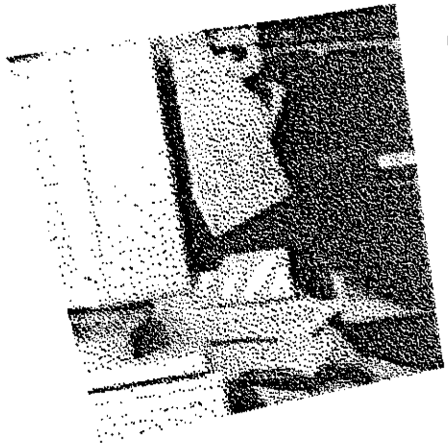
Review of exposure guidelines for electromagnetic fields (0 - 300 GHz) and ultraviolet radiation



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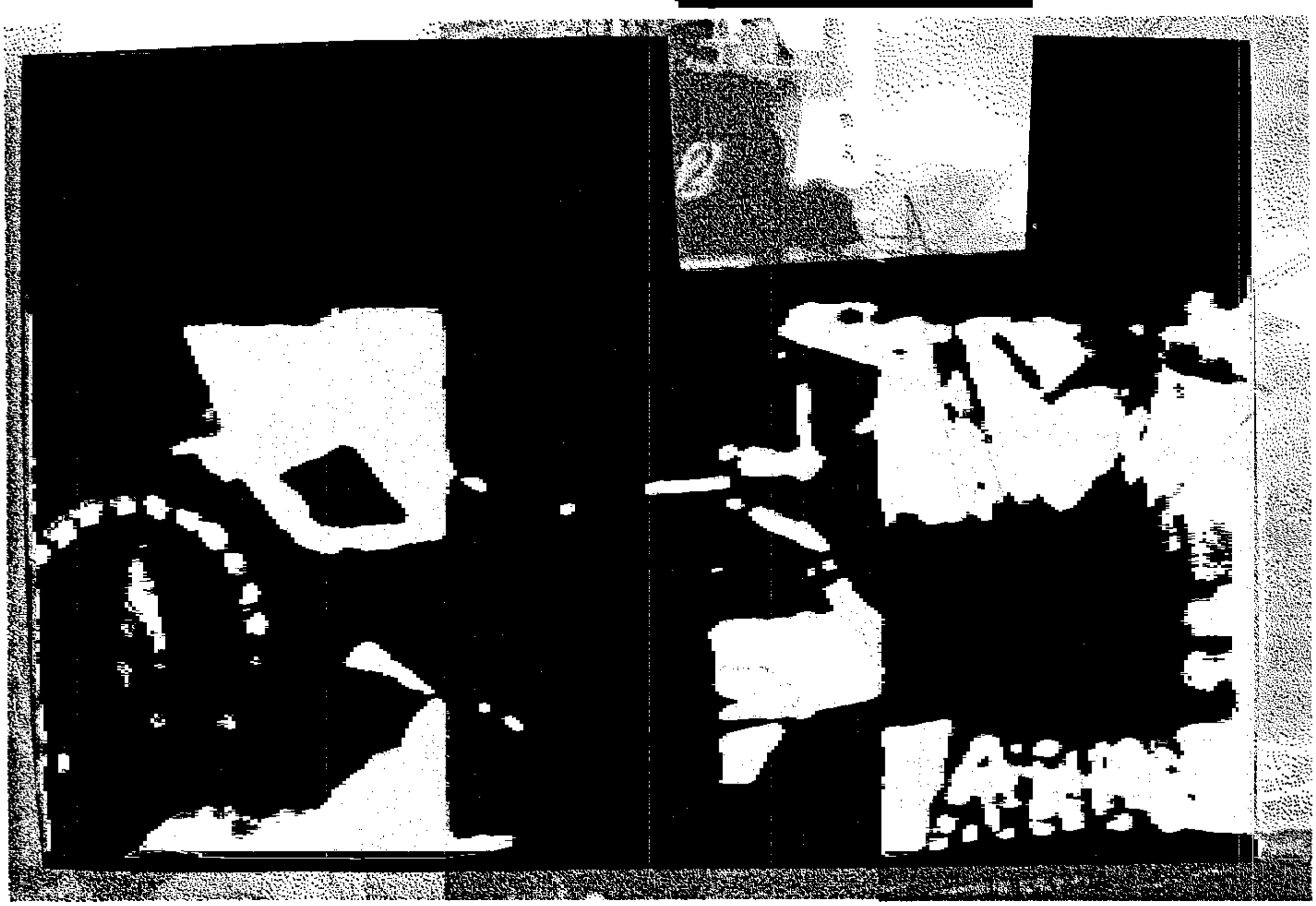
November 1997 B-051 [redacted] **RAPPORT**



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RAPPORT

This study was financed by the IRSST. The conclusions and recommendations are those of the authors.

NOTE TO READERS

This report was meant to facilitate the interpretation of exposure measurements. However, it cannot replace the source documents provided by the agencies responsible for the regulation of exposure to electromagnetic fields. Although the authors have taken great care to accurately record existing exposure standards and recommendations, readers preparing official positions should always refer to the original documents.

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INTRODUCTION

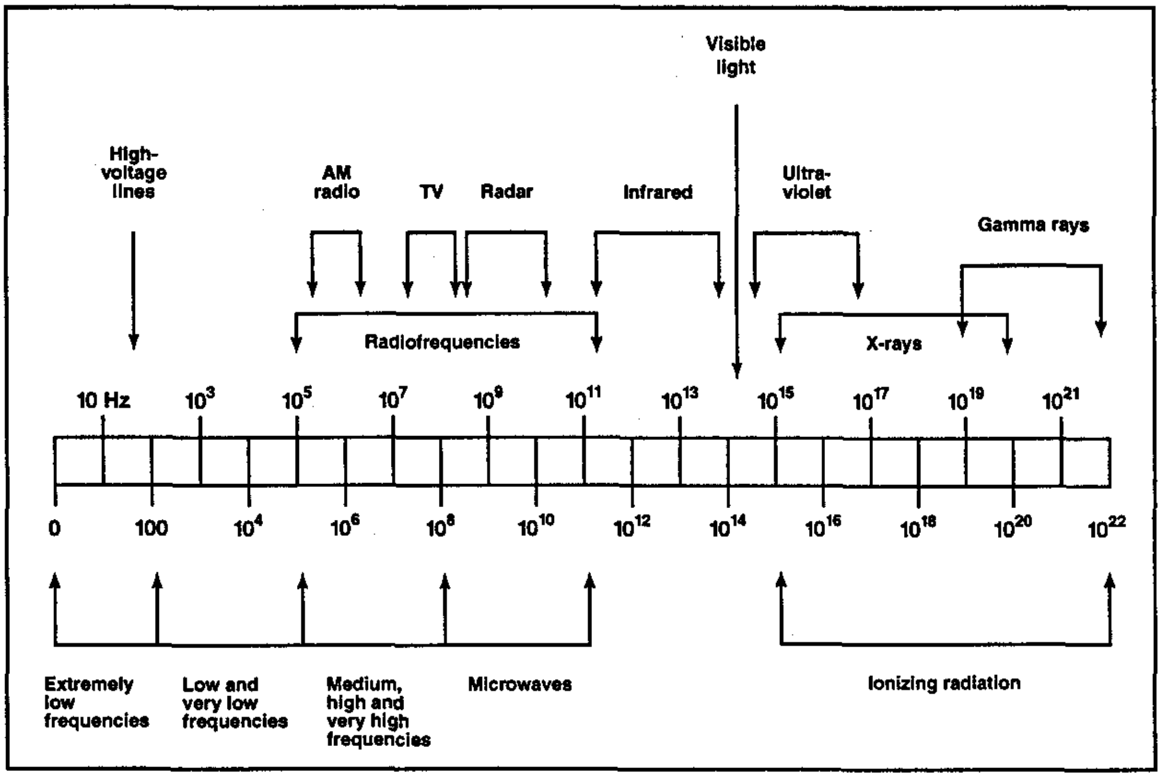
The subject of electromagnetic fields is vast, and the term "electromagnetic field" itself has different definitions, depending on the author. Some authors consider the term in a general way, i.e., applicable to the entire electromagnetic spectrum, while others limit its use to extremely low frequencies. In this report, the term will be considered a synonym for "non-ionizing radiation". In keeping with our mandate from the *Institut de recherche en santé et en sécurité du travail* (IRSST), we have focused on the literature on the frequency band between 0 and 300 GHz, and on ultraviolet radiation.

Although the fields generated by electromagnetic radiation all have the same general physical characteristics, they have very different mechanisms of action on humans. This is due in part to the energy transmitted by the wave, whose intensity increases significantly with decreasing wavelength. Furthermore, with near fields, as is usually the case for extremely low frequencies, the electric and magnetic components of the fields must be considered separately. This distinction does not apply to far fields.

Time and budget constraints forced us to limit our review to existing general standards and recommendations for each specific frequency band: static magnetic fields, extremely low frequencies (30–300 Hz), voice, low and very low frequencies (300 Hz to 100 kHz), radiofrequencies and microwaves (100 kHz to 300 GHz), and ultraviolet radiation (750–3000 THz) (Figure 1). With a few exceptions, recommendations for specific types of equipment are not presented. We have focused on the basis and the limitations of the recommendations for direct exposure (without contact with exposed objects). We have attempted to show the basis for the recommendations by emphasizing the uncertainties that argue for prudent interpretation of exposure measurements.

Despite the constraints under which this review was conducted, we believe that industrial hygienists and occupational physicians assessing the risks associated with exposure to electromagnetic fields will find it highly useful.

Figure 1: *The Electromagnetic Frequency Spectrum*



Chapter 1

Static magnetic fields

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1. STATIC MAGNETIC FIELDS

1.1 Description of parameters

A magnetic field can be defined as a region in space in which a force capable of modifying the path of charged particles operates. This field takes the form of concentric rings around an electrical conductor. The static magnetic current is produced by a direct current, i.e., by a current with a constant direction and intensity (Laliberté, 1995).

Magnetic field intensity is measured in amperes per metre (A/m), but is usually expressed as a magnetic flux density whose unit of measure is either the tesla (T) or the gauss (G) (1 tesla = 10,000 gauss). In non-magnetic environments, a field strength of 1 A/m is equivalent to a magnetic flux density of $4\pi \times 10^{-7}$ T.

Many devices emit static magnetic fields. These include anti-theft devices, airport security equipment, direct-current electrical power lines, magnetic-levitation transportation systems, electrolytic processes, high-energy particle accelerators, and thermonuclear reactors. In medical settings, magnetic resonance imaging equipment is the primary source of exposure to static magnetic fields (ACGIH, 1992; ICNIRP, 1994).

The main mechanism by which static magnetic fields interact physically with living things is the electrodynamic effects on circulating conducting fluids, mainly blood. Exposure limits are based on these electrodynamic effects or on the density of the induced current produced by the movement of a person in a static field (WHO, 1987; Health and Welfare Canada, 1987; Tenforde, 1992).

1.2 Current standards and recommendations

There are very few recommendations and even fewer standards for exposure to static magnetic fields. Some recognized agencies that have made recommendations are the International Commission on Non-Ionizing Radiation Protection (ICNIRP), the World Health Organization (WHO), and the American Conference of Governmental Industrial Hygienists (ACGIH). Other scientific organizations have also made recommendations on the subject, some of which apply specifically to the use of magnetic resonance imaging equipment.

1.2.1 International recommendations

1.2.1.1 International Commission on Non-Ionizing Radiation Protection (ICNIRP)

In May 1992, the International Commission on Non-Ionizing Radiation Protection (ICNIRP), an independent commission created by the International Radiation Protection Association (IRPA), approved recommendations on occupational and non-occupational exposure to static magnetic fields (ICNIRP, 1994). These recommendations are presented in Table 1.

Since most cardiac pacemaker functions do not appear to be affected by a field below 0.5 mT, ICNIRP therefore recommends that pacemaker users avoid locations where the magnetic flux density exceeds this value. Ferromagnetic implants and electrically active medical devices (such as hearing aids or prostheses) may also be affected by fields stronger than a few mT. Finally, ICNIRP points out that precautions need to be taken in order to prevent the risk of flying metallic objects whenever the magnetic field exceeds 3 mT.

These recommendations are based on the results of animal and human studies that suggest that transient exposure to a static magnetic field weaker than 2 T does not cause adverse health effects. Magnetohydrodynamic effects (slowing blood circulation and increasing blood pressure) may be caused by whole-body exposures of 5 T. Exposures of this magnitude are considered acceptable only for the extremities. Furthermore, ICNIRP indicates that, based on known interaction mechanisms (induced current and hemodynamic effects), long-term exposure to a magnetic field of 200 mT should not produce adverse health effects. In fact, a person moving in a 200 mT field produces an induced

Table 1: Exposure limits for static magnetic fields recommended by ICNIRP[1]

TYPE OF EXPOSURE	MAGNETIC FLUX DENSITY (T)
OCCUPATIONAL	
– entire work shift (TLV-TWA)	0.2
– ceiling value (TLV-C)	2
– limb exposure	5
GENERAL POPULATION	
– continuous exposure[2]	0.04

(1) These limits do not apply to users of cardiac pacemakers, other electrically active medical implants, or ferromagnetic implants.

(2) Occasional exposure may exceed 0.04 T if appropriately controlled at levels not exceeding recommended occupational exposures.

TLV-TWA: Threshold limit value, time-weighted average

TLV-C: Threshold limit value, ceiling value

SOURCE: ICNIRP, 1994

current density of 10–100 mA/m^2, a density compatible with the basic IRPA/ICNIRP limit for exposure to 50–60 Hz magnetic fields, given the known variation in these effects for frequencies below 10 Hz. This value, which ICNIRP considers conservative, is the result of the lack of data on the effects of chronic exposure. The exposure limit of 40 mT for the general population was arrived at by applying a further safety factor of 5.

