surveys of the magnetic field strength to which the operators are exposed have shown that these exposures are, in many instances, high compared with recommended exposure limits (Stuchly & Lecuyer, 1985; Conover et al., 1986; Stuchly, 1986; Andreuccetti et al., 1988; Stuchly & Lecuyer, 1989).

In many practical situations, exposure can be reduced either by administrative measures (Eriksson & Mild, 1985) or by the use of protective screening. Screening may be intentional (wire fences) or incidental (walls of buildings) and may function by reflection or by absorption. In general, both contribute to the total attenuation provided.

Thin metal sheets are adequate for the attenuation of RF electric fields. However, in many cases, it is usual to use wire screens or perforated sheets, since these have the advantages of transparency, ventilation, light weight, etc. In all cases, surveys are desirable to verify the integrity of such screens or shields. Faults in screens could, in some circumstances, be secondary sources of significant radiation or reactive fields (White, 1980).

The applications of video display units (VDUs) are numerous and their use widespread. Even more applications are anticipated in the future. In the RF region, they emit electric and magnetic fields from the cathode ray tubes (CRTs). The dominant sources are the horizontal and vertical sweep generators (fly-back transformers) operating at frequencies of some 15-35 kHz. VDUs produce fields that have complex waveforms. Typical electric field stengths at the operator position (0.5 m from the screen) range from less than 1 to 10 V/m (RMS). Magnetic flux densities range typically from less than 0.01 μT to 0.1 μT (RMS). In most VDUs, both fields are produced at the lower end of these ranges. VDUs also produce weak, electric and magnetic fields at the power line frequency (50 or 60 Hz) and its harmonics. All surveys have concluded that VDUs do not present any hazard for human health within the context of existing guidelines for exposures to non-ionizing electromagnetic fields (see section 10) (BRH, 1981; Stuchly et al., 1983b; Harvey, 1984; Repacholi, 1985; Elliott et al., 1986).

A statement has been published by the International Non-Ionizing Radiation Committee of the International Radiation Protection Association (IRPA, 1988b). Conclusions in this and other documents (WHO, 1987; ILO, 1991) are that, on the basis of current biomedical knowledge, there are no health hazards associated with radiation or fields from VDUs and that there is no scientific basis to justify radiation shielding or regular monitoring of the various radiations and fields emitted by VDUs.

3.3.4 Medical practice

Shortwave and microwave diathermy treatments are used to relieve pain through the non-invasive application of non-ionizing electromagnetic energy to body tissues. Several surveys have been published (EHD, 1980; Ruggera, 1980; Grandolfo et al., 1982; Stuchly et al., 1982; Delpizzo & Joyner, 1987), with the primary purpose of measuring the field strengths to which diathermy operators are exposed during typical treatments. Measurements of the magnitude of fields near diathermy electrodes (applicators) were made from shortwave diathermy units operating at 27.12 MHz, and from microwave diathermy units operating at 434 MHz and 2.45 GHz. They indicate emissions of high field and radiation levels in directions other than those intended for treatment. Operators, physiotherapists, and personnel performing service and maintenance tasks are exposed to stray fields and radiations. Reduction of unnecessary exposure of both operator and patient during microwave and shortwave diathermy treatments is technically achievable through adequate shielding of existing units, careful design of new equipment, and judicious planning of the treatment area (Bonkowski & Makiewicz, 1986).

Hyperthermia devices are used in cancer adjuvant therapies (Storm et al, 1981; Stuchly et al., 1983a; Hagmann et al., 1985). Treatments have been based on biological studies that suggest hyperthermia effectiveness in conjunction with radiotherapy and with chemotherapy. The evaluation of hyperthermia efficacy is proceeding through the development of therapeutic trials for specific tumours (Arcangeli et al., 1985; Perez et al., 1991). A few international and national organizations have independently determined and developed randomized trials (Lovisolo et al., 1988). For the purposes of safety evaluation, hyperthemia devices can be classified as: (*a*) those irradiating external to the body and intended for superficial and deep hyperthermia, and (*b*) those irradiating from inside the body and intended for interstitial and endocavitary hyperthermia.

All devices present, to a greater or lesser extent, problems of patient health protection. Adverse effects on patients have included pain, discomfort, burn, ulceration, and, for deep hyperthemia, tachycardia and faintness. These are due to an overheating of superficial tissues, tissues surrounding the tumour, and, in deep hyperthermia, other tissues far from the tumour and irradiated region (Myerson et al., 1989; Petrovich et al., 1989). The magnitude of the electromagnetic field around superficial, interstitial, and endocavitary applicators is relatively low and does not cause any health risk to the operators, though the possibility of leakage of RF energy from generators and connecting cables has to be considered in some models. Capacitive and phase array devices, however, may leak RF energy (Storm et al., 1981).

Hagmann et al. (1985) measured the stray electric and magnetic fields of angular phased array and helical coil applicators for limb and torso hyperthermia at 70.93 MHz. Field strengths were measured in excess of 300 V/m and 1A/m, respectively, at a distance of about 10 cm from the applicator. At 0.5 m, these values were reduced to 14 V/m and 0.1 A/m, respectively. In general, manufacturers of hyperthermia devices pay too little attention to minimizing the leakage of RF fields from generators, cables, and applicators, and each new model generator should be tested for RF emissions.

Magnetic resonance imaging (MRI) is now an established diagnostic technique while *in vivo* spectroscopy is undergoing rapid development. The complexity of exposure associated with MRI requires the safety consideration of three different fields (Tenforde & Budinger, 1986; Budinger, 1988). During clinical imaging, patients or volunteers, and operators are exposed to static magnetic fields, time-varying magnetic fields, and radiofrequency electromagnetic fields. RF fields in the frequency range 1-100 MHz, are deposited in patients, principally as heating associated with eddy currents induced by the RF magnetic field (Grandolfo et al, 1990). For MRI systems with static magnetic flux densities below 2 T, power deposition from electric fields associated with RF transmitter coils is relatively low, when efficient transmitter coil designs are employed. The power deposited by transient magnetic field gradients is similarly low (Bottomley et al., 1985). Staff operating the equipment are intermittently exposed to weaker fields that are present in the vicinity of the imaging equipment. Guidelines on "Protection of the patient undergoing magnetic resonance examinations" have been published by the International Non-Ionizing Radiation

Committee of the International Radiation Protection Association (IRPA, 1991).

4. EXPOSURE EVALUATION - CALCULATION AND MEASUREMENT

4.1 Introduction

Exposure evaluation provides information necessary to perform risk assessments. Two methods are available: (i) a theoretical estimation; and (ii) measurements of the fields or related parameters, such as energy absorption rates and currents.

Estimates of exposures are necessary before an installation is constructed. Whenever possible, estimates of radiation fields should be made before detailed surveys of potentially hazardous exposures are carried out. This procedure is needed to select suitable survey instruments, and to determine whether potentially hazardous exposure of the surveyor could occur, if the choice of the instrument were inappropriate or if the instrument were faulty.

4.2 Theoretical estimation

Electromagnetic waves may be harmonic, i.e., the electric and magnetic fields oscillate as sine waves, and power is generated as a continuous wave (CW) at essentially a single frequency. The waves may be also modulated, i.e., the amplitude, phase, or frequency may be changed in a chosen manner, for example, if pulse modulation, short-duration electromagnetic pulses are emitted at certain time intervals. The duration of the pulse (pulse length or pulse width), which may be of the order of small fractions of a second, is designated by t. Its reciprocal, the pulse repetition frequency (pulse repetition rate), is expressed in hertz. The product of pulse length and repetition rate is referred to as the duty cycle, D. In case of pulsed-wave generation, the emitted power increases rapidly, reaches a peak pulse power, and rapidly decreases.

This may be averaged for pulse length or per unit time, which introduces the concept of mean (average) power emitted, according to:

$$P_p = P_a/tf_r \text{ or } P_a = P_p f_r t \qquad \text{(Equation 4.1)}$$

where P_p is the peak power, P_a the average power, f_r the repetition frequency, and t the pulse length.

In practice, average power is usually measured, and, for safety purposes, mean power density is used. The peak pulse power may be many times higher than the average power output. The average and peak power flux densities (S_a and S_p) are given by:

$$S_a = DS_p \qquad \text{(Equation 4.2)}$$

Universally used sources with moveable antennas and/or beams, such as scanning or rotating radars, introduce an additional complication from the safety viewpoint. Electromagnetic power from such installations arrives intermittently.

The power flux density for a scanning antenna in motion can be estimated from the power flux density measured with the antenna stationary using the expression:

$$W_m = k_s W_s \qquad \text{(Equation 4.3)}$$

where W_m is the power flux density for the antenna in motion, k_s is the antenna rotational reduction factor, and W_s is the power flux density measured on the axis of the stationary antenna at a given distance.

In most radar installations, the antenna rotates and therefore an occupied position is exposed only when the radar beam sweeps it. The average exposure level is obtained by multiplying the measured or estimated level from a stationary antenna by the rotational reduction factor (RRF). In the far-field, RRF equals the ratio of the half power beam width to the antenna scan angle.

The rotational reduction factor (k_s) for the near-field region is equal to:

$$a/R_k \qquad \text{(Equation 4.4)}$$

where "a" is the dimension of the antenna in the scan (rotation) plane and R_k is the circumference of the antenna scan sector at the given distance r, at which the measurements have been made.

The region close to a source antenna is called the near-field. As shown in Fig.2, the near-field can be divided into two subregions: the reactive near-field region and the radiating near-field region. The region of space surrounding the antenna in which the reactive components predominate is known as the reactive near-field region. In the radiating near-field region, the radiation pattern varies with the distance from the antenna. The near-fields often vary rapidly with distance and mathematical expressions generally contain the terms $1/r$, $1/r^2$, ..., $1/r^n$, where r is the distance from the source to the point at which the field is being determined. At greater distances from the source, the $1/r^2$, $1/r^3$, and higher-order terms are negligible compared with the $1/r$ term and the fields are called far-fields. These fields are approximately spherical waves that can, in turn, be approximated in a limited region of space by plane waves. Measurements and calculations are usually easier in far-fields than in near-fields.

When the longest dimension (L) of the source antenna is greater than the wavelength (λ), the distance from the source to the far-field is $2L^2/\lambda$. For $L < \lambda$, this distance is $\lambda/2\pi$ (see Fig. 2). In practice, the distance from the source that represents the boundary between the near-field and far-field regions is often taken to be the greater of the two quantities, λ and $2L^2/\lambda$. However, the appropriate empirical relationship depends on the type of aperture of the source and, for example, for a circular aperture, such as on a microwave relay tower, the relationship L^2/λ may be more appropriate. In this case, with a frequency of 2 GHz (λ = 15 cm), L is approximately 3 m and, consequently, the quantity L^2/λ = 60 m. Because 60 m is much greater than 15 cm, this is the distance that can be assumed as a boundary between the near- and far-field regions.

The boundary between the near-field and far-field regions, however, is not sharp, because the near-fields gradually become less as the distance from the source increases.

In free space, electromagnetic waves spread uniformly in all directions from a theoretical point source. In this case, the wavefront is spherical. As the distance from the point source increases, the area of the wavefront surface increases as a square of the distance, so that the source power is spread over a larger area.

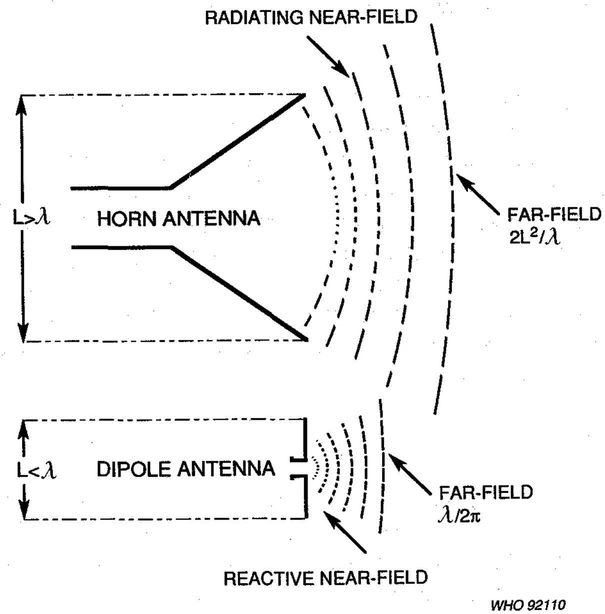

Fig. 2. Antenna size versus separation of the radiating near-field, the reactive near-field, and the far-field regions.

If the exposure takes place in the far-field of a well characterized antenna in free space, then S is calculated by the formula:

$$S = GP_t / 4\pi r^2 \ (W/m^2) \qquad \text{(Equation 4.5)}$$

where G is the far-field power gain, P_t is the power transmitted (W) and r is the distance (m) from the antenna.

For a horn or reflector type antenna:

$$G = 4\pi A_e/\lambda^2 \qquad \text{(Equation 4.6)}$$

where A_e is the effective area of the antenna.

If G is not known, a useful approximation of S can be obtained by substituting the physical area A for A_e in equation 4.6. This gives a somewhat larger value for S, since A is generally larger than A_e.

Although the equations are far-field relationships, i.e., correct for distances greater than approximately $2L^2/\lambda$ ($L > \lambda$), they can be used with an acceptable error for distances greater than 0.5 L^2/λ. The error is on the safe side, since the equations predict greater values of S. However, at distances closer than 0.5 L^2/λ, the values of S predicted by the equations become unrealistically large and radiating near-field estimates must be used. For commonly encountered horn and reflector type antennas, the maximum expected radiating, near-field, power flux density S_m can be estimated (Hankin, 1974) from:

$$S_m = 4P_t/A \qquad \text{(Equation 4.7)}$$

Unfortunately, there are no equivalent reactive near-field formulae for small radiators. The radiating near-field behaviour of horn and reflector type antennas is discussed in detail elsewhere (Bickmore & Hansen,1959; SAA, 1988). A detailed discussion of the reactive near-field of small radiators can be found in Jordan & Balmain (1968).

In the near-field, the situation is somewhat complicated, because the maxima and minima of E and H fields do not occur at the same points along the direction of propagation as they do in the the case of the far-field. In this region, the electromagnetic field structure may be highly inhomogeneous and typically, there may be substantial variations from the plane wave impedance of 377 Ω; i.e., in some regions, almost pure E-fields may exist and, in other regions, almost pure H-fields. Field strengths in the near-field are more difficult to specify, because both the E and H fields must be measured and because the field patterns are more complicated; the power density tends to vary inversely with r instead of r^2 (as in the far-field), and may display interference patterns. Near-field exposures become particularly important when considering fields from microwave diathermy equipment, RF sealers, broadcasting antennas, and microwave oscillators under test.

4.3 Measurements

4.3.1 Preliminary considerations

Several steps are necessary for the accurate assessment of RF exposure. The source and exposure situation must be characterized, so that the most appropriate measurement technique and instrumentation can be selected (ANSI, 1990; Tell, 1983). The correct use of this instrumentation requires knowledge of the quantity to be measured and the limitations of the instrument used. A knowledge of relevant exposure standards is essential.

In the following sections, information is given concerning preliminary RF survey considerations, measurement procedures, and calibration facilities.

Prior to the commencement of a survey, it is important to obtain as much information as possible about the characteristics of the RF source and the exposure situation. This information is required for the estimation of the expected field strengths and the selection of the most appropriate survey instrumentation.

Information about the RF source should include:

- frequencies present, including harmonics;
- power transmitted;
- polarization (orientation of E field);
- modulation characteristics (peak and average values);
- duty cycle, pulse width, and pulse repetition frequency;
- antenna characteristics, such as type, gain, beam width and scan rate.

Information about the exposure situation must include:

- distance from the source;

- existence of any scattering objects. Scattering by plane surfaces can enhance the E field by a factor of 2, hence, S, by a factor of 4. Even greater enhancement may result from curved surfaces, e.g., corner reflectors.

4.3.2 Near-field versus far-field

For the practical purposes of measurement, the reactive near-field exists within 0.5 λ from the source with a practical outer limit of several wavelengths (Jordan & Balmain, 1968). Both E and H field components must be measured within the reactive near-field. At present, no instruments are available commercially for the measurement of H-fields above 300 MHz, which imposes a de facto frequency limit on the measurements.

4.3.3 Instrumentation

An electric or magnetic field-measuring instrument consists of three basic parts; the probe, the leads, and the monitor. To ensure appropriate measurements, the following instrumentation characteristics are required or are desirable:

- The probe must respond to only the E field or the H field and not to both simultaneously.
- The probe must not produce significant perturbation of the field.
- The leads from the probe to the monitor must not disturb the field at the probe significantly, or couple energy from the field.
- The frequency response of the probe must cover the range of frequencies required to be measured.
- If used in the reactive near-field, the dimensions of the probe sensor should preferably be less than a quarter of a wavelength at the highest frequency present (see next section).
- The instrument should indicate the root mean square (rms) value of the measured field parameter.
- The response time of the instrument should be known. It is desirable to have a response time of about 1 second or less, so that intermittent fields are easily detected.

- The probe should be responsive to all polarization components of the field. This may be accomplished, either by inherent isotropic response, or by physical rotation of the probe through three orthogonal directions.
- Good overload protection, battery operation, portability, and rugged construction are other desirable characteristics.
- Instruments provide an indication of one or more of the following parameters:

  (*a*) Average power density (W/m^2, mW/cm^2);
  (*b*) Average E field (V/m) or mean square E field (V^2/m^2);
  (*c*) Average H field (A/m) or mean square H field (A^2/m^2).

However, no instrument actually measures average power density and this quantity is not useful in the near-field of antennas. Power density is measured in the far-field by E-field or H-field probes. The surveyor should be aware of the field parameter (E or H) to which the instrument responds, and that exposure standards generally stipulate limits corresponding to both field parameters. Equivalent plane wave power density is certainly a convenient unit, but in the reactive near-field, E and H field components must be measured and compared with the corresponding exposure limits.

Some factors that can influence the signal levels of the instruments (e.g.,influence of multiple signals, pulse modulation, lead pick-up, coupling into probes) are discussed in detail in ANSI (1981) and Joyner (1988).

4.3.4 Measurement procedures

If information on the RF source and exposure situation is well defined, then a surveyor, after making estimates of the expected field strengths and selecting appropriate instruments, may proceed with the survey using a high-range probe to avoid inadvertent probe burnout and a high-range scale to avoid possible over-exposure.

In the reactive near-field of radiators operating at frequencies of less than 300 MHz, an electrically small (largest dimension $< 0.25\ \lambda$) probe sensor is required since large gradients in field components exist. Spatial resolution is critical (large probes will yield spatially averaged values) and the use of an isotropic probe is strongly recommended. E and H field measurements should not be made closer than a distance of 20 cm from metallic objects. In some such cases, it may be possible to assess compliance with exposure standards by making contact current measurements.

Non-uniform field distributions result from reflections from various structures. Peaks in the field distribution are separated by at least one-half wavelength with the maximum levels of E and H fields occurring in different locations. Temporal variations occur also as a result of scanning antennas, scanning radiation beams, and changes in frequency. Therefore, it is imperative that any survey include a sufficiently large sample of data to preclude omission of hazardous combinations of conditions. When surveying sources of leakage radiation, such as waveguide flanges, equipment cabinet doors, and viewing or shielding screens, a "sniffing" procedure in the immediate vicinity of the equipment is required. A low-power probe and high-range setting should first be used to determine leakage sources from a distance, and lower-range settings used as a closer approach is made. Usually, leakage power varies as the inverse square of the distance.

When surveying radar antennas, it is necessary to have the antenna or the beam stationary, because the response time of the instruments is generally not short enough to indicate the maximum levels for common beam sweep and scan speed. It is important to estimate the peak exposure level, in order to ensure that the probe chosen can withstand such a peak level. Also, instruments that time-sample the field at insufficiently low sample rates should not be used for radar applications (Tell, 1983). Appropriate equations are then used to convert back to time-averaged levels for a rotating antenna.

All occupied and accessible locations should be surveyed. The operator of the equipment under test and the surveyor should be as far away as practicable from the test area. All objects normally present, which may reflect or absorb energy, must be in position. The surveyor should take precautions against RF burns and shock, particularly near high-power, low-frequency systems.

With careful measurement techniques and the correct choice of instrument, overall measurement uncertainties that are acceptable can be achieved. Direct field measurements frequently do not provide reliable means for exposure evaluation at distances from the field source (an antenna, or a re-radiating surface) of less than about 0.2 m or $\lambda/2$, whichever is smaller. In such a case, it may be necessary to evaluate the specific absorption rates (SARs) in a model of the human body using one of the dosimetric measures (Stuchly & Stuchly, 1986), or to measure directly the RF current flowing through the person (Blackwell, 1990; Tell, 1990a).

5. DOSIMETRY

5.1 General

Time-varying electric and magnetic fields induce electric fields and corresponding electric currents in biological systems exposed to these fields. The intensities and spatial distribution of induced currents and fields are dependent on various characteristics of the exposure field, the exposure geometry, and the exposed biological system. The exposure field characteristics that play a role include the type of field (electric, magnetic, or electromagnetic radiation), frequency, polarization, direction, and strength. Important characteristics of the exposed biological body system include its size, geometry, and electrical properties. The electrical properties of biological systems described by the complex permittivity and electrical conductivity differ for various tissues.

The biological responses and effects due to exposure to electromagnetic fields generally depend on the strength of induced currents and fields. However, only the external fields can be measured easily and dosimetry has been developed to correlate the induced currents and fields with the exposure conditions. Induced currents, as a measure of dose, have been used in the quantification of experimentally induced effects in animals and the results have been extrapolated to humans.

In the broad range of frequencies considered in this publication, i.e., 300 Hz-300 GHz, two different, but interrelated, quantities are commonly used in dosimetry. At lower frequencies (below approximately 100 kHz), many biological effects can be quantified in terms of the current density in tissue. Therefore, this parameter is most often used as a dosimetric quantity. At higher frequencies, where many (but not all) interactions are due to the rate of energy deposition per unit mass, the parameter specific absorption rate (SAR) is used. The SAR is defined as "the time derivative of the incremental energy, dW, absorbed by, or dissipated in, an incremental mass, dm, contained in a volume element, dV, of a given density, ρ" (NCRP 1981). The SAR is most often expressed in units of watts per kilogram (W/kg).

5.2 Low frequency range

At frequencies below approximately 0.1-1 MHz, interactions of electromagnetic fields with biological systems can be considered in terms of induced currents and their density. This approach is particularly well suited for calculations at frequencies for which the dimensions of the object are small compared with the wavelength. Under these circumstances, quasi-static approximations are valid, i.e., the effects of the electric and the magnetic field can be considered separately. The advantages of considering induced currents are twofold. First, the current densities induced in humans can be compared with those known to produce physiological responses, e.g., nerve or muscle stimulation, or they can be compared with endogenous body currents. Second, consideration of induced currents in ungrounded metallic objects can be used to assess thresholds for shocks and burns for people, who are fully or partially grounded and come in contact with such objects. Maximum current densities and the resulting maximum SARs, in some parts of the human body under certain exposure conditions, can be conveniently evaluated using the induced current approach. The direct evaluation of the internal electric fields would be much more complex and difficult. Under these conditions, limits of exposure may be expressed more appropriately in terms of induced currents rather than external field strengths.

The use of induced currents or current densities is appropriate for the assessment of acute, immediate, safety hazards, while it may have limitations for the complete evaluation of long-term effects. This has yet to be determined.

5.2.1 Magnetic fields

In accordance with Faraday's law, magnetic fields that vary in time induce the movement of electrical charge and cause potentials and circulating (eddy) currents in biological systems. These currents can be estimated using the following equation, provided that the current paths are circular:

$$J = \sigma E = 0.5\, r\sigma dB/dt \qquad \text{(Equation 5.1)}$$

where:

J = current density (A/m^2)
E = induced electric field strength (V/m)
r = radius of the loop (m) (usually several cm up to 20 cm)
σ = tissue conductivity (S/m)
dB/dt = rate of change of magnetic flux density B (T/s).

For sinusoidal fields of frequency f, equation 5.1 reduces to:

$$J = \pi r \sigma f B_0 \qquad \text{(Equation 5.2)}$$

where B_0 is the magnetic flux density peak amplitude.

The current density, internal electric field, and SAR, at any location in an exposed biological body, are inter-related as follows:

$$SAR = \sigma E^2/\rho \qquad \text{(Equation 5.3)}$$

where ρ is the physical density (kg/m^3) and

$$SAR = J^2/\sigma\rho \qquad \text{(Equation 5.4)}$$

Because of the paucity of experimental data on the biological effects of electromagnetic fields at frequencies below a few tens of megahertz, consideration of the following effects of induced current densities provides a useful alternative.

The magnitude of the magnetically induced electric fields and current densities is proportional to the radius of the induction loop in the body, to the tissue conductivity, and to the rate of change of magnetic flux density. The dependence of the induced field and current on the radius of the loop through which magnetic flux linkage occurs is an important consideration for biological systems. The induced current density is greatest at the periphery of the body, where the conducting paths are longest, whereas microscopic current loops anywhere within the body would have proportionally smaller current densities dependent on the loop size. The magnitude of the current density is influenced also by tissue electrical conductivity. In biological bodies, the exact paths of the current flow depend in a complicated way on the electrical conducting properties of the various tissues.

It is difficult to calculate the complex current distributions in biological bodies. Therefore, the treatment of this problem is restricted, at present, to relatively simplified situations.

Typical values for the low-frequency electrical conductivity are 0.1-0.35 S/m for cardiac muscle and 0.1-0.3 S/m for nerve tissue. Additionally, high ratios of transverse to longitudinal impedance up to 7:1 have been observed (Epstein & Foster, 1983).

There is very little experimental or theoretical work dealing with the coupling of magnetic fields to models of living organisms (e.g., Spiegel (1976) described magnetic field coupling with spherical models, Gandhi et al. (1984) calculated induced current densities in the torso of a human using a multidimensional lattice of impedance elements). Bernhardt (1979, 1985, 1988) performed calculations, using "worst case" assumptions, to estimate the order of magnitude for "safe" and "dangerous" values of magnetic field strengths and their frequency dependence. Considering the cardiac region and the brain as "critical" organs, approximate "worst case" calculations can be made (Bernhardt, 1979, 1985). For the purpose of these calculations, both regions can be considered as homogeneous spheres of different radii. Differences in electrical conductivity of the white and grey cerebral matter, and the anisotropic nature of conductivity at frequencies below approximately 10 kHz are not considered. A value of σ = 0.2S/m is used for the specific electrical conductivity of the cerebral substance, and a value of 0.25 S/m is used for the myocardial tissue. When a radius r of 7.5 cm of the induction loop is assumed for the head, and 6 cm for the heart, the product σr is the same for both the heart and head.

Therefore, approximately the same current densities are calculated to result in the peripheral regions of the heart and brain for a vertical magnetic field. Because of the uncertainties of the current loops and of the values for the electrical conductivities, the accuracies of these calculations are limited to about one order of magnitude. For larger effective current loops and electrical conductivities, smaller values of magnetic flux density may induce the same current densities.

The waveform is an important factor to be considered in the response of biological systems to a time-varying magnetic field. Many different waveforms of magnetic field are used in medicine and industry, including sinusoidal, square-wave, saw-tooth, and pulsed. For these fields, the parameters of key importance are the rise and decay signal times. These determine the maximum rates of change of the field (dB/dt) and the maximum instantaneous current densities induced in tissues. In order to provide an "effective" value for a variety of waveforms, root-mean-square (rms) values are often used. However, peak instantaneous field strengths appear to be important in considering nerve and muscle cell stimulation, and for perturbing cell functions. The effects depend strongly on frequency.

5.2.2 Electric fields

Exposure of a living organism to electric fields is normally specified by the unperturbed electric field strength. The fields that actually act on an exposed organism include electric fields acting on the outer surface of the body and electric fields and current densities induced inside the body. These fields can be different from the exposure, because of perturbations caused by placing the body in the external field. They must, however, be determined in order to specify exposure at the level of living tissues or to relate exposure levels and conditions from one species to another.

The electric fields that act directly on an exposed subject can be categorized as follows:

(*a*) *Electric fields acting on the outer surface of the body.*
These fields can cause hair to vibrate and thereby can be perceived; they may also be able to stimulate other sensory receptors in the skin.

(*b*) *Electric fields induced inside the body.*
These fields act at the cellular level, and their presence is accompanied by electric currents because of the electrically conductive nature of living tissues.

Secondary short-term effects must also be considered when evaluating health risks resulting from electric field exposure. Hazardous thresholds for some indirect effects are lower than the thresholds for biological effects due to the direct influence of electric fields. In this case, the following points are important:

- Contact currents enter a person through electrical conductors in contact with the skin.

- For static and low-frequency fields, spark discharges introduce transient currents into the body via an arc gap, when the electrical breakdown potential of air is exceeded.

- Electric or magnetic fields may interfere with the performance of unipolar cardiac pacemakers.

Therefore, a clear distinction is necessary between effects caused by the direct influence of electric fields and indirect effects caused by approaching or touching electrically charged objects, or by electromagnetic interference with implanted electromedical devices.

Within the body, the current and the current density are the two main quantities of interest. The total current is more easily measured or calculated, but the current density is more directly relevant to electric field effects in a particular tissue or organ. The electrical complexity of the interior of the human body, due to the presence of insulating membranes and tissues of various impedances, has so far frustrated confident analysis of precise interior current densities (Kaune & Phillips, 1980; Spiegel, 1981).

Electric field coupling occurs through capacitive and conductive mechanisms. A body is coupled to an electric field in proportion to its capacitance to the ground as one equipotential surface, such that the greater the capacitance the greater the current flow in the body. By definition, in capacitive coupling, the body, according to its capacitance C, "acquires" a certain amount of surface charge Q and attains a potential $V = Q/C$. The capacitance, and, thus, the induced current, decreases for a body separated from the ground and not close to an energized electrode. The capacitance is dependent on the size (especially on the surface area), the shape, and the orientation of the body. Internal currents will differ between fat and thin persons, between persons standing and reclining, and between persons walking barefoot and those wearing shoes or standing on a non-conductive platform. In all cases, it is necessary, to define the conditions under which the capacitance has been measured.

A short-circuit current, I_{sc}, flows in a body placed in an electric field and connected to the ground through a low resistance path (paws, bare feet, a hand grasping an earthed pole). This current is the sum of all the displacement currents collected over the surface of the body. The only place on the body where a current of the magnitude of the short-circuit current flows is where there is connection with the ground. The total current induced in the body is simply the Maxwell's displacement current density multiplied by the effective area of the body. Since the body is highly conducting, this current is completely independent of the body's dielectric parameters. Deno (1977) determined this effective area by measuring the surface currents induced in hollow metal mannequins exposed to 60 Hz electric fields. He characterized the complete current distribution and determined the total short-circuit current to ground.

The equivalent area for an adult human corresponds to an effective surface area of 5.08 m^2 for a 1.77 m-tall subject. This results in a total short circuit to ground current I_{sc} (mA) for a grounded person given by:

$$I_{sc} = 0.09\, h^2 E f \qquad \text{(Equation 5.5)}$$

where h(in m) is the height of the person, E (in kV/m) is the electric field strength, and f (in kHz) is the frequency.

From measurements by Guy & Chou (1982) and Tell et al. (1982), the values of short-circuit current obtained by Deno for the metal foil models were confirmed to be the same for humans at frequencies of up to 1 MHz.

The results are shown in Fig. 3, normalized to an exposure level of 614 V/m. Since the threshold for RF burns was found by Rogers (1981) to be 200 mA, it is clear that an exposure level of 614 V/m does not protect humans against RF burns resulting from contact with grounded objects.

Deno's current distributions can be used to calculate spatial distributions of SAR as well as average SAR for real human bodies exposed to electric fields of wavelengths that are large compared with the size of the body.

