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	McRee 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

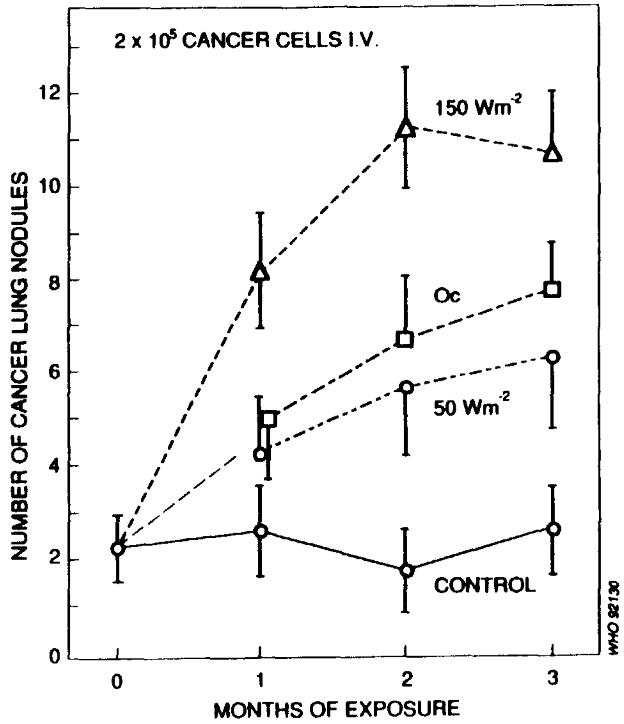

Fig. 22. Number of lung tumours (following intravenous injection of 2 × 10^5 viable sarcoma cells) in mice exposed to 2.45 GHz microwaves or non-specific stress (overcrowding; O$_c$). From Szmigielski et al. (1988).

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 corticosteroid levels. Other heat-related effects include temporary haematopoietic 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 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.

Table 30. Cutaneous perception in humans

Exposure conditions	Effects and thresholds	Reference
3 GHz to inner forearm	Threshold for pain	Cook (1952)
Area 9.5 cm^2 at 31 kW/m^2:	20 s latency	
at 8.3 kW/m^2:	180 s latency	
Area 53 cm^2 at 5.6 kW/m^2:	180 s latency	
	Pain at skin temperature of 46 °C	
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)	Threshold for perception:	Hendler & Hardy (1960); Hendler et al. (1963); Hendler (1968)
3 GHz, 1 s:	600 W/m^2	
3 GHz, 5 s:	320 W/m^2	
10 GHz, 1 s:	190 W/m^2	
10 GHz, 5 s:	130 W/m^2	
	Delay in response to warming 2.4-6.6 s	
2.88 GHz applied to forehead area 38 cm^2	Delay in response:	Schwan et al. (1966)
at 740 W/m^2:	15-73 s	
at 560 W/m^2:	50-180 s	
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)

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.

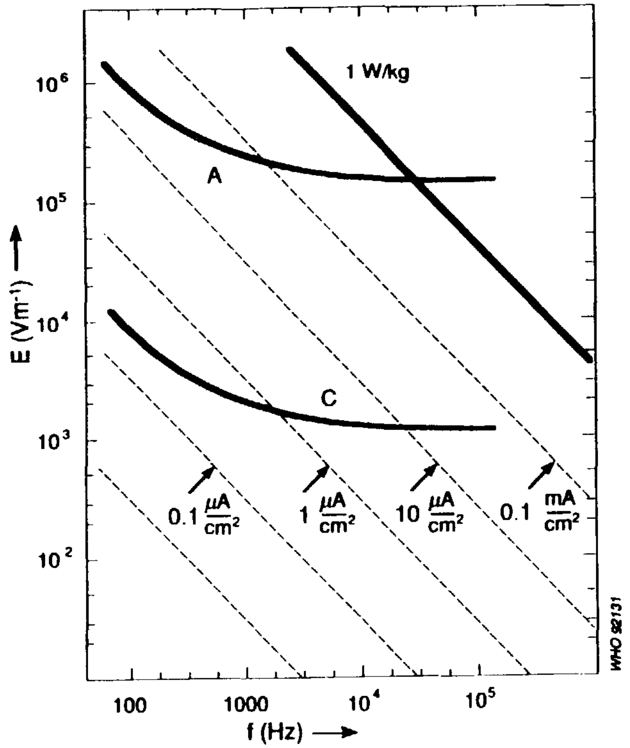

Fig. 23. Unperturbed electric field strength (E in V/m), as a function of frequency (f in Hz), that induces the indicated current density (μA/cm^2 or mA/cm^2) in the head or cardiac region of a person exposed with the long axis of the body parallel to the orientation of the E-field. From: Bernhardt (1985). 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.