1.2.1.2 World Health Organization (WHO)

The World Health Organization has not made recommendations for exposure to static magnetic fields. In its *Environmental Health Criteria 69* (WHO 1987), it states:

> *It can be concluded that available knowledge indicates the absence of any adverse effects on human health due to exposure to static magnetic fields up to 2 T. It is not possible to make any definitive statements about safety or hazard associated with exposure to fields above 2 T. From theoretical considerations and some experimental data, it could be inferred that short-term exposure to static fields above 5 T may produce significant detrimental effects on health.* (WHO 1987, p.20)

1.2.2 Canadian recommendations

At the present time, there are no Canadian standards or recommendations for exposure to static magnetic fields. In 1987, Health Canada's Environmental Health Directorate did, however, publish guidelines on exposure of patients and operators of magnetic resonance imaging equipment to the magnetic fields produced by this equipment (Health and Welfare Canada, 1987). They are:

- for operators, the recommended maximum exposure for a workday is 10 mT;

- for patients, exposure must not exceed 2 T.

These recommendations are among the most stringent applicable to magnetic resonance imaging equipment. Health Canada's guidelines allow the short-term exposure (approximately 10 minutes per hour) of operators to exceed this 10 mT, but stipulate that the number and duration of these high exposures should be as low as possible. It is also recommended that corrective measures be used in special cases, such as the exposure of individuals with cardiac pacemakers, metal suture staples or aneurism clips or metallic implants. No specific recommendation is presented, however.

According to Health Canada (Health and Welfare Canada, 1987), several studies have reported that there do not seem to be adverse effects among workers exposed to fields up to 2 T for several hours, or up to 0.5 T for prolonged periods. Finally, this department points out that the recommendations for personnel in nuclear physics laboratories in several countries may prove useful as reference levels for operators of magnetic resonance imaging equipment.

1.2.3 American recommendations

The American Conference of Governmental Industrial Hygienists (ACGIH), the United States Department of Energy (DOE), and two high-energy physics research laboratories in California have made recommendations on occupational exposure to static magnetic fields in the United States (Stuchly, 1986; Tenforde, 1990; WHO, 1987; ACGIH, 1994). The ACGIH recommendation will be discussed separately.

1.2.3.1 American Conference of Governmental Industrial Hygienists (ACGIH)

The 1994–1995 recommendations of the American Conference of Governmental Industrial Hygienists are presented in Table 2. ACGIH believes that these recommendations, based on extensive biological data, provide a sufficient safety margin to prevent the occurrence of adverse health effects in workers following chronic exposure to static magnetic fields. However, it mentions that further research on the mechanism of action of this type of field on living organisms is necessary.

ACGIH's recommended exposure limits are in fact the same as those of the Lawrence Livermore National Laboratory (U.S.), discussed below (*1.2.3.2.*). These limits are based on the possibility of producing a potential of 1 mV in the aorta of a person exposed to 60 mT, which is considered as negligible.

1.2.3.2 Other American recommendations

The recommendations proposed by other American agencies are presented in Table 3.

Those of the Lawrence Livermore National Laboratory are lower than those proposed by ICNIRP. The exposure limit of 60 mT is justified by the voltage of 1 mV induced in the aorta, a level considered to be safe for the heart and for hemodynamic parameters.

The maximum field strength of 2 T is derived from the results of laboratory studies on animals (Tenforde, 1990). Few data on the effects on humans are available. The Department of Energy's recommended limit of 10 mT, designed to limit the level of induced current in the cardiovascular system, is the most stringent recommendation applicable to an 8-hour work shift.

1.2.4 European recommendations

1.2.4.1 National Radiological Protection Board (NRPB)

In a report presenting occupational and non-occupational exposure limits for magnetic and electric fields, the National Radiological Protection Board (NRPB) of the United Kingdom (NRPB, 1991) indicated that it is reasonable to base limits for acute human exposure to static magnetic fields on the results of studies on animals and humans, given the current state of knowledge on this subject. The NRPB indicates that evidence suggests that exposure to fields of 4 T produces acute effects such as vertigo and nausea in workers, but that such effects

Table 2: ACGIH exposure limits for static magnetic fields

TYPE OF EXPOSURE	MAGNETIC FIELD
OCCUPATIONAL EXPOSURE	
– routine exposure	60 mT
– exposure of extremities	600 mT
– ceiling value	2 T

Users of cardiac pacemakers and similar medical devices should not be exposed to static magnetic fields above 0.5 mT.

SOURCE: ACGIH, 1994

Table 3: Other American recommended occupational exposure limits for static magnetic fields

DURATION OF EXPOSURE	PART OF THE BODY	RECOMMENDED MAGNETIC FIELD		
		Stanford Linear Accelerator Center	Lawrence Livermore National Laboratory	DOE
Work shift	• Whole body	20 mT	60 mT(1)(2)	10 mT
	• Arms, hands, extremities	200 mT	600 mT(2)	100 mT
Short term	• Whole body	200 mT	2 T	100 mT(3) 500 mT(4)
	• Arms, hands, extremities	2 T		1 T(3) 2 T(4)

(1) Trunk exposure.
(2) If the maximum field strength exceeds 500 mT, the time-weighted average is calculated for a daily exposure of 8 hours, rather than a weekly exposure of 40 hours.
(3) Exposure for 1 hour or less.
(4) Exposure for 10 minutes or less.

ADAPTED FROM WHO, 1987

would be avoided in occupational exposure to fields below 2 T. Since data on the possible effects of long-term exposures are lacking, it is recommended that the average occupational exposure over an entire work shift be limited to no more than 200 mT. These limits were reiterated by the NRPB in 1993 (NRPB, 1993) with the additional specification of 2 T for a general maximum exposure limit and 5 T for limb exposure. Exposure for users of cardiac pacemakers and prostheses, which are sensitive to static magnetic fields, should be limited to under 0.5 mT. It was recommended that, in magnetic fields above 3 mT, precautions be taken to prevent the risks due to the movement of ferromagnetic objects.

1.2.4.2 Comité européen de normalisation électrotechnique (CENELEC)

In November 1994, the *Comité européen de normalisation électrotechnique* (CENELEC) submitted draft pre-standards for human exposure to electromagnetic fields (EMF-HSD, 1995). As specified by this agency, the purpose of these limits is to prevent acute effects in humans exposed to static fields and to electric and magnetic fields in the frequency band from 0 to 10 Hz (CENELEC, 1994). CENELEC's recommended occupational exposure limits for magnetic fields in the frequency range of 0 to 0.1 Hz are the same as those of ICNIRP: 2 T for worker exposure; 0.2 T for an average exposure over 24 hours; and 5 T for limb exposure. The proposed limit for the general population is 0.04 T. The 2 T exposure limit is based on the possibility of vertigo, nausea, and health effects related to cardiac arrhythmia, disturbance in mental functions, and the induction of an electric field in the main blood vessels. The criterion of 5 T for limb exposure is based on the fact that these parts of the body contain no critical organs and contain smaller blood vessels.

CENELEC notes that cardiac pacemakers and other electrically active medical implants may be affected by magnetic fields weaker than the recommended exposure limits, and is preparing specific recommendations for these types of devices.

1.2.5 Other international recommendations

The Australian National Health and Medical Research Council has issued recommendations concerning occupational exposure to static magnetic fields related to the use of magnetic resonance imaging equipment (Repacholi, 1992). An exposure limit of 200 mT is recommended for the entire work shift, while limits of 2 T and 5 T are recommended for short-term whole-body and extremity exposure to the field generated by this equipment.

1.3 Basis for the recommendations

Exposure limits for static magnetic fields are primarily based on the results of animal studies. All of the studies tend to demonstrate no significant effect for an exposure below 2 T on the following biological systems: cell growth; reproduction; pre- and postnatal development; the bioelectric activity of neurons; behaviour; cardiovascular function; the circulatory system; immune system functions; physiological regulation, and circadian rhythm (WHO, 1987; Santé Canada, 1987; Tenforde, 1992; ICNIRP, 1994).

Some rare experimental studies conducted on volunteers provide useful information for establishing exposure limits. For example, it has been shown that in people placed in a 4 T field, rapid eye and head movements could produce vertigo, nausea, and magnetophosphenes, as well as a sensation of metallic taste. Chronic exposure to a magnetic field of 0.15 mT has been shown to have no effect on circadian rhythm (NRPB, 1991).

Very little epidemiological data is available on occupational exposure to static magnetic fields. Two studies on workers, one in the electrolytic cell industry (Marsh, 1982), and the other on another group of workers also exposed to static magnetic fields in another industry (Budinger, 1984), reported no adverse health effects among workers exposed to fields below 2 T. However, studies on workers in the aluminum industry exposed to strong magnetic fields have reported an increased mortality rate, attributable to leukemia. This may be due to a carcinogen, above and beyond the static magnetic fields (Rockette, 1993; Mur, 1987). The short-term exposure limit of 2 T is based on data on the acute and chronic effects observed in humans and animals, while the limit of 200 mT for the average exposure in an entire work shift appears to be based on the application of a safety factor of 10.

In fact, the main biological mechanism on which the stricter exposure limits for static magnetic fields are based is the creation of an electric current induced by the movement of ionic charges (such as those in the blood vessels) in the human body (WHO, 1987).

The Lawrence Livermore National Laboratory's recommendations are based on this principle. For a field of 60 mT, a maximum voltage of 1 mV will be induced in the aorta (Miller, 1987) which should not produce any adverse effects on cardiac performance and on the hemodynamic parameters (Tenforde, 1992).

In monkeys, it has been reported that acute exposure to a field of 1.5 T could result in significant electrocardiographic abnormalities (changes in the T wave), but produces no rise in blood pressure. In humans, exposure to fields of 5 T could reduce arterial flow by 7% (WHO, 1987; Tenforde, 1990). As there are no large blood vessels in the extremities, exposures to fields as strong as 5 T are permitted.

ICNIRP recommendations are also based on the principle of current induction created by the movement of a person in a field. The density of the current induced by a field of 200 mT (between 10 and 100 mA/m^2) would produce no adverse effect on the nervous system (ICNIRP, 1994). This statement is based on the equivalence of this level with the 10 mA/m^2 considered as acceptable for extremely low frequency fields.

According to unpublished data cited by Tenforde (WHO, 1987), the exposure limit recommended by the United States Department of Energy represents the threshold for magnetophosphenes production during exposure to alternating fields of extremely low frequencies. Also, this static field limit would correspond to the measurable threshold for induced voltage in the central circulatory system.

Finally, although the recommendations of the Stanford Linear Accelerator Center are the most widely adopted exposure limits in the United States (Tenforde, 1990), the relevant supporting data for these criteria is not readily available and was in fact unavailable to the authors of this report.

1.4 Limitations of the recommendations

1.4.1 Limitations in exposure assessment

The recommended exposure limits apply to single exposures to a continuous magnetic field. However, a person is generally exposed simultaneously to an alternating field. These two types of fields may interact (see Chapter 2) and this limitation must therefore be taken into consideration. Furthermore, most of the exposure recommendations are based on the risk of problems in the central nervous system and in blood circulation in large blood vessels caused by induced current in the human body (WHO, 1987). Other important mechanisms of action are most likely present, which could justify other exposure parameters being considered.

1.4.2 Limitations of the data available on the effects of acute exposure

Most studies on static fields have been conducted on animals, including primates. Few studies have been conducted on humans, and consequently there is no data available on the effects of prolonged high intensity occupational exposures (WHO, 1987). Furthermore, while 2 T appears to be the threshold for irreversible effects (WHO, 1987), reversible effects have been observed in laboratory experiments with exposures to weaker fields in the order of 0.1 T (WHO, 1987).

Although most of the abstracts of official documents consulted reported a NOAEL (No Observable

Adverse Effect Level) of 2 T, the maximum field strength used in many studies was 1.5 T (Tenforde, 1990). For example, the absence of blood pressure effects in monkeys was verified only up to 1.5 T (Tenforde, 1990).

1.4.3 Limitations of the data available on the effects of chronic exposure

There is very little data available on the possible effects of chronic exposure to magnetic fields. To our knowledge, there are no animal studies on carcinogenesis for this type of exposure. The data from epidemiological studies is limited but reassuring.

1.4.4 Limitations related to the mechanisms of action considered by agencies proposing exposure recommendations

The effect of current induction on the nervous and cardiovascular systems is the principal mechanism considered by the agencies making exposure recommendations. However, other mechanisms of interaction with the human body have been demonstrated. Of these, the magneto-orientation effect, causing molecular orientation, thus having an effect on retinal and sickle cells, has been particularly well documented. The absence of an electroretinographically detectable effect in monkeys exposed to fields up to 1.5 T is reassuring (WHO, 1987). However, the data on visual effects in humans is limited, and the possibility of adverse effects in individuals suffering from sickle-cell anemia should be taken into consideration (ICNIRP, 1994).

Another well-documented magneto-mechanical effect in animals is the translation effect, i.e., the induced movement of certain magnetite-containing cells. This effect would explain the ability of some animals (fish, birds) to orient themselves along a geomagnetic field whose intensity varies from 30–70 μT (Tenforde, 1990; ICNIRP, 1994). Although the human body appears to contain magnetite particles, the existence of cells capable of reacting to such weak static magnetic fields has not been demonstrated. Further research in this area is indicated.

1.4.5 Limitations related to the safety factors considered in establishing exposure recommendations

The safety margin used by ACGIH and ICNIRP in establishing ceiling values appears consistent with current practice in the field of radiation protection. However, it is difficult, in light of the limitations of the data available on the possible effects of chronic exposure, to assess the real value of the proposed safety factors. It should be noted that ACGIH's recommended limit for an entire work shift (60 mT) is one of the lowest.

1.5 Summary

Worldwide, certain recommendations have been made concerning occupational exposure to static magnetic fields. Current data indicates that acute exposure to static magnetic fields weaker than 1.5–2 T causes no significant effects on the main biological systems. None of the agencies recommended whole-body short-term ceiling values exceed 2 T. Short-term exposure of the limbs or extremities to fields no stronger than 5 T is permissible, since the hemodynamic effects possible at these levels cannot occur in the extremities. Lower limits are given for work shifts, due to the lack of knowledge about the effects of chronic exposure. These main work-shift recommendations are summarized in Table 4.