To make accurate calculations of the SAR distributions from the body current distributions for various exposure conditions, it is necessary to determine the electrical conductivity and resistance per

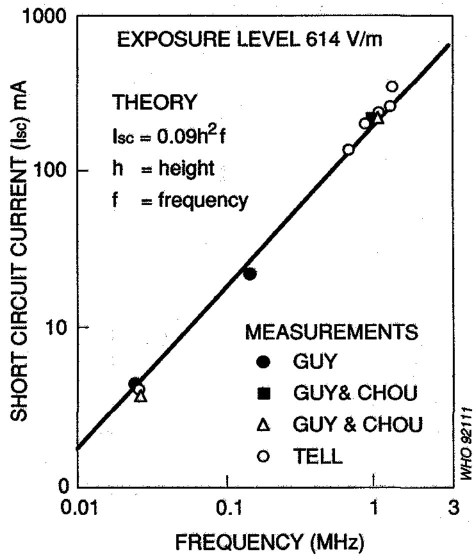

Fig. 3. Comparison of measured and calculated body-to-ground currents as a function of frequency for human subjects exposed to electric fields. From: Guy (1987).

unit length along the axis of the body and limbs. At frequencies between approximately 60 kHz and 3 MHz, this can be simply achieved by passing a known very low-level (VLF-MF) current through the whole body and measuring the potential at various points.

Calculations of SAR for exposure levels of 614 V/m, based on measured electrical conductivity and current distribution, are illustrated in Fig. 4 for exposure conditions where the feet are grounded. The maximum SAR values were obtained from the average values in each elliptical element by assuming that the current would be shunted through fat, bone, and muscle tissues, according to the ratios of the electrical conductivity of each tissue to the average electrical conductivity of the entire elliptical element.

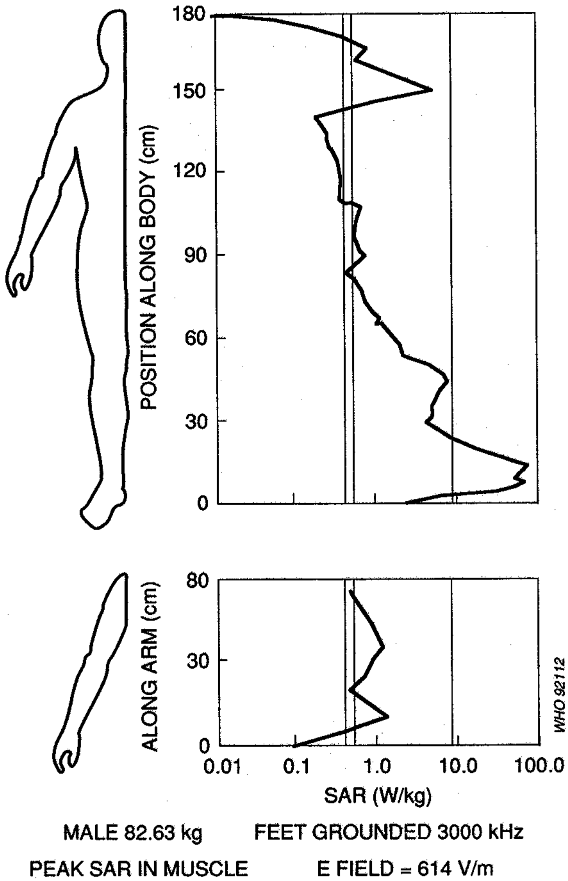

Fig. 4. The calculated peak specific absorption rate (SAR) distribution in human subjects exposed to an electric field with feet grounded. From: Guy (1987).

The peak SAR occurring in the muscle and blood vessels of the ankle, when the feet are grounded, reaches a value of 100 W/kg. Gandhi (1985) was the first to draw attention to this problem.

Although these SAR values are quite high, they occur in a relatively small volume and the thermal consequences are difficult to predict.

In studies on the distribution of the electric field or the absorbed power in different parts of the human body, it has been demonstrated that, for fields of frequencies below 10 MHz, the internal field strength increases in direct proportion to the frequency for a given external electric field strength. Therefore, a simple relationship exists between the internal and the external electric field strengths, depending on the body part or organ considered, on the electrical conductivity, and on the exposure conditions.

A detailed evaluation of current density thresholds as a function of frequency for various interactions, and an estimation of maximum current densities in models of humans exposed to electric and magnetic fields of frequencies of less than 100 kHz, have been reported (Bernhardt, 1985). Envelope curves of current densities that are required for cell stimulation, and those associated with endogenous currents in brain tissue have been established for fields of frequencies up to 100 kHz.

The current densities induced within the body by an external electric field E and frequency f were calculated using the formula $J=KfE$. The constant K depends on the part of the body considered (Bernhardt, 1985). The longitudinal axis of the body parallel to the external E field represents optimum coupling geometry and must be considered as the "worst case".

The K values can be determined by two different methods. Data from studies by different authors on absorption within the quasi-static range can be used, or K can be determined by calculating the current densities on the basis of the field strength measured on the body-surface at 50/60 Hz. The K values, determined by entirely different methods, coincide satisfactorily. The same value $K=3.10^{-9}$ S/(Hz m) was obtained for the cardiac region and head, however for other parts of the body the values of K may be larger (Kaune & Phillips, 1980; Guy et al., 1982; Kaune & Forsythe, 1985). The surface E field and current density data derived from human measurements (Deno, 1977) and animal data (Kaune & Phillips, 1980) demonstrate that the external unperturbed fields, which are almost always used to specify exposure, must be scaled to equalize internal current densities or surface E fields. This must be done in order to extrapolate biological data from one species to another. This process is complicated by the fact that the actual value of the scaling factor depends on the internal quantity that is being scaled.

Currents in electrically-grounded people exposed to fields at frequencies below 50 MHz have been measured (Guy & Chou, 1982; Gandhi et al., 1985b, 1986). The resulting SARs in a small volume within the ankle were estimated to be in the range of 200-540 W/kg for E fields of 61.4 V/m in the range of frequencies 40-62.5 MHz. However, lower values were found in a quantitative analysis by Dimbylow (1987, 1988).

The SAR in the wrist for contact with isolated metallic objects in an RF field has been calculated as a function of contact current for various frequencies used in broadcasting (Tell, 1990). The maximum contact currents to maintain the SARs below 8 W/kg and 20 W/kg are given in Table 5. The values in Table 5 are based on an assumed effective wrist cross section of 11.1 cm^2.

Table 5. Maximum contact currents to keep SARs in the wrist below 8 and 20 W/kg[a]

Broadcast band	Limiting current to control SAR (mA)	
	<8 W/kg	<20 W/kg
AM (0.55-1.6 MHz)	75.1	119
Low VHF (54-88 MHz)	84.1	133
FM (88-108 MHz)	87.3	138
High VHF (176-216 MHz)	93.6	148
Channel 14 (470-476 MHz)	99.7	158
Channel 20 (506-512 MHz)	100	159
Channel 66 (782-788 MHz)	124	197

[a] From: Tell (1990).

5.3 High-frequency range

The interaction of RF fields with matter can be described in terms of its electrical properties, which are the macroscopic reflection of interactions at the molecular or cellular level. The basic interaction mechanisms, which are discussed in section 6, involve relaxation phenomena due to the rotation of polar molecules, such as water, amino acids, protein, lipids, interfacial space-charge polarization due to non homogeneous structures (e.g., cell membranes), and ionic conduction.

The internal fields can be quantified in various ways. The magnetic permeability of tissue is practically equal to that of free space, and all known and anticipated interactions occur through mechanisms involving the electric field (including the current induced by the magnetic field). Therefore, the electric field vector, or its distribution throughout the exposed body, fully describes the exposure field-tissue interactions. Some additional information may be needed for full quantification, e.g., the frequency characteristics of the exposure field, such as modulation characteristics and modulation frequency.

A direct calculation of the expected temperature rise (ΔT in kelvin) in tissue exposed to RF fields for a time (t seconds) can be made from the equation:

$$\Delta T = (SAR)\, t \;/\; C \qquad \text{(Equation 5.6)}$$

where C is the specific heat capacity expressed in J/kg K. This equation, however, does not include terms to account for heat losses via processes such as thermal conduction and convection. Although it expresses the rate at which the electromagnetic energy is converted into heat through well established interaction mechanisms, it provides a valid quantitative measure of all the interaction mechanisms that are dependent on the intensity of the internal electric field in a non-linear manner. Some additional information may be relevant. For instance, since some effects of RF fields modulated in amplitude at ELF (extremely low frequencies) are dependent on the electric field intensity (Adey, 1981), they could probably be expressed in terms of the SAR, modulation characteristics, and the "zones" or windows of amplitudes of the SAR that are biologically effective.

The SAR concept has proved to be a simple and useful tool in quantifying the interactions of RF fields with living systems. It enables comparison of experimentally observed biological effects for various species under various exposure conditions and it provides the only means, however imperfect, of extrapolating animal data to potential hazards for humans exposed to RF. It also facilitates planning and effective execution of therapeutic hyperthermic treatment.

Dosimetry in bioelectromagnetic research has been developing in two parallel but interacting complementary ways, the theoretical and the experimental. RF dosimetry calculations can be performed by solving Maxwell's equations for a given configuration approximating the exposed object (an animal, a human being, a part of a human body) and for given exposure conditions (e.g., a plane wave at a given frequency, incident from a given direction). These data have been collected and discussed in the *Radiofrequency radiation dosimetry handbook* (Durney et al., 1986). However, even analyses of greatly simplified models provide valuable information for quantifying interactions of electromagnetic fields with biological systems. The results obtained from simple models often provide valuable insight and qualitative understanding that can facilitate the analysis of more complex models.

Fig. 5 illustrates the average SAR as a function of frequency for an average man exposed to a plane wave for three polarizations (Durney et al., 1978; Durney, 1980). Various models used in the calculations are also indicated.

From these data, the following conclusions can be drawn:

- the average SAR is a function of frequency;
- the average SAR depends on the wave polarization, and is greatest for the E polarization (electric field is parallel to the long axis of the body), except at higher frequencies, where it is slightly greater for the H polarization (magnetic field (H) is parallel to the long axis of the body);
- the average SARs for the E or K polarizations (when electric field (E) or wave propagation direction (K), respectively, are parallel to the long axis of the body) exhibit a maximum at certain frequencies, called the resonant frequencies.

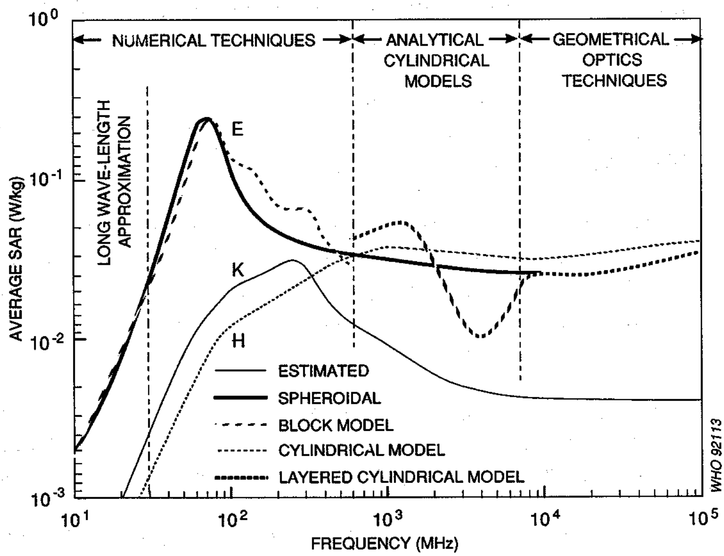

Fig. 5. Various techniques used to calculate the average SAR for models of the average man, irradiated by an EM plane wave of 10 W/m^2 power density. E, K, and H designate polarizations in which the incident electric field vector, propagation vector, and magnetic field vector, respectively, are parallel to the long axis of the body. From: Durney (1980).

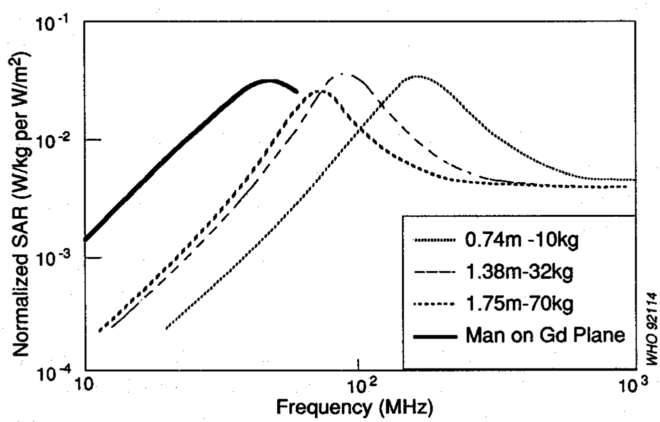

Fig. 6. Specific absorption rate for humans, according to size.

The frequency-dependent behaviour is illustrated in Fig. 6 for several human sizes. The average whole-body SAR in W/kg is plotted as a function of electromagnetic field frequency (MHz) for an incident average power density of 1 W/m^2.

Based on the absorption characteristics in the human body, the radiofrequency range can be subdivided into four regions (IRPA, 1988a), as shown in Fig. 7:

(*a*) The sub-resonance range, less than 30 MHz, where surface absorption dominates for the human trunk, but not for the neck and legs, and where energy absorption increases rapidly with frequency (in the neck and the legs significantly larger absorptions may occur).

(*b*) The resonance range, extending from 30 MHz to about 300 MHz for the whole body, and to even higher frequencies if partial body resonances, more particularly in the head, are considered.

(*c*) The "hot-spot" range, extending from about 400 MHz up to about 3 GHz, where significant localized energy absorption can be expected at incident power densities of about 100 W/m^2; energy absorption decreases when frequency increases and the sizes of hot spots range from several cm at 915 MHz to about 1 cm at 3 GHz.

(*d*) The surface absorption range, greater than about 3 GHz, where the temperature elevation is localized and restricted to the surface of the body.

The average SAR varies with species, as illustrated in Fig. 8. These data are of importance in extrapolation of the results from experimental animal studies to human exposures. The average SAR varies within one order of magnitude in the subresonance range, depending on the separation of an average person from the electric ground plane (with the highest SAR for a person on a ground plane).

Whole-body-average SARs have been measured for humans (Hill, 1984a,b,c; Hill & Walsh, 1985), and the spatial distribution of the SARs in full-scale, realistic models of the human body (Kraszewski et al., 1984; Stuchly M. et al., 1985, 1986; Stuchly S. et al., 1985). The whole-body average SAR was measured for human volunteers

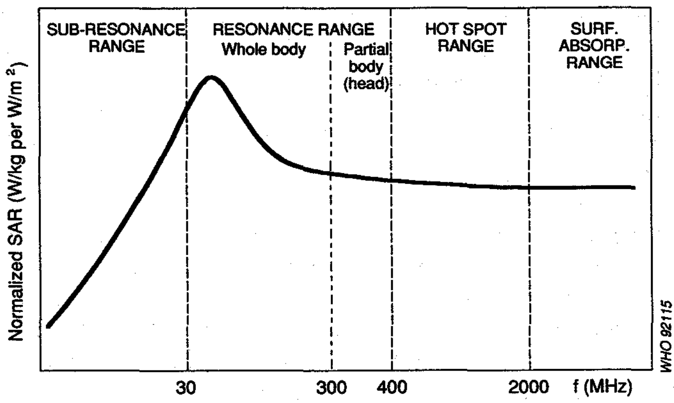

Fig. 7. Variation of normalized SAR with frequency and related absorption characteristics in living organisms.

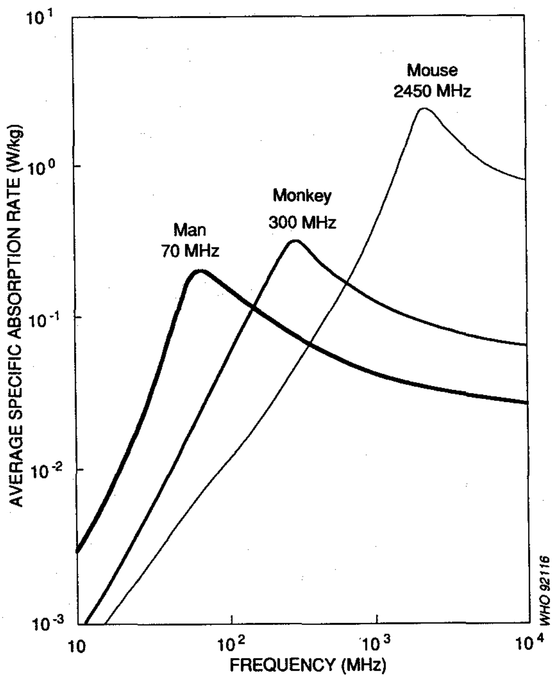

Fig. 8. Average SAR for 3 species exposed to 10 W/m^2 with the E vector parallel to the long axis of the body. From: Durney et al. (1978).

exposed to RF at a few frequencies between 3 and 41 MHz, which are below and close to the resonant frequencies of adult humans. The exposure conditions simulated free-space and grounded conditions in the orientation that results in the greatest SARs (Hill, 1984a, b, c). At all frequencies, the measured SARs exceeded the calculated values by a factor of 2.7-3.9 in free space, and 4.3-4.4 for the grounded condition.

Similar differences between the calculated and measured SAR for simple models were found on scaled-down models at 5-10 MHz (Guy, 1987). Spatial distributions of the SAR in models of the human body have been investigated experimentally (Guy et al., 1984; Kraszewski et al., 1984; Stuchly M. et al., 1986; Stuchly S. et al., 1987). Large differences, typically by a factor of 10-30, between the measured SAR values and those previously calculated using a block model, have been observed (Stuchly M. et al., 1986) at frequencies above resonance. However, despite the differences in spatial distributions, the ratios of peak to whole-body average SARs predicted theoretically and measured, were relatively small, except for the SAR at the body surface. With reference to developing human exposure limits, these results underscore the limitations of the theoretical methods of prediction available at present.

The measurements on a full-scale model (Olsen, 1982; Stuchly S. et al., 1986), on a scaled-down model of man (Guy et al., 1984), and on a full-scale model of a monkey (Olsen & Griner, 1982) all indicated that, for free space and the most absorbing orientation (E-polarization), measured values are close to those predicted from calculations at, and above, the resonant frequency (up to about 450 MHz).

Changes to the average SAR for important practical exposure conditions (e.g., separation between the subject's feet and the ground plane, the body position, articulations of the limbs, and two-body interactions) have been investigated using human volunteers (Hill, 1984b, 1984c). Footwear reduces the average SAR with the degree of reduction depending on the type of footwear and the frequency of the exposure field.

Similar effects have been observed in body currents measured in people exposed to HF and VHF antennas (Allen et al., 1988).

Similar effects have been observed in body currents measured in people exposed to HF and VHF antennas (Allen et al., 1988).

High local SARs also occur at frequencies around and below the resonant frequency at locations such as the ankles (Gandhi et al., 1985b, 1986) and the wrist (Guy & Chou, 1982). At frequencies above a few GHz (millimetre waves), high local SARs are produced at the body surface (Gandhi & Riazi, 1986). Exposures corresponding to 10 W/m^2 may result in perception of heating.

Data have also been collected on the SAR distribution for near-field exposures (Stuchly M. et al., 1985, 1986, 1987; Stuchly S. et al., 1985, 1986). One of the most important findings is that the SAR distributions are highly non-uniform, with typical ratios between spatial peak and whole-body average SARs of the order of 150:1 to 200:1 (Stuchly S. et al., 1985). At all frequencies investigated, the maximum SAR is at the body surface, with lower magnitude "hot spots" located inside the body. Practically all the energy, however, is deposited within about 20% of the body volume closest to the antenna. Knowledge of these SARs can be used in specifying, for instance, the maximum output power of portable transmitters that would be allowed under a selected limit of the SAR.

5.4 Derivation of exposure limits from basic quantities

For the assessment of the possible health effects of electromagnetic fields, it is useful to differentiate between basic limits and derived limits.

Basic limits may be directly correlated with biological effects. Using experimental data or related studies, a threshold exposure level can be determined, above which adverse health effects are increasingly likely, but below which no adverse effect occurs. The basic exposure limit is based on this threshold level.

Since basic limits in terms of SAR or induced current density cannot be measured easily in practical exposure situations, exposure limits in conveniently measured quantities are derived from the basic limit. These derived limits then indicate the acceptable limits in terms of measured and/or calculated field parameters.

Three categories of basic limits have been identified and quantitatively established.

1. The specific absorption rate (SAR) averaged over the whole body or over parts of the body:
   Whole body SAR is a widely accepted measure for relating adverse effects to RF exposure, especially for frequencies above about 10 MHz. Local SAR values are necessary to evaluate and limit excessive energy deposition in small parts of the body and to avoid hot spots resulting from special exposure conditions. Examples of such conditions are: a grounded individual exposed to RF in the low MHz-range; individuals exposed in the near-field of an antenna or individuals exposed at the higher end of the frequency range, where the penetration depth of the RF is low.

2. The induced electric field strength or current density:
   RF fields can induce sufficiently high current densities to stimulate excitable tissue (nerve or muscle) or to produce other potentially harmful effects, especially at frequencies below 100 kHz. The thresholds for biological effects are expressed in terms of current density and are strongly frequency dependent.

3. Contact current between a person and a charged object:
   A conductive object in an electric field can be energized by the field. For field frequencies below 100 kHz, contact between the object and a person may result in stimulation of electrically excitable tissue with pain and more severe effects (burns), if the current density is sufficiently high. For frequencies between about 100 kHz and 100 MHz, the hazard of burns from contact current will predominate.

Derived limits are necessary to provide a practical method to evaluate a given RF exposure. Derived limits obtained from one of these basic limits above include, e.g., electric and magnetic field strength, power density, contact voltage of the conductive objects, and short-circuit currents. The derived limits have to be calculated in such a way that, even under worst-case conditions of field exposure, the basic limits will not be exceeded. In many special exposure conditions, e.g., in the near-field, very close (less than 0.5 wavelength) to an antenna, the assessment of possible health effects may require separate measurements or calculations to investigate whether the basic limit is exceeded.

6. INTERACTION MECHANISMS

6.1 General

Electromagnetic fields in the frequency range 300 Hz-300 GHz interact with biological systems (humans and other animals) through direct and indirect mechanisms. A direct interaction produces effects in the exposed organisms directly from exposure to the electromagnetic field. An indirect interaction is mediated through the presence of other bodies in the electromagnetic field, and occurs as a result of an interaction (usually physical contact) between the biological body and another object, such as an automobile, fence, or even another biological body.

Direct interactions that are well understood can be quantified in terms of dosimetry, and can be considered as resulting from induced currents and internal electric fields. The macroscopic spatial distribution of these currents and fields within an exposed biological body is of importance and is determined by theoretical and experimental dosimetry. The spatial distributions of the currents and fields within, and around, the cell are also important. As outlined earlier, the patterns of induced currents and fields within biological systems usually are highly non-uniform and depend on the geometry and electrical properties of the exposed system, as well as on the field frequency, and, for lower frequencies, the type of field, whether electric or magnetic (where spatial separation of the electric and the magnetic field is realistic). The extent to which the electric or magnetic field plays a role is uncertain. However, apart from differences due to different current distributions, the frequency of the field clearly establishes the type of mechanism for the mechanisms that are well understood.

For frequencies below about 100 kHz, an established interaction mechanism is the stimulation of excitable tissues by induced currents. For higher frequencies, thermal interactions predominate. At the lower frequencies, much less of the electromagnetic field is absorbed by biological systems. Thermal interactions occur at energy levels much higher than interactions due to induced currents. Therefore, thermal interactions are usually of little interest for fields at levels at which people are exposed. Additionally, at frequencies below approximately 1 kHz and at higher frequencies amplitude modulated at extremely low frequencies (1-300 Hz), there is experimental evidence that interactions occur through mechanisms other than thermal or cell excitation. These mechanisms are not understood.

In the context of direct and indirect interaction mechanisms, the electrical properties of tissues have to be considered. Macroscopic electrical properties of tissues play a major role in defining induced currents and fields and their patterns inside the body. Microscopic electrical properties provide an insight into events at the molecular and cellular level that result from exposure of the biological body to an electromagnetic field.

A brief review of tissue electrical properties is presented in this section, together with a discussion of direct and indirect interaction mechanisms.

6.2 Electrical properties of cells and tissues

6.2.1 Permittivity

The interactions of an electric field with matter are described in terms of the complex permittivity, ϵ^*:

$$\epsilon^* = \epsilon' - j\epsilon'' \qquad \text{(Equation 6.1)}$$

where ϵ' is the dielectric constant, ϵ'' is the loss factor, and $j = \sqrt{-1}$.

Equation 6.1 is a representation in the complex plane of a physical property, in this case the permittivity. Such representation indicates two distinct properties. The dielectric constant, ϵ', is a measure of the ability to store electric field energy. The loss factor, ϵ'', describes a fraction of energy dissipated in the material per cycle.

The permittivity represents a combined macroscopic effect of various molecular phenomena causing electrical polarization. It includes contributions from relaxation phenomena due to molecules, cells, and ion layers surrounding molecules. For convenience, it also includes the contribution from ionic conductivity (movement of ions). The contribution of each of the phenomena varies with frequency.

Frequently, the relative permittivity is used, i.e., the permittivity normalized to that of free space (vacuum):

$$\epsilon^*_r = \epsilon'_r - j\epsilon''_r = \epsilon^*/\epsilon_o = \epsilon'/\epsilon_o - j\epsilon''/\epsilon_o \qquad \text{(Equation 6.2)}$$

where ϵ_o is the permittivity of free space, 8.85×10^{-12} F/m.

The loss factor, ϵ''_r, is related to the electrical conductivity of the material, σ, in the following way:

$$\epsilon''_r = \sigma/\omega\epsilon_o \qquad \text{(Equation 6.3)}$$

where $\omega = 2\pi f$, f is the frequency. The unit of electrical conductivity is siemens per metre (S/m). The electrical conductivity consists of two terms, the static electrical conductivity due to ionic conduction, and the electrical conductivity due to various polarizabilities.

Electrical properties of tissues change over a few orders of magnitude with frequency in the range as shown in Fig. 9 (note the logarithmic scale).

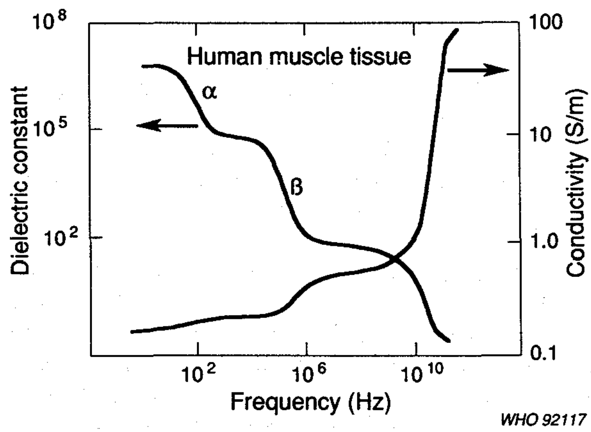

Fig. 9. The dielectric constant and conductivity of typical biological tissue as functions of frequency. From: Schwan (1985).

Biological tissues exhibit three strong relaxation phenomena (the α-, β-, and γ-dispersion) and one weak (the δ-dispersion) (Foster & Schwan, 1986, 1989). The molecular phenomena responsible for the α-dispersion are the least understood.

Relaxation of counter-ions about the charged cellular structure, intracellular structures, e.g., the tubular apparatus in muscle cells, relaxational behaviour of membranes themselves, may all contribute to this dispersion to various degrees. The β-dispersion is mostly due to membranes, which separate regions having different dielectric constants and electrical conductivities, resulting in an interfacial polarization causing the Maxwell-Wagner type relaxation. Smaller contributions result from the relaxation of proteins. The γ-dispersion is due to free water relaxation and the δ-dispersion results from relaxation of bound water, amino acid, and charged side groups of proteins.

The α-dispersion occurs at frequencies that are usually below 10 kHz, the β-dispersion at about 20 kHz-100 MHz, the δ-dispersion at 100-1000 MHz, and the γ-dispersion at 25 GHz (at 37 °C).

All the dispersions in most tissues occur over a broad range of frequency, because of the highly non-uniform structure of tissues, and usually with more than one specific interaction mechanism contributing to the dispersion (Foster & Schwan, 1986, 1989; Stuchly & Stuchly, 1990).

The permittivity of cells and tissues has been extensively studied and comprehensive reviews can be found (Foster & Schwan, 1986, 1989; Stuchly & Stuchly, 1990). A detailed description on the molecular/cellular level of all the relaxation phenomena is provided in a review by Foster & Schwan (1989).

Resonant dielectric absorption was reported in DNA solutions at 1-10 GHz (Edwards et al., 1984, 1985). Various theoretical hypotheses were proposed to explain the resonances (Scott, 1985; Van Zandt, 1986). However, more careful measurements were performed by three other research teams (Foster et al., 1987; Gabriel et al., 1987; Maleev et al., 1987) and a part of the original team that found the resonance (Rhee et al., 1988). None of the groups found resonant behaviour of DNA in aqueous solutions. A lack of resonant behaviour is in agreement with the earlier experimental data on the dielectric properties of DNA (Takashima et al., 1984).

6.2.2 *Non-linear effects*

The bulk dielectric properties of tissues reflect the passive properties of cells, e.g., the capacitance of cell membranes (Foster & Schwan, 1989). The physiological response of the membrane to the changes in the membrane potential, due to the applied field, results in nonlinearity. These phenomena include changes in the membrane conductance associated with gating and action potentials. An induced potential across the membrane of the order of 10 mV or more is required to produce firing of a resting nerve cell, which for a membrane thickness of, for example, 50 nm corresponds to an electric field strength of 200 kV/m. However, substantially lower electric field strengths can induce changes in the firing pattern of pacemaker cells (Sheppard et al., 1980; Wachtel, 1985). At high field strengths (voltages across the membrane), pores are formed in the membrane, and, eventually, at a few hundred mV across the membrane, breakdown occurs (Foster & Schwan, 1989).

Muscle cells exhibit an anisotropic excitation, which is consistent with the following phenomenon. The maximum voltage across the membrane for spherical cells is related to the electric field strength by the following relationship (Foster & Schwan, 1989):

$$V_m = 1.5\ rE \qquad \text{(Equation 6.4)}$$

where r is the cell radius, and E is the electric field strength in extracellular fluid (Fig. 10). For ellipsoidal cells, similar equations have been derived by Bernhardt & Pauly (1973). Their results show that electric fields axial to a cell induce a voltage across the membrane that is proportional to the length of the cell and to the extracellular electric field strength. Thus, asymmetrical muscle cells exhibit dimension-dependent induced voltages, when exposed to electric fields.

Gradients in the induced surface charge can also affect molecules and cells in solution. Polar molecules (e.g., water, proteins) align themselves with the field at high electric field strengths of the order of 10^6 V/m. Also, non-spherical cells align themselves with the field and form "pearl chains". The larger the cell, the lower the field strength required for orientation and formation of pearl chains. For instance, for a cell of radius 1 μm, an electric field of 10 kV/m is required (Foster & Schwan, 1989).

Counter-ion polarization is likely to produce a nonlinear dielectric response at moderate field strengths of the order of a few hundred V/m in tissue for large cells, but the response is slow to develop, and the relaxation frequency is a fraction of a hertz. There have been relatively few studies on the nonlinear responses of the counter-ion relaxation (Foster & Schwan, 1989).

6.2.3 Induced fields at the cellular level

Knowledge of the electric fields acting on specific parts of the cell due to a certain electric field in tissue is important in predicting cell stimulation. It is also important to evaluate the possibility of interaction with the genetic apparatus, when fields of sufficient strength are acting at the cell nucleus. A general analysis of these fields was performed by Schwan (1984) and Foster & Schwan (1989). The results of the analysis are illustrated in Fig. 11 showing the plasma-membrane potential, the cytoplasm field strength, and the nuclear membrane potential, as a function of frequency.

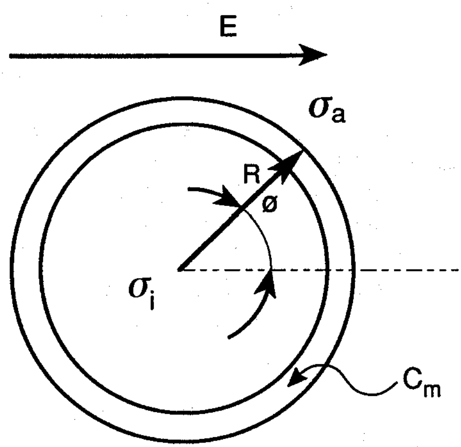

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Fig. 10. A spherical cell in an electric field.