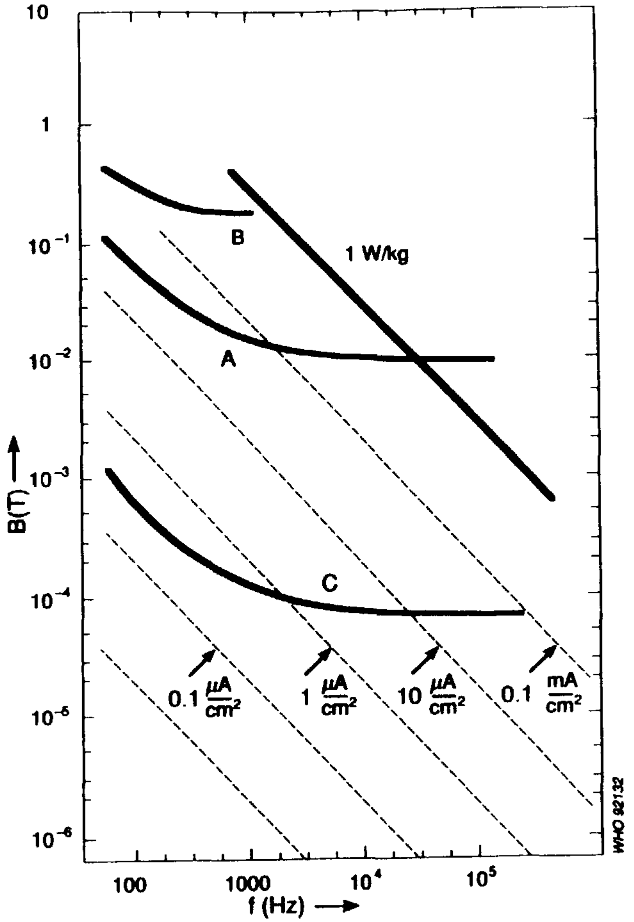

Fig. 24. Sinusoidal magnetic field (B in T) as a function of frequency (f in Hz) for inducing current densities (μA/cm^2) to the peripheral regions of the head or the heart. From: Bernhardt (1985). For larger effective current loops (e.g., for the trunk), the induced current densities may be larger at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

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/m²)[b]	(mW/cm²)[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/m²)[b]	(mW/cm²)[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.

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).

GLOSSARY

Wherever possible, this glossary gives terms and definitions standardized by the International Electrotechnical Commission in the International Electrotechnical Vocabulary (IEV) or by the International Organization for Standardization (ISO). In such cases, the IEV number, or the number of the ISO standard in which the definition appears, is given in parentheses. This glossary was compiled from WHO (1981) and US EPA (1984).

absorption. In radio wave propagation, attenuation of a radio wave due to its energy being dissipated, i.e., converted into another form, such as heat (IEV 60-20-105).

absorption cross-section effective area. Of an [antenna], oriented for maximum power absorption unless otherwise stated, an area determined by dividing the maximum power absorbed from a plane wave by the incident power flux density, the load being matched to the [antenna] (IEV 60-32-035).

antenna. The part of a radio system that is designed to radiate electromagnetic waves into free space (or to receive them). This does not include the transmission lines or waveguide to the radiator (IEV 60-30-005).

antenna, dipole. See dipole.

antenna directivity. See directivity.

antenna gain. See power gain of an antenna.

antenna, horn. See horn.

antenna isotropic. See isotropic radiator.

antenna pattern. See radiation pattern.

antenna regions. The distinction between electromagnetic fields far from, and those near to, the antenna. The regions are usually classified into three zones; near (static) zone, intermediate (induction) zone and far zone, located by drawing spheres of different radii around the antenna. The radii are approximately $r < \lambda$ for the near zone, $r \approx \lambda$ for the intermediate zone, and $r > \lambda$ for the far zone. Note that λ is the wavelength of the electromagnetic field produced by the antenna. In the far zone, field components (E and H) lie transverse to the direction of the propagation, and the shape of the field pattern is independent of the radius at which it is taken. In the near, and intermediate, zones, the field patterns are quite complicated, and the shape is, in general, a function of the radius and angular position (azimuth and elevation) in front of the antenna.

antenna scanning. See scanning.

attenuation. The progressive diminution in space of certain quantities characteristic of a propagation phenomenon (IEV 05-03-115).

athermal effect (nonthermal effect). Any effect of electromagnetic energy on a body that is not a heat-related effect.

blood-brain barrier. A functional concept to explain the observation that many substances transported by blood readily enter other tissues, but do not enter the brain. The barrier functions as if it were a continuous membrane lining the brain vasculature.

calcium efflux. The release of calcium ions from a sample into a surrounding solution.

circularly polarized. If the electric field is viewed as a point in space, the locus of the end point of the vector will rotate and trace out an ellipse, once each cycle.

conductance. The reciprocal of resistance (IEV 05-20-170). *Symbol*: G. *Unit*: siemens (S).

conductivity. The scalar or matrix quantity whose product by the electric field strength is the conduction current density (IEV 121-02-1). It is the reciprocal of resistivity.

continuous wave. A wave whose successive oscillations are, under steady-state conditions, identical.

current density. A vector of which the integral over a given surface is equal to the current flowing through the surface. The mean