Recommended work-shift exposures for static magnetic fields range from 10 to 200 mT. ICNIRP, ACGIH and NRPB recommend that users of cardiac pacemakers or other electrically active devices be exposed to no more than 0.5 mT, while the Lawrence Livermore National Laboratory's limit is 1 mT. Current scientific knowledge suggests that these limits provide adequate protection, but there is uncertainty surrounding the possible effects of chronic exposure to static magnetic fields. These uncertainties justify a reevaluation of the existing recommendations as new knowledge becomes available on the possible effects of these fields.

Table 4: Summary of the recommended occupational exposure limits for static magnetic fields

AGENCY	MAGNETIC FIELD (T)	
	Exposure for an entire work shift	Short-term exposure or ceiling value
ICNIRP*	0.2	2(2)
ACGIH*	0.06	2(2)
U.S. Department of Energy*	0.01	0.5(1)
Lawrence Livermore National Laboratory*	0.06	2(1)
Stanford Linear Accelerator Center*	0.02	0.2(2)
NRPB	0.2	2(2)

* Higher exposure levels are proposed by these agencies for hands, arms or extremities.
(1) Short-term exposures
(2) Ceiling value

SOURCE: WHO, 1987; ACGIH, 1994; ICNIRP, 1994

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Chapter 2

Extremely low frequency electric and magnetic fields (30–300 Hz)

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2. EXTREMELY LOW FREQUENCY ELECTRIC AND MAGNETIC FIELDS (30–300 Hz)

2.1 Description of parameters

By international convention, extremely low frequency fields (ELF fields) are fields with a frequency of 30–300 Hz. At these frequencies, the wavelengths considered are very long (>1000 km). Hence, the exposure parameters of interest are the electric and magnetic fields. ELF fields induce low current densities in the human body, and presently no other parameters are useful in estimating the effective absorbed dose. The main exposure parameters considered are the intensity of the fields, the density of the induced current, and the duration of exposure. Most studies on the effects of these frequencies involve the power frequency (50/60 Hz).

2.2 Current standards and recommendations

There are currently very few exposure standards for ELF fields. Recommendations have been made by various agencies and organizations, the best known being the International Radiation Protection Association (IRPA), the World Health Organization (WHO), and the American Conference of Governmental Industrial Hygienists (ACGIH).

2.2.1 International recommendations

2.2.1.1 International Radiation Protection Association (IRPA)

In 1990, the International Radiation Protection Association (IRPA) and the International Non-Ionizing Radiation Committee (INIRC) (now the International Commission for Non-Ionizing Radiation Protection (ICNIRP)) have published provisional recommendations on exposure to 50/60 Hz electric and magnetic fields (INIRC/IRPA, 1990). These recommendations, which were re-endorsed at the 1993 IRPA's conference (EMF-HSD, ICNIRP, 1993), are summarized in Table 5.

These maximum exposure recommendations are based on knowledge about the effects resulting from the current induced inside the human body following acute exposure. For electric fields, the criterion proposed for one work day is based on the induction of a current of 4 mA/m^2 in the head or trunk during exposure to an unperturbed field of 10 kV/m. Temporary occupational exposures up to 30 kV/m are permitted for a maximum of 2 hours and 40 minutes.

The maximum value recommended for a magnetic field for one work day could induce a current of 1 mA/m^2 in the trunk. The maximum recommended values for occupational exposures of less than 2 hours correspond to the possible induction of a current of 10 mA/m^2. In 1994, IRPA, in collaboration with the International Labour Organization, published a practical guide for the protection of workers exposed to EMF of 50/60 Hz (ILO, 1994). In addition to presenting the recommendations of IRPA and WHO, this guide supplies practical information on the roles and competencies of the decision-making authorities. It also presents occupational exposure monitoring, control and evaluation procedures.

2.2.1.2 World Health Organization (WHO)

The World Health Organization has not issued specific recommendations concerning occupational exposure to these fields. Table 6 summarizes the conclusions of WHO's Environmental Health Criteria 35 and 69 (WHO, 1984, 1987) dealing with these exposures.

WHO has not recommended exposure limits for magnetic fields, but states that no significant effect is observed with an induced current below 10 mA/m^2. Certain minor biological effects have been reported for short term exposures to 10–100 mA/m^2, such as phosphenes. There may be a significant risk associated with exposures above 100 mA/m^2 (WHO, 1987).

Table 5: Exposure limits for 50/60 Hz electric and magnetic fields, International Radiation Protection Association

TYPE OF EXPOSURE	ELECTRIC FIELD (kV/m) (rms)	MAGNETIC FIELD (mT) (rms)
OCCUPATIONAL		
– work shift	10	0.5
– short term	30(1)	5(2)
– limb exposure	—	25
GENERAL POPULATION		
– 24-hour	5	0.1
– several hours per day	10	1

(1) The duration of exposure to 10–30 kV/m fields can be calculated using the formula $t \leq 80/E$ where t is the exposure duration in hours and E is the electric field in kV/m.

(2) ≤2 h/day

SOURCE: INIRC/IRPA, 1990

Table 6: Recommended exposure limits for ELF fields, World Health Organization

TYPE OF EXPOSURE	ELECTRIC FIELDS	MAGNETIC FIELDS
OCCUPATIONAL	No limit, but avoid microshocks	No recommendation
GENERAL PUBLIC	<10 kV/m Long-term exposure should be as low as can be reasonably achieved	No recommendation

SOURCE: WHO, 1984 and 1987; Anderson and Kaune, 1991

2.2.2 Canadian recommendations

Currently, there are no Canadian recommendations or guidelines for ELF. According to the report of the Canadian task force on electric and magnetic fields, this is due to the lack of scientific data (Health and Welfare Canada, 1989).

2.2.3 American recommendations

2.2.3.1 American Conference of Governmental Industrial Hygienists (ACGIH)

In 1993, ACGIH adopted recommendations for sub-radiofrequencies (≤30 kHz), including ELF fields (ACGIH, TLV, 1993–94). These recommendations are described in the 1994–1995 version of ACGIH's Threshold Limit Values (TLVs) (ACGIH, TLV, 1994–95) and are summarized in Table 7.

In this version, ACGIH clearly states that the recommended exposure values are ceiling values that should never be exceeded. The maximum permissible exposure to 60 Hz fields is 25 kV/m and 1 mT, below those recommended by IRPA for few hours of exposure. According to ACGIH's documentation (ACGIH, 1991) justifying these recommendations, these values are intended to maintain an induced current equal to or less than 10 mA/m² in the body.

In recommending these ceiling values, ACGIH stated that, given the insufficient data on the effects of human exposure to EMF of extremely low frequencies, it was unable to propose time-weighted average exposure values (TWA) for a work day. Furthermore, considering that the risks to comfort and safety are secondary to the spark discharges and induced current generated by contact with an ungrounded conductors, ACGIH recommends grounding these objects once exposure exceeds 5 to 7 kV/m. If grounding is impossible, or once the electric field exceeds 15 kV/m, it is recommended that the worker use protective clothing (insulating).

Because power frequency electric and magnetic fields (50/60 Hz) may interfere with cardiac pacemakers, ACGIH recommends that individuals using these devices avoid exposure to fields stronger than 1 kV/m or 0.1 mT, unless otherwise advised by the pacemaker manufacturer.

Table 7: ACGIH ceiling TLVs for exposure to ELF fields*

FREQUENCIES (f)	ELECTRIC FIELD (kV/m) (rms)	FREQUENCIES	MAGNETIC FIELD (mT) (rms)
≤100 Hz	25	1–300 Hz	$\frac{60}{f}$ **
100 Hz to 4 kHz	$\frac{2.5 \times 10^3}{f}$		

f: frequency expressed in hertz.

* Recommendations for users of cardiac pacemakers are lower.

** For extremity exposure, the ceiling value is five times higher.

SOURCE: ACGIH, TLV, 1994-95

2.2.3.2 American Industrial Hygiene Association (AIHA)

The American Industrial Hygiene Association (AIHA) presented in 1993 its position on exposure to ELF (AIHA, 1993). Given the existing data, it was unable to take a position concerning the possible effects of this type of exposure. Also, because of conflicting data, it recommended a cautious approach. Briefly, its recommendations are:

- complete characterization of industrial exposures;
- education of workers about the possible effects of these fields, recommended exposure levels, and protective measures;
- compliance with ACGIH and IRPA/ICNIRP exposure recommendations.

2.2.4 European recommendations

Maddock (1992) recently reviewed most of the current European recommendations. Most countries have adopted recommendations similar to those of IRPA. Germany is the only country in western Europe with standards for occupational exposure: a maximum of 20.7 kV/m for electric fields and 5 mT for 50/60 Hz magnetic fields. These recommendations are based on the density of the current induced in the human body.

2.2.4.1 Comité européen de normalisation électrotechnique (CENELEC)

The *Comité européen de normalisation électrotechnique* (CENELEC) issued in 1994 draft pre-standards for maximum exposure to ELF fields (CENELEC, 1994). The proposed values, presented in Tables 8 and 9, were based on the possibility of inducing a maximum induced current of 10 mA/m^2.

2.2.5 Other international recommendations

2.2.5.1 Australia

Australia has proposed interim exposure limits for 50/60 Hz fields in 1989 (NHMRC, 1989) that are identical to those of IRPA (INIRC/IRPA, 1990). The National Health and Medical Research Council of Australia (NHMRC), which developed these recommendations, also recommends implementing workplace monitoring and education programs to ensure proper worker protection.

2.3 Basis for the recommendations

All the recommendations involving ELF are based on the same reasoning. In evaluating risks and standards, only the proven effects of exposure to electric and magnetic fields are taken into consideration. The only sufficiently understood and usable mechanism is current induction in the human body. The possible effects of this current induction are mainly the stimulation of nerve and muscle fibers. The current intensity ranges that may be responsible for such effects vary with the field frequency, but are rather similar in the ELF range (except for phosphenes).

Table 8: CENELEC pre-standards – Maximum exposure levels for electric fields

FREQUENCY (f) (Hz)	ELECTRIC FIELD (kV/m)
OCCUPATIONAL EXPOSURE	
0.1–50	30[a]
50–1500	$1500/f$[a]
GENERAL PUBLIC	
0.1–60	10
60–1500	$600/f$

a The duration of exposure to frequencies of 0.1–150 Hz must not exceed 80/E.
f: Frequency in Hz

SOURCE: CENELEC, 1994

Table 9: CENELEC pre-standards – Maximum exposure levels for magnetic fields

FREQUENCY (Hz)	ELECTRIC FIELD (mT)
OCCUPATIONAL EXPOSURE	
4–1500	$80/f$
GENERAL POPULATION[a]	
1.15–1500 (Version A)	$32/f$

a CENELEC proposes two versions of the standards to be studied by the member countries. Version A is based on the induced-current restriction.
f: Frequency in Hz

SOURCE: CENELEC, 1994

The first observable effects of induced current in humans are phosphenes, the phenomenon of bright flickerings seen by the eye in the absence of stimulation by visible light. This phenomenon, observed in ophthalmic migraine, may be caused by electric current in the retina with exposure to ELF magnetic or electric fields. It occurs immediately upon exposure and is completely reversible after the exposure ceases. Maximum retinal sensitivity for producing this phenomenon occurs with exposure to fields of 18–20 Hz (Tenforde, 1990). At 50 Hz, this phenomenon is generally observed with the induction of a current of 30–100 mA/m^2, equivalent to exposure to a magnetic field of approximately 10 mT (Maddock, 1992). The National Radiological Protection Board (NRPB) of the United Kingdom states that the maximum permissible induced current for 50 Hz fields should be 20 mA/m^2, given that phosphenes may appear above this level. However, it was recently estimated that, for a frequency of 60 Hz, phosphenes could be produced by retinal currents of approximately 10 mA/m^2 (Tenforde, 1990).

All the recommended exposure limits for ELF fields are based on the absence of significant risk when the induced current intensity does not exceed 10 mA/m^2. In particular, this is the reasoning given by WHO (WHO, 1987) and IRPA (INIRC/IRPA, 1990) to justify the proposed maximum exposure recommendations. WHO has published a review of the possible effects in relation to the induced current intensity (WHO, 1987) based on the work and reviews published by Bernhardt (Bernhardt, 1979). It is presented in Table 10.

Despite the fact that Bernhardt considers phosphenes, the only arguments justifying the recommended limit of 10 mA/m^2 are based on the possibility of human tissue stimulation (nerves and muscles), mainly above 100 mA/m^2, and on the observation that currents of 10–1000 mA/m^2 are observed in the human body during cardiac activity, for example.

WHO then added stimulation of ossification to the list of noted but non-hazardous effects. The induced magnetic field responsible for ossification would produce a current density from 2 to 20 mA/m^2 inside the bone (WHO, 1987). However, the fields involved are non-sinusoidal, as electric currents generally are. They are in fact pulsed magnetic fields at frequencies in the ELF band (mainly 60–75 Hz), but whose actual frequency varies from continuous to radiofrequencies (>10 MHz) (Bassett, 1989). This type of effect therefore cannot be related to sinusoidal frequency fields such as those in the power frequency.

Table 10: Current density necessary to produce biological effects in the 3–300 Hz frequency range

CURRENT DENSITY (mA/m^2)	EFFECTS
>1000	Possible extrasystoles and ventricular fibrillation: clear danger
100–1000	Modification of nervous system excitability, proven muscle stimulation: possible danger
10–100	Phosphenes, other possible nervous system effects, stimulation of ossification: clear effects whose deleterious nature has not been proven
1–10	Minor biological effects
<1	No proven effects

Adapted from WHO, 1987, and Bernhardt, 1988

Both IRPA and WHO mention the possible risk of interference by ELF fields with cardiac pacemakers, but only ACGIH has issued specific recommendations for users of these devices. The risks involve the modification of the functioning of these devices operating in "demand" mode (operating as needed) and mainly of the unipolar type (external stimulator acts as anode). Interference is possible for fields of 50/60 Hz, once the field intensities exceed 1.7 kV/m and 14 µT. (Bernhardt, 1992). However, only a small proportion of cardiac pacemakers may be sensitive to this interference, particularly above 0.2 mT (INIRC/IRPA, 1990; Bernhardt, 1992). ACGIH's recommended maximum exposure levels are therefore in this range of values and are based on data presented by IRPA (INIRC/IRPA, 1990).