Data shown in Fig. 11 can be summarized as follows: below the β-dispersion for the cells, the plasma membrane shields the interior of the cells; above the β-frequencies for the plasma membrane and the nucleus, the induced voltage drop across both membranes falls off as the inverse of the frequency. The greatest potential is induced on the nuclear membrane at frequencies between the β-dispersion frequencies for the plasma and the nuclear membranes, and this potential is approximately equal to the product of the external electric field and the nuclear radius (Foster & Schwan, 1989). Table 6 gives a summary of induced fields in various parts of the cell and Fig. 11 gives the induced membrane potentials and electric fields in various compartments (Schwan, 1985).

Table 6. Summary of the coupling properties of external fields to cellular membranes and compartments. f_r is the beta-dispersion frequency of the plasma cell membrane, where f_n is the beta dispersion frequency of the nucleus and other organelles. Approximate values of relaxation frequencies are given in brackets. [a]

	$f<f_r$ (approx 1 MHz)	$f_r<f<f_n$	$f>f_n$ (approx 10 MHz)
Cell:			
Membranes	Polarized	Not polarized	Not polarized
Interior	Doubly shielded	Shielded	Exposed
Organelles:			
Membranes	Not polarized	Partially polarized	Not polarized
Interior (Nucleic acids)	Doubly shielded	Shielded	Exposed
Connecting organelles:			
Membranes	Polarized	Not polarized	Not polarized
Interior	Not exposed	Exposed	Exposed

[a] From: Schwan (1985).

6.2.4 *Body impedance*

To determine the currents that flow when a person in an electromagnetic field comes into contact or close proximity with an isolated conducting object, it is important to consider the impedance

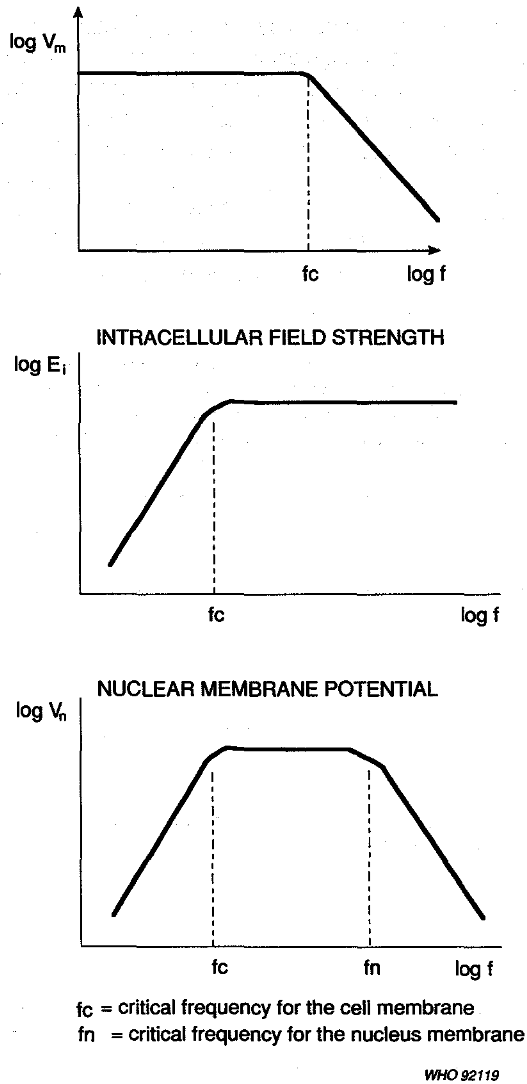

Fig. 11. Induced membrane potentials and electric fields in various cell compartments. From: Schwan (1985).

of the human body. The human body impedance can be considered as a composite of the impedances of various parts through which the current is flowing. For instance, for a finger contact with an automobile and a current flowing to ground, the total impedance is the sum of the following: the contact impedance, the finger impedance, the arm impedance, the body (trunk plus legs) impedance and the capacitance to ground. All these impedances are frequency dependent. Furthermore the contact impedance depends on the surface area and condition (dry or wet) of the contact surface, and at least at low frequencies probably on contact voltage as documented by measurements at 60 Hz (Tenforde & Kaune, 1987).

The complete body impedance can be represented by an equivalent circuit consisting of a number of resistive and capacitive components, some of them frequency dependent. Measurements of body impedance have been performed at 60 Hz (Tenforde & Kaune, 1987) and from 10 kHz to 3 MHz (Gandhi et al., 1985a).

6.3 Direct interactions - strong fields

Well established interaction mechanisms for the direct effects of electric and magnetic fields can be divided into two types, each dependent on the field frequency. For frequencies below approximately 100 kHz, the interactions (stimulation) with excitable tissue are of primary interest. Above about 100 kHz, the current density thresholds for stimulation and other effects due to interactions with excitable tissue are higher than those required to produce energy deposition rates of about 1 W/kg. At such rates of energy deposition in tissue, thermal interactions become important. In both frequency ranges, other forms of interactions are also observed for induced currents and fields below those associated with stimulation or heating.

6.3.1 Interactions with excitable tissues

In tissues, the induced electric fields are amplified across the cell membranes. At sufficiently high field strengths, these affect the electrical excitability of nerve and muscle cells. This inter-action occurs up to hundreds of kilohertz (Lacourse et al., 1985), but increasingly stronger fields are required above the β-dispersion. Changes in the membrane potential cause changes in the permeability to ions, conformational changes in the embedded proteins, a number of ion gates open, and eventually membrane depolarization results in an action potential. Threshold current densities for subtle modulations of excitable cells, and their biological significance, are less well understood. There is a substantial amount of data on tissue stimulation, extra-systole elicitation, and ventricular fibrillation. These data, as summarized by Bernhardt (1985, 1986, 1988), are shown in Fig. 12. The ventricular fibrillation thresholds are above those needed for stimulation. Thresholds for the stimulation of excitable tissue depend not only on the current density and frequency, but also on the waveform. In the case of pulsed fields, they depend on pulse duration and other parameters (Reilly, 1988).

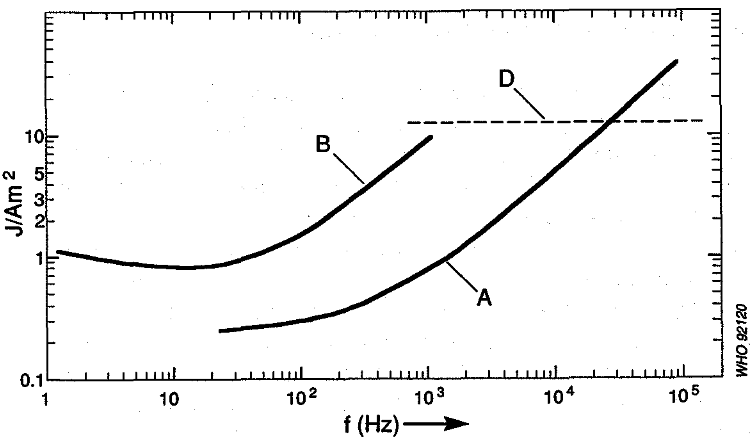

Fig. 12. Threshold current densities for effects on excitable cells. Curve A - envelope of thresholds for stimulation of various cells under various conditions; curve B - threshold for stimulation of extra-systole; and curve D - the current density approximately corresponding to SAR = 1 W/kg, in muscle tissue. Modified from: Bernhardt (1985, 1986).

6.3.2 Thermal interactions

As described in section 5, exposure to an electromagnetic field can result in a spatially nonuniform SAR in the body. The initial rate of temperature increase, when heat losses are neglected, is directly proportional to the SAR:

$$dT/dt = SAR/C \quad \text{(Equation 6.5)}$$

where T is the temperature, t is time, and C is the specific heat capacity of tissue.

At the molecular level, the phenomena involved in a conversion of RF energy into thermal energy are the relaxation processes described earlier. Deposition of RF energy in the body may not necessarily lead to a proportional increase in its temperature, because of thermoregulatory responses. Various mathematical models for human thermoregulation have been applied to evaluate thermal interactions of RF energy (Emery et al., 1976; Spiegel et al., 1980; Way et al., 1981; Spiegel, 1982).

The rapid rate at which heating can occur, and a uniquely non-uniform spatial pattern of energy deposition are important and unique to thermal interactions of electromagnetic energy. The rate of initial heating appears to be very important for pulsed fields. These two features make biological responses due to electromagnetic thermal loading unlike those due to other thermal agents. Thermal interactions are not necessarily accompanied by significant local or whole-body temperature increases.

In some thermal interactions, biological responses depend on the temperature-time profile, where such a profile is achieved by RF heating. In some other biological responses, the rate of temperature change is the critical parameter while the total temperature rise may be very small. Here again, RF energy (pulsed) can be very effective.

One of the most prominent, thermally-induced effects, where the temperature increases are very small, is the microwave hearing effect (Guy et al., 1975a; Lin, 1978). Exposure to one pulse of electromagnetic energy results in the perception of a click, and exposure to repeated pulses in a buzzing or hissing sound. The energy threshold for human beings is very low (16 mJ/kg) and the resulting temperature increase is estimated to be only about 5×10^{-6} °C (Guy et al., 1975a). The simplified mechanism of interaction is as follows: absorption of electromagnetic energy causes a rapid temperature increase, which, in turn, produces thermal expansion pressure initiating an acoustic wave that is detected by cochlea (Guy et al., 1975a; Lin, 1978).

6.4 Direct interactions - weak fields

6.4.1 General

There is a growing body of data from studies indicating that extremely low frequency fields (ELF) (Tenforde & Kaune, 1987; WHO, 1987) and RF amplitude modulated at ELF (Adey, 1981, 1988) interact with various biological systems at energy levels significantly lower than those needed for the stimulation of excitable tissues or for thermal interactions. The mechanisms of these interactions are not understood. Several mechanisms have been hypothesized, but these need further development and testing, and possibly still other considerations need to be taken into account to unravel the rather complex mechanisms behind the observed interactions.

Pericellular currents induced by electromagnetic fields produce electrochemical alterations in components of the cell membrane surface. These changes are hypothesized to cause signals across the cell membrane and produce intracellular alterations (Adey, 1981, 1988; Tenforde & Kaune, 1987).

Weak field interactions are sometimes criticized and dismissed on the grounds that the field intensities induced in the biological systems that produce them are lower than those associated with thermal noise. A recent analysis of noise and electric fields induced on a simple model of cell membranes by Weaver & Astumian (1990) indicates that induced fields of the order of 0.1-0.01 V/m are theoretically detectable above the broad band noise level. Much smaller fields, of the order of 10^{-4} V/m, are estimated to be detectable if only a narrow frequency band response of the membrane or signal averaging are assumed. The assumption of the narrow frequency band response is consistent with some experimental data on biological responses. The signal averaging is also supported by experimental work on enzyme-catalysed reactions.

A description of some hypothetical interaction mechanisms for ELF fields, which possibly also applies to the lower frequencies of concern here (probably below 1000 Hz) and to RF fields modulated at ELF can be found in Tenforde & Kaune (1987) and WHO (1987).

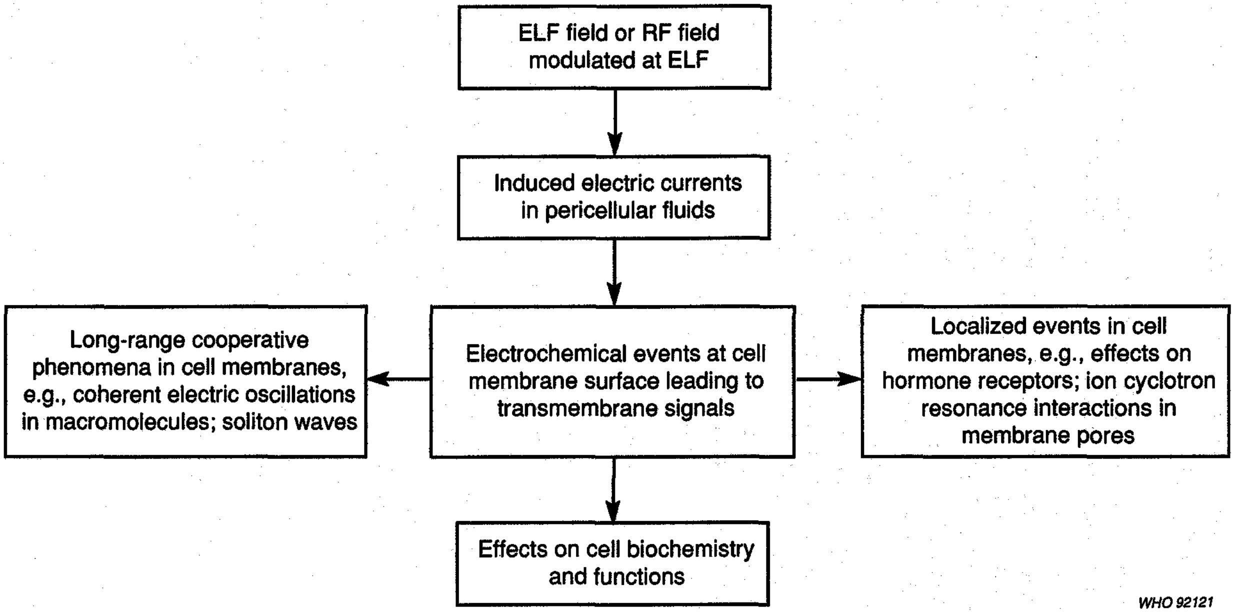

Fig. 13. Hypothetical interaction mechanisms of ELF fields or RF fields modulated at ELF. Modified from: Tenforde & Kaune (1987).

The hypothesized scheme of transductive coupling between induced electric currents in the extracellular medium and the intracellular events occurring in living cells is illustrated schematically in Fig. 13.

An alternative model involving magnetic-field induced changes in specific molecular species associated with the plasma membrane has been proposed by Blackman et al. (1988). In this model, as in others, an amplification step must be involved. Conditions for the cellular response may involve the induction of a weak electric field in the extracellular fluid, a molecular change in the membranes to "trigger" cooperative events within the cell membrane. The basic premise is that the cell membrane exists in a metastable, non-equilibrium state that can be significantly perturbed by weak stimuli. The stored energy is released by this process as metabolic chemical energy through the activation of ion pumps or enzymatic reactions within the membrane (Fröhlich, 1968, 1977; Adey, 1981, 1983). This general model may also be applicable to the results observed at 41 GHz (Grundler & Keilmann 1983, 1989). In this case, yeast growth rates have been affected at SARs as low as 0.2 W/kg.

6.4.2 *Microelectrophoretic motion*

Recent experimental evidence has given some support to the concept that the interactions of ELF fields with living cells occur at specific loci on the cell membrane. A model of membrane interactions in which a microelectrophoretic motion induced in the cell membrane by weak ELF electric fields influences the average distance between charged ligands and the cell-surface receptors to which they are bound was proposed by Chiabrera et al. (1984). In this theoretical model, the effect of the imposed electric field is to decrease the mean lifetime of the ligand-receptor complexes on the membrane surface. The authors proposed that this effect could influence various biological phenomena, such as the activation of lymphocytes by antigens and various lectins, and the gating mechanisms that control the membrane transport of various types of cations, such as calcium.

6.4.3 *Ion-resonance conditions*

Some experimental evidence suggests that effects occur at specific frequencies for ELF fields and static magnetic fields with strengths comparable to that of the geomagnetic field. Theoretically frequencies up to 1 kHz or higher, depending on the ion involved, can be effective under these conditions. It is proposed that the frequency of interaction is related to the ion characteristics and the static magnetic flux density according to the following relationship:

$$f = kBq/m \qquad \text{(Equation 6.6)}$$

where: f is the resonant frequency, k is a constant (integer), q is the ion charge, m is the ion mass, and B is the constant magnetic flux density. Some of the earlier models, such as the cyclotron resonance (Liboff, 1985; McLeod & Liboff, 1986), suffered from serious limitations (Halle 1988). Other models appear worthy of closer scrutiny (Lednev, 1990; Male & Edwards, 1990).

Overall, the experimental data for q/m effects on ion binding to the membrane or enzyme surfaces and on cation transport through cell membrane pores are intriguing, but there is a clear need for refinements in the theoretical description of this phenomenon and to substantiate the experimental results. Whether, and how, any of the resonance models (Chiabrera et al., 1984; Liboff, 1985; McLeod & Liboff, 1986; Lednev, 1990; Male & Edmonds, 1990) can be applied to RF fields amplitude modulated at ELF has not yet been considered or tested.

6.4.4 Calcium ion exchange

An observed change in the EEG pattern of cats exposed to 147 MHz fields amplitude modulated at ELF, prompted further investigation with an isolated chick-brain tissue preparation, to determine whether the presence of the peripheral nervous system was required to elicit a change in the central nervous system. Statistically significant increases in labelled calcium ion efflux were observed in isolated tissues exposed to 10-20 W/m^2, 147 MHz fields amplitude-modulated at frequencies from 6-20 Hz, but levels remained the same as control levels at modulation frequencies of less than 6 Hz or greater than 20 Hz. No effect on calcium ion efflux was observed from exposure to unmodulated RF fields (Bawin et al., 1975). The SAR was less than 0.004 W/kg. This field-induced effect is of interest because it occurs at SARs too low to implicate heating, and because calcium ions play a prominent role in the transductive coupling of many cell membrane-mediated responses. Thus, this *in* *vitro* result provides a means of interrogating the function and processes occurring at the cell membrane and of identifying possible subtle mechanisms of interaction of RF fields.

Using 50, 147, and 450 MHz carrier waves, this work has been replicated and extended with one or more modulation frequency or power density windows being reported (Blackman et al., 1979, 1980a,b, 1985, 1989; Sheppard et al., 1979). A power density window centred on 8.3 W/m^2 (0.0014 W/kg) has been reported. Six power density windows were observed for 16 Hz modulated 50 MHz, with five of the windows separated by a geometric relationship that may reveal a characteristic of the underlying mechanism (Blackman 1980a,b, 1985, 1989).

Lee et al. (1987) reported enhanced release of calcium ions from chick-brain tissue exposed in two power density regions of 147 MHz fields, modulated at 16 Hz, only when specific temperature conditions were instituted in the preparation of the tissue. The temperature conditions during sample preparation were also shown to affect the relative direction of the efflux and to control the sensitivity of the brain tissue samples to ELF signals (Blackman et al., 1991). The release of calcium ions from a rat synaptosomal preparation was also reported to be affected by 450 MHz, amplitude modulated at 16 Hz, at 10 W/m^2 (Lin-Liu & Adey, 1982).

Exposures at 315 Hz and at 405 Hz, at intensities of 15 V/m and 60 nT, were reported to enhance calcium efflux, whereas intensities between, above, and immediately below these values did not (Blackman et al., 1988). The 315 Hz exposure was dependent on the perpendicular flux density and orientation of the DC magnetic field of the earth (Blackman et al., 1990). Additional work at lower frequencies suggests that the DC magnetic field may have a direct influence on which frequencies are effective (Blackman et al., 1985).

Some investigators have reported null results with brain tissue preparations. Shelton & Merritt (1981) did not observe any changes in the release of calcium ions from an *in vitro* rat brain tissue preparation exposed to 1 GHz, pulse modulated at 16 or 32 Hz, at 5, 10, 20, or 150 W/m^2. Similarly, no effects were observed with rat tissue labelled *in vivo* and exposed *in vitro* or *in vivo* to 1 GHz or 2.06 GHz, pulse modulated at several ELF and power density combinations (Merritt et al., 1982). Null effects were also reported by Albert et al. (1987) using chick brain tissue exposed to a few power densities of 147 MHz, amplitude modulated at 16 Hz, under anoxic and under modified media conditions designed to supply more oxygen to the tissue.

In none of these null-effect experiments did the authors reproduce the exposure conditions used by Bawin or Blackman, particularly the medium composition, power density, sinusoidal modulation, or number of samples per experiment.

Increases in calcium ion efflux have been reported in two other biological preparations. Isolated frog hearts showed enhanced calcium ion efflux at SARs of 0.00015 and 0.0003 W/kg when exposed to 240 MHz, amplitude modulated at 16 Hz (Schwartz et al., 1990). Human neuroblastoma cells exposed in culture to amplitude modulated 147 and 915 MHz at SARs of 0.005 and 0.05 W/kg displayed maximal calcium ion efflux at modulation frequencies around 16 and 60 Hz (Dutta et al., 1984, 1989). The latter experiment was conducted under natural, cell-culture growth conditions and suggests that anoxia is not an absolute requirement for sensitivity of nervous system derived cells to RF fields modulated at ELF frequencies.

Overall, the exposure-induced release of calcium ions from tissues should be viewed as contributing to the characterization of exposure conditions required to elicit a response, and, thus, to the development of an underlying mechanism of action. The efflux assay system may ultimately be useful in defining the various aspects of the physical and biological exposure conditions that sensitize and affect membrane responses to electromagnetic field exposure. It should be emphasized that insufficient information is available to define the weak field interactions. Furthermore, the reported effects cannot be characterized as a potential adverse effect on health, since little or no confirmed information has been gathered that suggests this effect occurs in animals or humans.

6.5 Indirect interactions

Electromagnetic fields, at frequencies below about 100 MHz, interact with biological bodies through electrical charges induced on ungrounded or poorly grounded metallic objects, such as cars, trucks, cranes, wires, and fences.

Two types of interaction may occur:

(*a*) a spark discharge before a person touches the object;

(*b*) the passage of current to ground through a person coming into contact with such objects; the magnitude of these currents depends on the total charge on the object. This charge, in turn, depends on the frequency and electric field strength, the object geometry and capacitance, and the person's impedance to ground.

Above a certain threshold, the current to ground is perceived by the person as a tingling or prickling sensation in the finger or hand touching the charged object, for frequencies below about 100 kHz, and as heat at higher frequencies. A severe shock can be experienced at levels much higher than this threshold. The threshold currents depend on frequency, surface of contact area, and the individual. The thresholds for effects (perception, shock, etc.) are generally higher for men than for women and children, though there are also individual differences.

All effects due to induced charges on objects are defined below in order of increasing severity:

Perception - The person is just able to detect the stimulus. There is a difference in the current perception threshold for touch and grip contact.

Annoyance - The person would consider the sensation to be a mild irritant, if it were to occur repeatedly.

Startle - If a person receives one exposure, it is sufficient to motivate the person to avoid situations that would lead to a similar experience.

The remaining reactions apply only to contact of alternating currents at frequencies below 100 kHz.

Let-go - A person cannot let go of a gripped conductor as long as the stimulus persists, because of uncontrollable muscle contraction. If a person is exposed to prolonged currents, somewhat above the let-go level, through the chest, breathing becomes difficult and, eventually, the person may become exhausted and die.

Respiratory tetanus - A person is unable to breathe as long as the stimulus is applied, owing to the contraction of the muscle responsible for breathing.

Fibrillation - Uncoordinated asynchronous heart contractions produce no blood pumping action.

Threshold currents for their occurrence are given in Table 7. Fig. 14 and 15 show threshold currents for perception and let-go, for different percentages of the population at lower frequencies. Thresholds for perception and pain (well below the let-go) were evaluated for nearly 200 men and 200 women and also estimated for 10-year-old children (Chatterjee et al., 1986). The thresholds are lower for finger contact than for grasping contact. Fig. 16 and 17 show perception and pain for finger contact (Chatterjee et al., 1986). The stimuli in both cases are tingling/pricking at frequencies below about 100 kHz and heat/warmth at higher frequencies.

Currents flowing from an object to ground through a person who touches the object can be reduced if shoes are worn (Chatterjee et al., 1986). Electric charge induced on various objects and, therefore, contact currents for people, can be calculated for a known electric field strength. Results of such calculations are shown in Fig. 18 and 19 for finger contact for males, females, and children, respectively.

RF burns can occur when current enters through a small cross-section of the body, such as a finger, when the finger contacts an electrically charged object. Another interaction that may occur at lower frequencies is a transient discharge, which occurs between a person and a charged object either by direct contact or through an air gap (Tenforde & Kaune, 1987).

Table 7. Threshold currents (mA) for various effects at frequencies ranging from 50 Hz to 3 MHz (experimental data for 50% of men, women, and children)

Effect	Subject	Threshold current (mA) at various frequencies								
		50/60 Hz	300 Hz	1000 Hz	10 kHz	30 kHz	100 kHz	300 kHz	1 MHz	3 MHz
Touch perception (finger contact)	men	0.36	(0.47)	(0.79)	4	15	40	40	40	40
	women	0.24	(0.31)	(0.53)	3.2	12	35	35	35	35
	children	*0.18*	*0.24*	*0.40*	2.5	8	25	25	25	25
Grip perception	men	1.1	1.3	2.2	15	50	300	300	300	300
	women	0.7	*0.9*	*1.5*	10	35	200	200	200	200
	children	*0.55*	*0.65*	*1.1*	9	30	150	150	150	150
Shock, not painful (grasping contact)	men	1.8	(2.3)	(3.2)	17(10)	(25)	(25)			
	women	1.2	*1.5*	*2.1*	11	*16.7*	*16.7*			
	children	*0.9*	*1.1*	*1.6*	*8.5*	*12.5*	*12.5*			
Pain (finger contact)	men	(1.8)	(2.4)	(3.3)	10	30	55	50	50	50
	women	*1.2*	*1.6*	*2.2*	6.5	23	47	45	40	40
	children	*0.9*	*1.2*	*1.6*	6	18	33	30	28	28
Shock, painful; muscle control (let-go threshold for 0.5% of population)	men	9	(11.7)	(16.2)	55	(126)	(126)			
	women	6	*7.8*	*10.8*	*37*	*84*	*84*			
	children	4.5	*5.9*	*8.1*	*27*	*63*	*63*			

Table 7 (*continued*)

Effect	Subject	Threshold current (mA) at various frequencies								
		50/60 Hz	300 Hz	1000 Hz	10 kHz	30 kHz	100 kHz	300 kHz	1 MHz	3 MHz
Burn (finger contact)	men								200	200
Painful shock, let-go threshold	men	16	18	24	75(88)	(224)	(224)			
	women	10.5	*12*	*16*	*50*	*150*	*150*			
	children	*8*	*9*	*12*	*37*	*112*	*112*			
Severe shock, breathing difficulty	men	23	(30)	(41)	94(126)	(320)	(320)			
	women	15	*20*	27	63	*214*	*214*			
	children	*12*	*15*	*20.5*	*47*	*160*	*160*			

[a] From Dalziel 1954a,b; Deno, 1974; Guy & Chou, 1982; Guy, 1985; Chatterjee et al., 1986). Data in brackets were calculated by using the frequency factors for perception thresholds and for pain and let-go thresholds, given in IEC Publication 479. Data in italics were calculated by assuming thresholds for women two-thirds of that of men and thresholds for children one-half of that for men (IEEE, 1978; Guy, 1985).

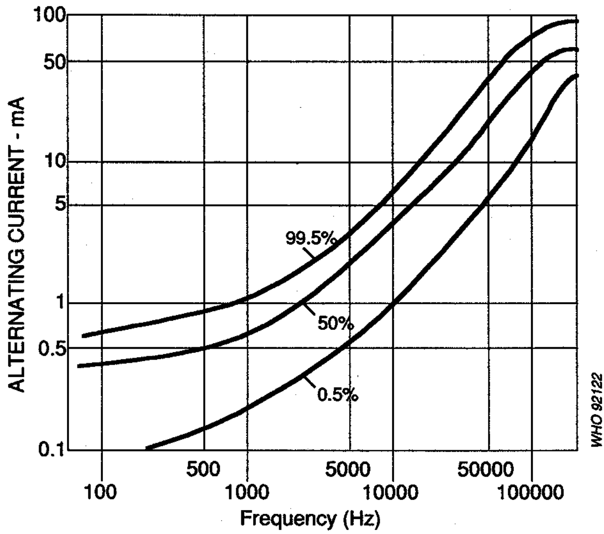

Fig. 14. Threshold currents for perception by various percentages of the population. From: EPRI (1979).

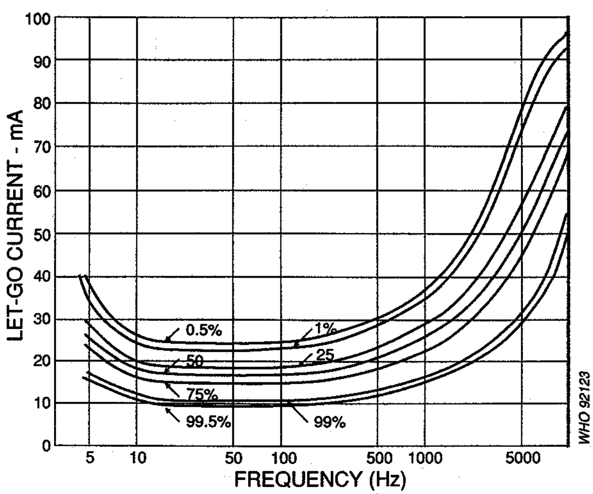

Fig. 15. Let-go currents for different percentages of the population. From: EPRI (1979).

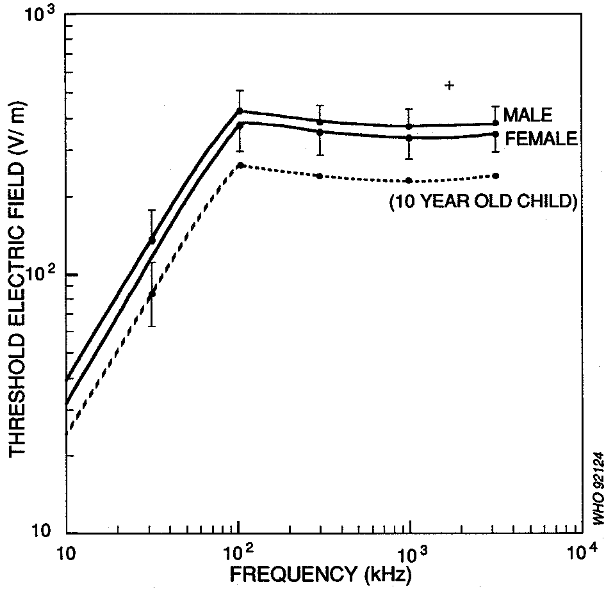

Fig. 16. Average threshold current for perception, finger contact, for adult males, females, and 10-year-old children (estimated). From: Chatterjee et al. (1986).

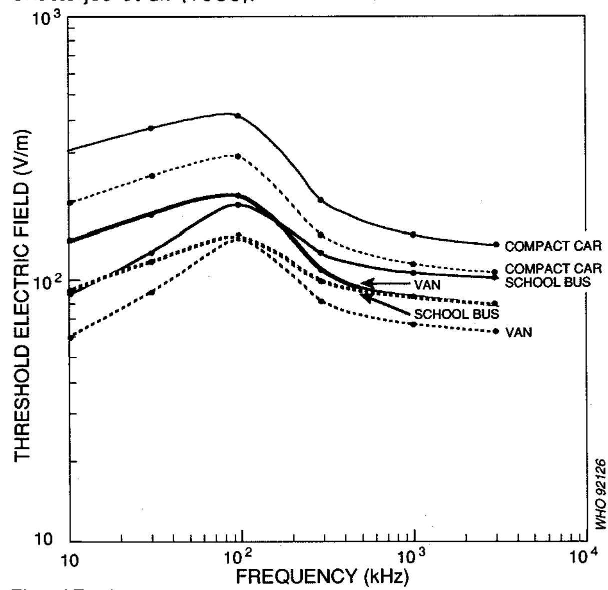

Fig. 17. Average threshold current for pain, finger contact. From: Chatterjee et al. (1986).

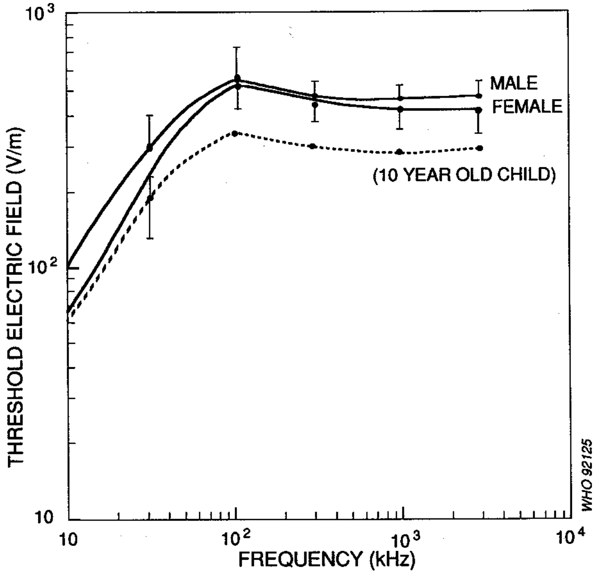

Fig. 18. Average threshold electric field for perception for grounded adult males (solid lines) and 10-year-old children (dashed-line) in finger contact with various vehicles. From: Chatterjee et al. (1986).

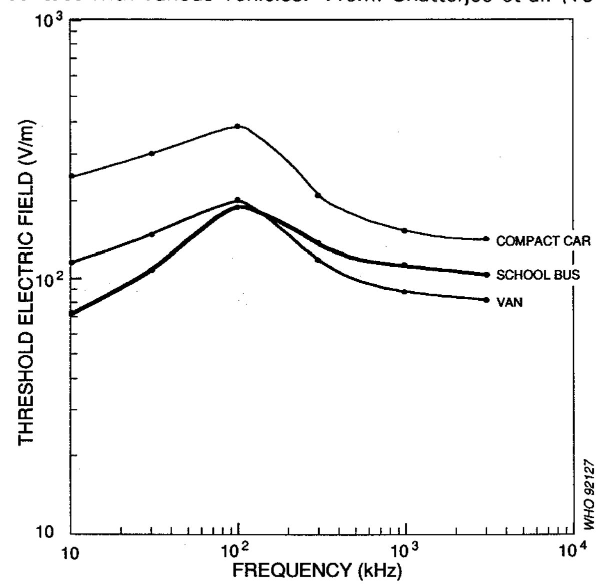

Fig. 19. Average threshold electric field for perception for grounded females in finger contact with various vehicles. From: Chatterjee et al. (1986).

7. CELLULAR AND ANIMAL STUDIES

7.1 Introduction

Numerous reviews and monographs dealing with the biological effects of electromagnetic fields have been published including: WHO (1981); Grandolfo et al. (1983); USEPA (1984); Akoev (1986); NCRP (1986); Polk & Postow (1988); Francescretti et al. (1989); WHO (1989); Adey (1989, 1990); Saunders et al. (1991). The purpose of this section is to provide an overview of the biological effects that are relevant to considerations of the health and safety of exposed people.

The available scientific data are unevenly distributed within the very broad range of frequencies that this publication covers. Considerable numbers of *in vitro* and experimental animal studies have been performed in the mega- and gigahertz range. Relatively few scientific reports of effects in the kilohertz range can be found and data are particularly sparse for the range between 300 Hz and about 10 kHz.

7.2 Macromolecules and cell systems

Studies of isolated (*in vitro*) components of a biological system offer possible insights into the mechanisms of RF action. *In vitro* systems are simple, allowing biological variables to be controlled and subtle effects to be identified without being masked by the homeostatic responses of the whole organism.

In addition, the precise control of the temperature of *in vitro* preparations during exposure should make it possible for thermal and athermal interactions to be clearly distinguished, though thermal gradients cannot be entirely eliminated from such systems. Effects to be tested *in vivo* (whole animal) can be identified from these studies.

From their review of RF effects on macromolecular and cellular systems, NCRP (1986) concluded that RF fields, at least continuous waves at frequencies above 5 MHz, have little, if any, effect on biopolymers, cell organelles, and microorganisms, other than effects associated with elevated temperatures. Likewise, they concluded that the effects of RF fields on the genetic material of cells have not been convincingly demonstrated, unless related to elevations of temperature.

More recently, Cleary (1989) noted that there was strong evidence from a number of *in vitro* experiments for the involvement of non-thermal RF interactions, as well as heating. He concluded that effects that may be attributed to RF-specific interactions include altered potassium and sodium ion transport across red blood cell membranes, changes in membrane calcium ion fluxes, decreased non-cAMP-dependent protein kinase activity, inhibition of T-lymphocyte cytotoxicity, biphasic effects on lymphocyte proliferation, changes in brain cell energy metabolism, altered firing rates and resting potentials of neurons, and effects on cell transformation rate. Many of these responses are discussed below.

7.2.1 Effects on cell membranes

The cell membrane has been suggested as a likely site for the interaction of RF fields (Adey, 1981; Cleary, 1987). Several studies (summarized in Table 8) have focused on effects on membrane permeability and integrity.

Baranski et al (1971) reported increased cation permeability and decreased osmotic resistance in rabbit erythrocytes exposed to 3 GHz for up to 3 h at power densities as low as 10 W/m^2; higher power densities produced effects of greater magnitude. Using thermal controls heated in a waterbath to the same temperature as exposed cells, Hamrick & Zinkl (1975) were unable to replicate these effects. Liu et al. (1979) attributed observed increases in cation permeability of erythrocytes to heating.

More recently however, it has been reported in several studies that exposure to RF fields caused specific increases in the cation permeability of the cell membrane. The results of these studies have been consistent with a sensitivity of the cell membrane at particular temperature-dependent energetic states; in some studies, effects have been reported only at apparent membrane phase transition temperatures (between 8 °C and 36 °C). Membranes loaded with cholesterol to eliminate the phase transition were unaffected by microwaves (Liburdy & Vanek, 1987). RF-induced changes in the activity of the membrane-bound enzyme Na/K ATPase have been suggested as a possible mechanism (Allis & Sinha-Robinson, 1987), but similar permeability changes have been reported in membranes with no associated protein (Liburdy & Magin, 1985).

Table 8. Membrane studies (*in vitro*)

Exposure condition	Effect	Reference
3 GHz (CW) at 10-100 W/m^2, for up to 3 h	Increased K^+ efflux and decreased osmotic resistance in rabbit erythrocytes compared with room temperature controls (increased effect at higher power densities)	Baranski et al. (1974)
2.45 or 3 GHz (CW) at 40-750 W/m^2 (3-57 W/kg), for up to 3 h	No effects on K^+ efflux or osmotic resistance in rabbit erythrocytes compared with thermal controls	Hamrick & Zinkl (1975)
2.45, 3 and 3.95 GHz (CW) at up to 200 W/kg (26 - 44 °C)	Increased K^+ ion and haemoglobin release and osmotic lysis by rabbit, canine, and human erythrocytes; similar effects with conventional heating	Liu et al. (1979)
2.45 GHz, at up to 390 W/kg, for 1 h	Increased passive efflux of Na^{22} and Rb^{86} from rabbit erythrocytes compared with thermal controls, only at the transition temperatures for efflux (8-13 °C, 22.5 °C and 36 °C)	Olcerst et al. (1980)
8.42 GHz, CW or pulse modulated, for 2 h, at up to 90 W/kg (23-28 °C)	Increased K^+ efflux from rabbit erythrocytes relative to thermal controls at around 24 °C	Cleary et al. (1982)
2.45 GHz (CW) at 2-3 W/kg for up to 2 h (7-35 °C)	Increased Na^+ efflux from human erythrocytes compared with thermal controls at 22-25 °C	Fisher et al. (1982)

Table 8 (*continued*)

Exposure condition	Effect	Reference
2.45 GHz (CW) at 60 W/kg, for 30 min (15-24 °C)	Increased passive Na^+ transport and protein shedding from rabbit erythrocytes compared with thermal controls, only at membrane phase transition temperatures of 17.7-19.5 °C	Liburdy & Penn (1984)
2.45 GHz (CW) up to 100 W/kg, for up to 60 min (13-43 °C)	Increased Na^+ permeability of rabbit erythrocytes compared with thermal controls, only at 17.7-19.5 °C; response abolished in cholesterol-loaded membranes with no apparent phase transition	Liburdy & Vanek (1987)
1.0 GHz (CW) at up to 15 W/kg, for up to 5 h (15-40 °C)	No effect on membrane fluidity of human erythrocytes, as measured by lateral diffusion of lipophilic dye	Allis & Sinha (1981)
2.45 GHz (CW) 6 W/kg, for 20 min (23-27 °C)	Inhibition of Na/K ATPase activity in human erythrocyte ghosts, only at 25 °C	Allis & Sinha-Robinson (1987)

7.2.2 *Effects on haematopoietic tissue*

A summary of *in vitro* studies conducted to determine haematopoietic and immunological end points is shown in Table 9. In general, these studies show that RF exposure, under temperature-controlled conditions, at SARs up to 28 W/kg have no effects on cell survival or mitogen-stimulated lymphoblastoid transformations.

In some studies, effects are reported at levels too low to involve significant heating, or at certain RF modulation frequencies. In one unreplicated study, depressed phagocytosis was reported in RF-exposed mouse macrophages. A slight rise in temperature in the culture medium would have tended to increase activity. T-lymphocyte cytotoxicity was depressed during low-level exposure to 450 MHz RF modulated at frequencies of 16 and 60 Hz, but not at other frequencies. In other studies, a lack of effects of sinusoidal or pulse-modulated RF fields on B-lymphocyte capping in mouse spleen cells, viability, and DNA synthesis in human mononuclear lymphocytes has been reported.

Table 9. Haematopoietic and immunological studies (*in vitro*)

Exposure conditions	Effect on exposed group	Reference
Colony-forming ability		
2.45 GHz (CW) up to 2 kW/kg, for 15 min	Dose-related, reduced colony-forming ability of mouse bone marrow cells - temperature kept constant; direct effect of RF on haematopoietic precursor	Lin et al. (1979)
2.45 GHz (CW), 2.4 kW/m^2, for 5 min; rise in temperature of mouse bone marrow suspension was from 20 to 45 °C	cells; spleen colonies in radiation-depleted recipients rose when temperature rose to between 33 and 40 °C, but fell above 41 °C	Rotkovska et al. (1987)
Mitogen responses		
2.45 GHz (CW), 19 W/kg, for 1-4 h, temperature controlled at 37 °C	No changes in cell viability or blastogenic responses of mouse spleen lymphocytes to several mitogens	Smialowicz (1976)
2.45 GHz (CW), up to 28 W/kg for up to 44 h, constant temperature. of 37 °C	No effects on spontaneous or mitogen-stimulated transformation of rat lymphocytes	Hamrick & Fox (1977)
2.45 GHz (CW) up to 4 W/kg, temperature rise of 0.9 °C	No effects on human leukocytes viability or on unstimulated or mitogen-stimulated lymphoblastoid transformation	Roberts et al. (1983)

Table 9 (*continued*)

Exposure conditions	Effect on exposed group	Reference
Modulated RF		
450 MHz, 15 W/m^2, sinusoidal-modulated at 3, 16, 40, 60, 80, 100 Hz	Suppression of mouse T-lymphocyte cytotoxicity, peak at 60 Hz (20%)	Lyle et al. (1983)
147 MHz, pulse-modulated at 9, 16, 60 Hz, 1.1-480 W/m^2	No change in mouse spleen B-lymphocyte capping as temperature maintained constant	Sultan et al. (1983b)
2.45 GHz, pulse-modulated at 16 or 60 Hz, up to 4 W/kg	No effects on human lymphocyte viability, unstimulated or mitogen-stimulated DNA synthesis, or total protein synthesis	Roberts et al. (1984)
Pulsed 9 GHz (1000 pps) 200 W/m^2 amplitude-modulated at 16 MHz (100% mod.) and 16 Hz (5% mod.) plus 0.8 Hz magnetic field 60 mT, 12 h per day, for 5days	Decrease in no. of plaque-forming cells and cytotoxicity of NK cells in mice	Bottreau et al. (1987)
Other		
2.45 GHz (CW), 500 W/m^2, for 30 min, temperature rise of 2.5 °C but below optimum temperature for phagocytic activity	Depression of phagocytosis in peritoneal mouse macrophages	Mayers & Habershaw (1973)
2.45 GHz (CW), for 30 min, up to 1 kW/m^2 (SAR up to 45 W/kg)	Ability of normal mouse B-lymphocytes to form a "cap" on the plasma membrane of antigen-antibody complex reduces with increasing temperature; if temperature kept constant, no difference between exposed and control cells	Sultan et al. (1983a)

7.2.3 *Isolated cerebral tissue, peripheral nerve tissue, and heart preparations*

Studies carried out on calcium ion exchange in chick cerebral tissue preparations and other tissues exposed to RF fields, amplitude modulated at ELF frequencies, are described in section 6 on interaction mechanisms.

Table 10. Peripheral nervous tissue studies

Exposure conditions	Effect on exposed group	Reference
2.45 GHz (CW or pulsed), 1 kW/kg, for several minutes, temperature controlled	No effect on compound action potential in functioning isolated frog and cat nerves or peripheral autonomic ganglia of rabbits	Chou & Guy (1973); Courtney et al. (1975)
1.5 or 2.45 GHz (CW), few minutes above threshold of approx. 5 W/kg	Reversible changes in firing pattern of pacemaker neurons of *Aplysia*	Wachtel et al. (1975)
2.45 GHz (CW or pulsed), temperature controlled above a threshold of 5-10 W/kg, for 30 min	Prolongation of refractory period of isolated frog sciatic nerves	McRee & Wachtel (1980, 1982)

Studies conducted on peripheral nerve tissue are summarized in Table 10. Most effects of RF exposure on the properties of isolated nerve preparations can be ascribed to heating. For example, the changes seen in the firing pattern of pacemaker neurons in Aplysia, exposed at 5 W/kg or above (Wachtel et al., 1975), were considered to be consistent with heating (Seamen, 1977). However, in two studies, changes were reported in the properties of frog nerves exposed above 5-10 W/kg, under constant temperature conditions. These changes were not induced by exposure to infrared radiation, suggesting an athermal response. The authors noted, however, that, even under temperature-controlled conditions, thermal gradients were difficult to eliminate.

Several studies (reviewed by Liddle & Blackman (1984) and NCRP (1986) have been performed on isolated heart preparations. Decreases in heart rate (bradycardia) have been reported in isolated turtle, frog, and rat heart preparations exposed to RF at intensities as low as 15 W/m^2 (NCRP, 1986). However, Clapman & Cain (1975) indicated that at least some of the effects observed with these preparations may have been caused by currents induced in electrodes in contact with the myocardia. Some support for this comes from the work of Yee et al. (1984), though a later study (Yee et al., 1988) also implicated the low temperatures and oxygen levels used in these experiments.

7.2.4 Mutagenic effects

Numerous tests have been carried out to examine the potential mutagenic action of RF field exposure. In general, no changes in mutation rate have been observed, except in cases where substantial temperature increases may also have occurred (USEPA, 1984; NCRP 1986).

Studies of the chromosomal effects resulting from RF exposure of somatic cells are summarized in Table 11. Most well-conducted studies report a lack of effect on chromosome aberration frequencies or sister chromatid exchange rates, even when RF exposure produces mild hyperthermic conditions. Increased aberration frequencies were reported in one isolated, long-term study of rat kangaroo cells exposed for 50 passages (over 320 days) to 2.45 GHz at 15 W/kg. However, these results may have been confounded by temperature and senescence (aging) in the cell populations.

Table 11. Mutagenic effects in somatic cells

Exposure conditions	Effect on exposed group	Reference
20 kHz sawtooth magnetic field, 16 μT pk-pk, for 72 h	Non-significant ($P=0.06$) increase in chromosome aberration frequency in human amniotic cells, DNA synthesis reduced	Nordessen et al. (1989)
2.45 GHz (CW), up to 200 W/kg, for 20 min temperature rose from 4 °C or 23 °C to 36 °C during exposure, second experiment temperature rose from 37 °C to 40 °C.	Human blood lymphocytes showed no increase in unstable chromosome or sister chromatid exchanges	Lloyd et al. (1984, 1986)
2.45 GHz (CW) 15 W/kg, for up to 320 days (50 passages)	Increased chromosome aberrations and polyploidy and decreased growth rate in rat kangaroo RH5 and RH16 cells	Yee (1982)

7.2.5 *Cancer-related studies*

Experiments on cell systems exposed to RF that have end points related to cancer are shown in Table 12. Cellular transformation studies are important assays of potential carcinogenicity, in which the potential is examined of a suspect carcinogen to abolish contact inhibition, an important regulator of cell division. They are, however, very susceptible to factors such as variation in growth media. Balcer-Kubiczek & Harrison (1985, 1989) reported enhanced transformation rates in mouse fibroblasts after RF exposure for 24 h at 4.4 W/kg (alone or combined with X-radiation), followed by treatment with the chemical promotor TPA. These experiments are not conclusive; there were inconsistencies between the studies in plating efficiency and in the response to RF combined with X-radiation. The authors also noted that the transformation rates were susceptible to temperature changes. However, these studies are important and should be replicated.

Protein kinases and ornithine decarboxylase are enzymes important in normal and neoplastic cell growth and division. Byus et al. (1984) reported an effect of exposure to amplitude-modulated RF on cAMP-independent kinase, but no effect on cAMP-dependent

Table 12. Cancer-related studies (*in vitro*)

Exposure conditions	Effect on exposed group	Reference
2.45 GHz (CW), 4.4 W/kg for 24 h, temperature constant at 37 °C	RF reduced plating efficiency of mouse embryo fibroblasts to half, but no effect on transformation rate was induced by treatment with benzopyrene or X-rays alone. Exposure of cells to RF and X-rays, then tumour promotor (phorbal ester TPA), caused a several-fold increase in transformation frequency compared with cells exposed to X-rays and treated with TPA	Balcer - Kubiczek & Harrison (1985)
2.45 GHz (CW), 4.4 W/kg for 24 h, temperature constant at 37 °C	Increased mouse embryo fibroblast transformation rate per surviving cell, in cells exposed to RF with, or without X-rays, and then treated with TPA. In contrast to 1985 study, no effect on cell plating efficiency or difference in transformation response to combined X-ray, RF and TPA compared with X-ray & TPA alone	Balcer-Kubiczek & Harrison (1989)
450 MHz, pulse-modulated at 3-100 Hz, 10 W/m^2, for up to 60 min	No effect on human lymphocyte cAMP-dependent protein kinase activity. cAMP-independent kinase activity fell to less than 50% of control levels after 15-30 min exposure, then returned to control levels at 45-60 min. Reduced enzyme activity occurred at 16, 40, 60 Hz modulation, not at 3, 6, 80 or 100 Hz, or unmodulated carrier	Byus et al. (1984)
450 MHz amplitude-modulated, 10 W/m^2, for 1 h	Increased ornithine decarboxylase (ODC) at 10, 16, 20 Hz modulation by Reuber H35 hepatoma cells, CHO cells, and human melanoma cells; RF (modulated at 16 Hz) exposure of CHO and hepatoma cells potentiated a TPA induced increase in ODC, but not in DNA synthesis in TPA-treated cells	Byus et al. (1988)

kinase, normally implicated in cellular responses leading to proliferation. Amplitude-modulated RF exposure was also found to enhance ornithine decarboxylase activity in several different cell lines (Byus et al., 1988), though only by a small amount compared with chemical promotors. No effect was seen on DNA synthesis (assayed 14 h after exposure), which is a subsequent step in the promotional sequence. It is not possible to draw any conclusions with respect to cancer from these studies.

7.2.6 Summary and conclusions: in vitro *studies*

The results of *in vitro* studies, conducted so far, suggest that the cell membrane is a site of interaction of RF fields and that alterations in membrane permeability can result, as well as changes in membrane cation fluxes, changes in the activity of certain enzymes, and suppression of some immune responses. RF fields are not mutagenic; an effect on cellular proliferation, particularly in relation to tumour promotion, by interactions other than tisue heating, has not been established. Evidence is presented that some effects may result from athermal interactions, particularly in response to amplitude-modulated fields. However, in many other cases, there is great difficulty in eliminating thermal gradients within exposure samples exposed at high levels.

7.3 Animal studies

While *in vitro* studies are important in determining the mechanisms of interaction and identifying appropriate biological end-points and exposure conditions to be tested in whole animals, they cannot serve as a basis for health risk assessment in humans. Whole animal studies are necessary in order to evaluate the integrated response of various systems of the body that serve to maintain homeostasis, the condition necessary for the proper functioning of the body. Three bodily systems can be identified as of particular importance in this respect: the nervous, endocrine, and immune systems. The coordinated interdependent interaction of these systems in response to chemical and physical stimuli provides a great capacity for adaptation and compensation in response to changes in environmental or internal bodily conditions.

Local hyperthermia, caused by exposure to strong RF fields, and damage to morphological structures of the above systems, can lead, in turn, to physiological deregulation. Exposure to weaker RF fields with minimal thermal loading can result in adaptive and compensatory shifts of these homeostatic mechanisms.

Another important end-point in the consideration of human health and safety concerns the possible effects on reproduction, and on pre- and post-natal development. In this context, the induction of mutagenic changes in germ cells by RF exposure might result in hereditary effects in offspring. In somatic cells, such changes could be associated with the induction of cancers.

The effects of exposure to RF fields on these various biological end-points is described in the following sections. It is important to note that, as far as thermal responses are concerned, experimental interpretation can be confounded by differences in ambient temperature, relative humidity, and air flow. In addition, the thermal load induced by a given SAR is different in different animals, generally increasing with body weight in small animal species. These two points have been evaluated by Gordon et al. (1986) and Gordon (1987), who argue for a conservative extrapolation of thermal effects from laboratory animals to humans.

7.3.1 Nervous system

Studies of the effects of RF exposure on the nervous system are shown in Table 13. Results of early studies suggested that the blood-brain barrier (which regulates cerebro-spinal fluid composition) was possibly susceptible to RF field exposure. For example, Frey et al. (1975) reported the penetration of the blood-brain barrier of anaesthetised rats by fluorescein after low-level, pulsed or CW exposure. Oscar & Hawkins (1977) reported increased permeability to radiolabelled saccharides after exposure of anaesthetized rats to low-level RF. However, later work (reviewed by Blackwell & Saunders, 1986; NCRP 1986) indicated that these responses may have been confounded by various factors, including alteration in cerebral blood flow, the effect of the anaesthetic, and changes in renal clearance.

The uptake of horseradish peroxidase by brain tissue is less susceptible to these factors. Increased uptake reported in conscious Chinese hamsters after exposure at 2 W/kg (Albert, 1977); decreased uptake has been reported at higher SARs (Williams et al., 1984b,d).

Table 13. Nervous system effects

Exposure conditions	Effect on exposed group	Reference
450 MHz (amp. mod. 16 Hz), for 60 min, to 30 W/m^2 (33 V/m, SAR: 0.29 W/kg)	Altered exchange rate of Ca^{++} during and after exposure of cat cortex	Adey et al. (1982)
2.06 GHz (CW or pulsed 18, 6, 32 Hz), 5-100 W/m^2 (SAR 0.12-2.4 W/kg)	No change in Ca^{++} mobility in rat cerebral tissue	Merritt et al. (1982)
2.45 GHz pulsed (2 μs pulses at 500 Hz) or CW for 45 min (SAR 0.6 W/kg)	Decreased choline uptake in the rat brain tissue; effect depended on exposure parameters	Lai et al. (1988)
2.45 GHz (pulsed - 2 μs pulses at 500 Hz) for 45 min. (SAR 0.3-1.2 W/kg)	Decreased choline uptake in the rat brain tissue at 0.45 W/kg and above	Lai et al. (1989)
915 MHz (CW), 10-400 W/m^2, for 15 min exposure of head (SAR threshold 2.5-5 W/kg)	Decreased latency of late components only evoked potentials in thalamus of cats	Johnson & Guy (1972)
147 MHz (amplitude-modulated 1-25 Hz) 10 W/m^2 (approx SAR 0.015 W/kg)	Altered EEG responses in cats exposed to field modulated at EEG frequencies	Bawin et al. (1973, 1974)
2.95 GHz, single or repeated exposure up to 50 W/m^2 (SAR 1 W/kg) 2 h/day for 3-4 months	EEG of rabbits unaffected by acute exposure; desynchronization of EEG from long-term exposure; pulsed (1 μs pulses at 1200 Hz) more effective for changes than CW	Baranski & Edelwejn (1975)
3 GHz (1 μs pulses at 500-699 Hz) 50 W/m^2 (SAR 1 W/kg) in rats, for 10 days	Transient enhancement of EEG at frequency of pulse repetition rate, persisted after exposure ceased	Servantie & Etienne (1975)
1-10 MHz (amplitude-modulated 14-16 Hz) E field 500 V/m, 2 h/day, for 6 weeks	Sustained changes in EEG after 2-3 weeks of exposure of rabbits	Takashima et al. (1979)
1-30 MHz (amplitude-modulated 60 Hz) single exposure, for 3 h	No effect	
500 MHz - 3GHz 25-50 W/m^2, for 15 days, at 0.5-1 W/kg	No effects on EEG in rats and monkeys	Klein et al. (1985)

Table 13 (*continued*)

Exposure conditions	Effect on exposed group	Reference
4 GHz, CW or amplitude-modulated at 16 Hz (70% mod.), for 30 min (SAR in cortex 8.4, 16.8, or 42 W/kg)	Slight changes in EEG pattern, particularly at 16.8 W/kg amplitude-modulated RF and 42W/Kg CW	Mangel et al. (1990)

More recently, changes in blood-brain barrier permeability have been reported after exposure to MRI field conditions; however, the evidence for an effect is contradictory, at present (Prato et al., 1990; Ross et al., 1990).

Pulsed RF fields appear to have various effects on the nervous system. Exposure to very high peak power pulses is reported to suppress startle reflex and evoke body movements in conscious mice (Wachtel et al., 1988; 1989). For evoked body movement, each pulse (10 μs in duration) produced a mid-brain specific absorption of around 200 J/kg, corresponding to an SAR of 20 MW/kg and was estimated to lead to a rise in mid-brain temperature of 0.05 °C. Pulsed fields were only about twice as effective as CW suggesting that the effect is unlikely to be due to thermoelastic mechanisms.

Pulsed RF exposure of rats for 45 min at SARs as low as 0.45 W/kg has been shown to affect the sodium-dependent, high affinity choline uptake (an indicator of cholinergic activity) in different parts of the brain (Lai et al., 1989). In a previous study, Lai et al. (1988) found that the effect varied with different exposure parameters. Further work (Lai et al., 1990) revealed that the concentration of benzodiazepine receptor (involved in anxiety and stress responses) in the brain of rats exposed for 45 min to pulsed 2.45 GHz or whole body SARs of 0.6 W/kg was increased in some parts of the brain, immediately after exposure. However, the effect diminished with repeated exposure over a 10-day period. The authors suggested that the data support the hypothesis that low-level RF exposure is a mild nonspecific stressor. There are a number of responses (heat, noise) that can be regarded as nonspecific stressors. This set of studies needs further elaboration to identify the extent and mechanisms of the stress involved, before its implication for health risk can be assessed. High levels of RF, sufficient to raise spinal or thalamic temperatures by several degrees Celsius, decreased the latency of late components of thalamic evoked potentials.

Exposure to low levels of amplitude-modulated RF has been reported to alter brain activity (measured using electro-encephalography) and to affect calcium ion mobility in the cortex. Exposure to 147 MHz fields, amplitude-modulated between 1 and 25 Hz, has been reported to affect the ability of cats to produce selected EEG rhythms. Changes have also been reported in the EEG frequency spectrum in rabbits exposed to long-term 1-10 MHz, amplitude-modulated at 14-16 Hz.

Small changes in EEG patterns, particularly earlier studies on desynchronisation, were reported in rats and rabbits, after exposure to an SAR at around 1 W/kg (Baranski & Edelwejn, 1975; Servantie & Etienne, 1975). However, later studies reported a lack of effect.

The exposure of cats at about 0.3 W/kg to 450 MHz, amplitude-modulated at 16 Hz, has been reported to alter calcium ion mobility in the cortex (measured as the efflux of labelled calcium ions from the cortex surface) (Adey et al., 1982). In contrast, exposure at between 0.12 and 2.4 W/kg to 2.06 GHz, pulse-modulated at 8, 16, or 32 Hz, was reported to have no effect on calcium ion exchange in the rat cortex (Merritt et al., 1982).

Exposure to RF has been shown by several authors to influence the effects of various neuroactive drugs (see Table 14). Acute and long-term exposure have been reported to potentiate the effects of stimulant and convulsant compounds (Baranski & Edelwejn, 1974; Servantie et al., 1974). Thermally significant exposures have been reported to decrease the period of barbituate-induced anaesthesia in mice and rabbits; Blackwell (1980) suggested thermally enhanced redistribution from brain tissue as a probable mechanism.

7.3.2 *Ocular effects*

The lens of the eye is potentially sensitive to RF exposure, because it lacks a blood supply and so has a reduced ability to dissipate heat compared withto other tissues. In addition, the fibres that make up the bulk of the lens have only a limited capacity for repair and tend to accumulate the effects of minor insults.

Table 14. Nervous system effects with drugs

Exposure conditions	Effect on exposed group	Reference
1.7 or 2.45 GHz (CW) up to 500 W/m^2 (up to 10 W/kg)	Rabbits injected with sodium pentobarbital and exposed to RF showed reduced sleeping times; correlated with increased rectal temperature	Cleary & Wangemann (1976)
2.45 GHz (CW), 250 W/m^2 and above (SARs >17 W/kg) (rectal temperature rise 3 °C)	SAR dependent reduction in hexobarbital-induced sleeping time in mice during RF exposure	Blackwell (1980)
3 GHz (CW) 70 W/m^2 (1.2 W/kg) for 3 h/day, for 200 h exposure	Variable effect on chlorpromazine and pentylenetetrazol changes in EEG activity in rabbits	Baranski & Edelwejn (1974)
3 GHz (pulsed 1 μs at 525 Hz), for unspecified duration, each day for 8-35 days, at 5 W/kg	Variable latency of response to pentylenetetrazol induction of convulsion activity	Servantie et al. (1974)
9.3 GHz (CW), 7-28 W/m^2 0.6 W/kg, for 5 min	No differences in EEG from normal sodium pentobarbital anaesthetic action	Goldstein & Sisko (1974)

Most experimental work on the RF induction of cataracts (see Tables 15 and 16) has been carried out using near-field exposures at 2.45 GHz, to selectively irradiate the eye or the side of the head, in order to avoid whole-body thermal stress. The intense exposures used in these studies have often led to other effects, such as lacrimation and oedema of surrounding tissue.

Exposure has usually been well above perception threshold and the animals have usually been anaesthetised. In most studies, the rabbit has been used as the experimental animal model, because the dimensions of its eye approach those of the human eye.

Different conditions of exposure can affect the type of opacity formed or be ineffective in inducing any permanent change. The efficacy with which the applied RF field can induce cataracts depends on the depth of penetration and hence the frequency. Below 1.5 GHz, the dimensions of the orbit-eye combination are too small to result in local field concentration. Above about 10 GHz,

Table 15. Ocular effects from acute exposure

Exposure conditions	Effect on exposed group	Reference
Rabbits		
2.45 GHz (CW); 4.2 kW/m^2, for 5 min, or 1.5 kW/m^2, for 60 min	Posterior cortical opacities within a week; first visible changes (milky bands) 1-2 days after exposure	Carpenter & VanUmmerson (1968)
2.45 GHz (CW); up to 2.5 kW/m^2 repetitive exposure	Ultrastructural changes in lenses seen with microscope; slit lamp picture appeared normal	Williams et al. (1975)
2.45 GHz (CW); single acute exposure of 1.5 kW/m^2, for up to 100 min (SAR peak in vitreous of 138 W/kg, 43 °C peak)	Threshold exposure to produce lens cataract	Guy et al. (1975b)
2.45 GHz (CW); SAR 100 100 W/kg, after >140 min	Cataract in rabbit	Kramar et al. (1978)
3 GHz (CW); (far-field) 5 kW/m^2, for 30 min	No lenticular changes, periorbital burns	Appleton et al. (1975)
107 GHz or 35 GHz, for 60 min, at 400 W/m^2	Keratitis in cornea; damage more immediate but recovery quicker at 107 GHz	Rosenthal et al. (1976)
Monkeys		
2.45 GHz; 5 kW/m^2, for 60 min	No cataract in rhesus monkey after 13 months	Kramar et al. (1978)

penetration decreases and power absorption becomes increasingly restricted to the superficial tissue (NCRP, 1986).