2.4 Limitations of the recommendations

Although the recommendations are based on solid experimental data, they nevertheless have certain limitations that must be taken into consideration when interpreting exposure measurements.

2.4.1 Limitations related to exposure assessment

Since the exact biological mechanism responsible for the observed effects of low-dose exposure is unknown, it is impossible to definitively identify the parameters necessary for the quantification of the effective dose (i.e., the dose responsible for the effects). Various parameters present during exposure to ELF electric and magnetic fields, which could be critical in the interaction with the human body, are not considered in establishing exposure recommendations. These include:

- the broadband spectral content;
- the intermittent nature of the exposure, the frequency and intensity of the high-intensity transients;
- the geomagnetic field and the possibility of resonance effects;
- the background level.

A workshop organized by the National Institute for Occupational Safety and Health (NIOSH) in the United States brought together various experts to determine the most useful parameters to be measured in epidemiological studies. The consensus, according to the report published on the results of the workshop, was to (EMF-HSD, NIOSH/DOE, 1994):

- characterize the AC broadband spectral content;
- measure the geomagnetic field;
- take into account the variability in exposure.

In fact, it will be some time before the most useful parameters can be precisely identified. For now, It should be understood that the parameters taken into consideration in exposure recommendations are probably insufficient and have no clear link to the risk related to chronic low-dose exposure.

2.4.2 Uncertainty related to the path of induced current in the body

The data for extrapolating induced current fields within the human body is uncertain. To take into account the uncertainties related to the assumptions used in these extrapolations, Bernhardt (1988) recommended the application of additional safety factors. The precise path of the induced current through the body is difficult to model, and the peak levels rather than mean levels of the induced current may be more responsible for cellular stimulation.

2.4.3 Limitations related to the evaluation of the effects of chronic exposure

All the exposure recommendations apply to acute exposure. ACGIH, in its TLV recommendations (ACGIH, TLV, 1994–95), took great care to emphasize that these are ceiling values. This precaution is not given in most of the recommendations of the other agencies. IRPA's permissible levels for exposure lasting several hours are higher than those of ACGIH, but it has issued provisional guidelines for exposures lasting an entire work shift.

The safety factors used by IRPA are essentially presented empirically, and illustrate the difficulty in evaluating the uncertainty surrounding the effects of chronic exposure. Bernhardt, whose work is the basis for the WHO and IRPA recommendations, has always been very careful about formulating recommendations for chronic exposure (Bernhardt, 1979; Bernhardt, 1988). Furthermore, he recently reported the lack of data on the possible long-term effects of chronic exposure to fields inducing currents of approximately 1–10 mA/m^2 (Bernhardt, 1992).

In light of the possible existence of a link between exposure to much weaker fields and cancer (Levallois and Gauvin, 1994; Levallois, 1994), it is important to keep in mind that current recommendations are based on the risks associated with short-term exposures. Although the use of safety factors is consistent with conventional practice in the field of radiation protection, it is unclear whether the safety factors proposed by IRPA afford sufficient protection in cases of chronic exposure.

2.4.4 Limitations related to indirect exposure (contact currents)

This section discusses exposure resulting from direct contact, either occupational or non-occupational, of a person in an exposed environment, with ungrounded objects. Contacts near charged objects produce a sensation of unpleasant electrical discharges, responsible for transient induced currents that are sometimes of high intensity. Direct contact will produce a steady current. The effects generally associated with contact currents, in progressive order of importance, are (Bernhardt, 1988; Bernhardt, 1992):

- perception of current;

- an unpleasant sensation;

- significant movement, sometimes secondary to surprise or the unpleasant sensation;

- inability to loosen grip, due to uncontrollable muscular contractions;

- respiratory tetanus, i.e., respiratory failure due to contraction of the respiratory muscles;

- cardiac fibrillation (asynchronous contraction of the cardiac muscle).

IRPA (INIRC/IRPA, 1990) and ACGIH (ACGIH, 1991) documents explain these phenomena and the appropriate preventive or protective measures. The latter include the grounding of exposed objects and the wearing of protective clothing. These currents are very rarely taken into consideration in assessing the risks associated with ELF fields, and the NRPB is the only agency to make recommendations on them. It should be noted that the recommended exposure limits for electric fields under high-voltage lines (8–12 kV in North America) are based on the risks associated with the current induced by contact with uninsulated objects (IRPA/INIRC, 1991; Levallois, 1994). These values are based on the U.S. National Electrical Safety Code (US-NESC), which recommends a maximum contact current of 5 mA [American National Standards Institute (ANSI), 1990], while CENELEC recommends maximum currents of 1.5 mA for workers and 1 mA for the general population.

The US-NESC recommendations are based on an estimated 1 in 200 risk of a current of 6 mA or more causing tetanic grip in women, who are the most sensitive to this effect (Bernstein, 1991). The threshold for the perception of current is much lower, however, with almost half the population capable of perceiving currents of 0.3–0.4 mA and above (Bernstein, 1991). In order to avoid these and other more serious problems, the maximum permissible contact current for electrical equipment in North America is therefore 0.5 mA (ANSI, 1988).

Should we be concerned only with the acute risks associated with those contact currents? The question is a good one. In fact, contact currents are markedly stronger than those directly induced by exposure to electric and magnetic fields. In fact, currents induced by imperceptible contact currents may be a significant source of exposure and certain biological effects (Bridges, 1994).

2.4.5 Limitations related to the mechanism of action

Current induction is the only mechanism of action taken into consideration in establishing the existing exposure recommendations. However, increasing evidence suggests that other mechanisms may also be relevant. Thus, in double-blind experiments, Graham and Cohen demonstrated that exposure, particularly intermittent exposure, to 60 Hz fields of 9 kV/m and 0.02 mT may slow the resting heart rate by several beats per minute and alter auditory and visual evoked potentials (Graham, 1985). Furthermore, several *in vitro* and *in vivo* effects are difficult to explain in terms of the simple physical effect of induced current. These effects include (Anderson and Kaune, 1991; Tenforde, 1990; Levallois, 1994):

- the alteration of transmembrane calcium transport in various cells exposed to fields producing induced currents in the order of one mA/m^2;
- a reduction in melatonin secretion in rats exposed to fields producing induced currents in the order of one mA/m^2;
- the alteration of RNA transcription and translation by fields producing currents as weak as 0.03 mA/m^2;
- the existence of a "window" effect, i.e., certain specific effects at certain frequencies and certain intensities.

Other mechanisms are therefore involved, and there is abundant speculation on this subject. Mechanisms currently discussed include:

- possible magnetic resonance caused by the interaction of the geomagnetic field with alternating fields (Tenforde, 1990);
- direct action of fields on receptors containing magnetic compounds (magnetites) (Kirschvink, 1992);
- multistage effects caused by intermittent exposures (Litovitz, 1992).

Bernhardt (1992) stated that the current-induction theory is inadequate for explaining the effects presented above, and that other mechanisms should be studied and possibly taken into account in evaluating the effects of low-dose chronic exposures. However, it is clear that answers to these questions will not be available in the next few years. For now, even if the concept of effects associated with induced current adequately explains acute effects, it cannot be used to estimate the possible effects of chronic exposures. This uncertainty explains the provisional nature of the IRPA/ICNIRP recommendations.

2.4.6 Limitations related to safety factors

The safety factors used by agencies in establishing exposure recommendations vary widely, and are rarely explicit. The safety factor used for magnetic fields (10) is different from that used for electric fields (3). According to IRPA data (INIRC/IRPA, 1990), a 10 kV electric field, considered an acceptable occupational level of exposure over an entire work shift, induces a current of 4 mA/m^2 in the trunk and head, while a magnetic field of 0.5 mT, also considered acceptable, induces a current of approximately 1 mA/m^2 in the body. The same observation can be made for the exposure of the general population, where additional safety factors of 2 and 5 are applied to electric and magnetic fields, respectively.

2.5 Summary

The exposure parameters usually taken into consideration for this frequency range (30–300 Hz) are the electric and magnetic fields. All the recommended exposure limits applicable to these fields, in North America and elsewhere, are based on the risks associated with acute exposure and the possible effect of the current induced by direct exposure. The maximum recommended induced current is 10 mA/m^2, which corresponds, for the power frequency (50–60 Hz), to a maximum exposure of 25 kV/m (undisturbed fields) and 5 mT.

Some agencies have proposed alternatives, but ACGIH is the only one to clearly specify that these limits are ceiling values. For a frequency of 60 Hz, ACGIH recommends ceiling values of 25 kV/m and 1 mT, while IRPA recommends ceiling values slightly higher than those of ACGIH, or 30 kV/m and 5 mT, which generally do not induce currents exceeding 10 mA/m^2 (except for the electric field, where the value of the induced current is slightly higher). IRPA has, however, proposed values for occupational exposure by applying safety factors whose real protective value in protecting long-term health is difficult to evaluate. In fact, most agencies making recommendations and the experts consulted agree that it is currently impossible to assess the risk associated with chronic exposure, and, by extension, to make exposure recommendations that provide protection against these possible effects.

Other limitations in the exposure-recommendation development process have been described. They are mainly:

- the difficulty in extrapolating the current induced in different parts of the body from the intensity of undisturbed fields;

- inadequate knowledge about the mechanisms of action that could produce effects resulting from low-dose chronic exposure;

- not taking into account the true exposure parameters, particularly the broadband spectral content, the geomagnetic field, and the variability of exposure;

- the lack of emphasis on indirect exposure caused by contact currents with ungrounded objects.

We have also noted that only the AIHA in the United States and NHMRC in Australia have recommended a cautious approach towards occupational exposure to these fields, including monitoring programs and worker education on the possible effects of these fields and on protective measures.

Table 11 summarizes the various recommended occupational exposure limits for extremely low frequencies.

Table 11: Summary of recommendations for occupational exposure to ELF electromagnetic fields

AGENCY	FREQUENCIES	ELECTRIC FIELD (kV/m)		MAGNETIC FIELD (mT)	
		Work shift	Short-term	Work shift	Short-term
IRPA/INIRC	50/60 Hz	10	30[a]	0.5	5[b,c]
ACGIH[d]	1–300 Hz				60/f [c]
	≤100 Hz	25			
	100 Hz–4 kHz	$\frac{2.5 \times 10^3}{f}$			
Germany	50/60 Hz		20.7		5
CENELEC	0.1–50 Hz		30[e]		
	50–1500 Hz		1500/f [e]		
	4–1500 Hz				80/f

a The duration of exposure to a field between 10–30 kV/m can be calculated using the formula t≤80/E, where t is the exposure in hours and E is the electric field strength in kV/m.

b ≤2 hours/day

c For the extremities, the ceiling value can be multiplied by a factor of 5.

d Ceiling value never to be exceeded.

e Between 0.1–150 Hz, the duration of exposure must not exceed 80/E.

f: frequency in Hz

SOURCE: INIRC/IRPA, 1990; WHO, 1984; ACGIH, 1994; CENELEC, 1994

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Chapter 3

Voice, very low and low frequency electric and magnetic fields (300 Hz–100 kHz)

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3. VOICE, VERY LOW AND LOW FREQUENCY ELECTRIC AND MAGNETIC FIELDS (300 Hz–100 kHz)

3.1 Description of parameters

Most agencies (WHO, 1993; ACGIH, 1994; AIHA, 1994) divide the frequency band between 300 Hz and 100 kHz into three sub-bands: voice frequencies (VF), from 300 Hz–3 kHz; very low frequencies (VLF), from 3–30 kHz; and low frequencies (LF), from 30–100 kHz.

Devices producing these frequencies include video equipment (15–35 kHz), transmitters (≥30 kHz), and industrial electric ovens (1–10 kHz). The wavelengths for these frequencies are between 1 and 100 km.

The main interaction phenomenon for these fields with the human body is the current induced by the electric and magnetic fields (WHO, 1993; Maddock, 1992). It is expressed in amperes per square metre (A/m^2). The parameters used in environmental assessments are the intensity of the electric field, expressed in volts per metre (V/m), the magnetic flux density in teslas (T), and their frequencies.

A few agencies express the exposure recommendations for magnetic fields in A/m rather than T. In this review, magnetic flux density will be expressed in teslas ($1\ A/m = 4\pi \times 10^{-7}\ T$ in a non-magnetic environment) (NRPB, 1989).

Other factors that should be taken into consideration are:

- the occupancy of exposed areas;
- the real duration of the exposure or, alternatively, the time-weighted averages;
- the spatial characteristics of the exposure (whole body or parts of the body);
- the uniformity of the field (spatial average).

Although some agencies have issued recommendations for exposure to contact currents and pulsed fields, these are not discussed here. Interested readers should consult the official publications of the agencies issuing these recommendations.

3.2 Description of current standards and recommendations

Very little scientific literature has specifically dealt with frequencies between 300 Hz and 100 kHz (Miller, 1987; Bernhardt, 1988). However, a few agencies and associations have made recommendations for this frequency band, and these are discussed in the following sections.

3.2.1 International recommendations

3.2.1.1 International Radiation Protection Association (IRPA)

IRPA has not issued any recommendations for these frequencies.

3.2.1.2 World Health Organization

The World Health Organization has not issued recommendations for frequencies between 300 Hz and 100 GHz. It has, however, produced a document on frequencies from 300 Hz to 300 GHz (WHO,1993), and made recommendations only for frequencies exceeding 100 kHz.

3.2.2 Canadian recommendations

3.2.2.1 Health Canada

Security Code No. 6 contains recommendations for the general public and for people working near devices emitting radiation. Health Canada recommendations cover frequencies between 10 kHz and 300 GHz. The limit values in Table 12 are values that should never be exceeded for these frequencies (mean exposure during 6 minutes).

These recommendations do not apply to portable transmitters or other devices operating at frequencies below 1 GHz, whose output power does not exceed 7 watts. Health Canada allows the limits presented in Table 12 to be exceeded under certain conditions. Exposures lasting no more than 6 minutes may be 1.1–2.4 times higher than the limits presented in Table 12 if subsequent exposure is reduced by a factor of 3. *Security Code No. 6* also contains recommendations for contact currents (Santé Canada, 1993).

Pregnant workers are included in the definitions of workers under radiofrequencies given by Health Canada.

3.2.3 American recommendations

3.2.3.1 Institute of Electrical and Electronics Engineers (IEEE)

In 1991, the Institute of Electrical and Electronics Engineers (IEEE) and the Standards Coordination Committee 28 on Non-Ionizing Radiation Hazards revised ANSI recommendation C95.1-1982. This

Table 12: Recommended average exposure limits for frequencies between 10 kHz and 1 MHz*, Health Canada

	ELECTRIC FIELD (V/m)	MAGNETIC FIELD (mT)
OCCUPATIONAL EXPOSURE	600	0.006
GENERAL POPULATION	280	0.003

* Average value over a 6-minute period

SOURCE: Health Canada, 1993

Table 13: Recommended maximum permissible exposure to VLF and LF fields in controlled and uncontrolled environments*, IEEE C95.1-1991

FREQUENCY (f)	ELECTRIC FIELD (V/m)	MAGNETIC FIELD (mT)
3 kHz–100 kHz	614	0.2

* The exposure values in terms of electric and magnetic field strengths are the values obtained by spatially averaging values over an area equivalent to the vertical cross-section of the human body (projected area).

SOURCE: IEEE, 1992

revision, known as IEEE C95.1-1991, was submitted to the American Standards Association (ANSI) and was approved in 1992. These recommendations apply to frequencies between 3 kHz and 300 GHz; the recommendations applicable to 3–100 kHz frequencies are presented in Table 13.

For the case of exposure in controlled environments with frequencies between 0.3 and 100 kHz, the IEEE recommendations call for a maximum induced current of 1000 mA in the body, calculated as a per-second average.

3.2.3.2 American Conference of Governmental Industrial Hygienists (ACGIH)

In 1993, ACGIH adopted occupational exposure recommendations for sub-radio frequencies (≤30 kHz), including VF, VLF and radiofrequencies between 30 and 100 kHz (LF) among others (ACGIH, TLV, 1993–94), and refined them in 1994 (ACGIH, TLV, 1994–95). These recommendations are presented in Table 14.

They are similar to those of the IEEE and are based on the density of the current induced in the body. For ELF fields, the maximum permissible density is 10 mA/m^2 (ACGIH, 1991). The exposure limits for this frequency band apply to both whole-body and partial body exposures.

3.2.4 European recommendations

3.2.4.1 National Radiological Protection Board (NRPB)

The National Radiological Protection Board (NRPB) of the United Kingdom (NRPB, 1989) has recommended action levels for this frequency band, which are presented in Table 15.

3.2.4.2 Comité européen de normalisation électrotechnique (CENELEC)

In September 1994, the *Comité européen de normalisation électrotechnique* (CENELEC) published a draft European pre-standard which is currently being studied by CENELEC's eighteen member countries. This draft pre-standard attempts to standardize the exposure levels for electromagnetic fields whose frequency is below 10 kHz, although member countries may establish stricter limits (CENELEC, 1994).

Table 14: Exposure limits (ceiling TLV)* for occupational exposure to electromagnetic VF, LF, and VLF fields, ACGIH

FREQUENCY (*f*)	ELECTRIC FIELD (V/m)	MAGNETIC FIELD (mT)
300 Hz–4 kHz	$\frac{2.5 \times 10^6}{f}$	0.2
4 kHz–30 kHz	625	0.2
30 kHz–100 kHz	614[(1)]	0.2[(1)]

* These recommendations may be unsafe for users of cardiac pacemakers.
f: frequency in Hz
(1) Average value over a 6-minute period

SOURCE: ACGIH, TLV, 1994–95

Table 15: Reference levels for exposure to electromagnetic fields with frequencies between 100 Hz and 100 kHz*, NRPB.

FREQUENCY (f)	ELECTRIC FIELD (V/m)	MAGNETIC FIELD (mT)
100 Hz–1 kHz	$614/f$ (kHz)	$0.2/f$ (kHz)
1–30 kHz	614	0.2
30 kHz–100 kHz	614	$6 \times 10^{-3}/f$ (MHz)

f: frequency in the multiples of Hz indicated between parentheses

SOURCE: NRPB, 1989

CENELEC's initiative is to define reference levels in addition to basic exposure limits that must not be exceeded.

The basic exposure limits are current densities (A/m^2) induced in the body which must never be exceeded.

Table 16 gives the basic current density limits for continuous exposure of the head or trunk to external alternating fields. Tables 17 and 18 present limits for electric and magnetic fields.

If electric and magnetic fields of the same frequency are present simultaneously, the corresponding induced-current densities should be added.

The reference levels are easily measured field strengths derived from basic exposure levels. Because of the wide range of possible exposure conditions, some of which may be extreme, this derivation includes a safety factor. The basic restrictions must not be exceeded if the field is below the reference level.

For workers whose exposure situation is in general clearly defined, the reference levels may be greater, as long as the basic exposure levels are not exceeded. This method of assessment may be necessary in environments where the fields are markedly non-uniform.

If electric and magnetic fields of several frequencies are present at the same time, formulae taking

Table 16: Recommendations on induced current density levels that must not be exceeded according to CENELEC

FREQUENCIES (f) (Hz)	CURRENT DENSITY INDUCED IN THE HEAD AND TRUNK (mA/m^2*) (rms)
4–1000	10
1000–10,000	$f/100$

* The induced current density must be calculated using a mean for areas of 100 mm^2 perpendicular to the current flow.

SOURCE: CENELEC, 1994

Table 17: Recommended reference levels for exposure to VF and VLF electric fields, CENELEC

FREQUENCIES (f) (Hz)	ELECTRIC FIELD (kV/m)
OCCUPATIONAL EXPOSURE	
300 – 1500	$1500/f$
1500 – 10,000	1
GENERAL PUBLIC	
300 – 1500	$600/f$
1500 – 10,000	0.4

SOURCE: CENELEC, 1994

Table 18: Recommended reference levels for exposure to VF and VLF magnetic fields, CENELEC

FREQUENCIES (f) (Hz)	MAGNETIC FIELD (mT) Head or trunk	Limbs
OCCUPATIONAL EXPOSURE		
300 – 1500	$80/f$	$1250/f$
1500 – 10,000	0.053	0.83
GENERAL PUBLIC (Version A*)		
300 – 1500	$32/f$	
1500 – 10,000	0.021	

* CENELEC proposes two versions of its standards for study by its member countries. Version A is derived from the basic induced current restriction.

SOURCE: CENELEC, 1994

into account the additive effects can be used to verify compliance with the recommendations.

These limits are based on well-established short-term effects involving the stimulation of electrically excitable nerve and muscle cells by induced current. The basic restrictions were established to prevent the adverse consequences of these effects.

Recommendations concerning exposure to contact currents have also been issued, but are not discussed here. CENELEC states that although currents weaker than those specified here may cause adverse long-term health effects, current research does not identify the parameters for limiting exposure.

Although most implantable devices, including cardiac pacemakers, are designed to function in the presence of electromagnetic interference, some devices and metallic implants may be affected even when exposure is below the recommended levels. CENELEC is currently preparing recommendations for cardiac pacemakers. However, these do not apply to individuals undergoing therapeutic or diagnostic procedures.

3.3 Basis for the recommendations

The recommendations applicable to these frequencies are primarily based on experimental studies. The principal effects identified in these studies involve the current induced in the body by electric and magnetic fields; the most important of these effects is the stimulation of nerve and muscle fibres, (WHO, 1993; ACGIH, 1991; NRPB, 1989; Tenforde, 1990; Maddock, 1992; Bernhardt, 1988). Most of the studies have focused on frequencies below those discussed in this section. Therefore, the effects of induced current identified at other frequencies are generally used as a reference for all of the frequencies whose primary mechanism is induced current.

However, several studies suggest that mechanisms of action other than current induction may be active. In some experimental studies dealing with the biological effects of fields, effects were observed for fields whose intensity was modulated by extremely low frequencies. The effects involved the following parameters: encephalogram in the cat and rabbit, mobility of calcium ions in brain tissue *in vitro* and *in vivo*, lymphocyte toxicity *in vitro*, and the activity of an enzyme involved in growth and cell division. However, some of these responses were difficult to confirm and the physiological significance of these effects is not clearly established (WHO, 1993).

The stimulation threshold for nerve and muscle tissue is highly frequency-dependent. The current-density threshold for nerve and muscle stimulation varies from 0.1–1 A/m^2 at 300 Hz to approximately 10–100 A/m^2 at 100 kHz (WHO, 1993). According to WHO, the exposure limits for induced current densities in the body should include a safety factor large enough to limit the density to 10 mA/m^2 at 300 Hz. This value is of the same order of magnitude as that for natural currents. At frequencies above 300 Hz, the current density necessary for nerve and muscle stimulation increases with the frequency, until thermal effects predominate (WHO, 1993).

Maddock (1992) claims that direct effects of induced current are rare, since they require relatively strong external fields. Furthermore, the only fundamental difference between the currents induced by magnetic and electric fields is their distribution in the body.

Few studies deal directly with the effects on humans of acute or chronic exposure to fields whose frequency is between 300 Hz and 300 GHz. According to WHO, the few epidemiological studies on these frequencies have failed to demonstrate any effect on health.

3.4 Limitations of the recommendations

Although these limits are based on *in vivo* and *in vitro* experimental studies, some effects are still poorly understood or inadequately documented.

3.4.1 Limitations related to exposure assessment

The only parameters currently taken into consideration in establishing exposure recommendations are the electric and magnetic fields as well as the dominant or chosen frequency. However, common measuring equipment is unable to characterize the broadband spectral content of the various frequencies present.

Since the exact biological phenomenon by which low doses produce the observed effects is unknown, it is impossible to devise an index for evaluating the effective dose.

Actual exposure recommendations do not take into account several parameters that are present during exposure to electric and magnetic fields below 100 kHz and that are likely to be determining factors in the effects on humans. These include:

- the broadband spectral content;
- the intermittent nature of the exposure, and the frequency and high intensity of the transients;
- the geomagnetic field and the possibility of resonance effects;
- the background level.

Furthermore, even if induced current seems to be the main parameter used in establishing exposure recommendations, it is difficult to measure. However, new devices may now be available for measuring this current (AIHA, 1994). It should also be recognized that it is very difficult to verify compliance with exposure recommendations that take into account the duration of exposure, such as those in Health Canada's *Security Code No. 6*, since no dosimeters exist for evaluating personal exposure to these fields.

Since electric fields are disturbed by the presence of objects and the human body, an undisturbed field may be very different from that in an occupational environment.

3.4.2 Limitations related to knowledge about possible effects related to chronic exposure

All the recommendations presented are based on the effects of short-term exposures. To date, there is no definitive evidence that electromagnetic fields are involved in carcinogenesis. Several experimental studies have demonstrated that these fields are not mutagenic and that they are probably not cancer initiators (WHO, 1993). However, some epidemiological studies have reported an increased incidence of cancer in populations exposed to magnetic fields (WHO, 1993).

There has been little research on the chronic effects of exposure, and the biological interactions of fields other than those originating from induced current are insufficiently understood to be useful in establishing exposure recommendations (Bernhardt, 1988).

At the present time, we do not know all the interaction mechanisms between fields and the human body. Several interactions are suspected but have not yet been verified. Effects have possibly been observed at the microscopic level, in the perturbation of biological systems such as cell membranes and intracellular structures (WHO, 1993).

A study of the various recommendations reveals a certain disparity in the recommended exposure levels. These differences between organizations originate from the different bases chosen, the uncertainty and significance of these bases, and finally, from the interpretation of the different scientific data. The recommendations also vary from country to country, reflecting different value judgements about scientific arguments or the relative importance of health effects (Maddock, 1992; Czerski, 1986).

3.4.3 Uncertainty related to the path of the induced current in the body

The data for extrapolating the induced current fields in the different parts of the body are uncertain. One of the main limitations observed in determining exposure recommendations involves the correlation of the current density in internal tissues and external magnetic exposure. Bernhardt (1988) emphasizes that the model used to calculate average exposure is based on the distribution of the electric field in the head and heart. However, the precise path taken by induced current is unknown, and may cause local damage.

The recommended exposure limits are based in large part on the results of animal experiments, rather than on human studies, and the data on induced current must therefore be extrapolated. This extrapolation increases the uncertainty of the effects of VF, VLF, and LF fields.

3.4.4 Limitations related to safety factors

It is very difficult to assess the value of the safety factors used in establishing the recommendations. The no-effect levels in humans for this range of frequencies are rather uncertain, and the safety factors which attempt to take into account existing uncertainties are rarely explicitly specified.

3.5 Summary

Few recommendations have been issued by international agencies for the frequency band from 300 Hz to 100 kHz. The recommendations that do exist are based on the possible effects of current induction in the body. For this frequency band, the limits for internal induced current are generally frequency-dependent. However, the frequency bands used in establishing the recommendations vary from agency to agency. Thus ACGIH, NRPB and CENELEC recommend that exposure to a 300 Hz electric field not exceed 8333, 2047 and 5000 V/m respectively, but all the agencies recommend the same maximum exposure of 614 V/m for 100 kHz fields (600 V/m in Health Canada's *Security Code No. 6*).

While both ACGIH and IEEE recommend a ceiling value of 200 mT for magnetic fields, ACGIH's recommendation applies to the entire band between 300 Hz and 100 kHz, while IEEE's recommendation applies only to frequencies between 3 kHz and 100 kHz. The recommendations of the other agencies vary significantly. In fact, NRPB recommends reference levels of 267 mT for 300 Hz and 80 mT for 100 kHz fields, while CENELEC recommends 270 mT for 300 Hz and 53 mT for 100 Hz. Health Canada's recommended limit of 6 mT for the frequency band between 10 kHz and 1 MHz is the lowest exposure limit for this frequency band.