In general, field intensities associated with the acute induction of cataracts in the rabbit are of such magnitude that they are lethal if applied to the whole animal. Studies on the acute exposure of rabbits' eyes suggest the existence of an RF exposure threshold for the production of a cataract. This is best shown in the data of Kramar et al. (1978) given graphically in Fig. 20. The threshold power density to produce a cataract is approximately 1500 W/m^2 for at least 1 h.

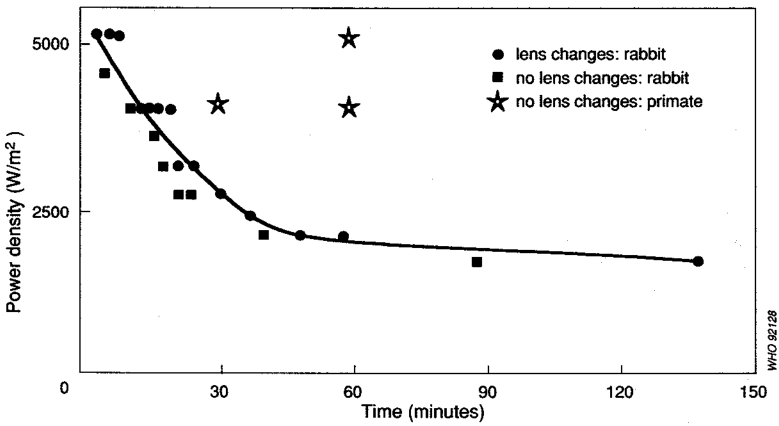

Fig. 20. Threshold for cataract formation in the rabbit exposed to 2.45 GHz microwaves. From: Kramar et al., 1978.

The possibility of a cumulative effect of repeated subthreshold exposure leading to the development of a cataract has been examined, as shown in Table 16. Subthreshold exposures of rabbit eyes caused reversible changes, and damage accumulated only when exposure was repeated before repair had occurred. However, these exposures were only just below the single acute exposure threshold (EPA, 1984). Long-term, whole-body exposures in the far-field at lower levels of power density have not produced any lens opacities.

Opacities were induced in the eyes of anaesthetized primates after exposures well above threshold levels for rabbits, or after long-term exposure of conscious primates (to 9.3 GHz) at up to 1500 W/m^2. It has been suggested that the difference in acute response between rabbits and monkeys reflects structural differences in the face and lens and, hence, energy deposition and heating in the eye.

Table 16. Ocular effects from repeated short-term threshold exposure

Exposure conditions	Effect on exposed group	Reference
Rabbits		
2.45 GHz (CW), at 4.2 kW/m^2	Various degrees of lens opacity :	Carpenter et al. (1960a,b)
4 min for 4 days	- in all rabbits	
4 exposures at 1-week intervals	- in 70% of rabbits	
4 exposures at 2-week intervals	- in 40% of rabbits	
3-min exposure, 5 times in week	- few opacities formed	
3-min exposure, 5 times in 5 weeks	- no opacities formed	
2.45 GHz (CW), at 100 W/m^2 (SAR 1.5 W/kg), for 8 h/day, 5 days/week for 17 weeks	No lens opacities for up to 3 months after exposure	Ferri & Hagan (1976)
2.45 GHz (CW), 1.8 kW/m^2, for 1 h repeated up to 20 times	Cataracts in 8 out of 10 rabbits	Carpenter et al. (1974),
1.5 kW/m^2, for 1 h, repeated up to 32 times	Cataracts in 4 out of 10 rabbits	Carpenter (1979)
1.2 kW/m^2, for 1 h, repeated up to 24 times	Cataracts in 1 out of 9 rabbits	
2.45 GHz (CW), 100 W/m^2 (SAR to head 17 W/kg max), 23 h/day for 180 days	No changes in rabbits eyes	Guy et al. (1980)
Monkeys		
9.3 GHz (CW), 1.5 kW/m^2, 10 h/day for over 3 months	No cataract or corneal lesions found in macaque monkey	McAffee et al. (1979)
2.45 GHz (pulsed-10 μs pulses at 100 Hz), 100 W/m^2, 2.6 W/kg, 4 h/day for 3 days, 2.45 GHz (CW), 200 W/m^2, 6.3 W/kg, 4 h/day for 3 days	Endothelial cell damage to the corneas of monkeys, leakage of iris vasculature; damage greater in timolol maleate-treated eyes	Kues et al. (1985, 1988)
2.45 GHz (10 μs pulses at 100 Hz), 0-100 W/m^2, 4 h/day for 3 days	Leakage of iris vasculature in timolol maleate-treated eyes of anaesthetized adult rhesus and cynomolgus monkeys; damage observed at 10 W/m^2, but not at 2 W/m^2	Monahan et al. (1988)

Histological evaluation of the irises of monkeys, exposed *in vivo*, long-term to 100 W/m^2 pulsed 2.45 GHz at an SAR to the eye of 2.6 W/kg, indicated an increased vascular leakage (Kues et al., 1988). The leakage was increased in exposed animals whose eyes were pretreated with the ophthalmic drug timolol maleate (timolol maleate is used by people with glaucoma to lower the intraocular pressure by reducing the production of aqueous humour). In an extension of this study, Monahan et al. (1988) observed vascular leakage in timolol maleate-treated monkey eyes at power densities as low as 10 W/m^2 (an SAR of only 0.26 W/kg).

The authors suggested that serum protein leakage could have contributed to the corneal endothelial lesions observed in an earlier paper (Kues et al., 1985). More recently, the authors briefly reported that exposure to 50 or 100 W/m^2 pulsed 2.45 GHz over a 10-week period resulted in degenerative changes in the retinal layer (Kues & McLeod, 1990). Timolol maleatic pretreatment increased the severity of the responses. Although requiring further study, these results, if established, could have important implications for the development of standards.

7.3.3 Auditory perception

Auditory perception of pulsed RF exposure by animals is well established (see Table 17). For short pulses, thresholds are dependent on the energy density per pulse (Guy et al., 1975a, Chou et al., 1985) rather than the average power density, indicating a thermoelastic interaction.

Table 17. Perception

Exposure conditions	Effect on exposed group	Reference
918 MHz (10 μs pulses at 10 Hz), peak SAR 75 W/kg	Pulsed RF produced similar auditory stimulus for rat behavioural response as a 7.5 kHz tone repeated at 10 Hz	Johnson et al. (1977)
2.45 GHz, pulses with width less than 30 μs 10-16 mJ/kg: 0.9-1.8 mJ/kg:	Threshold auditory perception of pulsed RF fields for cats for rats	Guy et al. (1975a) Chou et al. (1985)
2.45 GHz (CW), 0.6-2.4 W/kg, for 1 min	Threshold for perception of the RF field in rats	King et al. (1971)

Threshold specific energy densities for pulses shorter than 30 μs were reported as 10-16 mJ/kg for cats and 0.9-1.8 mJ/kg for rats. CW fields are ineffective in generating the rapid thermoelastic expansion necessary for this effect, but can be perceived if temperature sensors in the skin are stimulated; the perception threshold has been reported to lie around 0.6-2.4 W/kg (King et al., 1971).

7.3.4 Behaviour

7.3.4.1 *Thermoregulation*

Exposure to thermally significant levels of RF will induce a heat load in addition to metabolic heat production (and other sources of heat) and will elicit the various physiological and behavioural mechanisms animals use to regulate body temperature. The thresholds for such responses, given in Table 18, are dependent on the relationships between the total heat load, heat-loss mechanisms, which depend on ambient conditions, and small changes in heat storage. In cool environments, animals compensate for RF-induced body heating by lowering their rate of metabolic heat production. The threshold response of squirrel monkeys, exposed for 10-15 minutes to 2.45 GHz, varied between about 0.5 and 5 W/kg, depending on ambient temperature. Food intake is also reduced in proportion to SAR in animals exposed long-term to RF; a threshold response for rats occurs at around 2-3 W/kg.

Other thermoregulatory responses to RF heating include vasodilation, which increases skin thermal conductance, and sweating. Thresholds of between about 0.3 and 3 W/kg have been described in rats and monkeys. Similar responses have been reported in mice (Stern et al., 1979). Thresholds for behavioural thermoregulation, in which animals selected cooler environmental temperatures or selected shorter durations of infrared heating in response to microwave radiation of around 1 W/kg, have been described in rats and monkeys. Mice were shown to select a cooler environment by moving along a temperature gradient above a threshold SAR of 7 W/kg (Gordon, 1983). The threshold SAR necessary to activate a given thermoregulatory response or raise body temperature varied inversely with body mass (Gordon 1987). Thus, SAR dose-response data must be interpreted carefully when considering the extrapolation from experimental animals to humans.

Table 18. Thermoregulation

Exposure conditions	Effect on exposed group	Reference
Heat production/food intake		
2.45 GHz (CW)	Reduce endogenous heat production to compensate for RF body heating by rats	Ho & Edwards (1977); Phillips et al. (1975)
2.45 GHz (CW), up to 1.5 W/kg	Threshold RF exposure to reduce squirrel monkey metabolic heat production 0.6-0.9 W/kg	Adair & Adams (1982)
2.45 GHz (CW), 0.7 W/kg, 7 h/day for 98 days	No change in food or water intake or weight in rats	D'Andrea et al. (1986b)
915 MHz (CW) - up to 2 W/kg - at 3.2 W/kg	Food intake by rats - not reduced - decreased consumption	Lovely et al. (1977, 1983)
918 MHz (CW), 3.6 W/kg,	Decreased food consumption, but no change in water intake or body weight in rats	Moe et al. (1976)
Vasomotor/behavioural regulation		
2.45 GHz (CW), 5-min sessions, 1 W/kg	Threshold for detectable changes in thermal conductance of skin in squirrel monkeys; power density to cause vasodilation related to ambient temperature	Adair & Adams (1980a)
225 MHz (CW), 1.4 W/kg	Threshold for metabolic and vasomotor responses in rhesus monkeys	Lotz & Saxton (1987)
2.45 GHz (CW), 1.2 W/kg (ambient temperature of 36 °C)	Threshold for sweat response from foot in squirrel monkeys; increased threshold with decreased ambient temperature	Adair (1983b)
2.45 GHz (CW), 10-220 W/m^2, for 10 min	Threshold of approx. 1.2 W/kg for initiation of thermoregulatory behaviour in squirrel monkeys	Adair & Adams (1980b)
450 MHz (CW), for 10-180 min	Threshold of approx. 1.2 W/kg for initiation of thermoregulatory behaviour in squirrel monkeys	Adair & Adams (1988)

Table 18 (*continued*)

Exposure conditions	Effect on exposed group	Reference
2.45 GHz (CW), 1 W/kg	Threshold for initiation of thermoregulatory behaviour in rats	Stern et al. (1979)
2.45 GHz (CW) at 7 W/kg in waveguide with temperature gradient	Threshold for movement from preferred normal ambient temperature	Gordon (1983)
225 MHz (CW), for 6 x 10-min exposure or 120-min exposure, 12-100 W/m^2, 0.35-2.85 W/kg	Heat poorly dissipated by rhesus monkeys at 255 MHz compared with 1.29 GHz	Lotz & Saxton (1988)
1.2 GHz	Rats:	Frey & Feld (1975)
20 W/m^2 (CW):	No avoidance of RF field	
2 W/m^2 (pulsed):	Avoided RF fields	

The thermoregulatory responses elicited by RF exposure have been reviewed by Adair, 1988. They were found to be similar to those elicited by exposure to conventional radiant or conductive heat sources. However, the overall thermoregulatory response of an animal to RF exposure will depend on the distribution of RF energy absorption and, thus, on the RF frequency. At frequencies below about 10 GHz, RF radiation is more deeply penetrating than, for example, infrared radiation, and is thus less effective in stimulating the superficial temperature sensitive receptors involved in local (and whole-body) thermoregulatory responses (Adair, 1983a).

The effects of the distribution of RF absorption on thermoregulatory efficacy is particularly marked during exposure at frequencies near whole-body resonance. For example, although qualitatively similar, the thermoregulatory responses of squirrel and rhesus monkeys were less effective in preventing a rise in skin and body temperatures during exposure at resonance than during exposure at supra-resonant frequencies (Adair & Adams, 1988; Lotz & Saxton, 1988).

7.3.4.2 *Activity (spontaneous movement)*

Acute and long-term exposure of rats has been reported to reduce their spontaneous locomotor activity (e.g., Moe et al., 1976, Mitchell et al., 1988). The rats reduced activity to lower their endogenous heat production. In a lifetime study, activity levels were also reduced after 6 weeks continuous exposure of young rats at up to 0.4 W/kg, but values returned to control levels during subsequent exposure. No other effects on open-field behaviour were reported during 25 months exposure. Table 19 includes a summary of reports on the activity of RF-exposed rats.

7.3.4.3 *Learned behaviours*

Operant techniques that require behavioural responses, such as certain rates of lever pressing in response to a visual or auditory cue, provide a means of assessing the performance of specific learned tasks in a highly quantified and standardized manner. Such studies are summarized in Table 20. It is important to note, however, that threshold values for changes in behaviour will depend on many factors, such as the complexity of the task being performed. To quote single threshold values for a range of tasks is an oversimplification.

In rodents acutely exposed to RF, thresholds for the disruption of operant behaviour have been reported to lie between 2.5 and 8 W/kg, with concomitant rises in rectal temperature of around 1 °C. Deficits in performance have been reported following long-term exposure to 2.45 GHz at 2.3 W/kg. The acquisition of a learned task by rats appears more sensitive to disruption than performance. Thresholds have been estimated of between 0.14 and 0.7 W/kg for long-term exposure to continuous wave RF at 2.45 GHz and between 0.7 and 1.7 W/kg for acute exposure to pulsed 2.8 GHz RF. Auditory effects were avoided by testing after the exposure; however, the data were sometimes variable.

The responses of primates have been less extensively investigated. Operant task performance by rhesus and squirrel monkeys has been reduced by acute exposure to above resonant frequencies (1.3-5.8 GHz) at SARs of between 4 and 5 W/kg. Exposure of rhesus monkeys at whole-body resonance (225 MHz) resulted in reduced task performance at only 2.5 W/kg. However, both thresholds corresponded to raised body temperatures of about 1 °C; the lower threshold for body resonance presumably reflected the deeper heating and less efficient thermoregulation noted in the previous section.

The effects of drugs on behaviour were augmented after pulsed-wave RF exposures of 30 min at an average SAR of 0.2 W/kg (Thomas et al., 1979).

Table 19. Effects on behaviour - activity

Exposure conditions	Effect on exposed group	Reference
2.45 GHz (pulsed), 6.3 W/kg, for 30 min	No differences in the activity of rats	Hunt et al. (1975)
2.45 GHz (CW), 2.7 W/kg, for 7 h	Rats less responsive to novel acoustic stimuli, no effect on acquisition or retention of passive avoidance task, reduced locomotion and rearing	Mitchell et al. (1988)
918 MHz (CW), 3.6-4.2 W/kg, 10 h/night for 21 nights	Lower activity and different temporal distribution of activity of rats	Moe et al. (1976)
2.45 GHz (CW), 1.2 W/kg, 8 h/day, 5 days/week, for 16 weeks	Reduced activity of rats after exposure, but locomotor measures unaffected over long term	D'Andrea et al. (1979)
3 or 10.7 GHz (CW), up to approx. 0.3 W/kg, for 185 h continuously	Activity and stereotypic behaviour (rearing, sniffing etc.) of rats unaffected by RF exposure	Roberti et al. (1975)
2.45 GHz (CW), 7 h/day for up to 14 weeks, 0.7 W/kg intermittent exposures (25 W/m^2)	Decreased activity in rats 30 days after exposure, increased sensitivity to mild AC shock	D'Andrea et al. (1986b)
2.45 GHz (10 μs pulses at Hz, square wave-modulated at 8 Hz), up to 0.4 W/kg, from 2 to 27 months continuous exposure	Except for first session when general activity reduced, no difference in behavioural responses to lifetime exposure of rats	Guy et al. square (1985); Johnson et al. (1983)

Table 20. Effects on behaviour - operant performance

Exposure conditions	Effect on exposed group	Reference
Rats		
2.45 GHz (CW), 0.14 W/kg, 7 h/day, for up to 14 weeks 5 W/m^2	Variable changes in rate of acquisition of operant tasks, not confirmed by DeWitt et al. (1987)	D'Andrea et al. (1986a); DeWitt et al. (1987)
2.45 GHz (CW), 2.5-8 W/kg, for 60 min	Threshold for performance disruption in exposed rats	Sanza & de Lorge (1977); de Lorge & Ezell (1980)
360, 480, 500 MHz (CW), >4 W/kg 250 W/m^2, for up to 25 min	Threshold for reduced performance in rats; rectal temp rise >1 °C	D'Andrea et al. (1976)
600 MHz (CW), >6 W/kg, for up to 55 min	Threshold to stop pressing level for food	D'Andrea et al. (1977)
2.45 GHz (CW), 2.3 W/kg (mean) for 110, 5-h sessions over 22 weeks	Impaired operant performance in exposed rats	Mitchell et al. (1977)
2.37 MHz (CW), 10 or 50 W/m^2, 7 h/day, for up to 90 days	After 10 days exposure, increased learning of avoidance task; up to 90 days decreased retention and reaquisition	Shandala et al. (1977)
2.45 GHz (CW) at 100, 150, or 200 W/m^2, for 15 h (SAR 3, 4.5, or 6 W/kg) or 300 W/m^2 for 55 min (ambient temperature, 22 °C)	Reduced performance fixed ratio alternating operant schedule by rats	Gage (1979a)
2.45 GHz (CW) at 50, 100, 150 W/m^2 for 15 h (SAR 1, 2 or 3 W/kg). (ambient temperature, 28 °C)	Reduced performance random interval operant schedule by rats	Gage (1979b)
2.45 GHz (pulsed, 1 μs pulses at 500 pps), 2-6 W/kg, for 30 min	Impaired performance on discrimination tasks	Thomas et al. (1976)
2.8 GHz (pulsed, 2 μs pulses at 500 pps), 1.7 W/kg, for 30 min	Threshold for decreased acquisition of response sequence schedule	Schrot et al. (1980)

Table 20 (*continued*)

Exposure conditions	Effect on exposed group	Reference
Monkeys		
2.45 GHz (CW), 5 W/kg, for up to 2 h	Reduced performance and increased response time, rectal temperature increased by 2 °C in rhesus monkeys	de Lorge (1976)
2.45 GHz (CW), > 2.75 W/kg, for 60 min	Reduced performance of observing task in squirrel monkeys; correlated with rectal temperature increase	de Lorge (1979)
225 MHz (CW) 2.5 W/kg or 1.3 or 5.8 GHz (pulsed) 4-5 W/kg	Threshold for impairing performance of observing-response tasks; rectal temperature rise >1 °C in rhesus monkey	de Lorge (1984)
1.2 GHz (CW), 1.6 W/kg repeated 120-min exposures of head	Performance of visual tracking task by rhesus monkey unaffected	Scholl & Allen (1979)

7.3.5 *Endocrine system*

An extensive literature describes the endocrine responses of various species to RF exposure (Table 21). The endocrine responses to acute RF exposure are generally consistent with the acute responses to non-specific stressors, such as heat, or with changes in metabolism caused by hyperthermia (Roberts et al., 1986).

It has been reported in several papers that plasma corticosterone levels in rats were significantly enhanced by exposure above a threshold level that decreased with increasing duration of exposure. Similar effects were found in cortisol levels in primates. The response seems to be modulated in amplitude by the circadian rhythm of cortisol (or corticosterone) levels.

Stressful stimuli are known to depress circulating plasma levels of growth hormone and thyroxin hormones in rodents. Plasma levels of these hormones have been similarly reduced by whole-body exposure of rats to RF. In one study, a threshold response for changes in serum growth hormone levels was reported to be as low as 0.2 W/kg. In contrast, no significant effects on growth hormone or thyroxin levels has been seen in primates.

No effects on the endocrine system were seen in a lifetime study on rats exposed from 2 up to 27 months of age at SARs of up to 0.4 W/kg.

Table 21. Endocrine system effects

Exposure conditions	Effect on exposed group	Reference
Corticosterone/cortisol		
Rats		
2.45 GHz (CW); 500 W/m^2, up to 10 W/kg, for up to 60 min or 200 W/m^2, 3.2 W/kg, for 120 min	Threshold for significant increase in plasma corticosterone levels; Increased (0.7-1.5 °C) colon temperature needed for effect	Lotz & Michaelson (1978)
2.45 GHz (CW), 600 W/m^2, 9.6 W/kg, for 60 min, or 500 W/m^2, 8.3 W/kg, for 60 min for drug-injected rats	Plasma corticosterone levels not increased in hypophysectomized rats or rats injected with dexamethasone (suppresses ACTH release)	Lotz & Michaelson (1979)
2.45 GHz (CW), 100 W/m^2, approx 2.5 W/kg, for 16 h	No change in plasma corticosterone level or rectal temperature	Parker (1973)
2.45 GHz (CW), up to 400 W/m^2, up to 8.4 W/kg for 4 or 8 h	Alteration in normal circadian elevation in corticosterone levels	Lu et al. (1981)
918 MHz (CW), 100 W/m^2, up to 4.2 W/kg, 10 h/day, for 21 days	No change in rectal temperature or in basal or ether stress-induced serum corticosterone levels	Moe et al. (1976)
918 MHz (CW); 25 W/m^2, 1 W/kg (ave), 10 h/day, for 91 days	No change in rectal temperature or serum corticosterone levels	Lovely et al. (1977)
Monkeys		
1.29 GHz (pulsed), 3-4 W/kg, for 4 h	Increased serum cortisol levels and increased rectal temperature (0.7-1.6 °C) but no change in serum growth hormone levels or thyroxin in rhesus monkeys	Lotz & Podgorski (1982)

Table 21 (*continued*)

Exposure conditions	Effect on exposed group	Reference
1.29 GHz (pulsed) 380 W/m^2 4.1 W/kg, for 8 h	Increased serum cortisol levels when rhesus monkeys were exposed during day, but no change when exposed at night; rectal temperature rose by similar amount	Lotz (1983)
255 MHz (CW), 50 W/m^2, 3.4 W/kg, for 4 h	No change in serum cortisol level; rectal temperature increase of 1.5-2 °C in rhesus monkeys	Lotz (1985)
Growth/thyroid hormones		
2.45 GHz (CW), 90-360 W/m^2 SAR up to 7.5 W/kg, for 10-150 min	Decrease in serum growth hormone levels in young rats only when exposed to 7.5 W/kg for at least 60 min; colon temperature rose to more than 40 °C	Michaelson et al. (1975)
2.45 GHz (CW), 500 W/m^2, 10.5 W/kg, for 1 h, or 10 W/m^2, 0.2 W/kg for 2 h	Threshold to induce changes in serum growth hormone levels was dependent on baseline growth hormone level in rats at time of exposure; no change in thyroxin level; no effect with exposure > 4 h	Lu et al. (1980b)
2.45 GHz (CW), 58-190 W/kg, for 120 min	Increased thyroxin and tri-iodothyronine secretion when dog thyroid exposed; increased levels proportional to temperature increase	Magin et al. (1977a,b)
2.45 GHz (CW), 200 W/m^2 or higher, 4.2-5 W/kg, for 4 or 8 h	Depressed circulating thyroxin and TSH levels in rats; rectal temperature rose to about 40 °C	Lu et al. (1977, 1980b)
Other		
2.8 GHz (CW), 100 W/m^2, for 6 h/day, 6 days/week for 6 weeks	Increased luteinising hormone, no change in follicle-stimulating or gonadotrophic hormone levels in rats;	Mikolajczyk (1976)

Table 21 (*continued*)

Exposure conditions	Effect on exposed group	Reference
2.45 GHz (pulsed), 4.8 W/m^2, 0.15-0.4 W/kg, continuous exposure of rats from 2 to 27 months of age (lifetime exposure)	no differences in plasma endocrine levels between exposed and control animals	Johnson et al. (1983) Guy et al (1985)

7.3.6 *Haematopoietic and immune systems*

In a large number of studies, haematological effects have been found in animals exposed to RF, mainly when a significant rise in body temperature has been observed. Few effects have been reported in the absence of a detectable increase in temperature, as shown in Table 22. Athermal responses have not been established.

Smialowicz (1984) reviewed earlier studies and did not find any consistent effects of RF exposure on peripheral blood cells in developing rats. No consistent changes were found in erythrocyte, leukocyte, or differential leukocyte cell counts in rats exposed pre- and post-natally to RF fields.

RF exposure has been reported to affect various components of the immune system. Whilst both stimulatory and inhibitory responses have been reported, these have been mostly transient in nature and usually attributable to thermal stress.

Several authors have noted that exposure to thermogenic levels of RF will result in increased levels of circulating neutrophils and decreased levels of circulating lymphocytes (see Fig. 21 from Liburdy (1979) and Table 23). A lack of effect of low-level exposure on circulating blood cell count in rats has been reported in other studies. On the basis of his results, Liburdy (1979, 1980) suggested that whole-body RF exposure induces heat stress that activates the hypothalamic-hypophyseal-adrenal axis to trigger the release of adrenal steroids into the blood, leading to the transient changes in blood cell counts and other haematopoietic and immunological changes associated with RF exposure.

Table 22. Haematopoietic system effects

Exposure conditions	Effect on exposed group	Reference
Circulating blood cells		
800 MHz, 430 W/m^2 (average), 2 h/day, 5 day/week, for 35 weeks, SAR estimated at less than 1.5 W/kg	No change in erythrocyte count, haemocrit, or haemoglobin concentration in mice; 4 exposed mice died	Spalding et al. (1971)
2.95 GHz, 30 W/m^2 (average), for 158 h (CW or pulsed)	Decreased erythrocyte production in rabbits; pulsed exposure more effective	Siekierzynski (1972)
2.4 GHz (CW) 100 W/m^2 for 2 h/day, for up to 30 days, SAR approx 2 W/kg	Increased erythrocyte count; 1 ^{0}C rise in rectal temperature in rats	Djordjevic & Kolak (1973)
26 MHz(CW) SAR 13 W/kg, for up to 3 h; rectal temperature rose by 2-4 °C	Decreased peripheral lymphocytes, increased neutrophils in mice	Liburdy (1977)
2.45 GHz (CW) 300 W/m^2, for 30 min/day for 22 days, SAR 22 W/kg	No effect on peripheral blood cell count in mice	Smialowicz et al. (1979a)
2.4 GHz (CW) 50 W/m^2, 1 h/day for 90 days, SAR approx 1 W/kg	No effect on peripheral blood cell count in rats	Djordjevic et al. (1977)
970 MHz (CW) SAR 2.5 W/kg, 22 h/day for 70 days	No effect on blood count in rats	Smialowicz et al. (1981a)
2.45 GHz (CW) SAR 2.2 W/kg, for 8 h	No effect on peripheral blood cell count in rats	Galvin et al. (1982)
20 MHz (CW) SAR 0.3 W/kg, 6 h/day for up to 6 weeks	No effect on blood cells in rats	Wong et al. (1985)
2.45 GHz (CW), 5 W/kg 100 MHz (CW), 3 W/kg 425 MHz (CW), 7 W/kg	No consistent changes in erythrocyte or leukocyte counts in rats exposed pre- or postnatally, for up to 41 days	Smialowicz et al. (1979b, 1981b, 1982) Smialowicz et al. (1982)

Table 22 (*continued*)

Exposure conditions	Effect on exposed group	Reference
Bone marrow cells		
2.95 GHz (CW) 10 W/m^2, for 4 h/day for 14 days in guinea-pig; 4 h at 5 W/m^2 in mice	Shift in circadian rhythm of division of blast cells in bone marrow and lymphocytes; no statistical analysis, hence, response suggestive only	Czerski et al. (1974a); Czerski (1975)
2.45 GHz (CW), 150 W/m^2 SAR 11 W/kg, 30 min/day for 9 days	Reduced ability of mouse bone marrow cells to form myeloid or erythroid colonies *in vitro*	Huang & Mold (1980)
2.88 GHz (pulsed) SAR 4.5 W/kg, 7.5 h/day for 360 days	Significant but inconsistent alterations in bone marrow, blood cell and serum protein values in mice	Ragan et al. (1983)
General long-term studies		
2.45 GHz (CW), SAR 1.5 W/kg, 23 h/day for 180 days	41 parameters measured, only 3 of which changed; Lower eosinophil, serum albumin, and calcium levels in rabbits	McRee et al. (1980)
2.45 GHz (pulsed) SAR 0.15-0.4 W/kg, for 25 months	No effect on haematology or serum chemistry parameters in rats	Guy et al. (1985)

Exposure to thermogenic levels of RF fields has been shown to cause several effects including a depression of natural killer cell activity, implicated, for example, in tumour cell cytolysis, and macrophage activation. One group of workers (Wiktor-Jedrzejczak et al., 1977a,b, 1980) reported an increase in the number of lymphocytes bearing a surface marker (complement receptor) in mice exposed to high levels of microwave radiation. Smialowicz et al. (1979a) were unable to replicate this effect using a different strain of mouse. This difference in response between the two strains may be due to the presence of a single gene located on chromosome 5 (Schlagel et al., 1980, 1982). At present, this remains an unresolved issue.

Table 23. Immune system effects

Exposure conditions	Effect on exposed group	Reference
Mitogen response - blast transformation		
2.45 GHz (CW) SAR 21 W/kg, 15 min/day, for 5 days	Transient increase in transformation rate of peripheral blood lymphocytes (to lymphoblasts) in Chinese hamsters, decreased mitotic frequency in mitogen-stimulated lymphocytes	Huang et al. (1977)
2.45 GHz (CW) up to 150 W/m^2 SAR 11 W/kg, 30 min/day, for 17 days	Altered mitogen response of T- and B- lymphocytes in Balb/c mice	Huang & Mold (1980)
2.45 GHz (CW) up to 300 W/m^2 SAR 22 W/kg, 30 min/day, for 22 days, or 11 W/kg, 1.5 h/day, for 9 days	No effect on mitogen response of T- and B- cells in Balb/c mice or CBA/J mice	Smialowicz et al. (1979a, 1983)
10.5, 19.27, 26.6 MHz (CW) up to 2 W/kg, for 30 min	Enhanced mitogen response in lymphocytes from rhesus monkeys; rectal temperature increased up to 2.5 °C.	Prince et al. (1972)
Surface (complement receptor) marker		
2.45 GHz (CW) up to 15 W/kg, for 30 min	Increased lymphocytes with surface marker (complement receptor) in CBA/J mice	Wiktor-Jedrzejczak et al. (1977a,b,1980)
2.45 GHz (CW) up to 22 W/kg, for 30 min on 22 consecutive days	No increase in complement-receptor positive lymphocytes in Balb/c mice	Smialowicz et al. (1979a)
2.45 GHz (CW) 14 W/kg	Increase in complement-receptor positive lymphocytes in >12-week-old CBA/J mice; no effect in BALB/c mice	Schlagel et al. (1980, 1982)
2.45 GHz (CW) 28 W/kg	Increase in complement-receptor positive lymphocytes in 16-week-old CBA/J mice	Smialowicz et al. (1981c)

Table 23 (*continued*)

Exposure conditions	Effect on exposed group	Reference
Lymphocyte circulation		
26 MHz (CW); 5.6 W/kg, for 15 min (single or repeated) in warm air environment; rectal temperatures rose by 2-3 °C	Reduced mouse peripheral lymphocytes; increased neutrophils, T- and B- cells in spleen, elevated corticosteroid levels	Liburdy (1979)
2.6 GHz (CW), for 1 h	Lymphocyte circulation, lung, spleen, and bone marrow - changes only when rectal temperature of mice increased;	Liburdy (1980)
at 19 W/kg:	Altered significantly;	
at 3.8 W/kg:	Not affected	
Macrophage/NK T-cell activity		
2.45 GHz (CW); SAR 13 W/kg	Activation of macrophages in hamsters (depressed killer T-cell activity)	Rama Rao et al. (1983)
2.45 GHz (CW) for 1 h	Natural killer T-cell activity in hamster: (Changes due to heat stress?)	Yang et al. (1983)
at 13 W/kg, colon temperature >3 °C:	Transient decrease	
at 8 W/kg:	Unchanged	
2.45 GHz (CW); 21 W/kg; Increased rectal temperature	Transient decrease in killer T-cell activity; increased macrophage activity in mice	Smialowicz et al. (1983)
2.45 GHz (CW); 22 W/kg 5 × 30 min; no significant rectal temperature increase	No change in killer T-cell activity in mice; increased macrophage activity	Huang & Mold (1980)
Antibody response		
9 GHz (pulsed); 100 W/m^2 (average) SAR 4.7 W/kg, 2 h/day for 5 days	Stimulation of antibody response and increased survival time of mice injected with pneumococcal polysaccharide	Liddle et al. (1980)

Table 23 (*continued*)

Exposure conditions	Effect on exposed group	Reference
2.375 GHz (CW); 0.1, 0.5, 5.0 W/m^2, for 7 h/day for 45 days	Appearance of circulating autoantibodies in rats against brain and liver tissue and antibodies against fetal tissue in pregnant dams only at 5.0 W/m^2	Shandala & Vinogradov (1982, 1990)
As above, except SAR 0.47 W/kg	No effect on normal antibody response and survival	Liddle et al. (1986)
2.45 GHz (CW), for 1 h	Primary antibody response of spleen lymphocytes to sheep RBCs in hamsters:	Rama Rao et al. (1985)
8 - 13 W/kg	increased	
< 8 W/kg	no change	
Long-term: Juveniles/adults		
2.45 GHz (CW), up to 5 W/kg, for up to 41 days of age	Increased lymphocyte response to T- and B-mitogens in rats	Smialowicz et al. (1979b)
425 MHz (CW), up to 7 W/kg, for up to 41 days of age	Same as above	Smialowicz et al. (1982)
100 MHz (CW), SAR 2-3 W/kg, for 4 h/day, until 97 days of age	No effect on blood cell count, mitogen or antibody response in rats	Smialowicz et al. (1981b)
2.45 GHz (10 μs pulses, 800 Hz) 4.5 W/m^2, SAR 0.15-0.4 W/kg, up to 27 months of age	No significant differences in immunological parameters in rats; transient change in lymphocyte count and responsiveness at 13 months	Guy et al. (1985)

The results of studies on the developing immune system, shown in Table 23, may indicate an effect of the higher SARs on lymphocyte responsiveness. This effect is consistent with other reports and with observations of increased lymphocyte activity elicited by conventional heating (Roberts, 1979).

A lifetime exposure study (Guy et al., 1985) in which rats were exposed to up to 0.4 W/kg between 2 and 27 months of age did not reveal any effects on haematological or immunological parameters, except for a transient change in the number and responsiveness of B- and T-lymphocytes to specific mitogens after 13 months exposure.

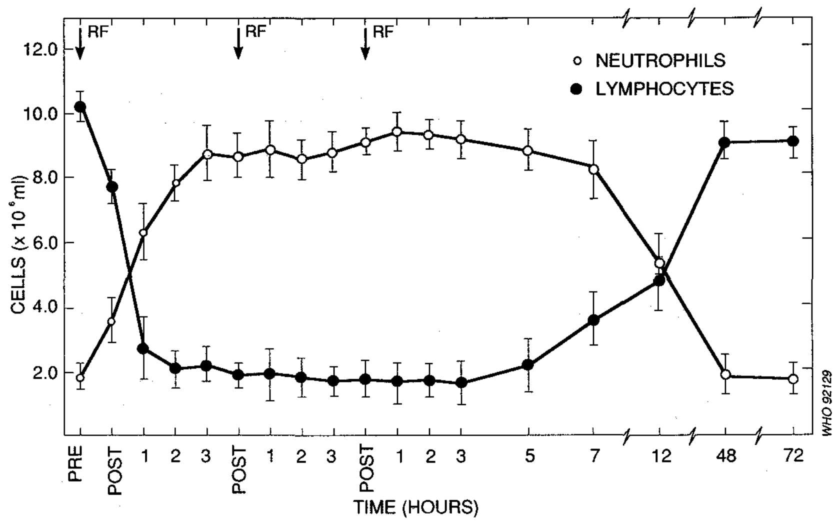

Fig. 21. Changes in neutrophil and lymphocyte counts in mice after repeated exposure to RF fields. "Pre" and "post" indicate counts immediately before and after RF exposure, respectively. Values represent means ± standard deviations. From: Liburdy (1979).

7.3.7 *Cardiovascular system*

The responses of the intact cardiovascular system to exposure to RF, as shown in Table 24, are consistent with those associated with conventional heating. Hence, depending on the ambient temperature, the SAR, and duration of exposure, increases in heart rate (tachycardia), no change, or decreases in heart rate (bradycardia) can be induced during, and following, RF exposure.

Table 24. Cardiovascular system effects

Exposure conditions	Effect on exposed group	Reference
During exposure		
2.45 GHz (CW); 100 W/m^2, SAR 2 W/kg, for 20 min applied to heads	No heart rate effects in rabbits	Birenbaum et al.(1975)
2.45 GHz (CW), 50 or 800 W/m^2 or 50 W/m^2 (pulsed) whole-body SAR up to 15 W/kg	Increased heart rate only at 800 W/m^2 in rabbits; normal response to heating	Chou et al. (1980)
2.45 GHz (CW); SAR 2.3 W/kg for 6 h	No effect on arterial blood pressure, but heart rate reduced by 10% in rats	McRee et al. (1988)
4 GHz, CW or amplitude-modulated at 16 Hz (70% mod.), for 30 min, SAR in cortex 8.4, 16.8, or 42 W/kg	Transient bradycardia during CW or modulated RF in anaesthetized rats	Mangel et al. (1990)
After exposure		
2.45 GHz (CW), 30 min to SARs up to 11.1 W/kg in rats; environmental temperature 24 °C	At 6.5 W/kg, mild bradycardia in rats for up to 3 h; at 11.1 W/kg, pronounced bradycardia for 2 h, followed by mild tachycardia and irregular heart rate for short periods; threshold between 4.5 and 6.5 W/kg	Phillips et al. (1975)
915 MHz (CW), SAR 2.5 W/kg, for 8 h/day, 5 days/week, for 16 weeks	No change in heart weight in rats	D'Andrea et al. (1980)
435 MHz (pulsed: 1 μs pulses at 1000 Hz) 10 W/m^2 whole-body SAR approx 0.35 W/kg, for 22 h/day over 6 months	No change in resting heart rate or mean arterial blood pressure in rats	Toler et al. (1988)

An increase in cardiac output, heart rate, and blood pressure, coupled with a decrease in peripheral resistance, has been reported in rabbits exposed at SARs estimated at 10-15 W/kg (raising body temperatures 0.5 °C) and in anaesthetized rats exposed at levels that increased body temperature by about 3.5 °C. Following exposure, heart rate decreased; the threshold for this effect was between 4.5 and 6.5 W/kg. Long-term exposure of rats at SARs of between 0.3 and 2.5 W/kg did not affect heart rate or heart weight.

7.3.8 Reproduction and development

The assessment of the toxic effects of an agent on fertility and the development of the embryo and fetus are of great importance. The processes of meiosis, fertilization and implantation, and the high rates of cell division and differentiation during development of the embryo and fetus tend to be more susceptible to toxic insults than many other processes in the tissues of the adult organism.

7.3.8.1 kHz studies

Studies in the kHz range are summarized in Table 25. The fields used are generally of the type generated by clinical exposure systems or by some types of visual display units. These studies have not shown consistently reproducible effects. Exposure of developing chick embryos to pulsed electromagnetic fields, including a signal of the type used clinically for bone healing, for up to a week, had no effect on malformation incidence (Sisken et al., 1986). Studies of effects on mammals are of greater relevance to human health.

Two teratological studies (Tribukait et al., 1987; Stuchly et al., 1988) on the effects of magnetic fields of the type used in VDUs reported increased numbers of malformed fetuses in rodents, but, when the results were analysed using the litter rather than the individual fetus as the unit of observation, the increases were not significant (Stuchly et al., 1988).

Table 25. Teratological studies in the kHz region

Exposure conditions	Effect on exposed group	Reference
Chicks		
Pulsed magnetic fields 10, 100, or 1000 Hz; up to 1.2 μT, for first 48 h of development	Abnormal development, particularly in cephalic region; effect most marked at 100 Hz	Delgado et al. (1982).

Table 25 (*continued*)

Exposure conditions	Effect on exposed group	Reference
Pulsed electromagnetic fields, 3.8 kHz, 50 ms burst repeated at 2 Hz (0.25 mT peak) or 4.4 kHz, 5 ms burst repeated at 15 Hz (1.6 mT) to embryos for first 24 h or 7 days of development	No significant increase in incidence of abnormalities	Sisken et al. (1986)
20 kHz sawtooth magnetic fields 0.1-16 μT applied to embryos for first 42 or 47 h of development	No effect on incidence of malformation	Sandstrom et al. (1987)
Mammals		
20 kHz sawtooth magnetic fields 1 or 15 μT applied to embryos on days 0-14 of gestation	Significant increase in number of mouse fetuses with external malformations at 15 μT (difference not significant if analysed by litter (Stuchly et al., 1988)	Tribukait et al. (1987)
20 kHz sawtooth magnetic fields 15 μT applied to embryos on days 0-19 of gestation	Increased number of implants and post-implantation deaths in mice; no effect on incidence of malformation	Frolen et al. (1987)
19 kHz sawtooth magnetic fields 5.7, 23, for or 66 μT, for 7 h/day, before and during gestation	No effect on post-implantation survival in rats; increase in minor skeletal defects in highest exposure group, but only if analysed by individual fetus and not by litter	Stuchly et al. (1988)

7.3.8.2 MHz and GHz studies

(*a*) *Fertility*. Most of the studies on reproduction and development in small mammals exposed to RF radiation have shown effects that can be related to an increase in temperature, and can be produced by thermal stress alone. It is well known that, in many species of mammal, the development of male germ cells can be adversely affected by increased testicular temperatures. The studies shown in Table 26 indicate that acute RF exposure of anaesthetized animals can, through raising testicular temperature, affect the spermatogenic

Table 26. Effects on male fertility

Exposure conditions	Effect on exposed group	Reference
Anaesthetized		
2.45 GHz (CW), or direct heating of lower half of body, for 30 min	Depletion of primary spermatocytes and spermatids in mice; threshold temperature for depletion 39 °C or SAR of 30 W/kg or greater; increased number of abnormal sperm at higher temperatures	Saunders & Kowalczuk (1981); Kowalczuk et al. (1983)
1.3 GHz (pulsed), 8-10 W/kg, for 60 min or more	Depletion of primary spermatocytes and spermatids in rats; threshold temperature 39-41 °C	Lebovitz et al. (1987)
Conscious		
2.45 GHz (CW), up to 20 W/kg, 16 h/day, for up to 30 days	No effect on sperm count or number of abnormal sperm in conscious mice	Cairnie & Harding (1981)
2.45 GHz (CW), 5 W/kg, for 120 h over 8 weeks, then mice mated over next 8 weeks	No effect on conscious, male mouse fertility, pregnancy rates	Saunders et al.(1988)
2.45 GHz (CW), 5.6 W/kg, for 80 h over 4 weeks	Transient reduction in conscious, male rat fertility, 50% of dams mated 3-9 days after irradiation of males showed pregnancies; rectal temperature 41 °C	Berman et al. (1980)
1.3 GHz (pulsed), 6.3 W/kg, 6 h/day for 9 days	No effect on sperm production, sperm morphology, testes mass, etc. in rats; body temperature rise of 1.5 °C; no effect on different stages of spermatogenesis, except for a reduction in heat sensitive pachytene spermatocytes	Lebovitz & Johnson (1983); Johnson et al. (1984)
1.3 GHz (CW), 9 W/kg, for 8 h, rectal temperature rise 4.5 °C	No differences in testicular function of conscious rats	Lebovitz & Johnson (1987)

epithelium and, thus, male fertility. However, the anaesthesia will have altered the animals' abilities to regulate their testicular temperatures (usually maintained 3-4 °C below body temperature). The exposure of conscious animals has been found to have little effect on testicular function, except after prolonged exposure at thermally significant levels. Male rats, exposed long-term at about 6 W/kg, showed a slight reduction in potential sperm production by the heat-sensitive pachytene spermatocytes (Johnson et al., 1984) and were reported to be temporarily less fertile (Berman et al., 1980).

(*b*) *Developmental (teratogenic) effects.* Exposure to high levels of RF will induce significant rises in maternal body temperature, and result in deformities or defects in the offspring, as shown in Table 27. O'Connor (1980) concluded, from a review of the teratogenic effects of exposure to RF, principally in mice and rats, that intense exposures that result in significant maternal heating can result in reduced fetal mass, specific abnormalities (especially exencephaly), and in increased embryo and fetal losses. For rats, most of the significant results were based on intense levels of exposure. The most commonly reported defects were decreased fetal mass and increased embryo and fetal losses.

RF teratogenesis has also been demonstrated in mice, though generally at higher SARs. In one study, it was reported that RF exposure at around 4-5 W/kg enhanced the effect of a chemical teratogen.

In their review, Lary & Conover (1987) concluded that heat causes birth defects and pre-natal mortality, when the temperature of the pregnant mother exceeds 40 °C. Exposure that increases the core temperature of pregnant dams to 39-41 °C does not usually result in gross structural malformations, but may significantly increase the incidence of pre-natal mortality, result in lower body weight, cause histological or physiological changes, or alter the behaviour of the exposed offspring. They suggest that only exposures that have an appreciable heating effect are likely to affect the human embryo adversely. In contrast, one study described teratological effects in rats after exposure to 27.12 MHz at a whole-body SAR of 10^{-4} W/kg. However, these results are difficult to reconcile with those of many other studies carried out at the same frequency.

Table 27. Teratogenic effects in the MHz-GHz region

Exposure conditions	Effect on exposed group	Reference
Rats		
27.12 MHz (CW), approx. 11 W/kg, for 20-40 min; rectal temperature to 43 °C	Embryo and fetal deaths, and abnormalities at all stages of development	Lary et al. (1982)
27.12 MHz (CW), 33 kV/m, 0.8 A/m; mated rats exposed on day 9 of gestation; temperature increase maintained at 2.5-5 °C	Various effects in offspring related to temperature increase and duration of exposure	Brown-Woodman et al. (1988)
27.12 MHz (CW), 1 W/m^2, 0.1 mW/kg, fetuses exposed from day 0 to 20 of gestation	Decreased post-implantation survival, reduced cranial ossification in exposed rat fetuses	Tofani et al. (1986)
6 GHz (CW), approx. 7 W/kg, for 8 h/day, throughout pregnancy	Slight growth retardation in fetuses, no increased deaths or structural abnormalities	Jensh (1984a,b)
2.45 GHz (CW), 4 or 6 W/kg, for 100 min/day, from day 6 to 15 of gestation	Maternal temperature raised to 40 °C; no abnormalities in fetuses; offspring exposed to higher levels had lower mean body weight	Berman et al. (1981); Berman & Carter (1984)
2.45 GHz (CW), 2-4 W/kg, for 6 h/day throughout gestation	No rectal temperature increase; no excess abnormalities in fetuses; no altered performance in neonatal reflex tests or adult behaviour, except increased activity in exposed offspring	Jensh et al. (1983a,b)
915 MHz (CW), 3.5 W/kg, for 6 h/day throughout pregnancy	No anatomical defects in fetuses or behavioural alterations; maternal temperature not increased	Jensh et al. (1982a,b)
100 MHz (CW), 0.4 W/kg, for 400 min/day, on days 6-11 of gestation	No teratogenic or embryogenic effects in offspring of rats	Lary et al. (1983b)
2.45 GHz (CW), 0.4 W/kg throughout gestation	No effects on weight and DNA or RNA content of fetal rat brain	Merritt et al. (1984)

Table 27 (*continued*)

Exposure conditions	Effect on exposed group	Reference
Hamster		
2.45 GHz (CW), 6 or 9 W/kg, for 100 min/day, during days 6-14 of gestation of hamster fetuses	Maternal rectal temperature increase 0.4 and 1.6 °C; no effect in low-exposure group; increased fetal deaths, decreased fetal weight, and decreased skeletal maturity in high-exposure group	Berman et al. (1982b)
Mice		
2.45 GHz (CW), 2.8 or 22 W/kg, for 100 min/day, throughout gestation	Mean mass of live fetuses decreased in high-exposure group	Berman et al. (1978)
2.45 GHz (CW), 7, 28, or 40 W/kg, 8 h/day, for various times during gestation	At 40 W/kg: reduced no. implantation sites per litter and fetal weight, and increased malformations	Nawrot et al. (1981)
2.45 GHz (CW), 16 W/kg, for 100 min/day during days 6-17 of gestation	Lower fetal weight, delayed skeletal maturation, lower brain weight in exposed fetuses	Berman et al. (1982a, 1984)
2.45 GHz (CW), 4-5 W/kg, for 2 h/day and 7 days per week from days 1 to 7, days 8 to 18, or days 1 to 18 of gestation	No teratogenic effects in offspring of exposed animals	Chazan et al. (1983)
2.45 GHz (CW), 1 or 10 W/m^2 (equal to 0.5, 4-5 W/kg) for 2 h/day, from day 1 to 18 of gestation	At 4-5 W/kg: reduced fetal body mass; exposure combined with injection of cytosine arabinocide enhanced incidence of abnormalities compared with those on drug alone	Marcickiewicz et al. (1986)

7.3.9 Genetics and mutagenesis

Since the potential to induce heritable changes would be of particular importance for protection standards, many studies designed to examine the genetic consequences of exposure have been conducted. Studies examining the possible hereditary consequences of RF exposure are listed in Table 28, including those on germ cell chromosome aberration frequencies and dominant lethal mutation

Table 28. Genetic and mutagenic effects

Exposure conditions	Effect on exposed group	Reference
Somatic cells		
2.45 GHz (CW), up to 21 W/kg (*in vivo*), rectal temperature rose by up to 1.6 °C	No increase in unstable chromosome aberrations in Chinese hamster blood lymphocytes	Huang et al. (1977)
2.45 GHz (CW), 21 W/kg, 8 h/day for 28 days	No sister chromatid exchanges in mouse bone marrow cells	McReé et al. (1981)
2.375 GHz (CW) and 2.75 GHz (pulsed). 0.1, 0.5, 5.0 W/m^2 7 h/day for 45 days	Partial hepatectomy in rats 5-6 days after exposure; cytological study showed decreased rate of chromosomal aberrations after 0.1 and 0.5 W/m^2; increased after 5.0 W/m^2	Antipenko & Koveshnikova (1987)
Germ cells		
2.45 GHz (CW), 0.05-20 W/kg, for 6 h over 2 weeks	Increased chromosome exchanges and other cytogenetic abnormalities in germ cells exposed as spermatocytes;	Manikowska - Czerska et al. (1985)
2.45 GHz (CW), 0.05-20 W/kg, for 6 h over 2 weeks	No chromosome abnormalities in germ cells exposed as stem cells; rectal temperature in 20 W/kg group rose by up to 3 °C	Beechey et al. (1986)
1.7 GHz (CW), 25-45 W/kg, for 30 min, or 5-9 W/kg, for 40 min over 2 weeks	Induction of dominant lethal mutations in exposed mice; data inclusive	Varma & Traboulay (1977)
2.45 GHz (CW), 1.7 kW/m^2, for 70 s	Increased dominant lethality reduced male fertility	Goud et al. (1982)
2.45 GHz (CW), 43 W kg, for 30 min	No change in dominant lethality, but reduced pregnancy rate and pre-implantation survival	Saunders et al. (1983)
2.45 GHz (CW), 5 W/kg, for 120 h over 8 weeks	No chromosomal abnormalities; no change in pregnancy rate or dominant lethality	Saunders et al. (1988)
2.45 GHz (CW) at 50 W/m^2 (0.9-4.7 W/kg) 4 h/day for > 90 days - at 100 W/m^2, 5 h/day for 5 day - at 280 W/m^2, 4 h/day, 5 days/week over 4 weeks	No consistent pattern of responses, increased fetal mortality not related to decreased live fetuses; no sperm cell mutagenesis	Berman et al. (1980)

frequencies (assessed as the decreased survival of implanted embryos and fetuses). Much experimental evidence suggests that acute or long-term RF exposures do not result in an increase in chromosome aberration frequency, when temperatures are maintained within physiological limits. One study reported an increased frequency of cytogenetic effects in mice exposed long-term at SARs between 0.05 and 20 W/kg. However, this study was not successfully corroborated using a different strain of mouse.

In general, the data in Table 28 suggest that the only exposures that are potentially mutagenic are those at high RF power densities, which result in substantial increase in temperature.

7.3.10 *Cancer-related studies*

A summary of cancer-related animal studies is given in Table 29. The number and types of studies are limited.

Exposure to RF levels sufficiently high to induce hyperthermia has generally resulted in tumour regression following transplantation of tumour cells (Preskorn et al., 1978; Roszkowski et al., 1980). In contrast, an increase in tumour progression has been observed in mice exposed long-term at lower, possibly thermogenic, SARs (Szmigielski et al., 1982). This effect was related to a non-specific stress. The authors suggested a transient shift in immune surveillance resulting in a lowering of resistance to neoplastic growth, as a likely explanation. Exposure at about 1 W/kg did not have any effect on melanoma growth in mice (Santini et al., 1988).

The effects of exposure on spontaneous or chemically-induced tumours have also been examined. In contrast to transplantation studies, these can test for an effect on the process of carcinogenesis. Two early studies (Prausnitz & Suskind, 1962; Skidmore & Baum, 1974), relevant to cancer induction, but in which the methodology was flawed in relation to an analysis of this end-point, are described for completeness. An increased incidence of monocytic leukosis (defined as a non-circulating neoplasm of white-blood cells) and lymphatic or myeloid leukaemia (defined as a circulating "leukosis") was reported in Swiss mice exposed to thermally significant levels (half the acute LD_{50}) of 9.27 GHz pulsed RF, for 5 days per week

Table 29. Cancer-related studies

Exposure conditions	Effect on exposed group	Reference
Transplanted tumour cells		
2.45 GHz (CW), 35 W/kg, for 20 min/day during days 11-14 of gestation; offspring injected with sarcoma cells at 16 days of age exposed for 36 days	Retarded tumour growth and tumour incidence in sarcoma-injected offspring of exposed pregnant mice; rectal temperature of dams rose over 2 °C; exposed mice had increased longevity	Preskorn et al. (1978)
2.45 GHz (CW), 25 W/kg, 2 h/day for 7 days; Injection of sarcoma cells in mice 14 days after, or just after, RF exposure	Temporary tumour regression followed by renewed tumour growth 12 days later, when exposure 14 days after tumour injection; accelerated tumour growth, if exposed before implantation of tumour; lung metastases increased	Roszkowski et al. (1980)
2.45 GHz (CW), 2-3 W/kg or 6-8 W/kg, 2 h/day, for 6 days/week; mice exposed from 6 weeks of age to 12 months of stress	RF caused increase in sarcoma colonies in lungs in mice injected intravenously with these cells; chronic via confinement caused similar increase in lung tumours as 2-3 W/kg, but 6-8 W/kg produced higher increase in tumours	Szmigielski et al. (1982)
2.45 GHz (CW and pulsed) 10 W/m^2, 1.2 W/kg prior to, and during, B16 melanoma tumour transplantation and growth; exposed for 2.5 h/day, 6 times/week for 15 days, prior to injection of melanoma cells, then exposed to same schedule until death	No difference in mean tumour surface area/animal, or in mean survival time between exposed or control mice	Santini et al. (1988)
Spontaneous or chemically-induced tumours		
2.45 GHz (CW), 2-3 W/kg or 6-8 W/kg, 2 h/day, for 6 days/week, mice exposed from 6 weeks of age to 12 months of stress	SAR-dependent acceleration of mammary tumours in mice genetically predisposed to these tumours, and acceleration of skin tumours in mice painted with the carcinogen 3,4-benzopyrene (BP)	Szmigielski et al. (1982)

Table 29 *(continued)*

Exposure conditions	Effect on exposed group	Reference
2.45 GHz (CW), 100 W/m^2 4-5 W/kg, for 2 h/day, 5-6 days/week for a few months	Increased development of chemically-induced hepatomas and sarcomas in mice; survival of exposed mice decreased; increased frequency of skin tumours in mice given subcarcinogenic dose of BP	Szmigielski et al. (1988)
2.45 GHz (10 μs pulses at 800 Hz) square wave-modulated at 8 Hz, 0.4 W/kg, continuous exposure at 2-27 months of age (lifetime study of rats)	Total incidence of neoplasia not significantly different from that in controls; however, increased number of primary malignancies (18) occurred early in exposed group compared with controls (5)	Guy et al. (1985)

for 59 days (Prausnitz & Susskind, 1962). However, the study suffered several deficiencies: leukosis and leukaemia were inadequately defined, infection may well have confounded the results, a large proportion of mice died without a cause of death being identified, and statistical analysis was absent (Roberts 1983; Kirk 1984).

Skidmore & Baum (1974) reported that exposure for 5 days per week for 33 weeks to very short pulses (5 ns rise time; 550 ms decay time) of high field strength (447 kV/m) pulsed at 5 Hz, resulted in a reduced incidence of leukaemia in AKR/J mice (which spontaneously develop a high incidence of lymphatic leukaemia between 26 and 52 weeks of age) compared with controls at the end of the exposure. However, the absence of a complete analysis of leukaemia incidence (and other causes of death) precludes any conclusion being drawn from this study. The authors also reported a zero incidence of mammary tumours in 1-year-old female Sprague-Dawley rats that had been exposed for 38 weeks; evaluation was probably premature for this end-point, the tumours occur spontaneously mainly in older rats. A later study (Baum et al., 1976) reported no effects on mammary tumour incidence and other lesions in rats exposed for 94 weeks.

Two studies merit particular attention. The long-term exposure of mice at SARs of between 2 and 8 W/kg resulted in an increase in the number of sarcoma cell colonies in the lungs (following the injection of sarcoma cells), as shown in Fig. 22, and in an SAR-dependent increase in the rate of development of spontaneous mammary tumours and chemically-induced skin tumours. Repeated microwave exposure, followed by a "sub-carcinogenic" dose of carcinogen, resulted in an increased number of skin tumours. A study of 100 rats exposed for most of their lifetime at about 0.4 W/kg did not show any increased incidence of non-neoplastic lesions compared with control animals; longevity was very similar in both groups. However, the overall incidence of primary malignancy in the exposed group (18) was significantly greater than the control

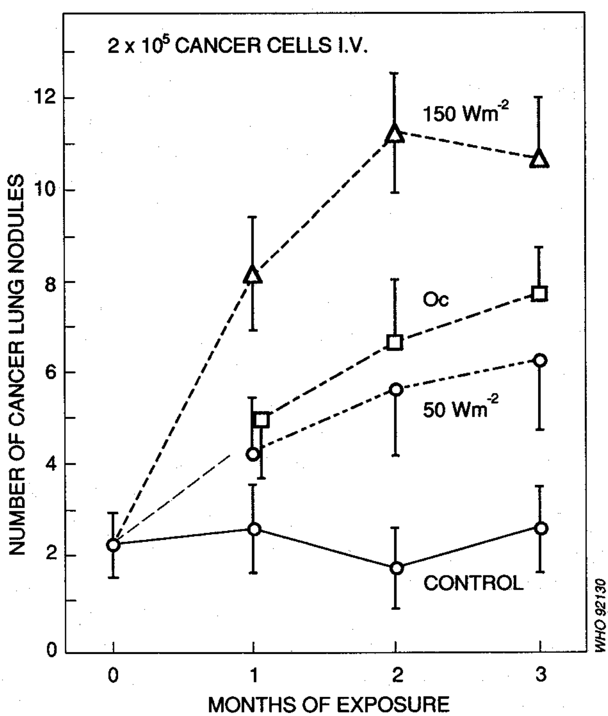

Fig. 22. Number of lung tumours (following intravenous injection of 2×10^5 viable sarcoma cells) in mice exposed to 2.45 GHz microwaves or non-specific stress (overcrowding; O_c). From Szmigielski et al. (1988).

value (5), but was reported to be similar to the spontaneous incidence given in the literature for the particular strain of rat. Under these circumstances, it is difficult to draw any firm conclusions.

Tumour weights were not significantly different in rats implanted with mammary adenocarcinoma tissue and either exposed 25 days later to 2 kHz magnetic fields of up to 2 mT for 1 h a day for 9 days or not exposed (Baumann et al., 1989). Handling and restraint stress in animals were identified as possible confounders for the detection of subtle magnetic field effects.

7.3.11 Summary and conclusions

Most of the biological effects of acute exposure to RF fields are consistent with responses to induced heating, resulting either in rises in tissue or body temperature of about 1 °C or more, or in responses for minimizing the total heat load. Most responses in different animal species, exposed under various environmental conditions, have been reported at SARs above about 1-2 W/kg.

These animal (particularly primate) data indicate the types of response that are likely to occur in humans subject to a sufficient heat load. However, direct quantitative extrapolation to humans is difficult, given species differences in responses, in general, and in thermoregulatory ability particularly.

The most sensitive animal responses to heat loads are thermoregulatory adjustments, such as reduced metabolic heat production and vasodilation, with thresholds ranging between about 0.05 and 5 W/kg, depending on environmental conditions. However, these reactions form part of the natural repertoire of thermoregulatory responses that serve to maintain normal body temperatures.

Transient effects seen in exposed animals that are consistent with responses to increases in body temperature of 1 °C or more (and/or SARs in excess of about 2 W/kg in primates and rats) include the reduced performance of learned tasks and increased plasma cortico-steroid levels. Other heat-related effects include temporary haemato-poietic and immune responses, possibly in conjunction with elevated corticosteroid levels. The most consistent effects observed are reduced levels of circulating lymphocytes and increased levels of neutrophils, decreased natural killer cell function, and increased macrophage activation; an increase in the primary antibody response of B-lymphocytes has also been reported. Cardiovascular changes consonant with increased heat load, such as increased heart rate and cardiac output, have been observed, together with a reduction in the effects of drugs, such as barbiturates, the action of which can be altered by changes in circulation and clearance rates.

Most animal data indicate that implantation and the development of the embryo and fetus are unlikely to be affected by exposures that increase maternal body temperature by less than 1 °C. Above these temperatures, adverse effects, such as losses in implantation, growth retardation, and post-natal changes in behaviour, may occur, with more severe effects occurring at higher maternal temperatures.

Most animal data suggest that low RF exposure that does not raise body temperatures above the normal physiological range is not mutagenic; thus, such exposure will not result in somatic mutation or hereditary effects.

There is much less information describing the effects of long-term, low-level exposure. So far, it is not apparent that any long-term adverse effects can result from exposures below thermally significant levels. The animal data indicate that male fertility is unlikely to be affected by long-term exposure at levels insufficient to raise body and testis temperatures. Cataracts have not been induced in rabbits exposed at 100 W/m^2 for 6 months, or in primates exposed at 1.5 kW/m^2 for 3 months.

A study of 100 rats, exposed for most of their lifetime at about 0.4 W/kg, did not show an increased incidence of non-neoplastic lesions or total neoplasias compared with control animals; longevity was very similar in both groups. There were differences in the overall incidence of primary malignancies, but these could not necessarily be attributed to the RF exposure. The possibility that exposure to RF might influence the process of carcinogenesis is of particular concern. So far, there is no definite evidence that RF exposure does have an effect, but there is clearly a need for further studies to be carried out. Overwhelmingly, the experimental data indicate that RF fields are not mutagenic, and so they are unlikely to act as initiators of carcinogenesis. In a few studies, evidence has been sought of an enhancement of the effect of a known carcinogen.

The long-term exposure of mice at 2-8 W/kg resulted in an increase in the progression of spontaneous mammary tumours and of skin tumours in mice the skin of which was tested with a chemical carcinogen. Repeated RF exposure followed by a "sub-carcinogenic" dose of carcinogen resulted in an increased number of skin tumours; however, this study has been reported only briefly, and the authors noted the need for experimental confirmation.