These recommendations are based on experimental data involving other frequencies and are often extrapolated for VF, LF and VLF frequencies. Neither WHO nor IRPA have issued exposure limits for these frequencies, because the experimental data do not clearly indicate whether these fields have an impact on health.

Table 19 summarizes the various agencies' recommendations for this frequency range.

Table 19: Summary of recommendations for maximum occupational exposure to VF, LF, and VLF electromagnetic fields for direct induced current

AGENCY	FREQUENCY RANGE	ELECTRIC FIELD (V/m)	MAGNETIC FIELD (mT)
Health Canada	10 kHz–100 kHz (1)	600	0.006
IEEE	3 kHz–100 kHz (1)	614	0.2
ACGIH	100 Hz–4 kHz (2)	$(2.5 \times 10^6)/f^a$	0.2
	4 kHz–30 kHz (2)	625	0.2
	30 kHz–100 kHz (1)	614	0.2
CENELEC[d]	300–1500 Hz	$1500/f^b$	$80/f^a$
	1500–10,000 Hz	1000	0.053

a *f*: frequency in Hz
b *f*: frequency in kHz
c *f*: frequency in MHz
d Recommended reference level (not a maximum level)
(1) Average value over a 6 minute period
(2) Ceiling Value

SOURCE: Santé Canada, 1993; IEEE, 1992; ACGIH, 1994; CENELEC, 1994

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Chapter 4

Radiofrequencies and microwaves (100 kHz–300 GHz)

Table of Contents

4. RADIOFREQUENCIES AND MICROWAVES (100 kHz–300 GHz)

4.1 Description of parameters

By international convention, radiofrequencies (RF) are the frequencies between 100 kHz and 300 GHz (IRPA, 1991; WHO, 1993). The part of the radiofrequency spectrum between 300 MHz and 300 GHz is often termed the microwave (MW) band. Radiofrequencies are often divided by wavelength as follows (WHO - Europe, 1991):

- medium frequencies (MF): 300–3000 kHz
- high frequencies (HF): 3–30 MHz
- very high frequencies (VHF): 30–300 MHz
- ultra high frequencies (UHF): 300–3000 MHz
- super high frequencies (SHF): 3–30 GHz
- extremely high frequencies (EHF): 30–300 GHz.

For radiofrequencies, the power density is generally used to define the level of exposure to electromagnetic fields. It is expressed in watts per square metre (W/m^2) or milliwatts per square metre (mW/m^2). However, when the exposed individuals are located close to the source of the radiofrequencies, it is necessary, in defining the electromagnetic field, to specify the intensity of the electric field and magnetic fields, expressed in volts per metre (V/m) and amperes per metre (A/m) respectively.

Other parameters may influence the amount of energy absorbed by the body and the biological effects, and must be taken into account when interpreting exposure measurements:

- the exposure frequencies;
- the type of modulation;
- the characteristics of the pulsed fields;
- the duration of exposure;
- the polarization (orientation) of the field;
- the part of the body exposed;
- the proximity to other objects;
- the spatial variation of the field at the point of measurement.

Above 100 kHz, several observed biological interactions can be correlated to the energy absorption rate per unit mass. This absorbed energy is expressed as a specific absorption rate (SAR), a measure of the effective dose producing tissue heating, and is expressed in watts per kilogram (W/kg) or milliwatts per gram (mW/g) and is generally estimated for exposure of the entire body or parts of it.

4.2 Current standards and recommendations

There are no exposure standards applicable to this frequency range, but instead there are widely disseminated recommendations on which a rather general consensus has been reached.

4.2.1 International recommendations

4.2.1.1 International Radiation Protection Association (IRPA)

IRPA recently updated its exposure recommendations for radiofrequencies (IRPA, 1991). The recommended occupational exposure limits are presented in Table 20.

It should be noted that the values listed in Table 20 are average values over a 6-minute period. Other requirements are presented to take specific situations into account:

- The grounded intra-corporeal induced current should not exceed 200 mA;

Table 20: Occupational exposure limits to radiofrequency electromagnetic fields, IRPA

FREQUENCY	UNDISTURBED FIELDS (rms) ELECTRIC (V/m)	MAGNETIC (A/m)	EQUIVALENT PLANE-WAVE POWER DENSITY (W/m^2)
100–1000 kHz	614	$1.6/f$	–
>1–10 MHz	$614/f$	$1.6/f$	–
>10–400 MHz	61	0.16	10
>400–2000 MHz	$3 f^{1/2}$	$0.008f^{1/2}$	$f/40$
>2–300 GHz	137	0.36	50

f: frequency in MHz

- The limit for pulsed fields (average over the entire pulse) is 32 times the field values given in Table 20 or 1000 times the power density;
- Under no circumstances should the 6-minute average SAR exceed 0.4 W/kg for the whole body, 20 W/kg in the extremities, and 10 W/kg in some other parts of the body;
- These limits apply to both continuous and modulated waves;
- In the case of frequencies exceeding 10 MHz under near-field conditions, the exposure limits for electric and magnetic fields may be exceeded if $5/6\,(E^2/120\pi) + 1/6\,(120\pi H^2) \leq$ the equivalent power density (W/m^2) in Table 21. E = electric field strength (V/m) and H = magnetic field strength (A/m);
- Contact currents with metal objects should be less than 50 mA in order to avoid burn hazards.

For the general population, the exposure recommendations are presented in Table 21. The same additional conditions for occupational exposures are applied, but the whole-body SAR must not exceed 0.08 W/kg.

In general, when exposure is to multiple frequencies, an additive exposure effect must be considered, and the sum of the fractions:

$$\frac{\text{measured value}}{\text{recommended value}^{1}}$$

the sum of these fractions should not exceed unity.

4.2.1.2 World Health Organization (WHO)

In 1993, WHO published a document on the effects of radiofrequencies (WHO, 1993). The document was the result of joint collaboration with IRPA, and adopts all of the IRPA recommendations previously discussed *(4.2.1.1)*.

4.2.2 Canadian recommendations

4.2.2.1 Health Canada

Health Canada has published recommended exposure limits for radiofrequencies (HWC, 1991). While these limits were designed mainly for personnel of federal departments and agencies, recommendations concerning the exposure of the general population have also been proposed. *Security Code No. 6* has become the *de facto* national guide in the field of radiocommunications. Industry

1 For electric and magnetic fields, the square of the values must be used.

Table 21: General – population exposure limits to radiofrequency electromagnetic fields, IRPA

FREQUENCY	UNDISTURBED FIELDS (rms) ELECTRIC (V/m)	MAGNETIC (A/m)	EQUIVALENT POWER DENSITY (W/m²)
100–1000 kHz	87	$0.23/f^{1/2}$	–
1–10 MHz	$87/f^{1/2}$	$0.23/f^{1/2}$	–
10–400 MHz	27.5	0.073	2
400–2000 MHz	$1.375/f^{1/2}$	$0.0037/f^{1/2}$	$f/200$
2–300 GHz	61	0.16	10

f: frequency (MHz)

Canada will not authorize the installation or modification of a transmission tower before its owner proves that the recommended guidelines will be respected.

Table 22 presents the proposed occupational exposure limits.

These limits are maximum permitted power density exposures expressed as average values over 6 minutes.

The limits for the general population are presented in Table 23. The maximum power density values are presented in the form of an average for a 6-minute period.

Table 22: Occupational exposure limits recommended by Health Canada for radiofrequencies

FREQUENCY	UNDISTURBED FIELDS (rms) ELECTRIC (V/m)	MAGNETIC (A/m)	POWER DENSITY (W/m²)
10–1000 kHz	600	$4.9/f$	–
1–10 MHz	$600/f$	$4.9/f$	–
10–30 MHz	60	$4.9/f$	–
30–300 MHz	60	0.163	10
300–1500 MHz	$3.46/f^{1/2}$	$0.0093/f^{1/2}$	$f/30$
1.5–300 GHz	140	0.36	50

f: frequency (MHz)

Recommendations are proposed for the contact (indirect) current, but not for current directly induced by the fields.

In the case of portable transmitters or other devices producing fields that exhibit high spatial variability, the values presented may be exceeded if the following SARs are respected:

SAR Limits (W/kg) for different populations

	OCCUPATIONAL	GENERAL POPULATION
Mean for 20% of the body	0.4	0.2
Local ocular exposure	0.4	0.2
Average for 1 g of tissue, except for the body surface and limbs	8	4
Local exposure of 10 g of tissue on the body surface and in the limbs	25	12

Table 23: General – population exposure limits for radiofrequencies, Health Canada

FREQUENCY	UNDISTURBED FIELDS (rms) ELECTRIC (V/m)	UNDISTURBED FIELDS (rms) MAGNETIC (A/m)	POWER DENSITY (W/m²)
10–1000 kHz	$280/f$	$2.19/f$	–
1–10 MHz	$280/f$	$2.19/f$	–
10–30 MHz	28	$2.19/f$	–
30–300 MHz	28	0.073	2
300–1500 MHz	$1.616/f^{½}$	$0.004/f^{½}$	$f/150$
1.5–300 GHz	62	0.16	10

f: frequency (MHz)

4.2.3 American recommendations

4.2.3.1 Institute of Electrical and Electronics Engineers (IEEE)

IEEE's recent recommendations on radiofrequencies were published in 1992 (IEEE, 1992), and later approved by the American National Standards Institute (Lin, 1994).

The recommendations applicable to occupational exposure (controlled environments) are presented in Table 24.

The exposure limits presented involve average field strengths or power densities for six minutes, except for frequencies above 15 GHz, where the duration considered decreases progressively, reaching 10 seconds at 300 GHz. These limits provide adequate protection if:

- The average per-second induced current in a standing individual does not exceed 100 mA in each foot in the frequency band between 100 kHz and 100 MHz;
- It is an average whole-body exposure;
- The additive effect of different frequencies must be considered (using the same procedure as IRPA);
- These frequencies must be modified for pulsed exposure, taking into account the exposure time and the pulse widths.

The recommended exposure limits for field strength and power density may be exceeded if the 6-minute SAR does not exceed 0.4 W/kg as an average whole-body exposure and 8 W/kg per gram of tissue, except for the extremities, where 20 W/kg calculated for 10 g of tissue is tolerated.

Other recommendations for exposure in uncontrolled environments, mainly for the general population, are presented in Table 25.

The same conditions relating to occupational exposure are added, except that the sampling period for measuring the electric field may be greater: 30 minutes from 3 MHz to 3 GHz, and the current induced in each foot must not exceed 45 mA for frequencies between 0.1 and 100 MHz.

The recommended field strengths may be exceeded if the SAR does not exceed 0.8 W/kg for the whole body and 1.6 W/kg locally, calculated per gram of tissue, except for the extremities, where 4 W/kg per 10 g of tissue is considered as the maximum value.

Table 24: Occupational exposure limits permitted by IEEE for radiofrequencies

	UNDISTURBED FIELDS (rms)		POWER DENSITY (W/m²)
FREQUENCY	ELECTRIC (V/m)	MAGNETIC (A/m)	
100–3000 kHz	614	16.3/*f*	—
3–30 MHz	1842/*f*	16.3/*f*	—
30–100 MHz	61.4	16.3/*f*	—
100–300 MHz	61.4	0.163	10
300–3000 MHz			*f*/30
3–15 GHz			100
15–300 GHz			100

f: frequency (MHz)

Table 25: Exposure limits recommended by IEEE for radiofrequencies for uncontrolled environments

FREQUENCY	UNDISTURBED FIELDS (rms) ELECTRIC (V/m)	UNDISTURBED FIELDS (rms) MAGNETIC (A/m)	POWER DENSITY (W/m²)
100–1340 kHz	614	16.3/*f*	—
1.34–3 MHz	823.8/*f*	16.3/*f*	—
3–30 MHz	823.8/*f*	16.3/*f*	—
30–100 MHz	27.5	158.3/*f* 1.668	—
100–300 MHz	27.5	0.0729	2
300–3000 MHz			*f*/150
3–15 GHz			*f*/150
15–300 GHz			100

f: frequency (MHz)

4.2.3.2 American Conference of Governmental Industrial Hygienists (ACGIH)

In its recent manual of TLVs (ACGIH, 1994), ACGIH modified its earlier recommendations to bring them in line with those of IEEE (IEEE 1992), described above *(4.2.3.1)*.

4.2.4 European recommendations

Several European countries, including Germany and the United Kingdom, have proposed exposure limits for radiofrequencies (Repacholi, 1990). These values are all based on the same principle as the preceding recommendations, namely the prevention of thermal effects. The United Kingdom, like WHO, IRPA and IEEE, recommends a maximum whole-body SAR of 0.4 W/kg for occupational exposures. Germany, however, gives higher field and power density values, based on a maximum SAR of 1 W/kg (Repacholi, 1990).

The Commission of the European Communities (CEC, 1992) has proposed exposure recommendations for frequencies between 30 and 300 MHz, the frequency range where energy absorption is the greatest. The recommendations are similar to those of IEEE and IRPA.

4.3 Basis for the recommendations

All the exposure limits for radiofrequencies proposed by national or international agencies are primarily based on the thermal effects caused by the conversion of radiofrequency photon energy into thermal energy in the body. This property of radiofrequencies was demonstrated as early as the end of the 19th century by d'Arsonval, and has subsequently been used in different processes including diathermy therapy (Cleary, 1990a).

However, it was not until much more recently, in the 1960s and 1970s, that certain determining factors for energy absorption were identified. These were the size, shape, orientation, and dielectric properties of the exposed objects or bodies. Once these factors were known, it was possible to extrapolate data obtained in animal experiments to humans, and to propose specific exposure limits for each wavelength. The results of dosimetry studies on humans have been used in proposing a unit by which the specific absorption at each wavelength could be taken into account: the specific absorption rate (SAR) (Gandhi, 1990). For thermal biological interactions, the absorbed energy rate can be considered as a measure of the thermal energy dose transmitted to the exposed body or object. Even if the SAR is difficult to measure in humans, it can be estimated by modelling, and the power density or field strength values corresponding to the SAR that has been established can be determined. Therefore, the lowest recommended power-density or field-strength exposure limits for radiofrequencies are in the frequency range in which the body is the most sensitive (from 30–300 MHz), called the resonance zone.

There has been a great deal of research aimed at identifying the lowest SAR capable of producing an effect in humans or animals (the LOAEL, or lowest observed adverse effect level). The principal agencies that have presented exposure limits for radiofrequencies have estimated that the LOAEL for the SAR is 4 W/kg. This conclusion was first presented in 1982 by ANSI (ANSI, 1982) and was reconfirmed by IRPA (1991) and IEEE (1992). IEEE reconfirmed the criterion of 4 W/kg based on the following considerations:

- The threshold for behavioural disturbance in non-human primates is always greater than a whole-body SAR of 3.2–4 W/kg;

- The heat generated in the body by a whole-body exposure of 4 W/kg is comparable to that resulting from moderate physical activity (e.g., housecleaning or truck-driving), and is therefore consistent with the normal mechanisms of thermoregulation.

Both IEEE (1992) and IRPA (1991) apply a factor of 10 to the criterion of 4 W/kg in defining the maximum whole-body SAR never to be exceeded (0.4 W/kg), in order to take into account the possible effects of chronic exposure (IRPA, 1991). However, IEEE (1992) which reconfirmed this safety factor of 10, showed that this value of 4 W/kg already contains several conservative hypotheses. Therefore, in reality, the safety factor provided by the true LOAEL would most often be much greater than 10. The arguments presented by IEEE are the following:

- The effect chosen for defining the LOAEL (behavioral change) is "not a defined hazard" since it is reversible and limited in scope. It is however considered that chronic exposure to the LOAEL could result in a health hazard;

- Because thermoregulation in humans is generally far more effective than in animals, extrapolation from animal data to humans is very conservative;

- Using a polarized field in dose estimates is the worst-case scenario, since other types of polarization always yield lower SARs.

- The proposed SARs take into account all possible body sizes, including children.

Furthermore, IEEE (1992) points out that the heat generated by a SAR of 0.4 W/kg is similar to that resulting from exposure to the sun or to the normal range of ambient temperatures.

The justification for the maximum SARs recommended for short-term exposure of a part of the body is less clear. Dosimetry studies conducted after the 1982 ANSI recommendations were presented have demonstrated that the heat generated in certain parts of the body could be very high even when the whole-body SAR of 0.4 W/kg is respected. The proposed values, namely 20 W/kg for the extremities and 8–10 W/kg for other parts of the body, avoid an increase in local heat capable of causing adverse local effects. The duration of exposure over which the average exposure is to be calculated is based on the time required to cause heating of the tissues (IEEE, 1992).

The recommended exposure limits for direct and indirect exposure to radiofrequency fields are intended to prevent burns and shocks in the case of indirect exposure (contact current) in sensitive parts of the human body (IEEE, 1992). In particular, the 200 mA limit for the total induced current is designed to prevent excessive heating of the wrists and ankles (IRPA, 1991).

4.4 Limitations of the recommendations

Despite all the explanations provided by the agencies recommending exposure limits for radiofrequencies, some aspects deserve further discussion for a better understanding of the limitations of the recommendations.

4.4.1 Estimation of the received dose

The recommended exposure limits are based on estimates of the energy dose received by the body, represented by the SAR. There are, however, a number of significant limitations to the method used to calculate SARs:

- Most of the studies of the effects of radiofrequencies have been conducted on animals, and extrapolation of SARs from animals to humans is a very complex exercise (Cleary, 1990a);

- Most of the experimental studies investigated only a limited number of frequencies (mainly between 900 MHz–10 GHz). Extrapolation to other frequencies is possible in theory but difficult in practice (Cleary, 1990a);

- Energy absorption in the body is not uniform and is based on many factors, including the emission source. It is therefore difficult to estimate the amount of energy transmitted to specific zones of the body. Foci of energy absorption may be present even when average exposure levels are within acceptable limits;

- The exposures used in the laboratory are generally rather homogeneous and continuous. Exposure to multiple frequencies or to pulsed or modulated fields has not been extensively studied.

The concept of the SAR was a major breakthrough in thermal energy dosimetry. Its use is valid only when thermal effects are the principal mechanism of interaction between the electromagnetic fields and the human body. Several laboratory studies have shown the induction of biological effects by radiofrequency fields too weak to cause thermal effects (Cleary, 1990a, 1990b).

Both IRPA (1991) and IEEE (1992) recognize the potential of radiofrequencies to cause nonthermal effects, but consider that the available data is inadequate for proposing other exposure limits. Both agencies are, however, aware that the research carried out on this subject may result in a change in their position.

4.4.2 Determining the LOAEL

All agencies that have recommended exposure limits agree on a LOAEL of 4 W/kg. However, several authors have reported various effects that can be observed at SARs below 4 W/kg (Cleary, 1990a). Table 26 summarizes the results of animal studies with different SARs. These results confirm that certain biological effects may appear at 1 W/kg (Stuchly, 1987).

The position of IRPA and IEEE is that a SAR of 4 W/kg is a reasonable LOAEL in humans, given the transient and limited behavioral effects observed. This conclusion was arrived at through detailed analysis of the scientific literature, focusing on studies meeting very stringent quality criteria. In particular, the studies considered had to provide extensive details about the method of estimating the SAR, and their results had to have been reproduced in different laboratories.

4.4.3 Effects of chronic exposure

The recommended LOAEL was arrived at from the biological effects resulting from the absorption of energy (thermal effects) over short periods (less than one hour in many *in vitro* studies). IEEE (1992) and IRPA (1991) recognize the lack of data on the effects of chronic exposure, but nevertheless state that the safety factor they apply is adequate in preventing the effects of chronic exposure. This position should be qualified, given the lack of knowledge about the mechanisms of action of chronic exposure. Therefore, even though this requires reconfirmation, one study has shown the promotion of chemically induced skin tumours in

Table 26: Biological effects observed in various organic systems in relation to the SAR

ORGANIC SYSTEM	SAR RANGE (W/Kg)	AVERAGE SAR (W/Kg)
Behaviour	0.4–7	2.5
Central nervous system	0.0001–12.5	1.8
Hematology/immunity	0.4–11.8	4.3
Hormones	1.0–5.0	4.8
Drug potentiation	0.2–1.0	0.6
Chromosomal mutations, abnormalities	0.05–5.0	2.5
Neurotransmitters	6.0	6.0
Fertility	5.6	5.6
Biochemistry	1.6–4.0	2.8
Cardiovascular system	3.0–8.0	5.8

Source: Cleary, 1990a, adapted from Elder J.A, Catill D.F., Biological Effects of Radiofrequency Radiation, Report No. EPA-6018-83-026F, 1984.

mice exposed for 2 hours each day to fields of 2.45 GHz, with a SAR of 4–5 W/kg (Szmigielski, 1988, cited by WHO, 1993, and NRPB, 1991).

The significance of this risk justifies that large-scale research programs be carried out, and the use of additional safety factors appears to be warranted. This is implicitly recognized by IRPA (1991), which states that unnecessary exposures should be minimized, given the sparse data on safe exposure thresholds for biological effects (IRPA, 1991, p. 76).

4.5 SUMMARY

The thermal effects of radiofrequencies have been known for some time and widely used in medicine and various industrial processes. The use of specific absorption rates (SARs) represents progress in standardizing the estimation of absorbed thermal energy. There is a wide consensus among agencies recommending exposure limits that a SAR of 4 W/kg represents the LOAEL in humans. This conclusion is based on the fact that a SAR of this magnitude induces transient behavioral problems is primates, and fails to raise body temperature abnormally. The proposed exposure limits expressed in terms of power density are based on energy transmission equivalent to a whole-body SAR of 0.4 W/kg. Exposures of this magnitude are not believed to cause health effects, even after chronic exposure.

The many uncertainties associated with the recommended limits suggest prudence in interpreting the levels currently considered acceptable. In fact, the only thermal effects resulting from acute exposures (<1 hour) were taken into consideration in establishing these limits. Other effects appear to be possible as the result of nonthermal mechanisms. Several authors recommend a cautious approach based on minimizing all unnecessary exposures. Several research programs are currently studying the different possible mechanisms of interaction of radiofrequencies with the human body.

The energy absorbed by the human body (internal dose) for a given power density (external dose) varies with the wavelength. The absorbed energy is highest between 30 and 300 MHz. Table 27 summarizes the various recommendations for this range of very high frequencies.

Table 27: Occupational exposure limits of various agencies for very high frequencies (VHF), 30–300 MHz

AGENCY	UNDISTURBED FIELDS (rms)		POWER DENSITY (W/m^2)
	ELECTRIC (V/m)	MAGNETIC (A/m)	
IRPA	61	0.16	10
Health Canada	60	0.163	10
IEEE	61.4	0.163*	10
ACGIH	61.4	0.163*	10

* For frequencies between 100 and 300 MHz

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Chapter 5

Ultraviolet radiation

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5. ULTRAVIOLET RADIATION

The IRSST has published a document on ultraviolet radiation measurement and exposure (Laliberté, IRSST, 1994). This document covers all pertinent information about the nature of ultraviolet radiation, its biological effects, as well as the proposed exposure limits. Interested readers should consult it for more detailed information on these subjects. This chapter presents the essential information on established criteria and ends with an evaluation of the basis for these recommendations.

5.1 Description of parameters

Ultraviolet (UV) radiation is a form of high-energy non-ionizing radiation with several unique characteristics since the energy carried by this type of radiation is significant. UV radiation is part of the electromagnetic spectrum between soft X-rays and visible light. Its wavelengths are between 100 and 400 nanometres (nm). UV radiation with a wavelength of 100 nm has a photon energy of approximately 12.4 electron-volts (eV). Significant ionization occurs in biologically exposed matter at levels above this value (Faber, 1991). UV radiation can therefore be considered as being located on the border between ionizing and non-ionizing radiation.

UV radiation is generally divided into three bands:

UV-A: 315–400 nm
UV-B: 280–315 nm
UV-C: 100–280 nm

UV-A radiation, sometimes known as black light, long UV, or near UV, produces fluorescence with some materials. UV-B radiation, known as medium UV or tanning rays, covers much of the biologically active solar UV radiation. UV-C radiation, also known as short UV, far UV, or germicidal rays, is emitted by germicidal lamps and arc-welding equipment. UV-C radiation is also emitted by the sun, but does not reach the surface of the earth (WHO, 1980; Faber, 1991).

UV radiation with a wavelength shorter than 180 nm has low biological activity, since it is absorbed by the air (IRPA, 1991). In humans, the most important effects generally involve UV radiation with shorter wavelengths, from 180–315 nm, commonly called actinic UV radiation (IRPA, 1991).

The main determinants of the biological effects of UV radiation are the spectral content of the source, irradiance measured in watts per square metre (W/m^2), and radiant exposure measured in joules per square metre (J/m^2).

The photon energy of UV radiation is stopped at the surface of the body and does not penetrate it. The target organs for UV exposure are therefore the eyes and skin, and the recommended limits reflect the exposure of these two organs. The effective irradiance of broadband UV radiation is calculated by weighting the contribution of each wavelength as a function of the spectral effectiveness peak (which occurs at 270 nm).

5.2 Current standards and recommendations

5.2.1 International recommendations

5.2.1.1 International Radiation Protection Association (IRPA)

The International Radiation Protection Association (IRPA) has recommended limits for the exposure of workers and the general public to UV radiation between 180 and 400 nm. These limits are intended to protect the population from the effects of acute exposure to UV radiation of the skin (erythema and burns) and eyes (photokeratoconjunctivitis). The recommendations should also reduce the effects of chronic exposure (IRPA, 1991). IRPA states that the recommended limits may not adequately protect individuals suffering from pronounced cutaneous photosensitivity (people with low skin pigmentation) or those exposed to the photosensitizers contained in certain cosmetics, foods, medication and chemicals.

IRPA recommends that the maximum exposure to UV-A radiation (315–400 nm) for unprotected eyes not exceed 10 kJ/m² for a period of no more than 8 hours. Wavelength-specific exposure limits for 8-hour exposures are listed in Table 28. The effective irradiance of a given wavelength, standardized for a 270-nm monochromatic source, can also be calculated using the wavelength's coefficient of relative spectral effectiveness.

The recommended maximum exposure for UV radiation with a wavelength of 270 nm is 30 J/m² for an 8-hour exposure. However, permissible exposure durations in seconds, intended to prevent

Table 28: IRPA recommendations for UV radiation exposure, as a function of wavelength

WAVELENGTH (nm)	EXPOSURE LIMIT (J/m²)	WAVELENGTH (nm)	EXPOSURE LIMIT (J/m²)
180	2500	310	2000
190	1600	313	5000
200	1000	315	1.0×10^4
205	590	316	1.3×10^4
210	400	317	1.5×10^4
215	320	318	1.9×10^4
220	250	319	2.5×10^4
225	200	320	2.9×10^4
230	160	322	4.5×10^4
235	130	323	5.6×10^4
240	100	325	6.0×10^4
245	83	328	6.8×10^4
250	70	330	7.3×10^4
254	60	333	8.1×10^4
255	58	335	8.8×10^4
260	46	340	1.1×10^5
265	37	345	1.3×10^5
270	30	350	1.5×10^5
275	31	355	1.9×10^5
280	34	360	2.3×10^5
285	39	365	2.7×10^5
290	47	370	3.2×10^5
295	56	375	3.9×10^5
297	65	380	4.7×10^5
300	100	385	5.7×10^5
303	250	390	6.8×10^5
305	500	395	8.3×10^5
308	1200	400	1.0×10^6

SOURCE: IRPA, 1991

Table 29: Permissible duration of exposure to UV radiation as a function of effective irradiance

DURATION OF EXPOSURE (per day)	EFFECTIVE IRRADIANCE (W/m^2)
8 hours	0.001
4 hours	0.002
2 hours	0.004
1 hour	0.008
30 minutes	0.017
15 minutes	0.033
10 minutes	0.05
5 minutes	0.1
1 minute	0.5
30 seconds	1.0
10 seconds	3.0
1 second	30
0.5 second	60
0.1 second	300

SOURCE: IRPA, 1992

risk to unprotected skin and eyes, can also be calculated by dividing the recommended value of 30 J/m^2 by the effective irradiance (W/m^2) (see Table 29).