In *in vitro* studies, enhanced cell transformation rates were reported after RF exposure at 4.4 W/kg (alone or combined with X-radiation) followed by treatment with a chemical promotor. The latter data have not always been consistent between studies. It is clear that studies relevant to carcinogenesis need replicating and extending further, to reduce uncertainties in this area.

A substantial body of data exists describing *in vitro* biological responses to amplitude-modulated RF radiation at SARs too low to involve any response to heating. Some studies have reported effects after exposure at SARs of less than 0.01 W/kg, occurring within modulation frequency "windows" (usually between 1 and 100 Hz) and sometimes within power density "windows".

Changes have been reported in the electroencephalograms of cats and rabbits, in calcium ion mobility in the brain tissue *in vitro* and *in vivo*, in lymphocyte cytotoxicity *in vitro*, and in the *in vitro* activity of an enzyme involved in cell growth and division. Some of these responses have been difficult to confirm, and their physiological or pathological consequences are not clear. However, any toxicological investigation should be based on tests carried out at appropriate levels of exposure. It is important that these studies be confirmed and extended to *in vivo* studies and that the health implications, if any, for exposed people are determined. Of particular importance, would be studies that link extremely low frequency, amplitude-modulated RF interactions at the cell surface with changes in DNA synthesis or transcription. It is worth noting that this interaction implies a "demodulation" of the RF signal at the cell membrane.

8. HUMAN RESPONSES

Epidemiology can be defined as the study of the occurrence of illness; its main goals are to evaluate hypotheses about the causation of illness and to relate disease occurrence to the characteristics of people and their environment. Epidemiological studies of human populations exposed to RF fields are few in number and are generally limited in scope. The principal groups studied have been people occupationally exposed in the military or in industry. Information about worker health status has generally come from medical records, questionnaires, and physical and laboratory examinations. Exposure data have come from personnel records, questionnaires, environmental measurements, and equipment-emission measurements. Determination of actual exposure to RF fields and to other risk factors for the same outcome is difficult in retrospective human studies.

Some studies of controlled exposures of volunteers have provided valuable information on responses to RF exposure. These studies include warming and pain thresholds for RF heating of the skin, RF hearing, and RF shocks and burns. Clinical studies of accidental overexposures provide information on acute-exposure responses.

8.1 Laboratory studies

8.1.1 Cutaneous perception

Exposure of the human body to RF fields can cause heating that is detectable by the temperature-sensitive receptors in the skin. Several investigators have determind experimentally the threshold intensities that cause sensations of perceptible warmth, pain, and delay in response to the stimulus in human subjects, as shown in Table 30.

Adair (1983a) noted that RF exposures to frequencies of 30 GHz and above would probably be similar to infrared in their perception threshold values. However, over much of the RF spectrum, current standards are set at levels that are below those that most would consider detectable by sensation. Thus, cutaneous perception may be an indicator of exposure only at RF frequencies of the order of several gigahertz or more, which have wavelengths that are small in comparison with the length of the exposed body, i.e., wavelengths comparable with, or smaller than, the thickness of skin. Under these conditions, most of the energy is absorbed in the outer tissue layers

Table 30. Cutaneous perception in humans

Exposure conditions	Effects and thresholds	Reference
3 GHz to inner forearm Area 9.5 cm^2 at 31 kW/m^2: at 8.3 kW/m^2: Area 53 cm^2 at 5.6 kW/m^2:	Threshold for pain 20 s latency 180 s latency 180 s latency Pain at skin temperature of 46 °C	Cook (1952)
3 GHz (pulsed) to inner forearm (area 13 cm^2) 3-25 kW/m^2	Latency varied between less than 0.5 and 3.5 s	Vendrik & Vos (1958)
3 and 10 GHz (pulsed) 3 GHz, 1 s: 3 GHz, 5 s: 10 GHz, 1 s: 10 GHz, 5 s:	Threshold for perception: 600 W/m^2 320 W/m^2 190 W/m^2 130 W/m^2 Delay in response to warming 2.4-6.6 s	Hendler & Hardy (1960); Hendler et al. (1963); Hendler (1968)
2.88 GHz applied to forehead area 38 cm^2 at 740 W/m^2: at 560 W/m^2:	Delay in response: 15-73 s 50-180 s	Schwan et al. (1966)
2.45 GHz (cw), 10 s to forearm, area 100 cm^2	Threshold for perception of warmth 270 W/m^2 (range 150-440 W/m^2); sensation of warmth persisted for 0.7 s after exposure ceased	Justesen et al. (1982)
2.88 GHz to forehead 7 cm diameter	Reaction time to warming not linearly proportional to reciprocal of incident power density	Schwan & Foster (1980)

containing thermal sensors. Cutaneous perception depends on the frequency of the incident RF field. In the resonance region, particularly, internal organs may suffer thermal damage (burns) without any sensation of warmth during the exposure.

The studies that were conducted to determine the thresholds of thermal pain and warmth sensations, were on human beings exposed to frequencies predominantly in the approximate range of 3-10 GHz. These data can be summarized as follows:

(*a*) There is a delay in response or reaction time, from the onset of RF exposure to the sensation of warmth, which is variable, from fractions of a second to many seconds, depending on the RF frequency and power density;

(*b*) Reaction delay to the warming sensation of the RF field does not appear to be linearly proportional to the reciprocal of the incident power density;

(*c*) The threshold intensity for perception of warming or pain from the RF field depends on incident RF frequency, and the area and location of the exposed part of the body;

(*d*) The sensation of warmth can persist for a short time (part of a second) after termination of exposure to the RF field.

It has been observed that pain thresholds are about two orders of magnitude above the detection threshold, but the value is less reliable and thermal damage can be produced at levels judged not painful, especially with deeply penetrating microwaves (Justesen, 1988).

At lower frequencies, where the wavelengths are approximately equal to, or longer than, the human body, modelling studies have shown that much of the energy is absorbed within the body below the superficial skin layers. Cutaneous perception of RF energy is not a reliable sensory response that protects against potentially harmful levels of RF over the broad frequency range of 300 kHz-300 GHz (US EPA, 1984).

8.1.2 Other perception thresholds

Recently, Meister et al. (1989) reported effects on perception, performance, and well-being in eight volunteers, exposed to a 2.45 GHz field with power densities of up to 10 W/m^2. Changes in visual perception thresholds were reported at 5 and 10 W/m^2, other effects were also found at 10 W/m^2. Although the health implication of these results seems to be questionable, replication studies should be done to validate the findings.

8.1.3 Auditory effects

Some people can perceive individual pulses of RF as audible clicks, chirping, or buzzing sounds, depending on the pulsing regime and intensity of the field. This phenomenon was first investigated by Frey (1961). Since that time, there have been many studies on the auditory responses of volunteers.

Other radiation parameters (peak power density, energy density per pulse, and pulse width) are important in determining the threshold for humans. The phenomenon depends on the energy in a single pulse and not on the average power density. For instance, at 2.45 GHz and a threshold energy density of 0.4 J/m^2 per pulse, an energy absorption per pulse of 16 mJ/kg, was calculated (Guy et al., 1975a).

Most experimental results indicate that the auditory perception of RF pulses is due to the induction of thermoelastic waves in the head, rather than to direct brain stimulation by the RF. For a more extensive review see US EPA (1984) and NCRP (1986).

8.1.4 Induced-current effects

Currents can be induced in humans by RF fields in two ways: by physical contact with metallic objects charged by RF fields (see section 6.5), and by direct exposure to the electric and magnetic field components of the RF field (see sections 5.2.1 and 5.2.2).

Currents induced in the body can be strong enough to exceed the stimulation thresholds of certain excitable tissues, such as nerves and muscles. At frequencies below about 100 kHz, biological effects produced by induced currents can be more important than heating.

As is explained in section 5, results of experimental animal studies and theoretical models can be used to identify frequency dependent stimulation thresholds as a function of electric and magnetic field strength. These are shown in Fig. 23 and 24, respectively.

Fig. 23 illustrates the unperturbed electric field strength as a function of frequency, which induces the indicated current density (the dashed, straight lines) in the head or heart region for a person exposed with the long axis of the body parallel to the orientation of the E-field. Curve A represents the threshold for stimulation of nerve or muscle cells and was derived from consideration of various data, including threshold values for the stimulation of sensory receptors, cardiac stimulation, stimulation of isolated neurons, stimulation thresholds for nerve/muscle systems, and induction of membrane potentials.

Fig. 24 represents the sinusoidal magnetic field as a function of frequency for inducing current densities to the peripheral regions of the head or heart. The curve A is the same as for Fig. 23. Curve B is the threshold for diastole stimulation and represents a threshold curve for injury (compare also with Fig. 12).

The data contained in Fig. 23 and 24 represent average values. The uncertainties in these data extend over a factor of about 10.

8.1.5 Thermoregulation

The need to understand and predict the thermal effects of electromagnetic energy deposition arises from several perspectives: in occupational and public health it is necessary to determine safe limits of environmental exposure to RF fields, in medical therapeutic applications there is a need to deposit electromagnetic energy in a predetermined quantity in a specific location and volume, and, finally, there is an RF energy deposition in diagnostic medical applications, such as magnetic resonance imaging.

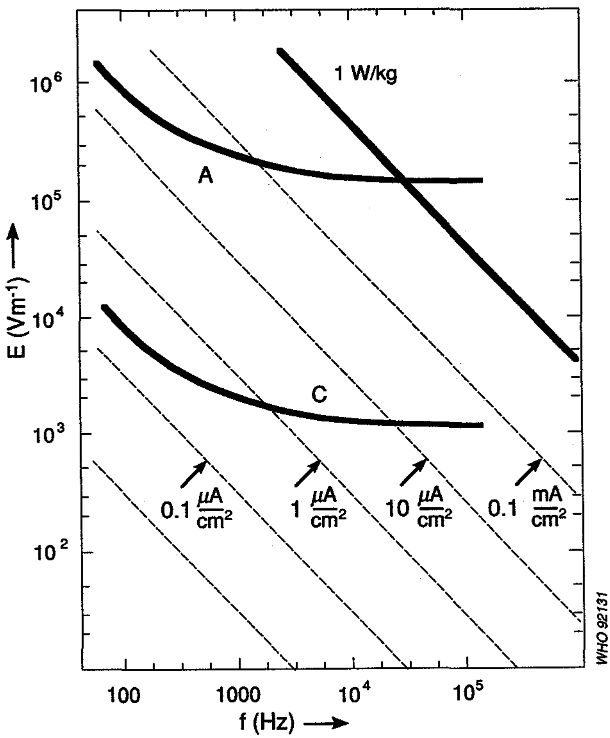

Fig. 23. Unperturbed electric field strength (E in V/m), as a function of frequency (f in Hz), that induces the indicated current density ($\mu A/cm^2$ or mA/cm^2) in the head or cardiac region of a person exposed with the long axis of the body parallel to the orientation of the E-field. From: Bernhardt (1985). In other parts of the body (e.g., neck, trunk, ankles), the current densities are larger at the same external field strengths.

Curve A: Threshold value for the stimulation of various cells under various conditions.

Curve C: Limit value curve with a safety margin of about 100 from potentially hazardous levels in Curve A.

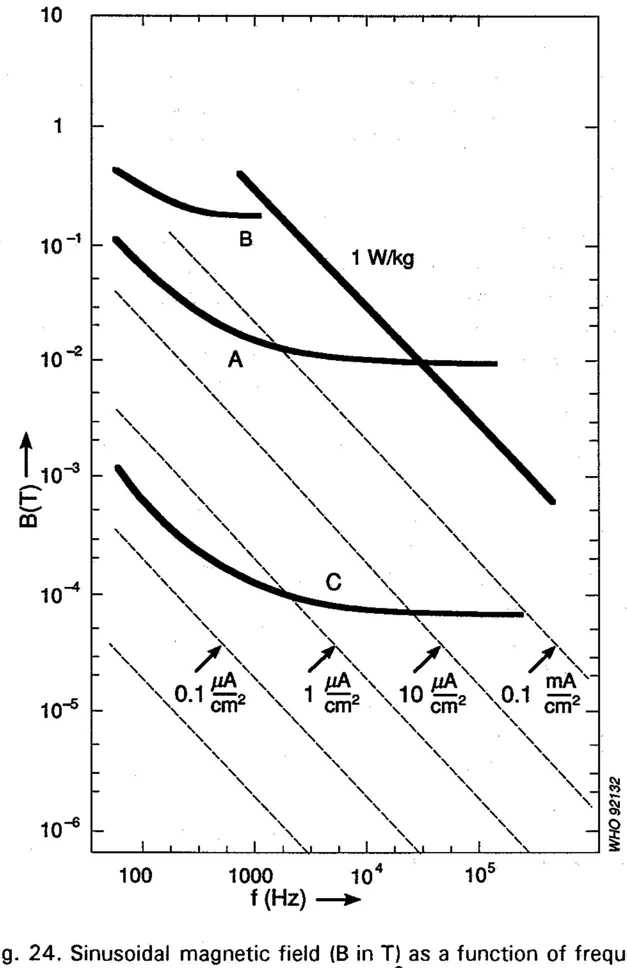

Fig. 24. Sinusoidal magnetic field (B in T) as a function of frequency (f in Hz) for inducing current densities ($\mu A/cm^2$) to the peripheral regions of the head or the heart. From: Bernhardt (1985). For larger effective current loops (e.g., for the trunk), the induced current densities may be larger at the same external magnetic flux density.

Curve A:	Threshold value for stimulatory effects in nerve or muscle tissue.
Curve B:	Threshold for diastole stimulation.
Curve C:	Limit value curve with a safety margin of about 100 from the potentially hazardous levels in Curve A.

In all these instances, there is concern with the effects of locally elevated temperatures resulting from the deposition of RF energy, and the ability of the thermoregulatory system to dissipate the thermal load without unduly stressing the physiological systems involved.

In "thermally neutral" environments, with the body at rest, the total heat production of the human body amounts to about 100 W, and this heat production is offset by a heat loss of 100 W with 15-20 W of evaporative heat loss from the skin and the respiratory tract; the remainder of the heat loss is through radiation, convection, and conduction to the surrounding environment. In strenuous exercise, and/or in environments with elevated ambient temperatures and water vapour pressure, the body temperature tends to increase. Healthy individuals can sustain an increase in internal temperature from a normal 37.0 °C to 39.0 °C with the latter temperature representing the upper safe limit, even for young and healthy individuals. At 39.0 °C, sweating at a rate of about one litre per hour is induced, and heart rates become considerably elevated. From considerations of metabolism and heat exchange, any metabolic heat production in a limited volume of tissue does not result in a temperature rise exceeding 0.8 °C above deep body temperature.

In normal, everyday life, thermal loads imposed by resting metabolism, the thermal environment, or by muscular activity, vary from a minimum of about 1 W/kg to 10 W/kg. Calculations relating whole-body SAR to increases in body temperature are, in general, supported by the limited results of studies of the responses of patients and volunteers exposed to RF fields in magnetic resonance imaging systems (Schaefer et al., 1985; Gordon et al., 1986; Kido et al., 1987; Shellock & Crues, 1987, 1988; Shellock et al., 1989).

In these studies, the subjects were at rest and in controlled environments. Exposure of healthy volunteers to up to 4 W/kg for 20-30 minutes resulted in body temperature increases in the range of 0.1-0.5 °C, confirming predictions derived from models of energy deposition and thermoregulatory response. These exposures resulted in minimal changes in blood pressure and respiration rate. At the higher SARs, subjects felt warm during the procedure and each of them had visible signs of sweating on their foreheads, chest, and abdomen.

Thermal stresses in the form of increased metabolic rates during exercise, deposition of RF energy, or exposure to solar radiation, tend to result in rises in body temperature and activation of thermoregulatory responses, such as sweating and vasodilatation. Different individuals have widely varying abilities to tolerate such responses, depending on age, physical fitness, clothing, adaptation, etc. Thermal stress from RF energy absorption is more severe when it is combined with heavy clothing, or a very hot and humid environment. The thermal effect of RF energy absorption could be beneficial and stress reducing if it occurred in a cold or cool environment.

Thermal stresses for vulnerable populations, such as infants who have an under-developed thermoregulatory system, or the elderly whose thermoregulatory systems are no longer fully competent, must be limited to less than that of an occupational population, but an absolute level is difficult to define.

Mathematical models of the human thermal system make possible reasonably accurate predictions of the steady state and the dynamics of both the whole body thermal state, and local tissue temperatures, under a variety of internal and external thermal stresses (Stolwijk & Hardy, 1966, 1977; Wissler, 1964, 1981).

The development of models of RF energy deposition was initially independent of the development of thermoregulatory models, though similar simplifications had to be accepted. The models for human thermoregulation and the models for RF energy deposition do not have the same priorities or the same capabilities for spatial definition. In addition, the level of knowledge of the parameters required for the implementation of these models is different for the two types of mathematical model. In human thermoregulation models, it is not of crucial importance to describe in detail the local blood flow response to tissue temperatures above 38 °C. However, in combined models, it is very important that this characteristic is adequately incorporated, particularly with respect to hyperthermia therapy.

Models that deal simultaneously with RF energy deposition in the human body, and with the effects of the thermal environment on thermoregulation and heat transfer in the human body have difficult trade-offs between the degree of spatial definition that is pursued, the degree of detail in the thermoregulatory response, and the cost of computation required to produce and evaluate the predictions from such combined models.

8.1.6 Contact currents

Persons coming in contact with ungrounded or poorly grounded metallic objects in an RF field may experience perception, pain, shock, burn, or even more severe reactions. Such phenomena occur for sufficiently large objects and intense fields. These interactions are described in section 6.5.

8.2 Epidemiological and clinical comparative studies

In studies on RF-exposed human populations, epidemiological results are frequently based on estimates only of exposure characteristics (RF frequency, power density, and exposure duration) and some solely on a description of occupation. Despite these limitations, they may provide useful information on the possible effects of actual RF exposure in humans. In the assessment of RF-field effects, comparative, clinical studies of a limited number of exposed persons and controls may be useful.

Studies of health effects from exposure to RF fields have been carried out since the 1940s, when man-made sources of RF energy led to the increasing exposure of occupational groups and the general population. These early studies have been reviewed (WHO, 1981). The majority of reports in the literature concern people exposed in military or industrial settings. Summaries of studies on the health of humans exposed to RF fields are given in Tables 31-33. A wide variety of conditions, symptoms, diseases, and clinical measurements have been evaluated.

8.2.1 Mortality and morbidity studies

In the 1960s and 1970s, Soviet and Eastern European literature described a collection of symptoms, reported to occur in personnel industrially exposed to microwaves. These symptoms, which have been variously called the "neurasthenic syndrome", the "chronic overexposure syndrome", or "microwave sickness", are based on subjective complaints, such as headaches, sleep disturbances, weakness, decrease of sexual activity (lessened libido), impotence, pains in the chest, and general poorly defined feelings of non-well-being (Baranski & Czerski, 1976).

Table 31. Morbidity and mortality studies

Exposure conditions	Effect on exposed group	Reference
Radar (pulsed),two groups: (i) <2 (ii) >2 up to 60 W/m^2, for 1-10 years	No difference in health status between 841 adult males in groups (i) and (ii)	Czerski et al. (1974b); Siekierzynski et al. (1974a,b)
Radar (pulsed), <50 W/m^2 (<0.2 W/kg), for 5-10 years	No effects in clinical evaluations in comparisons between 322 radar workers and 220 non-radar workers; however, more neurasthenic symptoms in exposed group	Djordevic et al. (1979)
0.2-5 GHz (pulsed), approx. 10 W/m^2, 0.05 W/kg (max). Occasional exposure to 1 kW/m^2	No effect on mortality in male military personnel followed for over 20 years, exposed for 2 years on average (over 40 000 personnel)	Robinette & Silverman (1977); Robinette et al. (1980)
Males: 2.56-4.1 GHz (CW), 0.05 W/m^2 (max), 0.0002 W/kg (max); Females: 0.6-9.5 GHz (CW),0.018 W/m^2 (max), 0.0007 W/kg (max), for 0.5-4 years average exposure	No effect on life span or cause of death of 1800 employees and 3000 dependents of US Embassy personnel	Lilienfield et al. (1978)
Long-term microwave exposure of military personnel (interviews)	Higher frequency of microwave exposure in 14 polycythaemia cases than in 17 age-matched controls	Friedman (1981)
Radar-exposed populations near air force bases	Increased cancer mortality compared with population-matched controls. No increase in cancer mortality compared with population-matched controls	Lester & Moore (1982); Lester (1985). Polson & Merritt (1985)
Children exposed to various air pollutants and RF	Duration and severity of tonsilitis increased	Shandala & Zvinjatskovsky (1988)

Table 31 (*continued*)

Exposure conditions	Effect on exposed group	Reference
27 MHz shortwave diathermy (questionnaire to 3004 physiotherapists)	Association between heart disease and work with shortwave therapy (number of treatments/week)	Hamburger et al. (1983)
Work at 27 MHz plastic sealers (70% of measurements at the head and hands >300 V/m)	Upper limb paraesthesia and eye irritation noted among 30 exposed workers compared with 11 partially exposed and 22 unexposed workers	Bini et al. (1986)
Military personnel exposed to RF/MW fields <2 W/m^2 with daily incidental (minutes) exposures of 2-10 W/m^2 (some times even 100-200 W/m^2)	Increased risk of cancer morbidity in a retrospective cohort study of military personnel (study group size not given)	Szmigielski et al. (1988)
51 male/62 female operators of plastic welding machines (27 MHz, 50% of welders exceeded 250 W/m^2) 23 female controls (sewing machine operators)	Increase rates of paraesthesia in hands, neurasthenia, and eye complaints; diminished 2-point discrimination ability	Kolmodin-Hedman et al. (1988)
Amateur radio operators	Deaths from all causes less than expected from national rates; increased risk of leukaemia	Milham (1985)
1.3-10 GHz, 0.1 to 10-μs pulses, RF exposure of radar mechanics often exceeded 10 W/m^2	No differences in neurological symptoms and findings between 17 exposed and 12 controls; increased protein band in CSF in the exposed group	Nilsson et al. (1989)

These early studies suffered from various deficiencies and their results have not been replicated in later surveys. Some of the results could have been attributed to other working conditions (e.g., Djordjevic et al., 1979), and, furthermore, it appears that the working environments for exposed and control groups were not similar in essential respects. Other factors could also have been operating to produce more subjective complaints among the exposed workers, e.g., a reporting bias because of enhanced awareness of the possible "microwave sickness" syndrome.

Later studies on mortality and morbidity among US naval personnel, occupationally exposed to radars, found no differences between exposed and control groups (Robinette & Silverman, 1977; Robinette et al., 1980).

In a study of US embassy personnel, with very low microwave exposures, no significant effects were found (Lilienfield et al., 1978). Studies on cancer mortality in populations around US Air Force bases have given conflicting results, even contradictory findings, when evaluating identical study groups (Lester & Moore, 1982; Polson & Merritt, 1985; Lester, 1985). However, there are studies indicating an increase in cancer in RF field-exposed populations. Friedman (1981) reported a limited number of polycythemia cases with histories of long-term exposure to microwaves, and, more recently, preliminary reports from a retrospective cohort study of Polish military personnel, occupationally exposed to RF, indicated an increased risk of cancer (Szmigielski et al., 1988). Also a case study on a radar mechanic, who developed acute myelogenous leukaemia, has been published (Archimbaud et al., 1989).

Milham (1985), using records of licensed amateur radio operators living on the west coast of the USA, derived standardized mortality ratios (SMRs) and compared them with the mortility rates for the population in the USA. Although the overall mortality rate was lower for the radio amateurs, significantly raised SMRs were observed for some types of leukaemias. However, it should be noted that around a third of the radio amateurs were engaged in electrical/electronics occupations. This may have involved exposure to solvents, PCBs, and metal fumes. In general, studies on increased cancer risks in certain "electrical" occupations (see, e.g., WHO, 1984, 1987) mainly refer to exposure to 50/60 Hz magnetic and electric fields with little or no contribution of 300 Hz-300 GHz radiation.

In studies on plastic welding machine operators, with RF exposure levels sometimes exceeding existing national standards, upper limb paraesthesias have been reported by Bini et al. (1986) and Kolmodin-Hedman et al. (1988).

In a small study on radar mechanics, in which no differences were found in neurological symptoms and signs compared with controls, changes were reported in a protein band of the cerebral spinal fluid (Nilsson et al., 1989). Because this study was small, its significance with respect to health is unclear. The clinical observations of Nilsson need to be confirmed.

Also described as part of the early "microwave sickness" syndrome (see above) were effects on heart rate including bradycardia as well as tachycardia, arterial hypertension (or hypotension), and changes in cardiac conduction. With reference to this, the increased risk of developing heart diseases found among physiotherapists working with shortwave diathermy (Hamburger et al, 1983) calls for further studies.

The combined effects on children of various pollutants in the environment (RF, noise, chemicals etc.) were studied by Shandala & Zvinjatskovsky (1988), who found that the duration and severity of tonsilitis were increased in the presence of RF.

8.2.2 *Ocular effects*

In health studies on RF field-exposed workers, general eye irritation was described (Bini et al., 1986; Kolmodin-Hedman et al., 1988). Lens opacities and cataracts have also been noted in some studies, as shown in Table 32. In the most extensive study, however (Appleton & McCrossan, 1972; Appleton et al., 1975), commented on by Frey (1985) and Wike & Martin (1985), no differences were found between exposed and unexposed military personnel. Where cases of confirmed cataracts have been reported, exposures have exceeded 1 kW/m^2.

8.2.3 *Effects on reproduction*

Only a limited number of studies, as shown in Table 33, have investigated potential reproductive effects in humans exposed to RF in the work environment. Sigler et al. (1965) found a higher incidence of Downs syndrome in children whose fathers had worked with radars in the military. From interviews of the fathers in the Sigler study and additional information obtained from military records, Cohen et al. (1977) could not confirm the result that the fathers had either an excess of radar exposure or a larger proportion were exposed personnel. The contradictory results probably reflect the difficulties in exposure assessment in retrospective epidemiological studies.

Table 32. Lens opacities and cataracts in humans

Exposure conditions	Effect on exposed group	Reference
US Army and Air Force veterans, radar personnel, 2644 exposed, 1956 controls	No difference in cataract incidence	Cleary et al. (1965)
Microwave workers, 736 exposed, 559 controls	More lens changes in exposed group	Cleary & Pasternak (1966)
Microwave workers, 60 MHz-10.7 GHz, 200 exposed, 200 controls	More lens changes in exposed group (168 vs 148)	Majewska (1968)
US military personnel, 91 exposed, 135 controls	No differences in incidence of lens opacities, vacuoles, or subcapsular iridescence	Appleton & McCrossan (1972)
US military personnel, 1542 exposed, 801 controls	Expanded study, same results	Appleton et al. (1975); Frey (1985); Wike & Martin (1985)
US military radar personnel 377 exposed, 320 controls	Lens abnormalities same in exposed controls, except higher in exposed with pre-existing visual defects	Odland (1973)
Two groups of microwave workers: group 1: <2 W/m^2 group 2: 2-60 W/m^2	No difference in lens opacities between the two groups	Siekierzynski et al. (1974a,b)
US Air Force and civilian personnel, 477 exposed, 340 controls	No difference in frequency of opacities, vacuoles or posterior capsular iridescence	Shacklett et al. (1975)
53 radio-linemen installing and maintaining radio, TV, and repeater towers; 558 kHz-527 MHz, 0.8-39.6 kW/m^2	Increased incidence of posterior subcapsular cataracts	Hollows & Douglas (1984)

Table 33. Reproductive effects in humans

Exposure conditions	Effect on exposed group	Reference
Work with radar in the military	Case-control study of the fathers of 216 children with Downs syndrome and 216 matched control fathers: association between radar exposure and Downs syndrome	Sigler et al. (1965)
Work with radar in the military	Extended study from Sigler et al. (1965) with additional 128 cases and 128 controls: no association between radar exposure of fathers and Down's syndrome	Cohen et al. (1977)
3.6-10 GHz, hundreds to thousands of mW/m^2, 0.003-0.04 W/kg	Decreased sperm number in 31 males (70% of whom with neurasthenia) exposed for 1-17 years (8-year average) compared with 30 healthy controls	Lancranjan et al. (1975)
Cohort study on pregnancy outcome of 2018 female physiotherapists giving birth to 2043 infants	Physiotherapists had a better than expected pregnancy outcome; higher use of shortwave units among physiotherapists giving birth to malformed or still-born infants	Kallen et al. (1982)
305 female RF welders	No differences in pregnancy outcome compared with Swedish birth registers	Kolmodin-Hedman et al. (1988)
Case-control study on physiotherapists working with shortwave diathermy	17% of "highly" exposed were boys; exposure also associated with still-birth/ death within a year, prematurity, and low birth weight	Larsen et al. (1991)

Analysis of semen of 31 technicians with a very low-level microwave exposure, revealed a reduced number of sperm compared with a control group of 30 persons (Lancranjan et al., 1975). However, 70% of the exposed group suffered from neurasthenia, which might wholly or partly explain the results.

In a health study on operators of plastic welding machines exposed to RF levels exceeding 250 W/m^2 (Kolmodin-Hedman et al., 1988), the pregnancy outcome for 305 female plastic welders during 1974-84 did not show any significant differences with the Swedish average concerning malformation or prenatal mortality.

During the 1980s, two epidemiological studies indicated an adverse pregnancy outcome among physiotherapists working with shortwave diathermy (Kallen et al., 1982; Larsen et al., 1991). Kallen et al. (1982), in Sweden, reported that physiotherapists as a group had a slightly lower risk of perinatal deaths and major malformations than the Swedish population for the same period. However, the physiotherapists who gave birth to a malformed child, or who had a perinatal death, had RF exposures (from microwave and shortwave diathermy) higher than those recorded for the other physiotherapists. In a Danish case-control study on physiotherapists working with shortwave diathermy, Larsen et al. (1991) found that only 17% of the "highly exposed" newborn infants were boys, and that exposure was associated with stillbirth/death within a year, prematurity, and low birth weight. The results suggest further study is necessary before conclusions can be reached.

8.2.4 VDU studies

Concern about the effects of exposure to electromagnetic fields and particularly about pregnancy outcome has been expressed with regard to the use of VDUs. Work with such equipment may involve job stress and ergonomic problems and these can be confounding factors in studies of associated pregnancy outcomes. Studies have been reviewed by Repacholi (1985), Bergqvist & Knave (1988), and Blackwell & Chang (1988).

Blackwell & Chang (1988) pointed out that, in the USA and the United Kingdom, about 10 million VDUs are in use. About 50% of these are possibly used by women of childbearing age, and there are some 20 000 groups of women, in each of which at least 10 women could become pregnant in one year. Since the naturally occurring pregnancy failure rate is about 15%, there is a chance of about 29 "clusters" each year in which more than half the pregnancies end in failure.

A large number of epidemiological studies have been conducted, in order to elucidate whether VDU work during pregnancy increases the risks of miscarriage or giving birth to a malformed child. While Goldhaber et al. (1988) suggested there was some evidence of increased spontaneous abortion rates among VDU operators, most studies have not shown this (Bryant & Love, 1989; Goldhaber et al., 1988; McDonald et al., 1988; Nielsen et al., 1989; Nurminen & Kurppa, 1988), or threatened abortion, changes in placental weight, and maternal blood pressure (Nurminen & Kurppa, 1988). Of these studies, just one (Schnorr et al., 1991) included the measurement and assessment of the emission of ELF and VLF electric and magnetic fields as exposure factors. In this study, a cohort of female telephone operators, who used VDUs at work, was compared with a cohort of operators who did not use VDUs. Exposure was assessed by the number of hours worked per week, from company records, and by measuring electric and magnetic fields (45-60 Hz and 15 kHz) at the VDU work stations and at the workstations without VDTs. Among 2430 women interviewed there were 882 pregnancies (366 exposed, 516 controls) that met the criteria for inclusion in the study. No excess risk of spontaneous abortion was found among women who used VDUs during the first trimester of pregnancy (OR = 0.93, 95% CL, 0.63-1.38). There was no risk associated with the use of VDUs when accounting for multiple pregnancies, early and late abortions, and all fetal losses. No dose-response relationship was apparent when examining the number of hours at the VDU, or the measured electric and magnetic fields.