IRPA points out that knowledge about the effects of chronic exposure is limited, and that recommended exposure limits should regularly be reviewed. It should be noted that IRPA has also formulated several recommendations aimed at promoting worker protection through the use of personal protective equipment.

5.2.1.2 World Health Organization (WHO)

In its *Environmental Health Criteria 14: Ultraviolet Radiation* (WHO, 1980), WHO makes two types of recommendations. The first involves solar UV radiation, and the second, occupational exposure to artificial UV radiation.

WHO recommendations for exposure to artificial UV radiation with wavelengths of 200–315 nm have been adopted by IRPA. They are the same recommendations as those presented in 5.2.1.1. The recommendations for UV radiation with wavelengths of 315–400 nm are 10 W/m^2 for exposures of 1000 seconds (approximately 16 minutes), or 10 kJ/m^2 for shorter periods.

5.2.2 Canadian recommendations

To our knowledge, there are no Canadian recommendations for exposure to UV radiation.

5.2.3 American recommendations

5.2.3.1 American Conference of Governmental Industrial Hygienists (ACGIH)

ACGIH's recommended exposure limits for UV radiation cover the spectrum from 180–400 nm and represent levels to which workers can be repeatedly exposed without suffering adverse effects. With the exception of recommended levels for ocular irradiance, these limits are similar to those of IRPA. For UV radiation with a wavelength of 320–400 nm, ACGIH recommends a limit of 10 kJ/m^2 for exposures up to 1000 seconds (approximately 16 minutes); for longer exposures, the limit is 10 W/m^2. For UV radiation with a wavelength of 315–400 nm, IRPA's limits are more stringent, with the same limit (10 kJ/m^2) but for an exposure duration of less than 8 hours. In 1991, ACGIH extended these recommendations to the spectrum between 180 and 200 nm.

Only acute effects were taken into consideration in establishing these recommendations. ACGIH recognizes that these limits do not protect individuals who are photosensitive, aphakic (i.e., lacking a crystalline lens), or exposed to photosensitizers.

5.3 Basis for the recommendations

The recommendations of the different agencies for UV radiation were established for occupational exposures. They may, however, with some precautions, also be applied to the exposure of the general population.

For skin effects, the permissible exposure limits are based on the minimum dose capable of producing erythema (minimum erythema dose, MED). The erythema induction threshold varies with the wavelength, energy level, type of skin, and duration of exposure. Erythema is a photochemical response of the skin resulting from overexposure to UV radiation, mainly for wavelengths between 180 and 315 nm (UV-C and UV-B). Studies have shown that maximum erythema is produced by wavelengths between 290 and 300 nm. The minimum erythema dose for pale untanned skin varies beween 6 and 30 mJ/cm^2 (Everett et al., 1965; Freeman et al., 1966; Parrish et al., 1982), which means that the recommended exposure limits for this type of skin provide a safety factor of 1.3–6.5 (IRPA, 1991). The safety factor is lower for photosensitive individuals, but increases with tanning. UV-A radiation (315–400 nm) also produces erythema, but only at much higher doses (>10 J/cm^2). It should be noted that UV-A radiation combined with UV-B radiation increase the skin's erythematous response. This synergistic effect is known as photo-augmentation.

The recommendations for evaluating the effects on the eye are based on the lowest dose capable of producing photokeratitis. UV radiation, particularly UV-C and UV-B radiation (220–310 nm), is strongly absorbed by the cornea and conjunctiva. The maximum sensitivity of the eye to photokeratitis occurs at a wavelength of 270 nm. The minimum dose capable of causing ocular erythema is between 4 and 14 mJ/cm^2 (Pitts et al., 1971). The exposure limits provide a safety factor of 1.3–4.6 (IRPA, 1991). These exposure limits do not apply to individuals who have undergone ablation of the crystalline lens. Exposure to UV radiation with a wavelength of 295–320 nm has been shown experimentally to produce cataracts in rabbits and monkeys. The energy threshold for producing opacities in the lens was between 0.15 and 12.6 J/cm^2 (Pitts et al., 1977).

The different agencies that issued recommendations for UV radiation agree that limits for the eye must be considered as maximum values that must never be exceeded (Sliney, 1972), while those for the skin should be considered as action levels for risk assessment (Després, 1978; Gezondheidsraad, 1978; Mayer et al., 1979; Sliney et al., 1980).

5.4 Limitations of the recommendations

The recommendations formulated by the different agencies are primarily intended for protecting workers from photokeratitis or skin erythema. In other words, this means that only the effects of acute exposure to UV radiation are considered.

These agencies' permissible exposure levels are therefore not based on the prevention of the effects of chronic exposure to UV radiation, such as skin cancer (epithelioma, melanoma), photo-aging, and immunosuppression (Faber, 1991). It should be noted that the UV bands responsible for carcinogenesis and erythema are very similar (Faber, 1991).

The intensity of skin erythema is proportional to the UV dose received (IARC, 1992) and the risks related to chronic exposure can therefore be evaluated in terms of the minimum erythema dose (MED) (Faber, 1991). The MED is defined as the weakest radiation capable of producing skin erythema within 24 hours of exposure (IARC, 1992). Table 30 presents the annual received dose of UV radiation, expressed as an MED, for a variety of activities.

Lifetime exposure to UV radiation is a well-documented risk factor for skin cancer, especially basocellular and spinocellular epithelioma (IARC, 1992). The cumulative dose of UV radiation is the sum of all exposures occurring as a result of occupational, leisure and vacation activities and artificial tanning. It is clear that exposure limits based almost exclusively on artificial occupational UV exposure do not afford protection of the worker against long-term adverse health effects caused by exposure to UV radiation from the sun or other sources. The case of outdoor work clearly illustrates the limitations of the standards recommended by ACGIH, IRPA, and WHO. On average, a person working outdoors receives three times the annual exposure to UV-B radiation than does an office worker (Diffey, 1987). Furthermore, the intensity of solar radiation (irradiance, in W/m^2) increases rapidly for wavelengths between 300 and 325 nm, and exceeds the ACGIH's exposure limits for an 8-hour exposure. As a result, it is important to take natural exposure to UV radiation into account when interpreting the exposure limits for artificial UV radiation.

When ACGIH, IRPA and WHO recommendations are converted to a minimum erythema dose, MED, and reevaluated on an annual basis, it becomes clear that the exposure limits do not seem to be very stringent for exposure to wavelengths longer than 315 nm, or UV-A radiation (Magnus, 1976; Parrish, 1982). Knowledge about the biological effects of high doses of UV-A radiation on the skin and eyes is limited. However, more and more specific effects of UV-A radiation are being recognized. These include: photo-aging of the skin (Anonymous, 1989), potentiation of the carcinogenic effects of UV-B radiation on the skin (Passchier et al., 1987), and the weakening of the immune system (Rivers et al., 1989; McKenzie et al., 1994).

Not only do the recommendations of ACGIH, WHO and IRPA not consider the possible effects of chronic exposure, they do not apply to individuals who are photosensitive, either naturally or as a result of exposure to photosensitizers, or to individuals without a crystalline lens.

Table 30: Annual solar and artificial UV exposure, expressed as a minimum erythema dose (MED)

ACTIVITY	MINIMUM ERYTHEMA DOSE
Leisure activities (excluding vacations)	20–100
Outdoor vacations (2 weeks)	30–60
Office workers	40–160
Outdoor workers	250
Artificial occupational UV sources, according to ACGIH (8 hours):	
– 270 nm (30 J/m^2)	36
– 365 nm (2,7 x 10^5 d/m^2)	324
Tanning salon (2 MED/session)	30–300

SOURCE: IARC, 1992; RHAINDS, 1995

5.5 Summary

The different agencies recommending exposure limits for UV radiation all base their recommendations on acute exposure and its adverse effects on the skin (erythema) and eyes (photokeratitis). Although the effects of chronic exposure (cancer, photo-aging, and immunosuppression) are known, they cannot currently be taken into account, due to the lack of dose-effect data. When the effects on the eye and skin are taken into account, the energy dose received by these organs can be considered in relation to the wavelength. The recommended exposure limits are designed to prevent these acute effects, but appear to provide inadequate protection for individuals who are photosensitive or without a crystalline lens. The prevention of the effects of chronic exposure should take into account multiple exposures to UV radiation, including sun exposure. It is probable that future recommendations will take the risks of chronic exposure into account.

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Conclusion

CONCLUSION

The field of non-ionizing radiation is vast. Despite the constraints involved in the production of this document, we believe that we have fulfilled our mandate, which was to review the standards and recommendations for electromagnetic fields for frequencies between 0 and 300 GHz, as well as for ultraviolet radiation.

Despite the wide variation in the energy carried by the different electromagnetic fields as a function of wavelength, several common features have emerged:

- Almost all the exposure recommendations are based on the effects of short-term exposures;

- The failure to take into account data on the effects of chronic exposure reflects the lack of information on the mechanisms underlying these effects;

- There seems to be widespread consensus among the official agencies making exposure recommendations, on the safety factors applied to no-effect levels observed during short-term exposures;

- The protection afforded by these safety factors against the possible effects of chronic exposures is unclear;

- Several authors and some agencies and associations have brought to light the uncertainties of current knowledge and recommend a cautious approach in order to limit chronic exposure;

- All the agencies recommending exposure limits are aware of the necessity of monitoring the scientific literature in order to ensure that the recommendations reflect the latest research.

Despite the care that went into the preparation of this review, we are aware that it is essentially a general introduction that attempts to demystify a complex field and make it more understandable. We could have discussed several aspects in the literature in much greater detail. In fact, each frequency band could have been the subject of a separate report. The epidemiological literature could have been covered in more detail, as well as the studies and guidelines concerning particularly sensitive individuals.

Despite these limitations, we hope that this report has helped the reader acquire a basic understanding of non-ionizing radiation, and especially of the recommendations applicable to it. We also hope that this document has helped the reader assess the value of these recommendations and that it will promote an ongoing evaluation of the knowledge in this field.

The reader is invited share any additional information with the authors that may help in producing subsequent editions of this document.

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Appendices

Abbreviations

ACGIH	American Conference of Governmental Industrial Hygienists
AIHA	American Industrial Hygiene Association
ANSI	American National Standards Institute
CENELEC	Comité européen de normalisation électrotechnique [European Committee for Electrotechnical Standardization]
DOE	U.S. Department of Energy
CEC	Commission of the European Communities
EHF	Extremely high frequency
ELF	Extremely low frequency
EMF/HSD	EMF Health and Safety Digest
HF	High frequency
HWC	Health and Welfare Canada
IARC	International Agency for Research on Cancer
ICNIRP	International Commission on Non-Ionizing Radiation
IEEE	Institute of Electrical and Electronics Engineers
INIRC	International Non-Ionizing Radiation Committee
IRPA	International Radiation Protection Association
IRSST	Institut de recherche en santé et en sécurité du travail [Occupational Health and Safety Research Institute (Québec)]
LOAEL	Lowest Observed Adverse-Effect Level
MED	Minimum erythema dose
MF	Medium frequency
MW	Microwave
NHMRC	National Health and Medical Research Council
NIOSH	National Institute for Occupational Safety and Health
NOAEL	No Observed Adverse-Effect Level
NRPB	National Radiological Protection Board
RNA	Ribonucleic acid
SHF	Super high frequency
TLV	Threshold limit value
TWA	Time-weighted average
UHF	Ultra high frequency
US-NESC	U.S. National Electrical Safety Code
VF	Voice frequency
VHF	Very high frequency
VLF	Very low frequency
WHO	World Health Organization

Glossary

Alternating current	Current that alternates or changes polarity at a given frequency. The current is positive for one half-cycle and negative for the other.
Contact current	Current flowing between an insulated (metallic) conductor and the earth in an electrical circuit with an impedance equivalent to the impedance of the human body at frequencies of 0.0001 Hz to 100 MHz.
Direct current	Electrical current with constant polarity and intensity.
Electric field	Force exerted by fixed electrical charges on other more or less distant charges. Electric fields result from the difference in potential between a conductor and its environment.
Electromagnetic wave	Wave characterized by variations in the electric and magnetic fields.
Far field (antenna)	Region where the angular distribution of a field is essentially independent of the distance from the antenna.
General population	Any person not a worker who is likely to be exposed to electromagnetic fields.
Hertz (Hz)	Unit of frequency, i.e., the number of oscillations or cycles of a phenomenon per second (1 hertz is equivalent to one oscillation or one cycle per second).
Magnetic field	Force exerted by a moving electric charge on other electric charges. Magnetic field strength is expressed in amperes per metre (A/m), or more usually, in terms of magnetic flux density, the units of which are the gauss (G) or tesla (T). One T is equivalent to 10,000 G.
Microwaves	Waves with frequencies of approximately 300 MHz–300 GHz.
Modulated wave	Wave defined as either pulsed, amplitude-modulated, frequency-modulated, or phase-modulated when it is modified by pulses or by variations in its amplitude, frequency or phase.
Near field (antenna)	Region between the induction field and the far field, in which radiation fields predominate and the field's angular distribution depends on the distance from the antenna.
Non-ionizing radiation	Electromagnetic radiation and fields that normally do not possess sufficient energy to ionize matter. This radiation has a photon energy of less than 12 electron-volts, a wavelength shorter than 100 nm, and a frequency below 300 tetrahertz.
Prolonged exposure	In animals, exposure during a significant portion of the life span. Its definition therefore varies from case to case, ranging from several weeks to many years.

Short-term exposure	A single exposure lasting between several seconds and 24 hours, or a series of daily exposures of several hours duration each, occurring several times per week.
Thermal effects	Effects in living organisms caused primarily by local heating or by an increase in the temperature of the whole organism.
Wave	Modification of the physical state of a medium that propagates, following a local perturbation.
Wavelength	Distance, in the direction of propagation of a periodic wave, between two successive points in which the oscillation has the same phase.