The study by McDonald et al. (1988) was designed around all women who reported to 11 Montreal hospitals during 1982-84 for childbirths or spontaneous abortion. They were interviewed on working conditions during their current and previous pregnancies. Apart from an isolated increase in renal urinary defects, the study showed no evidence of increased malformation. However, the results are not so clear for spontaneous abortion, especially among previous abortions. The design of this study does, however, tend to exaggerate the odds ratio for VDU exposed compared with non-exposed in previous pregnancies (Bergqvist, 1984; McDonald et al., 1988). By stratification, this systematic error has been eliminated, and then the apparent increase in odds among VDU exposed was absent (McDonald et al., 1988). A similar, but smaller, error is also likely with regard to spontaneous abortion among current pregnancies.

In a case-control study performed at three Kaiser Permanente clinics in Northern California (Goldhaber et al., 1988), there was an increase in spontaneous abortion among VDU operators compared with referents. However, this significant increase was due to a trend in one of the job categories (clerical workers), while a decrease in relation to VDU work was reported for another job category (managers, professionals). This contrary information from two job categories has two ramifications: (1) the summary across job categories is not justified; and (2) it makes the interpretation of magnetic fields as a cause rather dubious, but does, instead, suggest job-specific factors as possible causal factors.

Experimental studies, while showing a diverse outcome, have, as a whole, failed to demonstrate an effect on reproductive processes in magnetic field situations resembling those around VDUs. Epidemiological studies have failed to show a difference between women who worked and those who did not work at a VDU during pregnancy, and interest has now turned to possible differences related to work situations, e.g., stress, rather than physical emissions from the VDUs.

8.2.5 Conclusions

In summary, the epidemiological and comparative clinical studies do not provide clear evidence of detrimental health effects in humans from exposure to RF fields. Some occupational groups, such as exposed physiotherapists and industrial workers, should be studied further. The question of whether RF might act as a carcinogen should be further evaluated in epidemiological studies.

Occupational exposure to RF will be at higher levels than that encountered by the general population, and, thus, there is less likelihood of health effects in the general population as a whole.

8.3 Clinical case studies and accidental overexposures

In a survey of accidental overexposures to RF in the US Air Force (Graham, 1985), 26 out of 58 individuals, with exposures exceeding 100 W/m^2, reported that they had felt a warming sensation at the time of overexposure. In clinical examinations, no abnormal findings were recorded. Symptoms, such as headache, nausea, fatigue, malaise, and heart palpitations, were often reported, however. Some high-level exposures, e.g., at levels exceeding 5 kW/m^2, resulted in anxiety reactions so severe that hospitalization and sedation were necessary. Similar symptoms were reported in a one-year, clinical, follow-up study on two men who were accidentally, acutely irradiated with 600-900 W/m^2 RF fields (Forman et al., 1982). Several months after the incidents, hypertension was diagnosed in both patients. Exposures to power densities of about 50 W/m^2 for one or two hours were not found to result in harmful health effects (Hocking et al., 1988).

In case reports, long-term neuropathies and chronic dysaesthesias have been described after excessive microwave exposures from malfunctioning microwave-ovens (Ciano et al., 1981; Tintially et al., 1983; Fleck, 1983; Dickason & Barutt, 1984; Stein 1985). Also severe burns have been reported at work with microwave ovens (Nicholson et al., 1987). Similarly, Castillo & Quencer (1988) described the case of a pilot who inadvertently stood in front of a functioning microwave airfighter radar system for approximately five minutes. At that time a moderate sensation of heat was perceived in the head and neck, and after some time interstitial oedema and coagulation necrosis developed in muscles of the neck. The pilot also noted a loss of recent memory and extreme sleepiness.

9. HEALTH HAZARD ASSESSMENT

9.1 Introduction

The purpose of reviewing the scientific literature on effects of exposure of various biological systems to RF fields is to assess its possible impact on human health. Such an assessment is necessary for the development of standards and guidelines limiting exposure to RF of the general and working populations.

One of the problems encountered in assessing the possible health effects of RF exposure over the whole range of frequencies covered in this publication (i.e., 300 Hz-300 GHz) is that most studies have been conducted at frequencies particularly in the low GHz region. Little information is available from studies of human populations and only limited data have been obtained on other biological systems, particularly animals exposed to RF at frequencies below 10 MHz and above 10 GHz.

The following categories of effects must be considered for risk assessment. The first two of these are sufficiently well understood to be used in risk assessment and the development of recommended limits of exposure. The third category is reasonably well understood, but quantitative data are sparse and any comprehensive recommendations to protect workers and the general population have to be based on data at other frequencies. The effects noted in the last two categories are elaborately described and poorly understood. In view of their importance in the possible promotion of cancer or of reproductive failures, they must be considered. However, the lack of understanding and the total absence of quantitative relationships between these effects and either exposures or the outcomes in question makes it impossible to derive recommended limits of exposure.

Points to consider for a health risk assessment of exposure to RF fields are:

(*a*) Absorption of RF energy causes tissue heating. This is recognized and has been well studied. This effect occurs from the absorption of RF fields, especially at the higher end of the frequency range (above about 1 MHz). RF heating is not directly equivalent to heating by other forms of energy, because of the very non-uniform energy deposition that occurs in biological systems.

(*b*) At frequencies below about 100 MHz, currents can be induced in humans by physical contact with ungrounded metallic objects (see section 6.5). From 300 Hz to approximately 100 kHz, such currents may result in the stimulation of electrically excitable tissues above the threshold for perception or pain. At frequencies between approximately 100 kHz and 100 MHz, contact currents of sufficiently high density may cause burns.

(*c*) For frequencies below several hundred kHz, the predominant effect is stimulation of excitable tissue resulting from currents directly induced in the body by the RF fields. At these lower frequencies, thermal interactions occur only at energy levels much higher than interactions with excitable tissue.

(*d*) When RF energy is absorbed in the form of pulsed fields, the peak power density in the pulse should be considered separately from the average. Auditory perception is one example of a pulsed RF field effect.

(*e*) When RF fields are amplitude modulated, effects in tissues have been noted that do not manifest themselves with unmodulated RF fields. Such effects are reported to have a complex dependence on intensity and ELF modulation frequency. Too little information is available to determine whether such effects occur in humans and, thus, this effect cannot be used in a health risk assessment or for setting human exposure limits.

9.2 Thermal effects

A number of factors in everyday life tend to increase the heat load on the human body, such as high ambient temperatures, solar radiation, and basal and exercise metabolism. Energy production can reach levels of 3-6 W/kg in healthy people. In most individuals, the thermoregulatory system can remove heat from the body at these rates for extended periods of time. Limited experimental evidence and theoretical calculations suggest that the exposure of resting humans in moderate environmental conditions at whole body SARs of the order of 1-4 W/kg for 30 minutes results in body temperature increases of less than 1 °C. In addition, a review of the animal data (see section 7.3.4) indicates a threshold for behavioural responses in the same 1-4 W/kg range. Therefore, an occupational RF exposure guideline of 0.4 W/kg, based on thermal consideration, leaves a considerable margin of safety for other limiting conditions, such as high ambient temperature, humidity, or physical activity. Higher energy absorption rates in extremities and limited body regions, do not appear to cause adverse effects, for SAR values below thresholds that are dependent on the body part and the volume.

In infants, the frail elderly, and in individuals taking certain drugs, the thermoregulatory capacity may be much reduced and, as a result, their tolerance for the combined effects of RF exposure, exercise, solar radiation, and high ambient temperature, may be much lower. Recognition that this tolerance is lower dictates that guidelines for population exposure to RF fields be reduced. A whole-body average SAR of 0.08 W/kg offers an additional safety factor.

Significant overexposures at the higher frequencies that may occur in occupational environments may result in very high SARs in parts of the body, thus producing local burns. In such cases, the SAR is so high that the normal avenues of heat transfer from the exposed area are inadequate. The local tissue temperature quickly rises to levels that denature proteins. Such burns may occur at depths much greater than those usually associated with contact burns.

Thus, standards should be developed that, at a minimum, limit exposure of the healthy and aware (occupational) population, so that the whole-body average SAR does not exceed 0.4 W/kg. Additional precautions must be exercised for situations that might cause large peak values of the SAR, in order to eliminate rapid elevation of local temperature by more than 1 °C. This requires that the peak (or local) SARs should not exceed about 2 W/100 g in the extremities and 1 W/100 g in any other part of the body. The eye may need special consideration, possibly by averaging over a mass of 10 g (i.e., 100 mW/10 g).

9.3 RF contact shocks and burns

At frequencies below a few hundred kilohertz, the electrical stimulation of excitable membranes of nerves and muscle cells is a well established phenomenon. These effects exist at very high environmental field strengths, unlikely to occur in the general environment. On the other hand, current densities sufficient for stimulation and other potentially harmful effects can be produced, if an individual makes contact with a conductive object energized by the electric field component of an RF source.

For frequencies between 300 Hz and 100 kHz, perception, pain, startle, or even inability to let go, may result from physical contact with energized objects (see section 8.1.6). The thresholds are expressed in terms of the current and are strongly frequency dependent. Superficial and deep burns may occur as a result of contact with metallic objects exposed to RF fields over a wide frequency range. Sufficiently high current densities for contact burns can be attained in RF fields that are too low to cause direct heating or stimulation. Thresholds depend on the size and shape of the object, field frequency, length and type of contact, and other parameters.

Field exposure guidelines should also contain RF limits to eliminate hazards from shocks and burns. In this context, it should be kept in mind whether the exposures occur under controlled or uncontrolled conditions. Under uncontrolled exposure conditions, it is not always possible to limit contact currents for some objects (e.g., vehicles) so that electric field strengths have to be reduced to protect the general population. For workers, other measures, such as protective clothing or contact avoidance, provide viable alternatives for protection.

9.4 Induced current densities

At frequencies below approximately 1 MHz, interactions of RF fields with biological systems and potential hazards can be considered in terms of induced currents and their densities (see section 8.1.4). The use of induced current densities, however, is only appropriate for the assessment of acute, immediate effects, while it may have some limitations for the complete evaluation of long-term effects. The waveform of the RF field is an important factor to be considered in the response of biological systems. However, peak instantaneous fields strengths appear to be important in considering nerve and muscle cell stimulation and for perturbing cell functions. Generally, for frequencies above 300 Hz, the thresholds for effects increase with frequency, up to frequencies where thermal effects dominate. For the establishment of derived limits, the distribution of the current densities within the body induced from RF fields have to be considered. The treatment of this problem is restricted, at present, to relatively simplified situations.

9.5 Pulsed RF fields

Experimental data suggest that thresholds for the biological effects of absorbed energy at frequencies above hundreds of megahertz, when in the form of short duration pulses (approx. 1-10 μs), are lower than those for continuous fields at the same average energy level and the same SAR. This indicates that the peak value of energy transfer to the biological object can be an important determinant of the biological effect. A well-investigated effect is the perception of pulsed fields, such as from radar, as an audible sound described as a click, chirp, or knocking sensation (see section 8.1.3).

Pulsed RF exposure effects observed in animals are suppression of a startle response, stunning, ocular effects, and alterations in responses to certain drugs. Thresholds in terms of the energy density per pulse or the peak electric field strength for a given pulse duration are known for these effects only at a limited number of frequencies. Suppression of startle response was observed for pulse durations of up to a few seconds. Shorter pulses with the same or greater energy had a slightly enhanced effect on startle.

Since a single pulse, or a series of short pulses, of RF of very high peak power density, but very low average power density, can produce potentially harmful biological effects, it is necessary to limit the maximum energy density per pulse. The available scientific evidence is incomplete, and, therefore, the formulation of exposure limits for pulsed fields presents difficulties.

9.6 RF fields amplitude modulated at ELF frequencies

Effects have been reported in *in vitro* systems and animals exposed to RF fields of low intensities amplitude modulated at ELF. Some of the same or similar effects have also been observed as a result of exposure to ELF and VF fields. The effects usually exhibit "window" characteristics, i.e., the effects occur only within relatively narrow ranges, in both the modulation frequency and field intensity. Even though the intensities of the fields in tissue at which these effects occur are below the broadband thermal noise, there are hypotheses that might account for such apparently aberrant behaviour. The biological significance and possible adverse health impact, if any, of the reported effects cannot be determined at this time.

9.7 RF effects on tumour induction and progression

There have been isolated reports that, in certain cell lines and in intact animals, RF exposures have been associated with increased growth rates of cells and tumours and with increases in the incidence of neoplastic transformations. Very few epidemiological studies have been reported. The available evidence does not confirm that RF exposure results in the induction of cancer, or causes existing cancers to progress more rapidly. Because of incompleteness and inconsistencies, the available scientific evidence is an entirely inadequate basis for recommendations of health protection guidelines.

10. EXPOSURE STANDARDS

10.1 General considerations

The development of protection standards for any environmental agent is a difficult and complex task. Setting exposure limits requires an in-depth evaluation of the established scientific literature, since to base standards on preliminary data or unproven hypotheses means that the limit values may be either unprotective or unduly restrictive. Using established scientific data allows exposure limits to be determined with a higher degree of confidence about their level of protection.

Certain criteria must be met, if claims of positive effects or negative data are to be accepted within the body of scientifically established effects (Michaelson, 1983; Repacholi, 1990):

(*a*) Experimental techniques, methods, and conditions should be as completely described and objective as possible.
(*b*) All data analyses should be fully and completely objective, no relevant data should be deleted from consideration, and uniform analytical methods should be used.
(*c*) Results should demonstrate an effect of the relevant variable at a high level of statistical significance using appropriate tests. The effects of interest should ordinarily be shown by different test organisms and the responses found be consistent.
(*d*) Results should be quantifiable and susceptible to confirmation by independent researchers. Preferably, the studies should be repeated and the data confirmed independently; or the claimed effects should be consistent with results of similar studies, where the biological systems involved were comparable.

From the body of established literature, a distinction must be made between *in vitro* and *in vivo* studies. *In vitro* studies are conducted to elucidate the mechanisms of interaction or to identify biological effects or exposure parameters that need to be further investigated to determine if they occur *in vivo*. Standard-setting organizations can place only limited value on the results of *in vitro* experiments.

An important part of the rationale for any exposure standard is the definition of the population to be protected. Occupational health standards are aimed at protecting healthy adults, exposed as a necessary part of their work, who are aware of the occupational risk and who are likely to be subject to medical surveillance. General population standards must be based on broader considerations, including widely different health status, special sensitivities, possible effects on the course of various diseases, as well as limitations in adaptation to environmental conditions and responses to any kind of stress. Exposure limits for the general population must include an adequate additional safety factor, also taking into account the possibility of a 24-h exposure compared with 8-h occupational exposure (or whatever the duration of the workday). Additionally, the RF fields in the environment can be complex and may be affected by reflections from buildings.

A distinction should be made between exposure limits and equipment emission standards. The latter are based on safe operational considerations, and should not allow exposure above the adopted exposure limits.

Over the past decade, major advances in the study of RF fields have come from the development of dosimetry as reviewed in section 5. Methods of intercomparing the results of animal studies and relating them to the human situation, have been developed to facilitate standard-making. With increasing knowledge of RF dosimetry, standards are becoming more specific.

10.2 Present trends

Many countries have now established health protection standards or guidelines. There have been a number of in-depth reviews of current RF standards (Czerski, 1985; Sliney, 1988; Grandolfo & Mild, 1989; Repacholi, 1990; Szmigielski & Obara, 1989). Most of the early standards addressed the microwave region only (300 MHz-300 GHz), because of the introduction and proliferation of radars, telecommunications, and radio and TV broadcasting. Later standards recognised the vastly expanded use of the electromagnetic spectrum, especially at lower frequencies, where concerns were raised about RF exposures from induction heaters, heat sealers, and other industrial applications.

RF exposure standards development is continuing, at present, and with the availability of detailed reviews elsewhere, standards in various countries and their rationales are not discussed here.

The maximum RF exposure levels permitted in some standards differ by one to two orders of magnitude (factors between 20 and 100). It may be speculated that these differences result from: (a) the physical and biological effects data selected as the basis for the standards, (b) the interpretation of these data, (c) the different purposes to be served by the standards, (d) the compromises made between levels of risk and degrees of conservatism, and (e) the influence of preceding standards in each particular nation and in neighbouring areas having allied socio-political outlooks. In recent years, an increasing number of countries have adopted standards with limits identical, or very close, to those of IRPA.

10.3 Recommendations by the IRPA

A joint WHO/IRPA Task Group on Radiofrequency and Microwaves reviewed existing scientific literature (WHO, 1981). An evaluation of the health risks of exposure to electromagnetic fields was made and the rationale for the development of exposure limits was considered. The Task Group suggested that RF exposure to power densities in the range 1-10 W/m^2 were acceptable for occupational exposure throughout a complete working day and that higher exposures might be acceptable for some frequency ranges and occasional exposure. For the general population, it was suggested that lower, unspecified, exposure levels were appropriate.

In 1984, IRPA issued recommendations based on the WHO publication (WHO, 1981). These recommendations were more specific and provided guidance on limits of exposure to electromagnetic fields in the frequency range from 100 kHz to 300 GHz. The basic limits of exposure formulated for the frequency region of 10 MHz and above were expressed in terms of the specific absorption rate. In the frequency region below 10 MHz, basic limits were expressed in terms of the electric and magnetic field strengths.

The IRPA revision (1988a) of its 1984 guideline, shown in Tables 34 and 35, reaffirmed that research data, obtained over the past years, did not alter the threshold whole-body exposure for health effects on which the basic limit was derived: i.e., occupational whole-body exposure to RF fields should not exceed 0.4 W/kg. The revision was essentially a "fine tuning". Although the whole body average SAR might not exceed 0.4 W/kg, several reports indicated that, under certain conditions, local peak SARs in the extremities

Table 34. IRPA occupational exposure limits for RF fields[a]

Frequency range (MHz)	Unperturbed rms electric field strength (V/m)[b]	Unperturbed rms magnetic field strength (A/m)[b]	Equivalent plane-wave power density (W/m^2)[b]	(mW/cm^2)[b]
0.1-1	614	1.6/f	-	-
>1-10	614/f	1.6/f	-	-
>10-400	61	0.16	10	1
>400-2000	$3f^{0.5}$	$0.008f^{0.5}$	f/40	f/400
>2000-300 000	137	0.36	50	5

[a] From: IRPA (1988a).
[b] f = frequency in MHz.

Note: Hazards of RF burns should be eliminated by limiting currents from contact with metal objects. In most situations, this may be achieved by reducing the E values from 614 to 194 V/m in the range from 0.1 to 1 MHz and from 614/f to $194/f^{0.5}$ in the range from >1 to 10 MHz.

Table 35. IRPA general population exposure limits for RF fields[a]

Frequency range (MHz)	Unperturbed rms electric field strength (V/m)[b]	Unperturbed rms magnetic field strength (A/m)[b]	Equivalent plane-wave power density (W/m^2)[b]	(mW/cm^2)[b]
0.1-1	87	$0.23/f^{0.5}$	-	-
>1-10	$87/f^{0.5}$	$0.23/f^{0.5}$	-	-
>10-400	27.5	0.073	2	0.2
>400-2000	$1.375f^{0.5}$	$0.0037f^{0.5}$	f/200	f/2000
>2000-300 000	61	0.16	10	1

[a] From: IRPA (1988a).
[b] f = frequency in MHz.

(particularly wrists and ankles) could exceed the 0.4 W/kg value by a factor of up to 300, at certain frequencies. Because of this, an additional recommendation was introduced to limit the body-to-ground current to 200 mA. It was also found that there was no adequate basis for identifying SAR limits as averaged over any gram of tissue. IRPA therefore recommended that the local SAR should not exceed 2W/100g in the extremities (hands, wrists, ankles, and feet) and 1 W/100g in any other part of the body.

Occupational exposure to frequencies up to 10 MHz should not exceed the levels of unperturbed electric and magnetic field strengths (rms), given in Table 34, when the squares of the electric and magnetic field strengths are averaged over any 6-min period during the working day, provided that the body-to-ground current does not exceed 200 mA, and the hazard for RF burns is eliminated. In general, RF burns will not occur if the current at the point of contact does not exceed 50 mA.

The limits of occupational exposure given in Table 34 for the frequencies between 10 MHz and 300 GHz are the working limits derived from the SAR value of 0.4 W/kg. They apply to whole-body exposure from one or more sources, averaged over any 6-min period during the working day.

Exposure of the general population at frequencies up to 10 MHz should not exceed the levels of unperturbed electric and magnetic field strengths (rms) given in Table 35, provided that any hazard from RF burns is eliminated.

For RF-field exposure of the general population at frequencies above 10 MHz, a SAR of 0.08 W/kg should not be exceeded when averaged over any 6 min and over the whole body. The limits of RF exposure of the general population given in Table 35 for the frequencies between 10 MHz and 300 GHz, are derived from the SAR value of 0.08 W/kg. These limits apply to whole-body exposure from either continuous or modulated electromagnetic fields from one or more sources, averaged over any 6-min period during the 24-h day.

Although very little information is available at present on the relation of biological effects with pulsed fields, a conservative approach is to limit pulsed electric and magnetic field strengths, as averaged over the pulse width, to 32 times the appropriate values given in Tables 34 and 35 for workers and the public; or to limit the equivalent plane-wave power density, as averaged over the pulse width, to 1000 times the corresponding values in Tables 34 and 35. In addition, the exposure as averaged over any 6 min should not exceed the values indicated in these tables.

10.4 Concluding remarks

Various approaches have produced different philosophies of protection guidelines and, thus, different exposure limits. It is apparent that, in the light of the continuous advancement of scientific results, the differences are decreasing and the revisions of existing standards or the setting of new ones reflect, at least, the tendency to merge to a common area.

The international cooperation in the development of more uniform standards should be encouraged, because the lack of international agreement on the protection standards to be used for non-ionizing radiation constitutes a major drawback for the development of safety regulations in countries where they do not yet exist (Duchêne & Komarov, 1984). Efforts, outlined above, to achieve international cooperation in the field of non-ionizing radiation together with progress in knowledge on the biological effects will, hopefully, allow protection against non-ionizing electromagnetic fields to develop in a climate of international agreement.

11. PROTECTIVE MEASURES

In situations where recommended limits can be exceeded, protective measures need to cover at least three types of potential hazards.

- exposure to RF electric and magnetic fields;
- contact with ungrounded or poorly grounded metallic objects; and
- interference with implantable and other medical devices.

A programme of measurement surveys, inspections and education on worker safety, is necessary for an effective protection programme. Protective measures can be broadly divided into three categories: engineering controls, administrative controls, and personal protection.

11.1 Engineering measures

Engineering controls for limiting human exposure to RF fields include design, siting, and installation of generating equipment. These depend on the purpose of the equipment and its operational characteristics. While strong fields around antennas of deliberate radiators, such as broadcast transmitters or radars, are unavoidable, appropriate design of the generating equipment can ensure negligibly weak fields around cabinets housing generators and other electronic circuits, and around transmission lines, such as cables and waveguides. The limitation of leakage fields at the design and manufacturing stages is more effective and less costly than later remedies, such as additional shielding, barriers, etc. At the frequency bands allocated for telecommunication, leakage (stray) fields are frequently at such low levels that they are an electromagnetic interference (EMI) problem rather than a health problem.

However, at frequencies allocated for industrial, scientific, and medical (ISM) uses, human exposure to strong stray fields is more likely to occur, as exemplified by RF industrial heaters (West et al., 1980; Stuchly et al., 1980; Eriksson & Mild, 1985; Joyner & Bangay, 1986b).

The siting and installation of deliberate transmitters must take into account exposure standards, as well as other technical considerations. It is important that an assessment of RF fields around various antennas is made and particularly, in the near-field, is verified by measurements. In siting deliberate radiators and evaluating exposure fields, the existence of multiple RF sources has to be taken into account where applicable. Often, broadcasting and other communication or navigation transmitters are located on the same tower. Furthermore, metal structures can cause reflections, and, thus, produce local enhancement of the fields. However, depending on the shape and location of the structure, it may also reduce the field. The reduction usually occurs for fields of frequencies below approximately 10 MHz. If after the erection of a radio-transmitting structure, a building is also to be erected, then it is recommended that planning authorities seek guidance as to whether the new building could reflect fields in such a way that exposure limits could be exceeded. This would entail:

(*a*) obtaining assurances from the broadcasters that the field intensities at the new site will not exceed relevant exposure limits, and

(*b*) seeking assurances from the broadcasters and the builders that the new building will not adversely affect broadcast coverage or significantly increase fields in the vicinity, due to reflections, such that the new levels exceed exposure limits.

Engineering controls against excessive contact currents include the grounding of metal fences and other permanently located metal objects, and the installation of special grounding straps on mobile metal objects. Special techniques have to be used to ensure the effective grounding of fences and other objects. Furthermore, the contact currents should be measured after the grounding of the object.

RF hot spot - a special case

Tell (1990) conducted measurements and calculations directed to applications in the VHF and UHF broadcasting bands, but the concepts are also applicable to assessing RF hot spots near AM radio stations. He summarized the problem of RF hot spots as shown below.

An RF hot spot may be defined as a point or small area in which the local values of electric and/or magnetic field strengths are significantly elevated above the typical ambient field levels and often are confined near the surface of a conductive object. RF hot spots usually complicate the process of evaluating compliance with exposure standards, because it is often only at the small area of the hot spots that fields exceed the exposure limits.

RF hot spots may be produced by an intersection of narrow beams of RF energy (directional antennas), by the reflection of fields from conductive surfaces (standing waves), or by induced currents flowing in conductive objects exposed to ambient RF fields (re-radiation). RF hot spots are characterized by very rapid spatial variation of the fields and, typically, result in partial body exposures of individuals near the hot spots. Uniform exposure of the body is essentially impossible because of the high spatial gradient of the fields associated with RF hot spots.

Several conclusions relevant to the exposure limit compliance issue have been drawn from the results and experience of this investigation:

(*a*) In the RF hot-spot situation, involving re-radiating objects, the high, localized fields at the hot spot do not generally have the capacity to deliver whole-body SARs to exposed individuals in excess of exposure guidelines, where SARs are limited to 0.08 W/kg, regardless of the enhanced field magnitude. When the ambient RF field strengths are already at, or above, the exposure limits, the partial body exposure that accompanies proximity of the body to the object will generally increase the whole-body SAR only slightly.

(*b*) The high-intensity, electric and magnetic fields accompanying RF hot spots are not good indicators of whole-body or spatial peak SARs in the body, because of the high variability in coupling between the body of an exposed person and the hot-spot source.

(*c*) A measurement of the contact current that flows between the exposed person and a re-radiating object provides a meaningful alternative to field measurements and makes possible the evaluation of the peak SAR that may exist in a person touching the hot-spot source.

(*d*) For most practical exposure situations, when hand contact is made with a RF source, the greatest RF current will flow in the body, resulting in the worst-case situation for peak SAR. The contact case will result in significantly greater local SARs than for the non-contact condition and should be assumed to be the exposure of possible concern. This maximum SAR will be in the wrist, the anatomical structure with the smallest cross-sectional area through which the contact current can flow.

(*e*) Determining the wrist SAR for contact conditions requires a measurement of the contact current, knowledge of the conductivity of the tissues, and knowledge of the effective, conductive, cross-sectional area.

(*f*) To determine whether a particular RF source meets absorption criteria would be difficult and could be done only by a properly qualified laboratory or by an appropriate scientific body for a general class of equipment. In no case could a routine field survey determine conformance with the SAR criteria. The dosimetric procedures required for accurate SAR assessments remain complex and are relegated, for many cases, to the laboratory setting.

(*g*) Complex exposure environments, such as the interior of antenna towers, that present highly localized RF fields on climbing structures (e.g., ladders) are candidate locations where contact current measurements may prove effective in evaluating compliance with the exposure standards.

(*h*) Contact current measurements appear the only practical avenue of evaluating RF hot spots found in public environments, where ambient field levels are usually well within the standards, but local fields are apparently excessive.

(*i*) Maximum contact currents are associated with the points on a conducting object that generally exhibit the greatest surface electric field strengths. Apparently this is because such points have relatively low impedance and current is transferred when contacted by the relatively low impedance of the human body.

11.2 Administrative controls

Administrative controls that can be used to reduce or prevent exposure to RF fields are:

- access restriction, e.g., barrier fences, locked doors;
- occupancy restriction (only to authorized personnel);
- occupancy duration restriction (applicable only to workers);
- warning signs, and visible and audible alarms.

Protective measures should be applied also against ancillary hazards such as the ignition of flammable gases and detonators or blasting caps. Specific guidance on how to deal with these problems is given elsewhere (Hall & Burstow, 1980; ANSI, 1985).

11.3 Personal protection

Protective clothing, such as conductive suits, gloves, and safety shoes, can be used. However, very few are commercially available and they are useful for RF shielding only over a specific frequency range. The results of testing a few microwave suits have been published recently (Guy et al., 1987; Joyner et al., 1989). Such suits should not be used indiscriminantly. Their use should be confined to ensuring compliance with exposure standards, when engineering and administrative controls are insufficient to do so (Joyner et al., 1989). Safety shoes have been proposed to reduce high local SARs for people on the ground plane (Kanai et al., 1984). Safety glasses have also been proposed for RF protection, but there is no convincing evidence that any of them are effective. On the contrary, they may act as receiving antennas and locally enhance the field.

11.4 Medical surveillance

Medical surveillance of workers should only be instituted if, in the normal course of their work, they could be exposed to RF-field intensities that would significantly exceed the general population limits. Other than a pre-employment general medical examination to determine baseline health status, a medical surveillance programme would serve little purpose, unless workers could reasonably be exposed to RF levels that approach or exceed occupational limits.

Medical surveillance of RF workers involves:

(*a*) The assessment of the health status of the worker before commencing work (pre-employment assessment), during work, if overexposures occur, and on termination of work involving RF exposure.

(*b*) The detection and early treatment of signs of any adverse health effects that might be due to RF exposure.

(*c*) The maintenance of precise and adequate medical records for future epidemiological studies. The nature of the work and the physical parameters of RF exposure (field strengths, exposure durations, etc.) for each worker should be documented very carefully.

In many countries, the initial and periodic medical examinations of workers are a legal requirement; in others, industries and governmental agencies may require pre-employment and periodic examinations. Contraindications to employment involving RF exposure should be identified by national authorities.

Over-exposures

When RF exposure exceeding occupational limits occurs, depending on the circumstances, a medical examination may be required. It should be noted that no unique syndrome for RF exposure has been identified requiring highly specialized treatment. Treatment can be expected to be symptomatic. From very high local exposures to RF of frequencies in the GHz range, deep burns and local tissue necrosis may be observed with a long-term and severe evolution. Very strong fields in the kHz and low MHz range could result in symptoms due to involuntary muscle contractions or stimulation of nervous tissue.

When RF over-exposure exceeds occupational limits, the following is suggested (Hocking & Joyner 1988):

(*a*) The circumstances causing the over-exposure should be determined and corrected.

(*b*) An investigation should determine the extent of over-exposure of the worker(s).

(*c*) A medical examination should be conducted using data on the over-exposure to direct the type of clinical examination.

11.5 Interference with medical devices and safety equipment

The susceptibility of electronic devices, particularly emergency equipment, to interference from electromagnetic fields must be evaluated in hospitals, clinics, and industry. Certain devices are subject to interference at some frequencies at electric field strengths below those permitted in many standards (Maskell, 1985). Shielding of the devices or hospital rooms is a practical solution to the problem.

A separate concern relates to electromagnetic interference with implantable medical devices and, most prominently, cardiac pacemakers. Improvements in pacemaker design have largely eliminated their susceptibility, however, in some instances, interference may still occur (Irnich, 1984; Sager, 1987). Cardiac pacemaker wearers need to be informed by their physician about its susceptibility to electromagnetic interference. RF workers who have implanted medical devices should be evaluated prior to commencing (or resuming) work (Hocking et al., 1991).